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Thermodynamic insights and assessment of the ‘circular economy’

Samuel J.G. Cooper [a, *], Jannik Giesekam [b], Geoffrey P. Hammond [a, c], Jonathan B. Norman [a], Anne Owen [b], John G. Rogers [a], Kate Scott [b]

[a] Department of Mechanical Engineering, University of Bath, BA2 7AY, UK
[b] School of Earth and Environment, University of Leeds, LS2 9JT, UK
[c] Institute for Sustainable Energy and Environment, University of Bath, BA2 7AY, UK

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ABSTRACT

This study analyses the effect on energy use of applying a wide range of circular economy approaches. By collating evidence on specific quantifiable approaches and then calculating and analyzing their combined full supply chain impacts through input-output analysis, it provides a more complete assessment of the overall potential scope for energy savings that these approaches might deliver than provided elsewhere. Assessment is conducted globally, across the EU-27 and in the UK.

Overall, the identified opportunities have the potential to save 6%–11% of the energy used to support economic activity, worldwide and in the EU, and 5%–8% in the UK. Their potential is equivalent to the total scope for other industrial energy efficiency savings.

The potential savings are further divided into those due to sets of approaches relating to food waste, steel production, other materials production, product refurbishment, vehicle provision, construction and other equipment manufacture. Each of these sets of approaches can make a key contribution to the total savings that are possible.

Complementary use of energy and exergy metrics illustrates the way in which energy use might change and for the first time provides indication that in most cases other energy efficiency measures are unlikely to be adversely affected by the circular economy approaches.

Potential for savings in the energy embodied in each key product input to each major sector is assessed, enabling prioritization of the areas in which the circular economy approaches have the greatest scope for impact and identification of supply chains for which they are underrepresented.

1. Introduction

1.1. The circular economy

Popularized through the concept of the ‘circular economy’, the potential for resource efficiency to reduce environmental burdens and to increase resilience to resource scarcity is increasingly recognized globally.

The desirability of these approaches was formally recognized by China in 2002 which enacted legislation in 2009 to incentivize and enable them (Mathews and Tan, 2011; Yuan et al., 2006). More recently, the European Commission (2015a, 2015b, 2015c, 2015d) has proposed directives around the theme of promoting the circular economy. These cover a wide range of approaches: ecodesign and production, consumption (e.g. encouraging repair), increased recycling (especially for packaging) along with additional focus on food waste, construction waste, critical raw materials and bio-based materials. The UK government has announced their intention to pursue the economic and environmental benefits of ‘circular economy’ approaches, focusing on waste prevention through measures to encourage product longevity (DEFRA, 2013).

Although commonly framed using the “Reduce, Reuse, Recycle” paradigm (Ghisellini et al., 2014), the Ellen MacArthur Foundation (2013a) has been influential in promoting related presentations such as the ‘power of inner circle’ (expanding the waste hierarchy), ‘circling longer’, enabling cascaded use, and the adoption of pure, benign or easier to separate materials. They cite several additional benefits to these approaches such as increased employment, more effective value capture, mitigating exposure to supply chain and market risks, and the development of customer relationships. The reassignment of material flows is conceptualized in Fig. 1, taken

* Corresponding author.
E-mail address: sjgcooper@bath.edu (S.J.G. Cooper).

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0959-6526/

from Rogers et al. (2015).

1.2. Aims and significance of this study

This study analyzes the energy demand reductions that may be achieved through a range of circular economy opportunities. By analyzing a broad range of approaches within the scope of the UK, EU and globally, the total potential for these opportunities can be assessed and compared to the results of studies investigating conventional energy saving schemes.

The breadth and detail of the collection of circular economy opportunities analyzed make it the most comprehensive collection that the authors are aware of. The use of an input-output based framework enables the effect on embodied energy to be analyzed throughout the full supply chain to an extent not possible in studies based upon simple extrapolation of effects. Complementary energy and exergy metrics (see section 1.3) are used to quantify the magnitude of the potential savings but also provide insights into the effect they may have on other energy efficiency approaches. Novel presentation of the energy embodied in key inter-sectoral product flows is provided, assisting with prioritization of areas for intervention and anticipating the way this may change if circular economy principles are employed.

The complete impacts of each circular economy approach can only be understood with reference to the full supply chain that is affected. This is well appreciated, and addressed in much of the literature that analyses aspects of the circular economy (e.g. Cooper et al., 2016; Neuwahl et al., 2008; Pfaff and Sartorius, 2015; Scott et al., 2009; Walz, 2011) but it is unfortunately lacking from some studies that provide details of the direct implications of approaches. Supply chain effects also relate to the contrast between the international nature of trade and the national scope of environmental regulation (Wiedmann and Barrett, 2013). Only part of the effect of applying circular economy approaches (e.g. a reduction in energy demand) will occur in the region that the approaches are applied in. Conversely, that region will experience some effects from approaches applied elsewhere. These considerations are explored in this study through the use of multi-regional Input Output Analysis (IOA) and by comparing the effect of adopting circular economy approaches with global, EU and UK scopes.

The detail of the implications of circular economy approaches indicates that considering only their savings without their costs or other side effects is likely to significantly overestimate their net benefits (e.g. see Tukker's (2015) review of product service system studies). This is addressed in the present study by integrating an extensive collection of side effects into the modelling framework. This collection is based upon a review of relevant bottom-up studies. As such, the effects can be related to specific technical approaches. This contrasts with the useful and complementary but rather broader results typically associated with the output of an econometric model (e.g. Meyer et al., 2011).

While several studies have investigated individual or limited groups of circular economy approaches in detail (for example Feng et al., 2014; Li, 2012; Yifang, 2007), the present study enables comparison across a broad range of them using a consistent framework and set of assumptions. In particular, the level of application for different circular economy approaches has been harmonized across the range of those studied. In addition to the overall results, the analysis distinguishes the effects of subsets of the opportunities relating to key industries and types of approach.

Note that the aim of this paper is not to define the circular economy or provide a definitive list of approaches that constitute it, but rather to provide indication of the effect that the approaches listed could have and to identify priority areas for change.

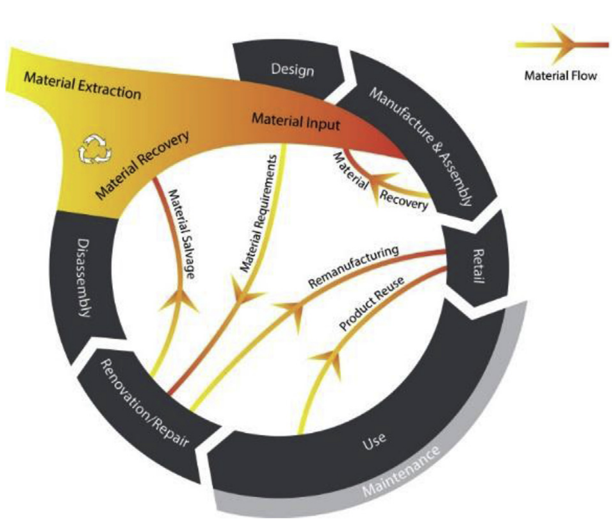

Fig. 1. Material flows in a circular economy (from Rogers et al., 2015).

1.3. Energy and exergy

Two complementary sets of metrics are used to present the results of this analysis: energy extraction and energy dissipation. Considering the extraction of Primary Energy (or "harvesting" in the case of renewables) can provide insights into the effect of demands on upstream impacts.

Considering the dissipation of energy (i.e. the nature by which it leaves the technoeconomic system) can provide insights into the requirements for its use and the scope to change this. For this latter perspective, exergy can be particularly useful. Exergy is equivalent to the energy that is available for conversion to work, it includes a measure of the thermodynamic quality of an energy carrier (Hammond, 2007). As such, exergy can complement energy in the analysis of trends (Serrenho et al., 2014) or in highlighting where there is potential scope for improvement (Cullen and Allwood, 2010; Hammond and Stapleton, 2001).

