Exergy: a universal metric for measuring resource efficiency to address industrial decarbonisation

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Abbreviations

Table 1: Abbreviations

Abbreviation	Description
CE	Circular Economy
EC	European Commission
EE	Energy Efficiency
EI	Energy Intensity
GDP	Gross Domestic Product
IPCC	Intergovernmental Panel on Climate Change
ME	Material Efficiency
RE	Resource Efficiency

Abstract

To achieve agreed targets for reducing global carbon emissions, industry must become more resource-efficient. To this end, two viable strategies exist: energy efficiency and material efficiency. Despite the inherent interdependence of energy and materials in industrial processes, policy and industry treat these two strategies as isolated pursuits, which provides only a partial insight into potential gains from resource efficiency. To resolve this disconnect, we review 34 resource efficiency metrics from the literature and evaluate their effectiveness at driving the sector's low-carbon transition. We then evaluate five selected resource efficiency metrics, in more detail, against the RACER evaluation methodology, using the criteria: Relevance, Acceptance, Credibility, Easiness and Robustness.

The results point to the effectiveness of employing a Resource Efficiency metric based on the thermodynamic concept of exergy. Exergy-based Resource Efficiency metrics score highest in Relevance and Robustness, traits which are inherent to the metric and cannot be changed. However, exergy efficiency scores lower for Acceptance, indicating further advocacy is required for it to be accepted as a mainstream measure of resource efficiency. More work is required to provide simple guides, training and software tools, to facilitate wider use of exergy efficiency in the resource efficiency narrative. We hope that this paper, is a first step towards demystifying exergy and will spur further discussion about the use of exergy-based metrics for measuring Resource Efficiency.

1 Introduction: the hidden climate instrument

The latest IPCC report provides a stark reminder of the challenges of mitigating climate change. Pathways with higher chances of holding warming to below 1.5°C (average global temperature)[1] require net zero CO_2 emissions to be reached by 2050, and a corresponding 45% decline in CO_2 emissions decline from 2010 to 2030 (Rogelj et al., 2018). Efforts to date have focused mainly on switching to lower carbon fossil fuels, deploying renewable energy, improving energy efficiency (EE), methane abatement, limiting deforestation and carbon capture and storage technologies. And yet, despite these aspiring goals and considerable effort, unconditional measures pledged by countries under the Paris Agreement still fall short of what is required; additional decarbonisation strategies are needed.

In light of these challenges, a growing academic community has begun advocating for a more holistic approach which addresses inefficiencies in material production. These decarbonisation options fall under several banners: material efficiency (ME) (Allwood et al., 2011, Cullen et al., 2012, Worrell et al., 1995), resource efficiency (RE) (EC, 2011, Gonzalez Hernandez, Paoli and Cullen, 2018, Valero et al., 2015), life-cycle thinking (ISO, 2006, Pennington et al., 2004, World Aluminium, 2017, worldsteel, 2017) and circular economy (CE) (Circle Economy, 2017, 2019, Di Maio and Rem, 2015, Linder et al., 2017). Together they include the untapped potential of recycling, product re-use, remanufacturing, product light-weighting, manufacturing yield improvements, product life-extension, and by-product recovery (among others) and can be leveraged to support more traditional decarbonisation strategies.

Overwhelming evidence suggests that the improvement potential of circular and resource efficiency measures is vast. Global circularity is estimated to be only 9% by mass and this fraction is trending down, rather than up (Circle Economy, 2019). This estimate includes both materials and fossil fuels (measured in mass) which are either recycled or reused in a circular fashion. If we consider the quality of these materials and the energy required to close material loops through recycling, global circularity fractions for major energy-intensive materials are: 20% for aluminium, 14% for steel, 7% for plastics, 4% for paper and 0% for concrete (Cullen, 2017).

Such fractions point to large potential gains in efficiency, but should be read with caution, as there are significant challenges to increasing the circularity of materials (e.g the mismatch between available scrap supply and material demand). Yet, we can conclude that strategies to improve the efficiency of energy and material systems, what we call *Resource Efficiency*, could deliver significant reductions in material demand, energy use and carbon emissions.

