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Measuring resource efficiency and circular economy: A market value approach

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ABSTRACT

This paper proposes a new value-based indicator to assess the performance of actors in the supply chain in terms of resource efficiency and circular economy.

Most of the methodologies developed so far measure resource efficiency on the basis of the environmental burden of the resource relative to the value of output. However, the key point of circular economy is keeping resources within the economy when products no longer serve their functions so that materials can be used again and therefore generate more value.

The unit in which resource efficiency and circular economy are measured greatly affects both the ease of acceptance by policymakers and the direction in which green policy will change our society.

Whereas the most common approaches to assessing resource efficiency and circular economy use mass, in this paper we advocate measuring both resource efficiency and circular economy in terms of the market value of 'stressed' resources, since this value incorporates the elements of scarcity versus competition as well as taxes representing urgent social and environmental externalities. The market value of resources is well-documented and responds automatically to the locality and time at which resources are used.

Applying this unit, circularity is defined as the percentage of the value of stressed resources incorporated in a service or product that is returned after its end-of-life. Resource efficiency is the ratio of added product value divided by the value of stressed resources used in production or a process thereof. It is argued that precisely the concept of a free market, in which materials, parts and components are exchanged purely on the basis of their functionality and cost, allows the resource efficiency of a process (KPI for industry and governance) to be distinguished from the resource efficiency of a product (KPI for consumers and governance).

Using standard industry data from Statistics Netherlands, the resource efficiency of several Dutch industries were evaluated using the new methodology and compared with a traditional mass-based approach.

1. Introduction

Europe has the world's highest net imports of resources per person, and its open economy relies heavily on imported energy and raw materials. Secure access to resources has become an increasingly strategic economic issue, while possible negative social and environmental impacts on third countries are an additional concern. In 2013, a total of 8.0 billion tonnes (McKinsey and Company, 2015) of materials were used by the European Union economy to create goods and services. In terms of value, this amounts to about 560 billion euros.[1] This is why policy attention to natural resource security is growing worldwide with the aim of decreasing dependence on international trade in securing raw materials and of minimising the risks associated to the rising prices of raw materials (European Commission, 2011; National Research Council, 2008).

Besides the implications of the fact that most materials extracted from the earth and utilised for economic purposes are not literally 'consumed' but become waste residuals that do not disappear and may cause environmental damage and result in unpaid

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[1] The value of materials at the point where they are in their final chemical composition, but not yet manufactured as a part or component.

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social costs (Ayres and Kneese, 1969), experts have calculated that without a rethink of how materials are used in the current linear 'take-make-dispose' economy, the virgin stocks of several key materials appear insufficient to sustain the modern 'developed world' quality of life for the global population under contemporary technology (Gordon et al., 2005). It is therefore necessary to move towards an industrial model that decouples economic growth from material input, by using waste and bio-feedstock as inputs for industry: the circular economy. Circular Economy models maintain the added value in products for as long as possible and minimise waste. They keep resources within the economy when products no longer serve their functions so that materials can be used again and therefore generate more value (Pearce and Turner, 1990). Thus, circular business models create more value from each unit of natural resource compared to traditional linear models (Di Maio and Rem, 2015). In addition to secondary resources through recycling, advanced methodologies of design and manufacturing can produce the same functional value using less resources (natural resources and recycled resources alike).

According to Brundtland (World Commission on Environment and Development, 1987), sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Resource efficiency can be considered one of the interpretations/consequences of Brundtland's definition of sustainable development. Although it may seem odd to quote Brundtland's statement on sustainable development so long after she made it and now that almost everyone is aware of it, we believe that this meaningful quotation has been translated so many times into derivatives that we have somehow lost track of the message she wanted to convey. Moreover, Brundtland's statement helps us to clarify our definitions of both resource efficiency and stressed resources.

Resources can be divided into abundant and scarce resources. The former are available for everybody and will remain so in the future. However, if we use the latter resources, we prevent somebody else from using them now and in the future. We define those resources as stressed resources. When we discuss resource efficiency in this article, we mean efficiency in the use of stressed resources.

What needs attention in the coming years is the methodology of measurement of resource efficiency. The details of this methodology will define to a great extent both the direction in which the European economy will change as a result of this new policy, and the speed and economic efficiency of this change.

There is, in particular, a major difference in direction of change resulting from minimising, for example, the mass or the value of resources that are used in producing some service or product. Minimising the environmental impact of the resources used in producing services or products creates yet another direction of change. In other words, resources can be measured in different units, and the selection of a unit of measurement is directly linked to the effect of policy. Another issue is whether the measurement of resource efficiency is focused on a particular good or service, or is applied to a certain part of the production process along the value chain. Focusing on products[2] might be considered a global methodology of measurement, as it delivers a number related to the entire process of delivering a product to the market. Focusing on individual production process steps is in effect a local measurement, as it tells us only how much resources are used by a single actor in the supply chain. A global measurement takes into account the whole supply chain and requires more assumptions than a local measurement. It is therefore typically more expensive and less robust (i.e. it is more error-prone) than local (i.e. national) measurement. A global measurement tells us whether the product or service is 'bad' or 'good' in terms of resource efficiency, and improvements in the resource efficiency of a product or service involve a series of actors along the supply chain, who have to work together and may be active in different countries.