Energy analysis could be used to determine the split between energy lost to inefficiencies (during either energy transformation or another process) and the remaining energy that is actually used. However, exergy analysis provides additional insight into the destination of the exergy that isn't lost to inefficiencies. Exergy analysis can distinguish between the supply of work (or equivalent exergy as heat) to processes and that which is destroyed due to heat transfers. It also provides quantification of the chemical exergy content of materials produced (see Fig. 2). The significance of these additional characterisations lies in the fact that different energy (or exergy) efficiency strategies are applicable to each. Changing their relative significance is likely to affect the overall potential for these energy efficiency strategies:

- Chemical exergy of materials can only be reduced by decreasing the output of that material.
- Exergy dissipated by processes can be reduced by decreasing the need for them (e.g. through substituting other processes or ensuring that they only occur when necessary).
- There may be additional options to reduce the exergy destroyed in the provision of finite temperature heat (e.g. through technological options, process substitution or better matching of heat demands and sources).
- Exergy lost due to inefficiencies can generally be minimized through technological options such as improved equipment.

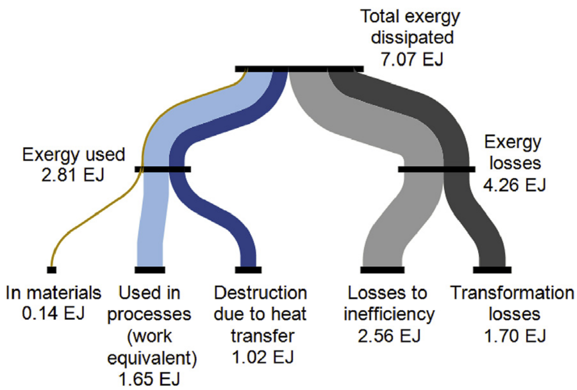

Fig. 2. Categorization of industrial exergy use (figures relate to UK industry, 2007).

In general, these options also cascade; that is, reducing the energy dissipated in processes will also reduce energy lost due to inefficiency (as less is demanded) but not vice-versa.

While the effect of the circular economy approaches on the total energy dissipation is important, the use of exergy to elaborate on how this occurs will provide insights regarding the scope for secondary impacts on other energy efficiency strategies.

1.4. Scope of circular economy approaches considered

This analysis focusses upon the industrial energy use associated with the production of goods and services. The effect of circular economy approaches on the in-use impacts associated with goods may also be significant (Bakker et al., 2014; Gutowski et al., 2011; Rogers et al., 2015) but is excluded from consideration here to ensure that the effects are not conflated.

This analysis is intended to identify the effect of adopting the identified circular economy opportunities against baseline data for 2007. In the time required to apply these approaches, it is likely that other trends would continue and have additional effects on energy demand. However, in order to clearly identify the changes relating to the circular economy opportunities, these trends are excluded from consideration. Unlike Scott et al. (2009) or Wilting et al. (2008) this analysis does not apply exogenous changes to the size or structure of the economy relating to future growth or other changes apart from the circular economy approaches (though see section 2.4, below). The energy efficiency of individual processes is kept constant. Where results relate to changes in average energy efficiency, these changes therefore reflect changes in the structure of economic activity rather than changes in the energy efficiency of individual processes.

A general philosophy of the modelling assumptions used in this study is that the way the opportunities are adopted should not affect the level of utility supplied to consumers. That is, approaches that would reduce consumption are either amended to ensure that the utility supplied is maintained or excluded from consideration if that is not feasible. Where possible, the changes required on the part of consumers are minimized. For example, an increase in the reuse of consumer products is assumed to take place through the increased activity of a business that resells the products rather than via an increase in peer to peer arrangements.

Finally, the study includes circular economy approaches that can be identified in the literature with some evidence to support quantification of their effects. This is a conservative approach. A relatively small group of approaches were excluded because no reasonable estimation of their effect could be made. It is possible that a larger group of opportunities have not yet been identified but might still contribute to resource efficiency in the future; the potential effect of these approaches is also excluded from consideration. In this respect, the analysis reported here should strictly be understood to reflect the modelled effect of the circular economy approaches that are summarized in Table 1 and detailed in Supplementary Information C: "Circular economy approaches"; it should not be considered to be a definition of "The Circular Economy", nor a comprehensive listing of other approaches that might be or become available.

2. Method

2.1. Overview

The analysis for this study required two steps. Firstly, information about the circular economy approaches that can be identified and quantified was gathered from the literature. The full supply chain effect of adopting these approaches was then assessed using a modelling framework based upon input-output analysis. These two steps are described in the following two subsections before a further two subsections address the treatment of economic and rebound effects and the derivation of exergy based metrics.

2.2. Circular economy approaches

Information on circular economy approaches that have been suggested was gathered from the literature. Where possible, this included quantitative estimates of the savings that can be made and the secondary impacts (e.g. increased labor requirements) of the approaches. A detailed list of the approaches with supporting references is provided in Supplementary Information C: "Circular Economy Approaches" and they are summarized in Table 1.

For the purposes of this study, the approaches were considered under two general types: those that reduce the need for specific inputs into industries ("putting less in") and those that reduce demand for the output of industries ("getting more out"). These are similar to categorizations used elsewhere (e.g. European Commission, 2015d; Allwood et al., 2012; Ellen MacArthur Foundation, 2013b) but should not be considered definitive; in some instances there is a case to recategorize them (e.g. reuse of materials could be thought of as "putting less in", especially when occurring onsite). The distinction between different levels of refurbishment to enable reuse can vary and involve other approaches such as improved longevity. It should also be noted that while approaches such as repair are being categorized as life extension type options, much of the activity to facilitate them may occur elsewhere (e.g. at the design stage and in planning to ensure the availability of spares).

In addition to the primary change caused by the approach (e.g. a reduction in the demand for new electrical equipment when refurbishment is increased), where possible the additional changes caused by the approach have also been included (e.g. an increase in collection services to facilitate the refurbishment, a reduction in the requirement to treat waste). The specific details and assumptions relating to each approach are listed in Supplementary Information C: "Circular Economy Approaches".

In several cases, data specific to different regions was available whereas for others global averages were used. The use of region specific data in the modelling framework also enabled changes to be implemented in proportion to the regional distribution of production or consumption as appropriate. For example, this enabled the effect on steel recycling of the decreased availability of scrap metal due to improved fabrication yields to be distributed regionally according to current recycling activity, rather than according to the geographic distribution of the improved fabrication yields that

Table 1
Categorization and examples of circular economy approaches.

Categorization	Examples
Putting less in: Reducing the need for (high impact) inputs to produce products.	
Reducing material content of products (16)	Optimised shapes (e.g. concrete beams designed to resist bending moments where they occur rather than uniform cross section) More careful design (e.g. not over-specifying) More effective materials (e.g. stronger steel)
Reducing losses of material throughout supply chain (13)	Improving material production forming yields (e.g. proportion of steel supplied as steel products compared to total steel produced) Improving manufacturing yield (e.g. better tessellation of patterns)
Encouraging/enhancing recycling (6)	More careful selection of materials - e.g. reducing toxins and hard to separate plastics.
Material substitution (3)	Timber construction. Note that the scope for material substitution is only minimally assessed (i.e. in construction) in this analysis.
Getting more out: Reducing need for products	
More intensive use (6)	Sharing schemes Optimising scheduling of use (e.g. transport, machinery) Reduced wastage (at point of use)
Longevity (8)	Encouraging continued use/less discarding of functional items More durable design
Life extension (21)	Reuse of products with minimal processing Refurbishing (range of levels up to full remanufacture). Retrofit (e.g. of buildings – extensive refurbishment in which primary use of the product changes) Reuse of components (e.g. steel beams)

(Numbers in parentheses represent the number of specific approaches modelled under each category in this study.).
Note that approaches that improve the value represented by materials (e.g. improvements in the performance of computers) can improve resource productivity but for the purpose of this study are not considered typical of circular economy principles and are not included.

dictate the overall size of the effect.

The potential effect of each approach upon the relevant intersectoral flow was modelled as the product of three factors: the proportion of the flow that it relates to, the relative change that it causes and the level of adoption that might be achieved. For example, the lightweighting of cars will reduce the flow of steel into the motor vehicle sector. Relative to this flow, the direct reduction will be the product of the proportion of the flow that relates to cars (i.e. rather than other motor vehicles), the proportional lightweighting that can be achieved (e.g. the steel per car might be reduced by 10%) and the extent to which this approach is adopted (e.g. the lightweighting might be adopted across 60% of car manufacturing).

A variety of barriers may limit the actual uptake of circular economy approaches (Shahbazi et al., 2016). In this study, an intermediate and advanced level of adoption were considered. Many of the literature sources indicate reasonable estimates of these. In other cases, the factors were standardized at 30% and 60% for the “intermediate” and “advanced” levels of adoption, respectively. A third “maximum technical potential” level was considered in order to provide comparison to other studies in which effects are reported assuming full adoption of the approach; however, this should not be taken to indicate that the technical potential is actually realizable. In some cases, the potential level of adoption will depend upon further factors (for example, an increase in recycling is relative to that already taking place). Supplementary Information C: “Circular economy approaches” details the factors the factors that have been used for each of these proportions and provides additional notes specific to them.