A criticism of current metrics for measuring circularity and RE is their quantification of material flows without considering the energy and environment impacts of interventions (European Commission, 2015). Cullen (2017) explain that “material losses and energy inputs

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[1] This is a pathway with no or limited overshoot of 1.5°C. In contrast, pathways allowing for a temporary temperature overshoot rely on large-scale deployment of CO_2 removal measures, which remain uncertain and entail clear risks.

associated with recycling can usurp many of its environmental benefits." Furthermore, circularity metrics provide insight at the country or global level, yet are often difficult to apply to linear sub-sections of the circle, such as resource-intensive material producers. For such industries, applying circularity strategies to reduce emissions in practice means reducing overall resource inputs (energy and materials) per tonne of product.

If the efficient use of resources is to become an inveterate climate instrument, emissions-intensive producers will need to develop a proper thermodynamic understanding of their production systems, including the links between materials, energy and emissions (Schalkwyk et al., 2018). This is challenging as energy and material use are measured in different units (tonnes versus Joules) and current organisational structures mean most producers measure EE and ME separately. Energy teams are responsible for reducing energy use, and they do so one asset at a time (e.g. boilers, heaters, electric motors), while material teams monitor product quality, optimise material procurement costs and attempt to improve yield rates. Yet, the assessment of energy efficiency and material efficiency in isolation fails to capture the full improvement potential from efficiency, as interactions between energy and materials – which is the whole purpose an industrial process – are overlooked.

Resource Efficiency entails delivering future energy and material services with reduced resource use and environmental impact. Becoming more resource efficient requires clear targets and the means to measure progress with appropriate metrics at multiple levels, from policymakers to plant operators. This study seeks to define such a metric for RE; one that considers resource interactions; is comparable across different processes and sectors; reflects both resource quantity and quality; is applicable at different spatial boundaries and temporal scales.

The paper is structured into four sections: (1) a review of approaches to measuring resource efficiency, including economic, physical, and impact-oriented metrics, followed by a review of metric evaluation criteria; (2) a description of the proposed RE metric and evaluation method; (3) a presentation of the results of the RE metric evaluation; (4) a discussion of the usefulness and limitations of the RE metric.

2 Review: resource efficiency metrics and evaluation criteria

Much has been written about improving the RE of emission-intensive industries, with many studies pointing to significant potential for economic and environmental gains. RE indicators are employed in every sector – from policy and governance to industry firms – and for multiple purposes. Unsurprisingly, a plethora of metrics is available to quantify RE, many of which are expressed as ratios of two measured quantities. The differences found across RE metrics result from the scope of resources considered, the targets/aspects that resource-use is measured against, and the units chosen.

This section reviews the most relevant RE metrics proposed in academic literature, industry practice and policy. Metrics are classified into three groups: economic (Section 2.1), physical (Section 2.2) or impact-oriented (Section 2.3). Section 2.4 describes how six metrics are selected for further evaluation, and Section 2.5 outlines the set of relevant criteria that were used for testing the RE metrics.

2.1 Economic-based indicators

Economic-based indicators are typically employed in policy to track macro-level changes in resources and economic activity. For example in energy policy, EE (energy efficiency) is often expressed as *energy productivity* (the ratio of value-added per unit of energy used (IEA, 2014*b*)) and is used to assess long-term interactions between economic-activity and environmental performance. Atalla and Bean (2017) claim that energy productivity is a more "direct measure of a country's economy", is more intuitive, and is better aligned with efficiency than physical metrics. For this reason, many countries target policies to improve energy productivity (e.g. US (Keyser et al., 2015) and Germany (BMWi, 2016)). Table 2 presents are summary of the economic metrics discussed.

Table 2: Review of economic-based resource efficiency metrics.

Metric	Unit	Scope	Reference
Energy Productivity	Value added per unit of energy used	From Global to Sector	(IEA, 2014*b*)
Domestic Resource Productivity	GDP per Domestic Material Consumption	From Global to Sector	(EC, 2011, 2015)
Resource Productivity	GDP per Raw Material Consumption	From Global to Sector	(EC, 2011, 2015)
Physical Trade Balance	Imports - Exports	Regional	(European Communities, 2001)
Exergy Productivity	GDP per Exergy	From Global to Sector	(Eisenmenger et al., 2017)
Emissions Efficiency	GDP per total emissions	Global, Regional	(IEA, 2009)

Resource productivity is the analogous metric used to explain trends in resource (rather than energy) use. It is a lead indicator in the EUs circular economy (CE) package (EC, 2011, 2015) and depicts RE as the economic output (GDP) per unit of resource input (domestic material and energy consumption, measured in mass). Many alternative definitions of resource productivity also exist. For example, GDP per input of natural resources (DMI) and GDP per Raw Material Equivalent (Etkins and Hughes, 2016) or GDP per input exergy (Eisenmenger et al., 2017).