Local measurement identifies single actors as 'bad' or 'good', so improvements concern only the process step of this actor and therefore can be realised more easily. At the country level, a local measurement may evaluate the local actors, so improvements concern only the process step of this actor and can easily be linked to national policy decision making.

Focusing on a product may tell us whether the resource efficiency of a product is 'bad' of 'good' in terms of resource efficiency, but provides no information about the related industry. Thus, it is less clear whom to address to steer or manage it. There can be many steps/actors involved in the process of making a product. If a product is evaluated as being 'bad', all steps/actors should be studied to find out where the process can be improved. This will make it possible to address the actors in the supply chain who made the parts and the semi-finished product, provided the transport, etc. and to steer them in the right direction. This is difficult in terms of governance because at the product groups level, different actors may be active in different countries and it is difficult to compute what each actor adds to the product value, in particular its marginal addition to the product value in relation to the resources it used.

We therefore believe that the crucial next step for Europe is to develop a methodology to assess the resource efficiency performance of all individual actors in the supply chain.

In an ideal world, an environmentally and societally corrected efficiency indicator would be needed. In such an indicator, the inputs would be weighted by their environmental and societal impact. However, the impacts are many and cannot be fitted to a common unit of impact. The concepts and methodology to calculate such an indicator do not exist. Since these numbers and methodologies are missing, the use of the market value of resources is a good proxy solution. Assuming that the high-value inputs have a higher environmental impact, a kilogram of gold has a different societal and environmental impact than a kilogram of clay (Di Maio and Rem, 2015).

Moreover, the mass of inputs does not necessarily address all implications. This shortcoming can be overcome by weighting in the value of the used resources, rather than focusing only on the physical units.

The research underlying this paper used existing robust statistical frameworks, such as the Netherlands' System of National Accounts and its Material Flow Monitor, to construct new resource efficiency indicators that incorporate the value. This is useful to measure the performance of different industries, and can potentially reduce significantly the number of indicators to evaluate policymaking.

2. Resource efficiency measurements

Considering the large number of natural resources with different characteristics, it is extremely complex to develop indicators that properly reflect resource use and its impacts on environment, economy and security (Behrens et al., 2015). BIO Intelligence Service et al. (BIO Intelligence Service, 2012) distinguish between four key categories of resource use: material use, energy use & climate change, water use and land use. For each one, they present indicators related to the scale of consumption (resource use) and to the impact of consumption on the environment. They also distinguish between indicators that reflect domestic consumption and impacts, and those that relate to global demand and impacts. In total, they

[2] Goods or services.

propose 16 indicators that are capable of measuring certain aspects of resource use. However, taking into account that an indicator is a tool made and used by experts to inform industry, politicians and consumers, two main problems arise from considering so many indicators for one topic (Behrens et al., 2015).

First, for communication purposes it is important that all stakeholders understand the content of the indicators and the decision making process that is based on them. Indicators must therefore be simple and intuitive. To further facilitate the measuring of progress towards agreed targets and to simplify the communication to the public, aggregate indicators (ideally a single one), rather than many of them, are to be preferred.

Second, for decision making purposes, it is crucial that the indicators are robust and that they actually link simultaneously to all relevant issues of the stakeholders at a specific place and point in time. Moreover, indicators are usually calculated using different methodologies and data. The variability in accuracy and robustness, as well as the economic structures within a country, affects the reliability of the related indicators and complicates the interpretation, harmonisation and comparison between countries. To address this issue, indicators should be calculated using similar methodologies and harmonised statistics. Countries with relatively large service industries have less material use than countries that rely on resource-intensive sectors, such as mining and forestry (European Environment Agency, 2015; Dittrich et al., 2011).

Concerning the environmental issues that have gained attention in recent decades, researchers have made considerable efforts to develop methods to assess the environmental performances of actors involved in production processes (Figge and Hahn, 2004). A large number of approaches to environmental impact assessment have been proposed (e.g. Fagge and Hahn, 2004; Heijungs, 1992a,b; Odum, 1996; Yang and Nielsen, 2001; EUROSTAT, 2001; Bare et al., 2003; Frischknecht et al., 2007). The main purpose of these approaches is to assess the environmental impact that results from making or using a product. However, most of such indicators cannot provide information about environmental impact thresholds and the related desired policy targets, because it is not clear what the real bio-physical limits are before crucial tipping points are exceeded. For example, it is difficult to establish how much toxins can be released into a river without affecting the wellbeing of the flora and fauna living in it and of the humans interacting with it.