2.3. Modifying input-output table

The effects of these approaches were modelled by modifying an input-output table (IOT) and determining the resultant change in the energy consumption of each sector. Input-output tables record the use of outputs from each economic sector (in this case, in monetary terms) as inputs to each sector and to satisfy demand by consumers and governments. By assuming a linear relationship between the total output of each sector and its inputs, analysis of the IOT can reveal the total (i.e. full supply chain) impact of a change in demand for a product or service (Miller and Blair, 2009).

The method of modifying an IOT to model similar technological changes has been used extensively elsewhere (e.g. Rose, 1984; Walz, 2011; Malik et al., 2014; Scott et al., 2009; Pfaff and Sartorius, 2015; S. Cooper et al., 2016). Walz (2011) argues that the benefit of high sectoral disaggregation offered by IOT's outweighs the benefit of capturing additional phenomenon (e.g. substitution elasticity) in alternatives such as computable general equilibrium models. This is particularly the case given that the modifications largely relate to exogenously defined innovations in the “production recipe” of industries; that is, the key contribution of the IOT is to ensure that the upstream impacts of the approaches are captured in a hypothetical scenario in which they are applied, it is not to fully model the economic effect of doing so. If analysis needs to investigate the effect of prices or similar drivers in achieving a level of change then partial equilibrium models will be more appropriate (Bouman et al., 2000 discuss their relative merits) but have far greater data requirements to achieve the same level of sectoral or geographic coverage. Alternatively, econometric modelling (see, for example Meyer et al. (2011)) can be used to analyze macro level effects such as economic growth but will not typically relate these effects to the specific technical approaches by which the resource efficiency might be achieved.

The general method used fits within Rose's (1984) definitions of ‘process analysis type’ methodology for ‘innovation based’ technical change. That is, the evidence describing the circular economy approaches is used to determine the changes to the production recipe of industries that may occur. Malik et al. (2014) note that these changes will result in an ‘unbalanced’ table of intersectoral flows (i.e. the tabulated production of industries will not match the tabulated demand for their products). However, a new vector of the total output from each sector that will result in a balanced table can be determined using Leontief's inversion method (detailed, for example, by Miller and Blair, 2009).

The Multiregional Supply-Use format tables for 2007 created by the Exiobase project (Tukker et al., 2013; Wood et al., 2014) were used. These provide a high level of sector disaggregation, especially relating to relevant industries such as individual recycling sectors for key materials. The Supply-Use format allows for greater flexibility in modelling different types of circular economy approaches. The consistent sector definitions facilitate the numerous changes relating to the circular economy approaches across each region.

Approaches that reduce the demand for a product can be modelled by reducing the demand for that product by other industries or by reducing the inputs into the industry that produces it. In most cases, the former method is appropriate. However, in cases for which the reduction in demand is due to activity organized by the producing sector, the latter was used. For example, if the refurbishment of a product would be arranged by the industry that produces it (such that it is functionally invisible to the users of it), this has been modelled through changes to the production recipe of that industry rather than changes in the products and services supplied to the users of the product.

Some approaches have the potential to conflict with one another. Where appropriate estimates are available in the literature, this was dealt with by discounting the potential saving that can occur (notably, Waugh (2013) provides separate estimates of steel savings that can be achieved by individual approaches when they are used alone and used together). In cases in which a waste stream feeds directly into recycling (Milford et al. (2011) provide the example of steel yield losses within the steel mill), reducing these losses is generally desirable but it will have the effect of reducing the need to recycle that material rather than reducing primary inputs. This was resolved in the present work by ensuring that the reduction in the demand for the secondary material was scaled in proportion to the scope for improvement in the total material production (redistributed in proportion to the geographic distribution of current relevant sectoral activity).

Because of the extensive and varied nature of the collection of approaches, care was needed in order to ensure that their combined effects were appropriately handled. For example, approaches that affect different subsets of flows are additive (e.g. lightweighting steel structures and steel rebar in construction) while approaches that affect the same flows are generally multiplicative (e.g. lightweighting steel structures and using less steel structures). To assist with this, changes were implemented by substituting proportions of existing flows in the IOT, rather than by using the "augmenting" approach used by researchers such as Malik et al. (2014).

2.4. Economic and rebound considerations

This subsection describes the treatment of prices (relating to both the gross value added (GVA) of sectors and to resold products) and the treatment of gross domestic product (GDP) in this study. The effect of this treatment on the rebound effects that are captured is discussed.

A circular economy approach that reduces the volume of material used by an industry is likely to reduce the cost of these inputs while also increasing the GVA of that industry. Part of this increase will be due to the increased labor requirements associated with many of the approaches (e.g. to enable sharing schemes, refurbish goods or create more careful designs). Part of it will be associated with the additional capital requirements to enable the circular economy approaches to be taken. It is also possible that the profit made and the tax paid (or subsidy received) by the industry will be affected.

In this study, it was assumed that the profit and net tax components of GVA will be adjusted such that the decreases in costs associated with inputs would be matched by increases in the GVA of that industry, resulting in consistent prices. This is consistent with comparable studies (e.g. Scott et al., 2009; Walz, 2011) and can be justified on the basis that an increase in prices would not be attractive and therefore likely to require some form of subsidy (decreasing the net GVA) whereas a decrease in costs could lead to increased profitability until the approach is applied universally. Walz and Schleich (2009) provide further discussion of this. Azid et al. (2007) and Wilting et al. (2008) point out that in a sector with heterogeneous production recipes, prices may be set by the highest cost manufacturer that is required in order to satisfy demand.

In approaches involving the reuse or refurbishment of consumer products, the refurbished product substitutes some of the demand for the new product. Typically, the price of refurbished goods is less than their new price. Some studies have assumed the potential for 1:1 substitution of goods, i.e. each refurbished unit substitutes for one new unit. Here, it was assumed that the substitution is made on a price basis, i.e. if the refurbished units sell for half the price, they only substitute half as many new units. This modelling decision was based on the principle that the lower price must reflect some lower utility in the refurbished units (perhaps lower expected life or lower performance – consumers might need to buy more of the refurbished product or might buy it instead of a lower class new product (Van Weelden et al., 2015)). Neither assumption will fully capture the market response to the introduction of refurbished goods but making substitutions on a price basis will reduce their direct effect (as less of the original product is substituted) while also removing direct rebound effects due to the additional consumer spending that would otherwise occur.

GDP was defined exogenously in this study (in common with most IOA based studies). In contrast to studies such as those by Scott et al. (2009) and Wilting et al. (2008), GDP was kept constant. Econometric trends were not considered so that the effects reported are of the circular economy approaches and are not conflated with other effects such as increased consumption. Alongside the treatment of prices outlined above, this means that the distribution of final demand is also kept constant and so there is no direct rebound effect due to reallocation of spending. This is an assumption – approaches that require subsidies or that increase profits are likely to change GDP. Pfaff and Sartorius (2015) explore this issue in more detail for specific examples of material efficiency in Germany. Their use of complete process data for 16 material efficiency approaches enabled them to predict an increase in economic activity (i.e. consistent with the argument above) and calculate the resultant economy scale rebound effect. However, the evidence of the overall costs of applying the wider set of circular economy approaches proposed in the literature is currently insufficient to have confidence in the direction of this overall effect.

The reduced demand for intermediate products (i.e. by industries adopting circular economy approaches) may decrease the prices of those products. This change is different to that covered by the assumptions listed above. The related indirect rebound effect was therefore not captured by the method used and is considered beyond the scope of the present study. The price reduction may also correspond to a change in the aggregate production recipe of the industries for which demand is reduced as the change in output may disproportionately affect certain parts (e.g. less productive plant). This effect is also beyond the scope of the present study but could be the subject of productive study as it may enhance the effect of the circular economy approaches.