Di Maio et al. (2017) propose a RE metric defined as the value added of resources output by a sector, per volume of resources used, weighted by market price. The authors argue that price reflects "both the quality and the scarcity" of resources and conclude that monetary metrics are both better at capturing local situations and easier to communicate, than mass-based equivalents. Etkins and Hughes (2016), Huysman et al. (2015), Van der Voet et al. (2005) provide reviews covering an extensive range of policy-level RE indicators.

A good reason to use economic measures is the "availability of detailed data for analysis" (Cullen, 2009). If the monetary value of resources, waste disposal and process operations align with the resources used, economic metrics can be a suitable proxy for RE. However, if alignment is not found and inefficient resource use results in increased profitability, it is "unlikely that a market operating solely according to market rules will deliver a resource-efficient outcome in physical terms" (Etkins and Hughes, 2016). Economic metrics are criticised for being "insensitive to changes in the environmental pressures" and scarcity (Valero et al., 2015, Van der Voet et al., 2005) because environmental impacts vary significantly across materials. Analysis must therefore rely on baskets of indicators, each of which is designed to measure a specific aspect of RE, making cross-material comparisons difficult.

2.2 Physical-based indicators

A portfolio of physical metrics can be used to track resource use in emissions-intensive industries. Three types are reviewed: energy-, material- and exergy-based.

Energy efficiency

The most well-understood physical measure of energy efficiency for industry is energy intensity (EI), typically but not always, measured in units of joules per tonne of material output. Energy-intensity indicators have the advantage of being applicable at any system level, from individual processes through to entire regions. Table 3 summarises a selection of studies that have developed or employed EE metrics for energy-intensive industries.

Worrell et al. (2008) published a widely-cited study on global best-practice energy use for many industries. For steel, for example, it evaluates energy intensities (GJ/t, using both primary and final energy) of steel products with inputs disaggregated by fuels, steam and electricity. Phylipsen et al. (1997) proposed a modified energy-intensity metric called the Energy Efficiency Index (EEI), which enables the comparison of EE between countries. The EEI metric accounts for structural effects by measuring the ratio of average to best practice energy intensity for each country. This method has been applied to benchmark industry sectors Phylipsen et al. (2002); in detailed EE studies of steelmaking (Siitonen et al., 2010) and to global industry benchmarks (Ke et al., 2013, Saygin et al., 2011, UNIDO, 2010).

EI indicators have achieved the closest to a universal acceptance, including as a policymaking tool (IEA, 2008). One example is the EUs ODEX index which the European Commission uses to track EE improvements (EC, 2012b). Yet EI metrics only quantify the extent to which fuels are used, and material product and by-products are produced, ignoring the value of material by-products and material inputs. By virtue of having different denominators, EI metrics are inappropriate for comparing performance across different sectors. To capture the effectiveness of material use, many other metrics have been developed under the rubric of material efficiency or circular economy.

Material efficiency and circular economy metrics

Material efficiency (ME) and circular economy (CE) metrics can take multiple forms as shown in Table 3; more extensive reviews can be found in Allwood et al. (2011), Cleveland and Ruth (1998), Shahbazi et al. (2017).

Table 3: Review of physical- and impact-based resource efficiency metrics. Con (consumption); Cum (cumulative).