To quantify resource efficiency and to support decision making, metrics of economy-wide material flow accounting have been adopted by governments and authorities (Wiedmann et al., 2012). For example, the European Commission proposes ‘resource productivity,’ defined as gross domestic product (GDP) divided by domestic material consumption (DMC), as the headline indicator of its ‘resource efficiency roadmap,’ one of the main building blocks of Europe’s resource efficiency flagship initiative as part of the Europe 2020 strategy (European Commission, 2011). Eurostat monitors GDP/DMC as one of the key indicators for the European Union’s sustainable development strategy (Eurostat, 2012). The Organisation for Economic Cooperation and Development (OECD) (OECD, 2011a) and the United Nations Environment Programme (OECD, 2011b) also use GDP/DMC as an indicator for their green growth strategies. To include the upstream raw materials related to imports and exports originating from outside the focal economy, material footprint indicators have been proposed (Wiedmann et al., 2012). Nevertheless, these material flow productivity indicators in the form of ratios of (value added)/(amount of material in mass) are not that precise in describing the link with policy and they do not reflect anything that plays a role in decision making. Stating that European domestic material consumption (DMC) per capita was around 13 tonnes in 2014 does not offer any guidance for making Europe less dependent on raw material import. This is because the mass mentioned does not distinguish, for instance, the use of minerals from the use of rare earth metals. Whereas the consumption of some minerals is not a concern from a geopolitical, economic or environment point of view, the use of a specific rare earth metal is.

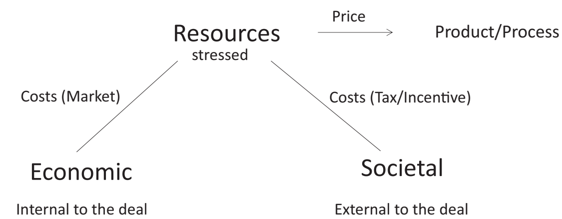


Fig. 1. Economic and societal stressed resources.

3. Is economic value useful for measuring resource efficiency?

Economic value is an indicator that is extensively used in decision making. In this paper we argue that economic value is also the key parameter to measure resource efficiency and that using value to measure resource efficiency is beneficial to address the weaknesses of the current resource efficiency indicators. Eventually everything is translated into value. Also environmental issues should be translated into value, as they are when, for instance, waste water is discharged into a river. In such cases, the environmental cost and other external costs are taken care of by taxes, and permits required to use the river as a waste sink. A key advantage of using economic value is that while mass represents only quantity, economic value embodies both quantity and quality. Moreover, considering that the objectives and targets underlined in most governmental and corporate reports and policies are mainly expressed in terms of economic values, value-based performance indicators are better aligned with policies and strategies. Therefore, value-based indicators will be more effective in policymaking and management. They can play an important role in increasing resource efficiency, allowing policymakers to identify stressed resources and to properly formulate, monitor and assess policies and strategies.

Stressed resources can be divided into two categories: economic and societal. A resources can be stressed because there is shortage of that resource on the market. If demand is constantly higher than supply, the resource becomes stressed. On the other hand, resources can be stressed because extracting them may create externalities, which can be either positive or negative (tax or incentives). The costs of externalities might be present due to market failure so that the true environmental costs to society that are not fully reflected in the price of a product can be internalised by taxes or levies. When resources are needed to make a product or run a process, the prices of the resources reflect both the economic costs (market driven) and the societal costs in the form of a tax or incentive (see Fig. 1).

In order to appreciate the features of the value-based resource efficiency indicator, it is useful to underline that there are different actors and policies playing a role in the open market. A short description of these is provided in the following paragraphs.

The three actors are consumers, industry and government (cf. Fig. 2). They all need information to take their decisions. When a consumer decides whether to buy a product, he/she does so on the basis of the product’s characteristics. For the consumer, it is not very relevant to know all the operations and industries that made

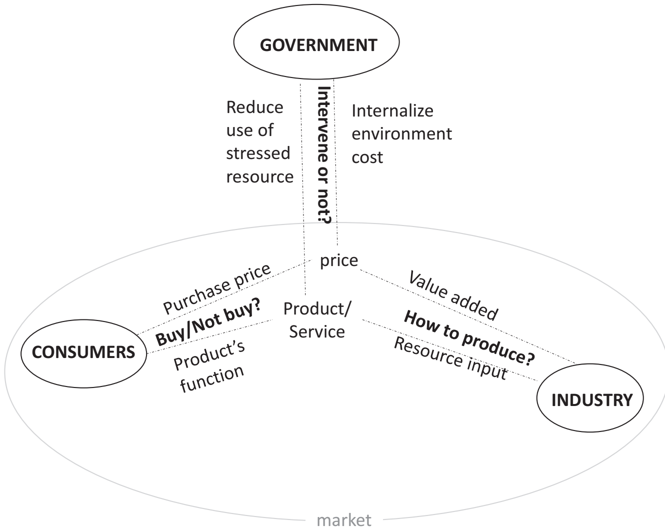


Fig. 2. Actors and policies playing a role in the open market.

it possible to deliver that product/service.[3] Thus, consumers need information only about the product as a whole.

Industries look only at their processes and at the component they manufacture (or at the service they provide). Their main concern is the value added and the amount of resources they use. What comes before and after that in the value chain, takes place in the market and might not be easily influenced, at least from the perspective of a single company. Therefore, for most companies it does not matter where the input (material, components, etc.) comes from or where the output goes. The open market is in that sense self-regulating and, as a basis for our society, it is assumed that nobody manipulates it. Then for decision making regarding the resource efficiency of an industry actor, it matters only what the industry actor does individually.