2.5. Exergy extension data

To create the exergy extensions table, the energy uses and factors provided by Serrenho et al. (2014) were converted to a format consistent with the energy carrier and sector definitions of the energy extension data included with the Exiobase dataset. The method suggested by Serrenho et al. (2014) was followed with minor variations. Additional ambient temperature data was used for the regions that they did not consider. The temperature of some processes could be refined due to the increased level of disaggregation available (e.g. cement rather than non-metallic minerals). The chemical exergy content of some key materials was determined as the product of their production (United Nations Statistics Division, n.d.) and the specific exergy of those materials (data from Assari et al., 2014; Ayres et al., 2006; Dewulf and Van Langenhove, 2004; Lucia and De Manfrida, 1990; Van Gool, 1998). Details of the factors and proportions used to create the exergy extensions are provided in Supplementary Information B: "Exergy extension method", enabling the process to be repeated.

3. Results & discussion

Circular economy approaches have the potential to save energy (Fig. 3). Applying them globally could reduce the global demand for Primary Energy (PE) by around 5%–9%, with similar reductions in the EU and slightly lower reductions in the UK (4%–6%). For comparison, this is similar to the 5%–8% reduction in PE use that global industrial energy efficiency has the potential to achieve (International Energy Agency, 2007). The equivalent reductions in the exergy dissipated due to economic activity (6%–11% globally and in the EU, 5%–8% in the UK) are also similar to the savings that are possible through energy efficiency; the World Energy Council (2013) suggests that cost effective savings are possible that are equivalent to 7%, 6% or 5% of the industrial exergy dissipation due to global, EU or UK economic activity respectively.

The differences between the regional results in PE extraction are primarily due to their different roles in PE extraction whereas the differences between the regional results for exergy dissipation are primarily due to different levels of exposure to the effects of the circular economy approaches. These results relate to 2007; changes have occurred since then and some of the approaches have already been applied to a lesser extent. The majority of the differences between the global PE and corresponding exergy results that are presented as percentages is due to the use of different denominators; PE is expressed relative to total PE use whereas exergy is expressed relative to exergy dissipation in economic activity only.

The results of this study are, of course, sensitive to the level of adoption of the circular economy approaches adopted. As much of the evidence for the effects of these approaches relates to marginal changes, additional studies that consider the effect of scaling them up would be a welcome addition to the literature. It should be remembered that these results relate to the set of approaches that have been identified (see sections 1.4 and 2.2); it is possible that other approaches either exist or will be developed.

Fig. 4 breaks down the savings that could be achieved through different subsets of approaches. Where approaches were already used (e.g. recycling), these savings are the potential result of increases in the level of application (i.e. the saving due to an increase in recycling, excluding the saving that was already made by it). Applied at the EU level, approaches that 'get more out' have roughly the same potential as those that 'put less in'. However, the approaches associated with 'getting more out' have greater potential than those associated with 'putting less in' when applied to the UK. This partially reflects the relatively high proportion of imported products that are consumed in the UK but also that relatively fewer of the products manufactured in the UK are suited to the 'putting less in' approaches.

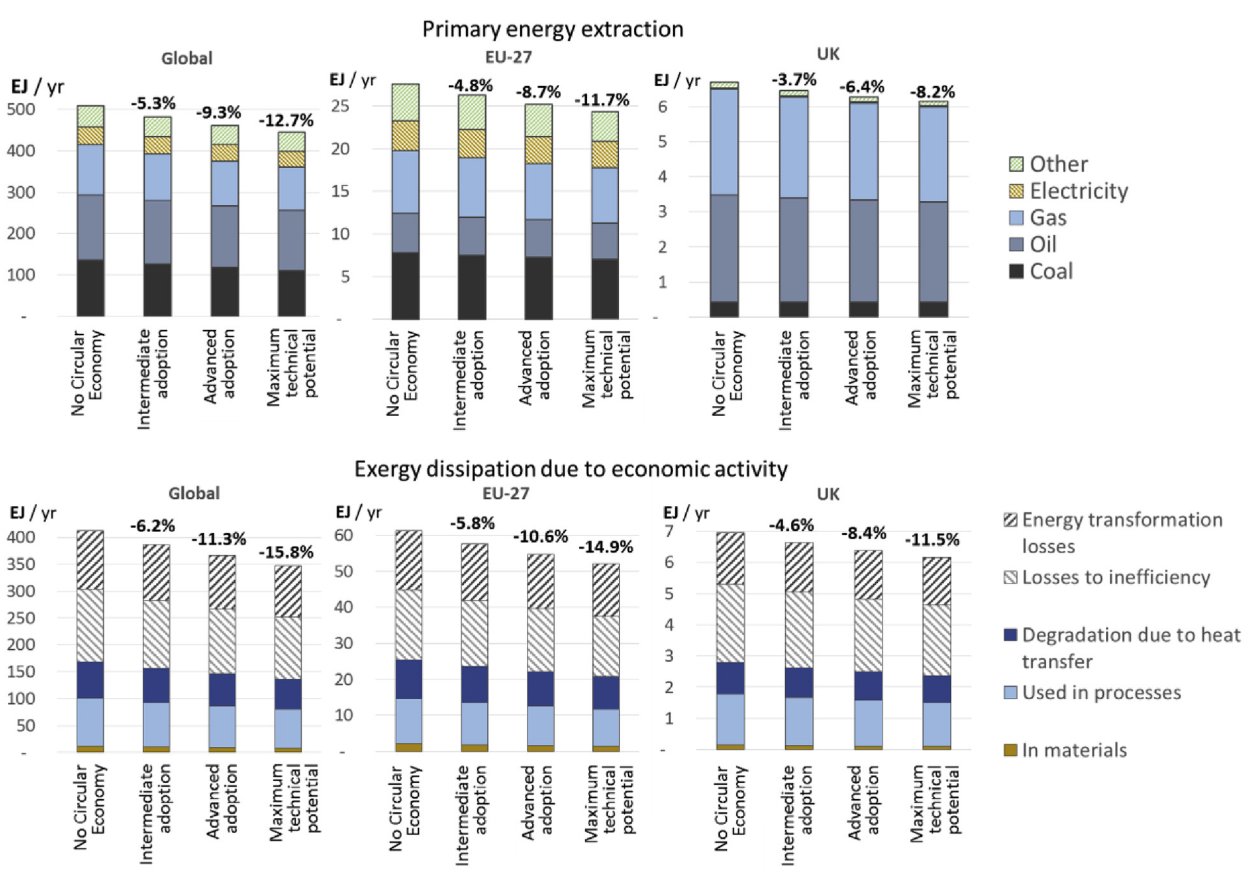

Fig. 3. Results of circular economy approaches applied globally on energy extraction and exergy dissipation.