Metric	Unit	Scope	Reference
Energy metrics			
Final Energy Use	GJ of final energy input	Global, Regional, Sector	(IEA, 2017)
Energy Intensity	GJ of energy per tonne output	Global, Regional, Sector	(UNIDO, 2010)
Energy Efficiency	GJ of energy per GJ of energy	Site, Plant, Process, Unit	(IEA, 2008)
Energy Efficiency Index	Ratio of Current EI to Best Practice	Regional, Sector, Site	(Phylipsen et al., 1997)
Material metrics			
Raw Material Con. Intensity	Tonnes of raw material/tonnes output	Sector, Site, Plant	(Etkins and Hughes, 2016)
Domestic Material Con.	Tonnes	Global, Regional	(EC, 2016)
Total Material Requirement	Tonnes	Global, Regional, Sector	(EC, 2016)
Material Input per Service	Tonne in tonne product	Global, Regional, Sector	(Hashimoto, 2004)
Material Circularity	Percentage (%)	Sector, Supply chain	(Ellen MacArthur Foundation, 2015)
Product-Level Circularity	Cost recirculated part/Cost all parts	Product	(Linder et al., 2017)
Circularity Index	Percentage (%)	Sector, Supply chain	(Di Maio and Rem, 2015)
Waste rate	Waste produced per unit product	Sector, Plant, Product	(Gao et al., 2016)
End-of-life (EOL) recycling	recycled EOL/ EOL products	From Sector to Product	(Graedel et al., 2011)
Recycled Content	used scrap /total material input	From Sector to Plant	(Graedel et al., 2011)
Direct Material Input	Tonnes	Global, Regional	(Schandl et al., 2016)
Re-use Rate	Percentage (%)	From Global to Plant	(Densley Tingley et al., 2017)
By-product Recovery	By-prod used / by-prod produced	From Global to Plant	(Hashimoto, 2004)
Material Use Time	Stocks / used products recovered	Global, Regional, Sector	(Hashimoto, 2004)
Material Yield	Percentage (%)	Site, Plant, Process	(worldsteel, 2009)
Exergy metrics			
Exergy Efficiency	Percentage (%)	From Global to Unit	(Szargut et al., 1988)
Cum. Degree of Perfection	GJ of output exergy / cum. GJ input	Supply chain, Site, Plant	(Szargut et al., 1988)
Exergy Intensity	GJ per tonne of output	From Global to Plant	(Costa et al., 2001)

Material Intensity (MI) is a popular metric which is defined using several ratios, including tonnes per GDP (Cleveland and Ruth, 1998, EC, 2011b) and tonnes per area, volume, hour or service (Allwood et al., 2010, Eisenmenger et al., 2017, Gao et al., 2016). Industry often quantifies output-to-input ratios of metal contents to measure yield improvements, such as the output of steel per input of iron in steelmaking (worldsteel, 2009).

Recycling is, by far, the most widely studied ME intervention, and yet, it is measured by a confusing array of recycling metrics: recycling rates, recycled content (Allwood, 2014, Esch et al., 2010, Graedel et al., 2011), and scrap usage (BIR, 2016). Even within recycling-rate metrics, multiple definitions exist, each of which is designed for different "types of material cycles" and "sections of the materials life cycle" (Hashimoto, 2004).

Recently, ME has been re-branded as a circularity strategy. So far, however, no standardised circularity metric has been defined. Linder et al. (2017) compiled a selection of metrics, highlighting their benefits and shortcomings. For example, (Ellen MacArthur Foundation, 2015)) propose a mass-based metric, Material Circularity Indicator (MCI), for quantifying product circularity. The rest of the metrics reviewed are either based on life-cycle assessments (e.g. Eco-efficient Value Ratio by (Scheepens et al., 2016)), focused solely on recycling (e.g. Circular Economy Index by Di Maio and Rem (2015)) or based on cost (e.g. product-level circularity by Linder et al. (2017)).

The ME and CE indicators described above quantify specific aspects of material use but provide no indication of the energy or environmental implications of a given ME intervention. Cullen (2017) propose a Circularity Index to quantify the energetic implications of looping materials, defined as the product of two quantities: one measures the mass of end-of-life materials available relative to the total demand, while the others measures the energy needed for material recovery relative to that needed in primary production.

In a recent study, Shahbazi et al. (2017) review ME metrics currently used by manufacturers. The authors conclude that the literature does not address the practical aspects of "how to manage ME performance, how other indicators interact with ME measurements, and how they are connected to overall goal and strategy of company." A significant barrier to tracking resource interactions is the measurement of energy and ME indicators in different units. To resolve this, some academics promote the use of exergy to measure energy and material use in a single, integrated metric.

Exergy metrics

Exergy is defined as "the maximum theoretical useful work obtained if a system is brought into thermodynamic equilibrium with the environment" (Sciubba and Wall, 2007). Exergy has been predominantly applied as an engineering method to analyse the efficiency of production systems, and has been recognised as a promising decision-making tool to "locate inefficiencies and irreversibilities within [a] process or system" (Gaudreau et al., 2009).