The government is the institution of society that establishes and enforces policies. It observes both the consumer and industry. When it monitors industries, government is (or should be) interested in knowing what the value added is in relation to the resources used. This makes it possible to compare and rank different industries in one country according to their efficiency and to compare national industries to their counterparts in other countries. Should the resource use in terms of value added not be satisfactory, government can decide to stimulate innovation to promote reducing the resource use or increasing the value added.

When government looks at consumers, it is (or should be) mainly concerned about knowing what kind of products are bought in relation to resource use (in this context, resource efficiency). Should consumers buy the 'wrong' products, government can use taxes to artificially increase their prices to take into account the environment, or someone's health cost (as it is done with cars, cigarettes, etc.). Alternatively, subsidies can be given to the 'right' products to reduce their prices and make them more attractive to consumers.

The proposed resource efficiency indicator uses value added, divided by the amount of all inputs. The novelty is that the amount of physical inputs is expressed in monetary value, instead of a mass. The monetary value is composed of a price times a physical volume. Thus, value-based indicators reflect both the quantity and the quality of resources at the same time.

We argue that the inclusion of the price information is crucial in order to create a more correct weighting of societal stresses and environmental costs.

4. Is social value useful for measuring resource efficiency?

Along with economic value, social value is an indicator that is widely used in decision making. This consideration is supported by the fact that many countries and societies impose taxes and create incentives to deal with employment and environmental issues that eventually affect the prices of raw materials. For example, many countries impose significant taxes on motor fuels like petrol and diesel because their use contributes to global warming and local air pollution (UNEP, 2011). In other cases, governments/countries provide incentives to create labour opportunities.

For instance, some countries discount the cost of energy below market price (for instance reducing the taxes companies pay on energy) to secure the production of energy-intensive products at specific locations. In other cases, reasons for incentive and taxation are in place, and in these cases politicians deliberately do not take action. For example, some governments do not impose taxes on oil refinery activities because they prioritise sustaining the employment rate over decreasing environmental burdens. In such cases, employment is more valued than the environment.

Because of the above considerations, it is clear that the proposed value-based resource efficiency indicator also takes into account (through the mechanism of taxes) social value, even though societies could work on making the relation between taxes and incentives and social value more explicit.

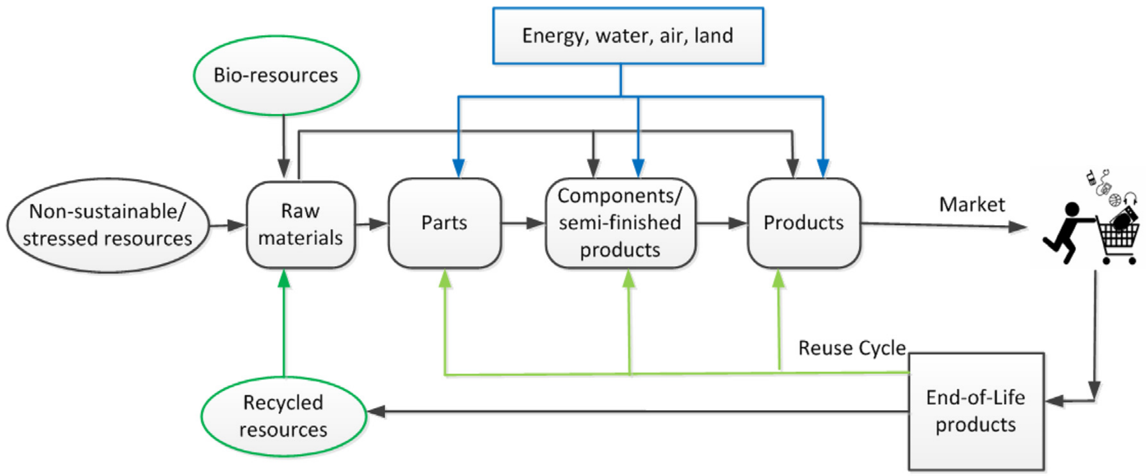
5. Proposed value-based resource efficiency (VRE) indicator for measuring circular economy and resource efficiency

The value-based resource efficiency (VRE) indicator proposed in this paper is as simple as the mass-based resource efficiency indicators but better aligned with social, environmental and economic policies. At the same time, it is simpler to compute than the indicators based on lifecycle assessment or footprint analyses. Moreover, the VRE indicator could potentially replace some existing mass-based and impact-based resource efficiency indicators, although for monitoring specific progress or policies mass-based indicators will still be useful. However, as both quality and quantity are considered in the value, and if the pricing reflects market equilibrium, the novel indicator is expected to show a smaller bandwidth than mass-based indicators where environmental damage per kilogram varies significantly. As most of the monitoring in society is already done in monetary terms, the indicator can be computed relatively easily, and it is also more straightforward to communicate. This will facilitate measuring progress towards the objectives of decision makers, and will also promote the effectiveness of policies and incentive systems. As the indicator can be measured with existing globally harmonised statistics, it benefits from existing harmonisation and can be compared across European Union member states.