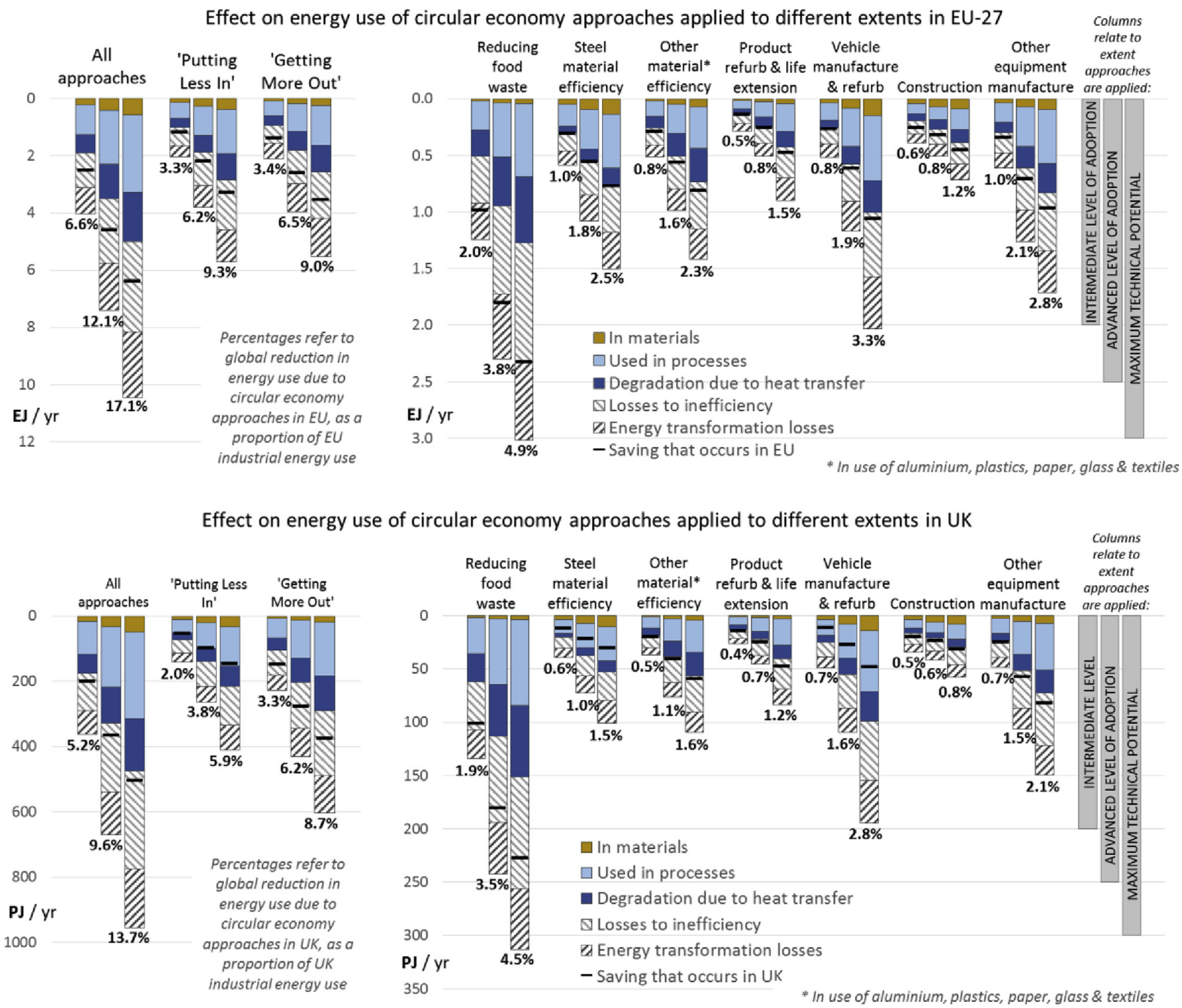

Fig. 4. Reduction in energy use possible through different subsets of circular economy approaches.

Overall, around half of the reduction in energy use that could be achieved by measures in the EU or UK occurs within each region, but underlying this are some differences. Excluding food waste, the proportion of savings that are 'local' in the EU is greater than in the UK. This reflects the greater extent to which trade is internal to the EU (relative to the UK) and underlies the importance of applying the approaches as widely as possible if the energy savings are to be felt by the group applying them.

The results relating to steel material efficiency include approaches such as reducing yield losses in forming. The widespread use of steel in construction, vehicles and other goods means that total potential savings that could be associated with steel are higher (i.e. those savings are included within the results relating to other sectors, not in the 'steel results' in Fig. 4). The relative prominence of the 'reducing food waste' approaches relates primarily to their broad applicability (e.g. in contrast to construction based approaches that often focus on specific types of construction). It should be noted that some of the potential reductions in food waste in the UK have already been achieved. For each group of circular economy approaches, the potential energy saving is highly dependent upon the extent to which the approaches are applied. It should be noted that the large 'maximum technical application' savings are not considered realistic and are included in order to provide comparison with other studies. Care should be taken when interpreting results from studies that rely on extrapolating approaches to similarly large proportions of the products available.

Fig. 5 shows the sectors in which energy is dissipated in order to support the production of steel, the manufacture of electrical products & equipment, and in construction. It also differentiates the ways in which the energy is dissipated (e.g. as losses due to inefficiency or as the service such as mechanical work that is used in processes). It illustrates the sectors in which energy efficiency measures have the greatest scope to affect the total (direct and embodied) energy use associated with those products. In the figure, energy dissipated in the electricity sector relates to that leaving the system due to generation (e.g. losses) while the dissipation of the electricity is included under the sectors that use it. The electricity is both used directly in the producing sector and it is embodied in goods supplied to it. The energy associated with products used as an input to their own production has been removed from the appropriate embodied energy column to avoid double counting with the direct energy use column.

The energy dissipated directly (and due to electricity generation) is relatively high for the production of materials such as steel.

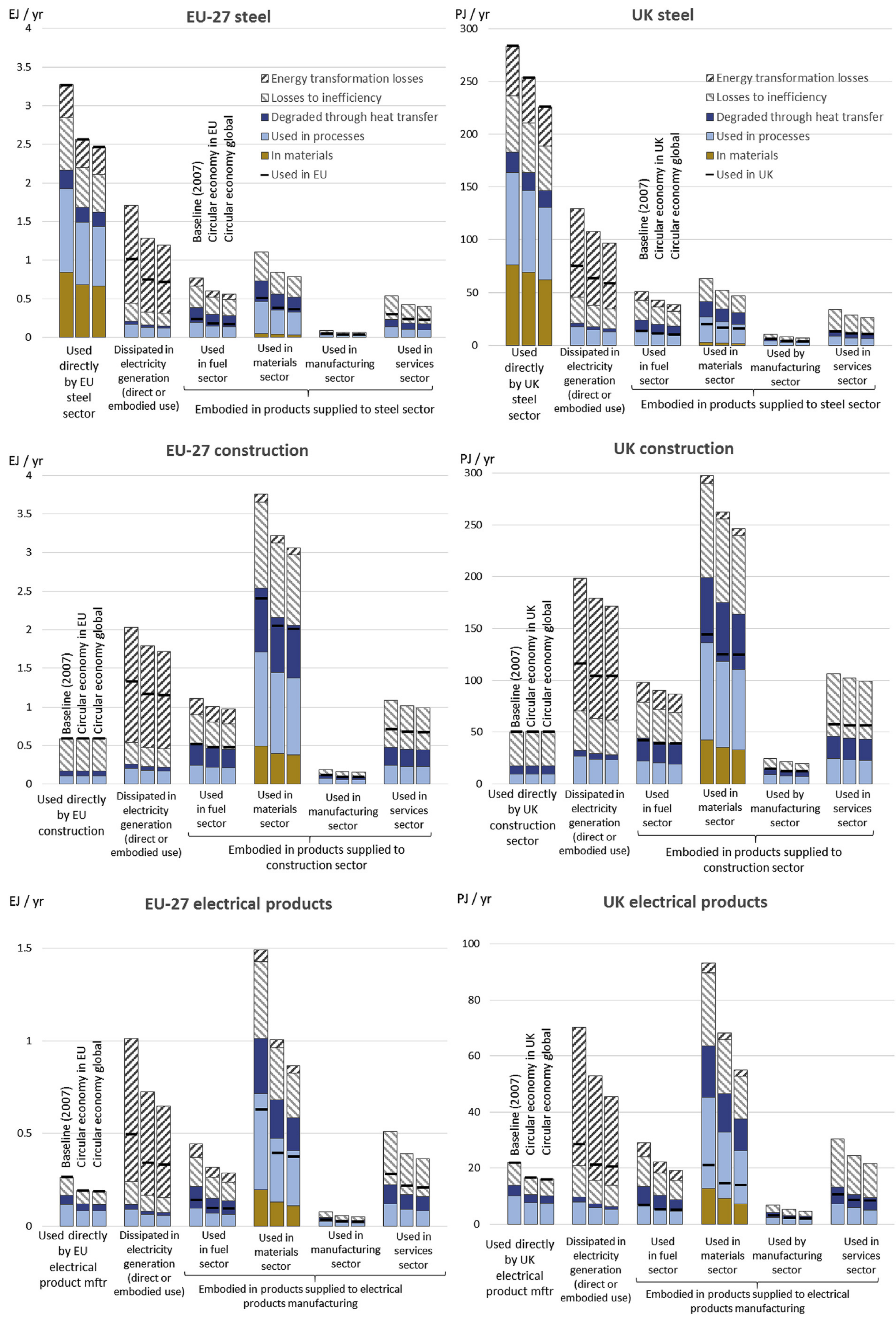

Fig. 5. How and in which sectors, energy is dissipated in order to support activity in selected industries.