Moreover, existing mass-based and impact-based indicators are not well suited to make regional comparisons. For instance, resource-intensive countries show different resource efficiency indicators' values than service-oriented countries. However, one needs all parts of the value chain, and this can lead to flawed outcomes that need additional interpretation. Such flaws are overcome with the current indicator, as the price per unit of mass increases from raw materials (e.g., ores) to intermediate goods and final products. In a way, the price also reflects better effort, or environmental damage earlier in the supply chain.

A related observation is that existing mass-based and impact-based indicators do not reflect local situations. However, the use

[3] Although conscious consumers have recently started to pay more attention to it.



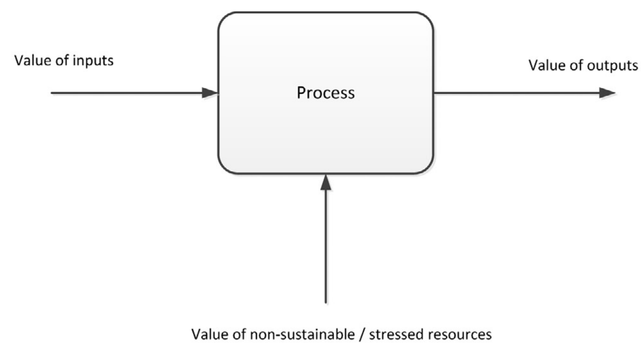


Fig. 3. (Top) Assessment of the resource efficiency of a product in terms of the environmental impact of the resources used for its production: the impact per functional unit of the product linked to the items shown in boldface is compared for *similar types of product*. (Bottom) Assessment of the resource efficiency of a process step: the value of non-sustainable resources used per unit added value of the process is compared for *similar types of processes*.

of resources (and therefore the performance of the supply chain) clearly depends on time and location. For example, if an operation uses fresh water, the value-based resource efficiency indicator will change according to whether the operation is located in the Netherlands or in the south of Spain. This means that a value-based indicator can also deal more effectively with locally stressed resources. The mass-based indicators will not be affected. Impact-based indicators could be affected, but they are less suitable for policymaking and need to be modelled, and are consequently vulnerable to the modelling choices made.

In other words, the VRE indicator takes into account more factors that affect product/service value, such as the prices of stressed resources. It is therefore a suitable indicator to monitor, steer and manage the performance of actors in the supply/value chain and, thus, the total supply/value chain (see Fig. 3). In addition, VRE indicators can be used to assess whether a sector or the total economy uses resources in an efficient way, and are available in the supply and use tables of the System of National Accounts.[4]

The value-based resource efficiency (VRE) indicator is defined by

$$VRE = \frac{Y}{\sum_i W_i X_i} \tag{1}$$

where Y is output value, X_i are resources (in volumes) and w_i are weights. The numerator of the indicators thus represents a weighted sum of the resources. To measure the resource efficiency, ideally w_i would represent the environmental and societal impact of the use of input X_i in the production p. Such information is in general not available. In market-based economies, however, the prices of materials and energy reflect both the quality and the scarcity of resources. Therefore, our proposed indicator uses market prices p_i as weights.

Oput is preferably measured by value added. In this case, output refers only to what is actually produced by a certain industry, rather than reflecting the total value built up across the entire value chain. It can be measured in current or constant (i.e. base year) prices, depending on whether one wants to control for inflation (that is, one can use the actual value of output, or its 'volume' in monetary terms expressed in the price level of certain base year). Similarly, resource prices p_i can be expressed in current or constant prices. Because both quality and scarcity tend to change over time, it seems natural to use current prices. Note that the mass indicator corresponds to $w_i = 1, \forall i$; that is, all volumes of input are simply added together and all resources receive equal weight.

Finally, unlike other efficiency measures such as labour productivity, the inputs considered affect both the numerator and the denominator. That is, by accounting identity, value added equals gross output (GO) minus intermediate inputs (II), that is

$$Y = GO - II = Go - E - M - S$$

[4] The System of National Accounts is the central accounting framework to calculate GDP.

[5] The methodology requires measures to avoid double counting.

where E, M, S is the input value of respectively energy, material and services, i.e. $E = p_E X_E$ and $M = p_M X_M$. Therefore,

$$VRE = \frac{GO - E - M - S}{E + M} = \frac{GO - S}{E + M} - 1$$

indicator can be seen to be monotonously increasing in resource use. Hence, it provides consistent rankings of resource efficiency.[5] It should be noted, however, that the cutting or intensifying of resource usage leads to a 'double whammy' in the indicator when the level of output remains constant, in the sense that both the denominator and the numerator are affected. Cutting resources leads to a higher resource efficiency because of lower resource usage *and* an increase in value added, and vice versa for intensifying resource usage.

Note that the VRE can be defined at both the process (or marginal) and the product (or cumulative) level. At the process level, Y of Eq. (1) is the value added of the industry along the value/supply chain. At the product level, Y of Eq. (1) is the final selling price times the number of units of final production (cf. Fig. 3 bottom).

If, for instance, the final product requires some components made of steel, the first sector in the supply chain is that of ore mining. Because the product value may be small compared to the resource value used, the sector shows a limited slope in Fig. 4. Because the value added by the steel producing sector (Sector 2 in Fig. 4) is higher in comparison to the resource value used, the slope in Fig. 4 is steeper. The last sector along the supply chain is the retail sector.

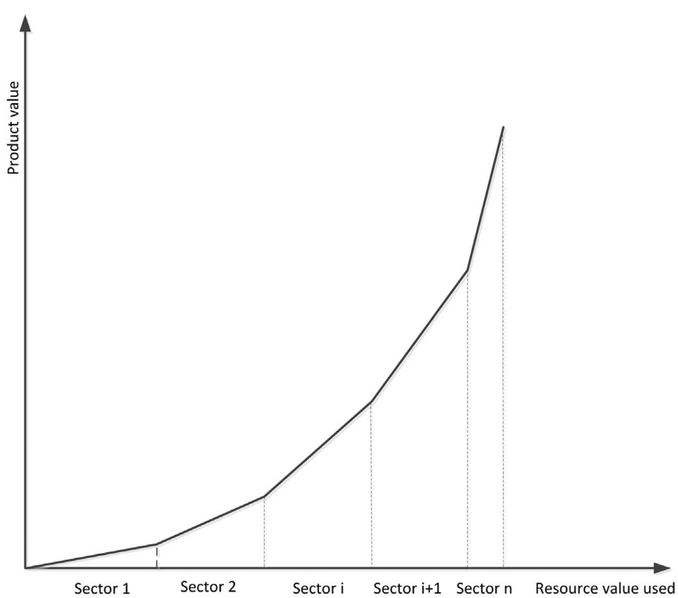


Fig. 4. Value-based resource efficiency curve.

The process VRE can be used to monitor actors in the supply chain/or industry sectors, whereas the product VRE can be used to monitor consumers. Consumers will pay attention to product VRE, but as long as decision makers focus on products rather than processes, it is going to be difficult to improve the resource efficiency of the sectors along the supply chain. To achieve this important target, it is necessary to assess the resource efficiency of all sectors that play a role in delivering the product.

6. Use of the indicator

It is evident that in circular economy, a central aim is to preserve or even upgrade the value of components and waste streams. Our novel indicator is well suited to monitor this goal. All available data are present in the System of National Accounts, and can thus harmonised for all European Union member states.

The proposed VRE indicator focuses on the value of non-sustainable/stressed inputs to the economy, in relation to output. Inputs are what traditional industry sectors use, such as energy, raw materials, labour, semi-finished components, etc. The output is the value added of the economy or the industry/sector.

As an example, in an ideal case, a circular economy uses sustainable resources, such as renewable inputs from the biosphere, upcycled components and recycled wastes that have low prices/values per kilogram. It uses as little non-sustainable/stressed inputs as possible, and creates jobs and a high value added.

7. Methodology for experimental computation of the VRE

All monetary inputs in the System of National Accounts were analysed for 2010. The VRE was computed by dividing the value added by the monetary value of total inputs, except for labour. This was done for 40 relevant sectors of Dutch industry. Small sectors (in terms of material inputs that are service oriented) were excluded from the analysis. Two indicators were calculated and compared to each other:

- The proposed VRE (value added/value of inputs)
- The traditional resource efficiency (value added/kg material input).

The monetary data come from the Netherlands' System of National Accounts (CBS, 2015), the physical data from the Material flow Monitor (Delahaye et al., 2015).

8. Results of the VRE compared to traditional resource efficiency indicators

After computing the indicators, each sector was ranked from most resource efficient to least resource efficient. The effects of and the novel message from the VRE are shown for the sectors that show significant deviation in ranking. Prominent examples of sectors that

Table 1
Sectors that rank less resource efficient with the VRE indicator (2010 data).

Sector	Ranking of the value-based indicator compared to mass-based indicator	Value added of sector [million euros]	Mass input for sector [million kg]
Manufacture of computers, electronic and optical products	35 steps less efficient	4453	835
Manufacture of other transport equipment	20 steps less efficient	1936	1079
Construction of buildings and development of building projects	11 steps less efficient	10,409	31,576
Manufacture of motor vehicles, trailers and semi-trailers	10 steps less efficient	1784	2158
Manufacture of textiles	9 steps less efficient	1033	1074
Manufacture of machinery and equipment NEC	9 steps less efficient	7837	4335
Manufacture of paper and paper products	8 steps less efficient	1580	7815
Manufacture of food products	7 steps less efficient	8904	77,087

Table 2
Sectors that rank more resource efficient with the value-based indicator (2010 data).

Sector	Ranking of the value-based indicator compared to mass-based indicator	Value added of sector [M euro]	Mass input for sector [M kg]
Mining and quarrying (no oil and gas)	23 steps more efficient	285	24,296
Extraction of crude petroleum and natural gas	21 steps more efficient	16,998	73,848
Fishing and aquaculture	16 steps more efficient	293	1021
Supply of electricity, gas, steam and air conditioning	16 steps more efficient	7301	89,074
Manufacture of other non-metallic mineral products	14 steps more efficient	1867	31,431
Sewerage	11 steps more efficient	2036	14,123
Agriculture and related service activities	10 steps more efficient	10,431	116,053