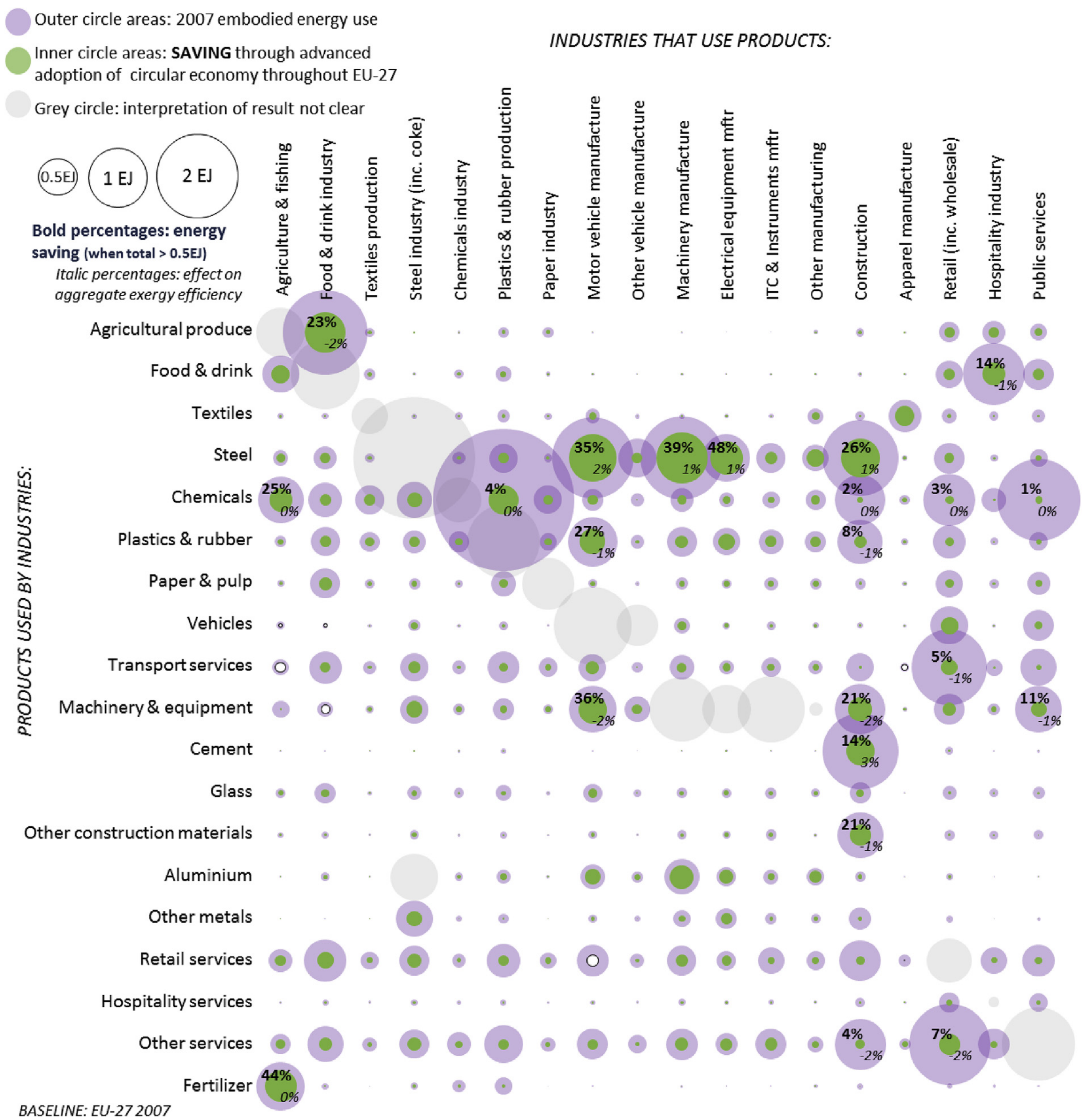

Fig. 6. Potential effect of circular economy approaches applied in the EU on energy use embodied in inputs to EU industries.

It is also subject to the largest savings when the circular economy approaches are applied. The materials sector is the largest source of energy dissipation relating to activity in the electrical equipment manufacture and construction sectors. The circular economy approaches have their greatest effect on this source of energy dissipation and relatively little effect on the energy directly dissipated by these sectors. This means that the scope for additional energy efficiency measures targeting these sectors is relatively unaffected.

Extending the geographic scope in which the approaches are applied to global (from either UK or EU) tends to reduce the energy dissipation embodied in materials (as many of these are imported into the regions) but has relatively little effect on the direct energy dissipation caused (apart from the case of UK steel production which was significantly exported).

Figs. 6 and 7 illustrate the total (full supply chain) energy use that is embodied in the flow of key products into industries in the EU and UK respectively. For example, the area of the circle just right of the top left corner in Fig. 6 indicates that around 2 EJ/yr are embodied in the flow of agricultural produce into the EU food and drink industry. The inner circles reflect the reduction that circular economy approaches (with intermediate level of adoption) could achieve (i.e. the area of the inner circle is the saving possible, not the resulting embodied energy). The interpretation of results relating to flows of products into the industry that produces them is less clear as it may relate to energy embodied in products for resale rather than actual production inputs, these results are therefore greyed out.

The potential savings are for complete supply chains, they relate to the combination of: a reduction in the need for that input, a reduction in the output/overall activity of that industry and a reduction in the upstream requirements for that input. For example, the potential reduction in the energy embodied in

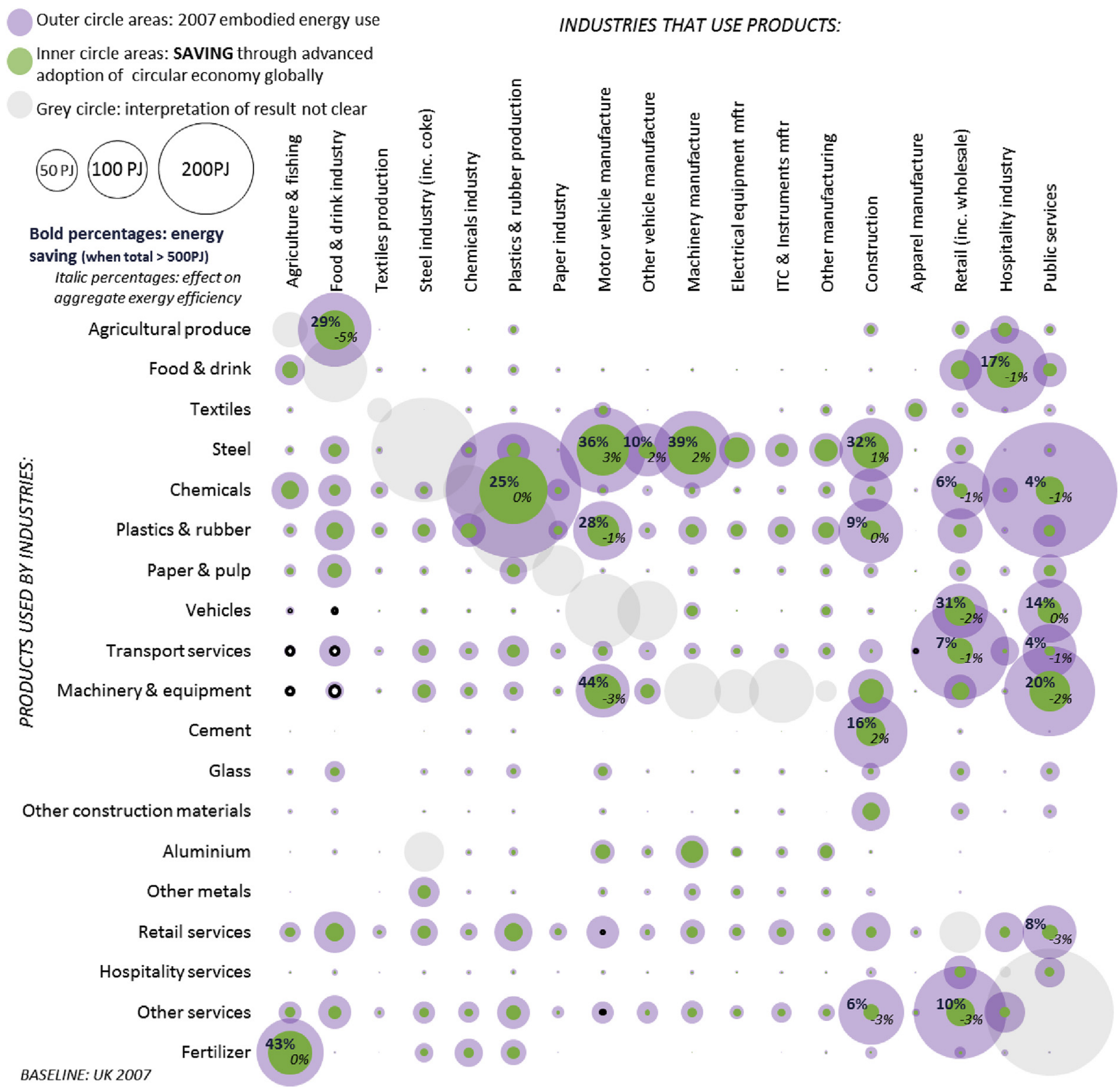

Fig. 7. Potential effect of circular economy approaches applied globally on energy use embodied in inputs to UK industries.

agricultural produce used by the food and drink industry relates to a reduction in the losses of agricultural produce by the food and drink industry, a reduction in the demand for food and drink (i.e. through reduced wastage by consumers and the hospitality sector) and a reduction in the input of fertilizer to create the agricultural produce.

While the savings in Fig. 6 relate to circular economy approaches applied in the EU, those in Fig. 7 relate to approaches applied globally. In most cases, the proportional savings that are possible are similar. However, the proportional saving in the flow of chemicals into the plastics sectors (mainly influenced by overall demand for primary plastics) is far greater when the relevant approaches are applied globally – reflecting that much of the energy embodied in the use of plastic to support EU activity is used outside of the EU.

Savings are possible in most of the major flows associated with steel, food & drink, plastics and construction. However, there are some flows that embody large quantities of energy use but are relatively unaffected. These are attractive avenues for future research. The use of transport services by the retail & wholesale sectors and the use of chemicals by public services are particularly interesting (though it should be noted that the large flow indicated for the flow of chemicals into public services might also reflect the aggregation between pharmaceuticals and other chemicals in the Exiobase IO data).

There are many intersectoral flows that embody large quantities of energy. The potential savings that can be encouraged by interventions is greater if they are sufficiently broad reaching to affect several of these flows. For example, there is a significant quantity of energy embodied in the flow of steel into many industries so an intervention that can affect all of these has greater scope than an intervention that focusses on only one of them. Figs. 6 and 7 illustrate that in some cases groupings of intersectoral flows that embody large amounts of energy can be formed down columns (i.e. relating to industries such as construction that uses products), whereas in other cases the groupings can be made across rows (i.e. relating to industries such as steel that supply products to many industries). It is important that interventions are targeted at appropriate industries on both sides of the supply-use relationship. Where there is an intersectoral flow that embodies a large quantity of energy but relatively little in the flows of that product into other industries and of other products into that industry (e.g. the flow of agricultural produce into the food and drink industry or the flow of chemicals into the plastics and rubber production industry) then it is feasible that interventions with large scope for savings could be designed to influence from either direction; it is likely that the suppliers and users of the product will exhibit significant interaction already.

Average exergy efficiency tends to go down slightly (by around one percentage point) when the circular economy approaches are applied. This is not due to the energy efficiency of processes changing (this is exogenous and kept constant in this study) but, rather, that the demand for processes that are already energy efficient is reduced slightly more than the demand for other processes. This implies that the circular economy approaches are unlikely to make additional energy savings disproportionately harder to achieve (assuming that those processes with higher energy efficiency have less improvement potential).

4. Conclusions

The identified circular economy approaches have the potential to reduce the global energy use relating to economic activity by 6%–11%. For context, this energy saving is slightly greater than the International Energy Agency (2007) assessment of the scope for industrial energy efficiency savings (5%–8%).

The majority of these savings are embodied in the input of goods and services to other industries and to the final demand of consumers and government. In contrast, studies that have focusing on only the direct energy implications of the circular economy approaches are likely to have significantly underestimated the potential savings.

For many industries, the use of materials embodies the greatest use of energy. However, the upstream energy demands for the processing of fuel and the additional service based inputs into industry also embody significant energy use. Circular economy approaches have the potential to reduce this embodied energy but their effect is greatest for material inputs.

The high level of energy embodied in goods and services that are traded internationally means that much of the reduction in energy use that results from applying circular economy approaches will occur outside of the region in which they are applied. Similarly, the energy demand due to exports from a region is likely to decrease due to circular economy approaches applied elsewhere. In order for the benefit of reduced energy demand to be maximized, measures to encourage the adoption of circular economy approaches should be applied widely and consistently; reflecting the international nature of supply chains.

The actual approaches are varied in their nature and their scope. In general, the approaches exhibiting the greatest potential energy savings are those that can either be applied broadly or relate to relatively concentrated flows of goods or services. For example, some options to reduce food waste can be applied to a large proportion of the existing food waste whereas some of the options to improve resource efficiency in manufacturing or construction are specific to particular processes. This does not negate the value of the approaches that are specific but indicates that policies with broad applicability may have greater scope to facilitate change. Broad groups of the approaches with potential energy savings can be associated with both key users of goods (e.g. construction, retail, public services) and with some of the key materials that are supplied. Measures to encourage the uptake of circular economy approaches should therefore target both sides of the supply relationship, according to where the greatest potential lies. The importance of key materials and products observed elsewhere (e.g. by Allwood et al., 2012) is supported by the analysis in this study. Additionally, investigation into the use of transport services by the retail and wholesale sectors and into the use of chemicals and pharmaceuticals by public services would be worthwhile additions to the circular economy literature. Within the UK there is greater overall scope for energy savings through approaches that reduce consumption than through those that make production more resource efficient. However, the potential for each type of approach is significant.

The circular economy approaches tend to reduce demand for energy efficient processes slightly more than those with low energy efficiency. Therefore, from an overall perspective, the circular economy approaches are unlikely to make further energy efficiency savings disproportionately harder to achieve.

Circular economy approaches have the potential to make significant energy savings that are complementary to other energy efficiency measures and equivalent to their potential. In addition to their other benefits, they can be considered an important option in the task of reducing energy demand.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.jclepro.2017.06.169.

References

Allwood, J.M., Cullen, J.M., Carruth, M.A., Cooper, D.R., McBrien, M., Milford, R.L., Moynihan, M.C., Patel, A.C., 2012. Sustainable Materials with Both Open Eyes. Cambridge University Press, Cambridge, UK.

Assari, M., Basirat, T., Najafpour, E., Ahmadi, A., Jafari, I., 2014. Exergy modeling and performance evaluation of pulp and paper production process of bagasse, a case study. Therm. Sci. 18, 1399–1412. http://dx.doi.org/10.2298/TSCI110715141A.

Ayres, R.U., Ayres, L.W., Masini, A., 2006. An application of exergy accounting to five basic metal industries. In: Sustainable Metals Management. Springer, Netherlands, pp. 141–194.

Azid, T., Anwar, M., Khawaja, M.J., 2007. Management of energy recourses, marginal input- output coefficients, and layers of techniques: a case study of US chemical industry. Pak. Dev. Rev. 46, 517–536.

Bakker, C., Wang, F., Huisman, J., Den Hollander, M., 2014. Products that go round: exploring product life extension through design. J. Clean. Prod. 69, 10–16. http://dx.doi.org/10.1016/j.jclepro.2014.01.028.

Bouman, M., Heijungs, R., Van Der Voet, E., van den Bergh, J.C.J.M., Huppes, G., 2000. Material flows and economic models: an analytical comparison of SFA, LCA and partial equilibrium models. Ecol. Econ. 32, 195–216.

Cooper, S., Skelton, A., Owen, A., Densley Tingley, D., Allwood, J., 2016. A multi-method approach for analysing the potential employment impacts of material efficiency. Resour. Conserv. Recycl 109, 54–66. http://dx.doi.org/10.1016/j.resconrec.2015.11.014.

Cullen, J.M., Allwood, J.M., 2010. Theoretical efficiency limits for energy conversion