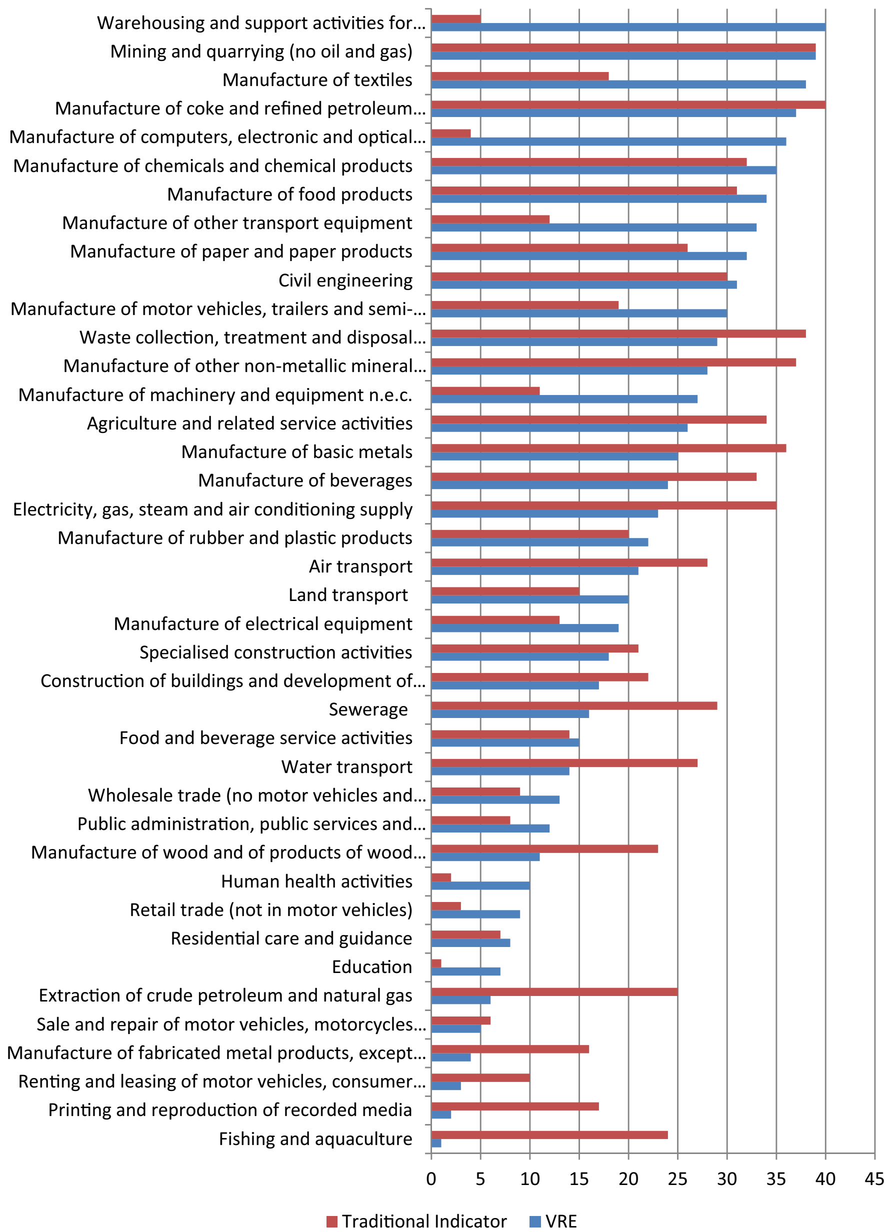


Fig. 5. Rank of the traditional indicator versus the rank according to VRE.

rank less resource efficient according to the VRE, as opposed to the mass-based indicator, are shown in Table 1. As expected, the sectors that are shown to be less resource efficient are those where the prices of the inputs used are high. For instance, the 'manufacture of computers, electronic and optical products' sector is typically high (i.e. low resource efficiency), as it uses high concentrations of gold and high purity silicon. The mass of those inputs is not very great, but the environmental damage and societal costs are significant earlier in the supply chain.

Table 2 shows those sectors where it is the other way round. Sectors that rank more resource efficient with the value-based indicator are usually resource intensive. But the resources generally

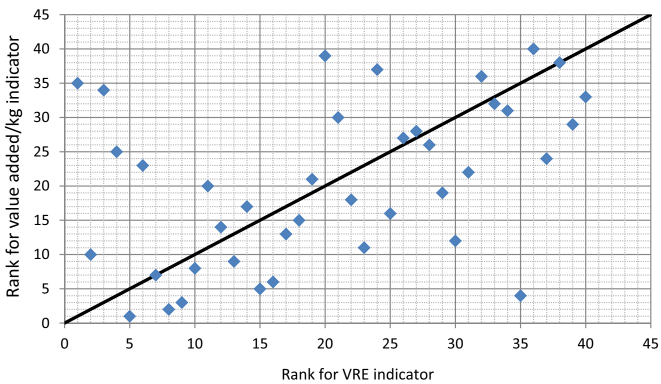


Fig. 6. Scatter plot of the VRE indicator and the mass-based indicator. Each dot represents one sector. The diagonal line represents where the sector has the same ranking (note: this is not a regression line).

have a lower price per unit. Overall, the results suggest that the differences in outcomes and ranking can be substantial. Although some industries rank the same, the assessment of the resource efficiency of a sector can be totally different depending on the indicator used. Fig. 5 presents the comparison of ranks for all sectors, whereas Fig. 6 shows a scatter plot of the rankings. Finally, the Appendix presents the actual numbers for both indicators for all sectors considered. There is no significant correlation between the indicators (in fact, the Pearson correlation coefficient is close to zero).

The conclusion that the indicators tell a different story about which sectors are resource efficient and which are not, clearly has important implications for resource efficiency policymaking when it comes to deciding which sector to target.

9. Conclusions

In this paper we proposed and presented a test of the value-based resource efficiency (VRE) indicator – a new method to measure resource efficiency and circularity that is more aligned with the market value of resources.

The underlying research used standardised data on industry sectors from Statistics Netherlands to compare the resource efficiency of 40 Dutch sectors indicated by the VRE and by a traditional mass-based approach.

The sectors that rank less resource efficient according to VRE than the mass-based indicator are those where the prices of the inputs used are high. In particular, the 'manufacture of computers, electronic and optical products' and the 'manufacture of other transport equipment' sectors stand out in this respect.

Sectors that rank more resource efficient with the value-based indicator are typically resource intensive. However, the input resources usually have a lower price per unit. In particular, the 'mining and quarrying (no oil and gas)' and the 'extraction of crude petroleum and natural gas' sectors are more efficient under the new indicator.

We believe that because of its simplicity, robustness, cost effectiveness and adaptability, as well as its alignment with policy and other economic indicators, and its correlation with environmental impact, the VRE indicator can be useful to monitor and assess progress towards greater resource efficiency at both the local and the global scale.

10. Outlook

By repeating the same calculation for other countries, the VRE index will show the more resource-efficient sectors in an international context, and it will be possible to assess the effect of national policies on the resource efficiency of the sectors under investigation. Sectors may be more resource efficient, not only because they use more sustainable (or circular) materials, but also because they can be more efficient in the way they use non-sustainable resources (e.g. better design).

Appendix

Sector	Ranking of the value-based indicator compared to the mass-based indicator	Value added of sector (million euros)	Mass input for sector (million kg)
Mining and quarrying (no oil and gas)	19 steps more efficient	285	24,296
Fishing and aquaculture	13 steps less efficient	293	1021
Waste collection, treatment and disposal activities; materials recovery	Equal	497	18,581
Manufacture of coke and refined petroleum products	4 steps more efficient	670	75,209
Manufacture of wood and of products of wood and cork, except furniture; manufacture of articles of straw and plaiting materials	17 steps more efficient	878	2801
Manufacture of textiles	4 steps less efficient	1033	1074
Manufacture of beverages	7 steps less efficient	1241	12,189
Manufacture of paper and paper products	2 steps less efficient	1580	7815
Manufacture of motor vehicles, trailers and semi-trailers	10 steps less efficient	1784	2158
Manufacture of other non-metallic mineral products	13 steps more efficient	1867	31,431
Manufacture of basic metals	4 steps more efficient	1888	25,109
Manufacture of other transport equipment	18 steps less efficient	1936	1079
Printing and reproduction of recorded media	3 steps more efficient	1958	1863
Manufacture of electrical equipment	4 steps less efficient	2001	1479
Sewerage	10 steps less efficient	2036	14,123
Water transport	1 step more efficient	2205	11,499
Manufacture of rubber and plastic products	9 steps more efficient	2362	3294
Air transport	1 step more efficient	2840	16,990
Manufacture of computers, electronic and optical products	31 steps less efficient	4453	835
Civil engineering	9 steps more efficient	4918	40,677
Manufacture of fabricated metal products, except machinery and equipment	9 steps less efficient	5966	5657
Renting and leasing of motor vehicles, consumer goods, machines and other tangible goods	8 steps more efficient	6146	2985
Food and beverage service activities	2 steps more efficient	6521	5118
Supply of electricity, gas, steam and air conditioning	34 steps more efficient	7301	89,074
Sale and repair of motor vehicles, motorcycles and trailers	10 steps less efficient	7645	1839
Manufacture of machinery and equipment NEC	12 steps less efficient	7837	4335

Manufacture of chemicals and chemical products	1 step less efficient	8293	79,536
Warehousing and support activities for transport	10 steps less efficient	8444	1995
Manufacture of food products	3 steps less efficient	8904	77,087
Construction of buildings and development of building projects	9 steps less efficient	10,409	31,576
Agriculture and related service activities	31 steps more efficient	10,431	116,053
Land transport	3 steps less efficient	10,964	8949
Specialised construction activities	2 steps more efficient	15,204	23,585
Extraction of crude petroleum and natural gas	21 steps more efficient	16,998	73,848
Residential care and guidance	Equal	17,953	4399
Retail trade (not in motor vehicles)	6 steps less efficient	21,401	3649
Human health activities	6 steps less efficient	27,841	3398
Education	4 steps less efficient	29,571	2590
Public administration, public services and compulsory social security	2 steps less efficient	43,404	13,015
Wholesale trade (no motor vehicles and motorcycles)	4 steps less efficient	45,617	17,142

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