devices. Energy 35, 2059–2069. http://dx.doi.org/10.1016/j.energy.2010.01.024.
DEFRA, 2013. Prevention Is Better than Cure. The Role of Waste Prevention in Moving to a More Resource Efficient Economy. HM Government, London, UK.
Dewulf, J., Van Langenhove, H., 2004. Thermodynamic optimization of the life cycle of plastics by exergy analysis. Int. J. Energy Res. 28, 969–976. http://dx.doi.org/10.1002/er.1007.
Ellen MacArthur Foundation, 2013a. Towards the Circular Economy, 1: Economic and Business Rationale for an Accelerated Transisiton. Ellen MacArthur Foundation, Cowes, UK.
Ellen MacArthur Foundation, 2013b. Towards the Circular Economy, 2: Opportunities for the Consumer Goods Sector. Ellen MacArthur Foundation, Cowes, UK.
European Commission, 2015a. Proposal for a Directive of the European Parliament and of the Council Amending Directive 2008/98/EC on Waste. European Commission, Brussels, Belgium.
European Commission, 2015b. Proposal of a Directive of the European Parliament and of the Council Amending Directive 94/62/EC on Packaging and Packaging Waste. European Commission, Brussels, Belgium.
European Commission, 2015c. Proposal for a Directive of the European Parliament and of the Council Amending Directive 1999/31/EC on the Landfill of Waste. European Commission, Brussels, Belgium.
European Commission, 2015d. Closing the Loop - an EU Action Plan for the Circular Economy. European Commission, Brussels, Belgium.
Feng, Y., Tian, Y., Zhu, Q., 2014. A combined input-output/decision making trial and evaluation laboratory method for evaluating effect of the remanufacturing sector development. J. Clean. Prod. 114, 103–113. http://dx.doi.org/10.1016/j.jclepro.2014.10.048.
Ghisellini, P., Cialani, C., Ulgiati, S., 2014. A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems. J. Clean. Prod. 114, 11–32. http://dx.doi.org/10.1016/j.jclepro.2015.09.007.
Gutowski, T.G., Sahni, S., Boustani, A., Graves, S.C., 2011. Remanufacturing and energy savings. Environ. Sci. Technol. 45, 4540–4547. http://dx.doi.org/10.1021/es102598b.
Hammond, G.P., 2007. Industrial energy analysis, thermodynamics and sustainability. Appl. Energy 84, 675–700. http://dx.doi.org/10.1016/j.apenergy.2007.01.002.
Hammond, G.P., Stapleton, A.J., 2001. Exergy analysis of the United Kingdom energy system. Proc. Inst. Mech. Eng. Part A J. Power Energy 215, 141–162. http://dx.doi.org/10.1243/0957650011538424.
International Energy Agency, 2007. Tracking Industrial Energy Efficiency and CO_2 Emissions. International Energy Agency, Paris.
Li, S., 2012. The research on quantitative evaluation of circular economy based on waste input-output analysis. Proced. Environ. Sci. 12, 65–71. http://dx.doi.org/10.1016/j.proenv.2012.01.248.
Lucia, M., De Manfrida, G., 1990. Breakdown of the exergy balance in a glass furnace. Trans. ASME 112, 124–129.
Malik, A., Lenzen, M., Ely, R.N., Dietzenbacher, E., 2014. Simulating the impact of new industries on the economy: the case of biorefining in Australia. Ecol. Econ. 107, 84–93. http://dx.doi.org/10.1016/j.ecolecon.2014.07.022.
Mathews, J. a., Tan, H., 2011. Progress toward a circular economy in China: The drivers (and inhibitors) of eco-industrial initiative. J. Ind. Ecol. 15, 435–457. http://dx.doi.org/10.1111/j.1530-9290.2011.00332.x.
Meyer, B., Meyer, M., Distelkamp, M., 2011. Modeling green growth and resource efficiency: new results. Min. Econ. 24, 145–154. http://dx.doi.org/10.1007/s13563-011-0008-3.
Milford, R.L., Allwood, J.M., Cullen, J.M., 2011. Assessing the potential of yield improvements, through process scrap reduction, for energy and CO_2 abatement in the steel and aluminium sectors. Resour. Conserv. Recycl 55, 1185–1195. http://dx.doi.org/10.1016/j.resconrec.2011.05.021.
Miller, R.E., Blair, P.D., 2009. Input–output Analysis, Foundations and Extensions. Cambridge University Press, Cambridge, UK.
Neuwahl, F., Löschel, A., Mongelli, I., Delgado, L., 2008. Employment impacts of EU biofuels policy: combining bottom-up technology information and sectoral market simulations in an input-output framework. Ecol. Econ. 68, 447–460. http://dx.doi.org/10.1016/j.ecolecon.2008.04.018.
Pfaff, M., Sartorius, C., 2015. Economy-wide rebound effects for non-energetic raw materials. Ecol. Econ. 118, 132–139. http://dx.doi.org/10.1016/j.ecolecon.2015.07.016.
Rogers, J.G., Cooper, S.J.G., Cooper, S., Tingley, D.D., Braithwaite, N., Moreno, M., Rodrigues, A., Salvia, G., 2015. Product longevity and shared ownership: sustainable routes to satisfying the world's growing demand for goods. AIMS Energy 3, 505–519. http://dx.doi.org/10.3439/energy.2015.4.547.
Rose, A., 1984. Technological change and input-output analysis: an appraisal. Socioecon. Plan. Sci. 18, 305–318. http://dx.doi.org/10.1016/0038-0121(84)90039-9.
Scott, K., Barrett, J.R., Baiocchi, G., Minx, J., 2009. In: Meeting the UK Climate Change Challenge: the Contribution of Resource Efficiency. EVA 128. WRAP, Oxon, UK.
Serrenho, A.C., Sousa, T., Warr, B., Ayres, R.U., Domingos, T., 2014. Decomposition of useful work intensity: the EU (European Union)-15 countries from 1960 to 2009. Energy 76, 704–715. http://dx.doi.org/10.1016/j.energy.2014.08.068.
Shahbazi, S., Wiktorsson, M., Kurdve, M., Jönsson, C., Bjelkemyr, M., 2016. Material efficiency in manufacturing: Swedish evidence on potential, barriers and strategies. J. Clean. Prod. 127, 438–450. http://dx.doi.org/10.1016/j.jclepro.2016.03.143.
Tukker, A., 2015. Product services for a resource-efficient and circular economy - a review. J. Clean. Prod. 97, 76–91. http://dx.doi.org/10.1016/j.jclepro.2013.11.049.
Tukker, A., de Koning, A., Wood, R., Hawkins, T., Lutter, S., Acosta, J., Rueda Cantuche, J.M., Bouwmeester, M., Oosterhaven, J., Drosdowski, T., Kuenen, J., 2013. Exiopol – development and illustrative analyses of a detailed global Mr ee Sut/Iot. Econ. Syst. Res. 25, 50–70. http://dx.doi.org/10.1080/09535314.2012.761952.
United Nations Statistics Division, n.d. Industrial Commodity Statistics Database [WWW Document]. URL http://data.un.org/Explorer.aspx?d=ICS (Accessed 02April 2016).
Van Gool, W., 1998. Thermodynamics of chemical references for exergy analysis. Energy Convers. Manag. 39, 1719–1728. http://dx.doi.org/10.1016/S0196-8904(98)00089-2.
Van Weelden, E., Mugge, R., Bakker, C., 2015. Paving the way towards circular consumption: exploring consumer acceptance of refurbished mobile phones in the Dutch market. J. Clean. Prod. 113, 743–754. http://dx.doi.org/10.1016/j.jclepro.2015.11.065.
Walz, R., 2011. Employment and structural impacts of material efficiency strategies: results from five case studies. J. Clean. Prod. 19, 805–815. http://dx.doi.org/10.1016/j.jclepro.2010.06.023.
Walz, R., Schleich, J., 2009. The Economics of Climate Change Policies. Springer-Verlag, Berlin.
Waugh, R.L., 2013. Options for Acheiving a 50% Reduction in Steel Industry CO_2 Emissions by 2050. University of Cambridge, PhD.
Wiedmann, T.O., Barrett, J.R., 2013. Policy-relevant applications of environmentally extended MRIO databases – experiences from the UK. Econ. Syst. Res. 25, 143–156. http://dx.doi.org/10.1080/09535314.2012.761596.
Wilting, H.C., Faber, A., Idenburg, A.M., 2008. Investigating new technologies in a scenario context: description and application of an input–output method. J. Clean. Prod. 16, S102–S112. http://dx.doi.org/10.1016/j.jclepro.2007.10.017.
Wood, R., Stadler, K., Bulavskaya, T., Lutter, S., Giljum, S., de Koning, A., Kuenen, J., Schütz, H., Acosta-Fernández, J., Usubiaga, A., Simas, M., Ivanova, O., Weinzettel, J., Schmidt, J., Merciai, S., Tukker, A., 2014. Global sustainability accounting—developing EXIOBASE for multi-regional footprint analysis. Sustainability 7, 138–163. http://dx.doi.org/10.3390/su7010138.
World Energy Council, 2013. Energy Efficiency Technologies Annex 1-Energy Efficiency Potentials and Barriers for Realization in the Industry Sector. World Energy Council, London.
Yifang, L., 2007. The input-output analysis of the circular economy. In: 16th International Input-output Conference, 2–6 July 2007. Istanbul.
Yuan, Z., Bi, J., Moriguichi, Y., Yuan, 2006. The circular economy: a new development strategy in China. J. Ind. Ecol. 10, 4–8. http://dx.doi.org/10.1162/108819806775545321.