The application of the exergy method has led to the use of exergy efficiency metrics as a way of measuring a process' efficiency. Exergy efficiencies are commonly defined as the ratio of exergy inputs to exergy outputs, and can include either energy or materials alone, or a combination of both. The numerator and denominator are measured in joules of exergy, yielding a dimensionless metric. Exergy, unlike energy, incorporates the first and second law of thermodynamics, allowing both resource quantity and quality to be measured.

Exergy efficiency definitions can be adapted to specific applications (Brodyansky et al., 1994, Marmolejo-Correa and Gundersen, 2012) depending on: the specific system level (i.e. whether a device or a sector); the nature of the transformations and losses involved (i.e. whether energy or materials are being transformed); and the particular purpose of the study.

One way of classifying exergy efficiencies is by distinguishing between total or rational definitions. The total exergy efficiency is described as the ratio of total output to total input exergy flows (Fratzscher and Beyer, 1981, Nesselmann, 1952). This original definition has been modified to account for external exergy losses contained in waste—denoted as *useful exergy efficiency*; its denominator is still the total amount of resource inputs, but the products are instead classified into useful and wasted streams. Conversely, rational efficiencies distinguish between energy and materials flows that undergo transformations—and that are therefore consumed—and those that remain un-reacted (Brodyansky et al., 1994).

The exergy concept has been widely advocated for within the academic community as a method to assess sustainability and to perform resource accounting (e.g. Costa et al. (2001), Masini and Ayres (1996)). Despite the recognised versatility of exergy metrics, the cumbersome nature of exergy calculations have hindered its use in production management (Khattak, 2016), benchmarks, and policy targets. However, more recently academics have provided clarity in the use of efficiency definitions for different processes, attempting thereby to standardise use (Cornelissen, 1997, Lior and Zhang, 2007, Renaldi et al., 2011, Tanaka, 2008). Allowing for the variations in definitions, it is thus possible to apply the RE metric, using units of exergy, across all sectors.

Brunner and Rechberger (2004) and Gaudreau et al. (2009) contend that using exergy to describe resource quality can be biased towards energy carriers. The exergy of fuels clearly reflects their function: providing heat (either directly or indirectly) to a process/reaction. For materials, however, quantifying the work that can be extracted from these may not be the most suitable measure for truly capturing their utility. In response to this, Bakshi et al. (2011) argue that the chemical exergy of materials is meaningful because it expresses the theoretical amount that can be saved if these are input as raw materials elsewhere.

2.3 Impact-based indicators

The multi-dimensional nature of RE means that a multitude of environmental impacts can be quantified, from toxicity to eutrophication, global warming potential or ozone depletion, among others. As a result, impact-oriented metrics are typically used as part of a basket of indicators, often in life-cycle analyses or input-output economic assessments. For example, in the EU-funded project *TOP-REF*, the authors propose a selection of 16 key indicators for use by production facilities in the process industries (Deloitte and CIRCE, 2014).

When addressing the challenge of decarbonisation, impact indicators often measure indirect or embodied energy (GJ/t) and emissions (tCO2/t) for specific products. For example, Milford et al. (2011) compute the embodied energy and emissions that could be saved by improving yields, whereas Cooper et al. (2014) use these to estimate the optimum life-time of appliances. Embodied exergy indicators have also been proposed by Szargut et al. (1988), including: cumulative exergetic consumption (CExC) as the sum of resources consumed across the entire production process of a material in units of exergy per tonne.

Some academics believe that indicators can only meaningfully inform decisions about RE performance if they combine all three aspects: physical, economic and environmental. At one end, Huysman et al. (2015) propose a systematised framework to classify all three types of RE indicators, where physical metrics are proposed at the micro-scale (i.e. gate-to-gate) and economic/impact indicators are proposed for the macro-scale (i.e. national and international). At the other end, Aghbashlo and Rosen (2018) propose a single metric to integrate all three aspects: eco-cost per value ratio – where eco-costs “represent the virtual prevention costs of [the] environmental burden[s] of a product, while the value shows its actual price or cost in the [...] economy”.

Table 4 depicts a selection of impact-based metrics found in the literature. Overall, impact-oriented indicators are useful for comparing the energy or emissions savings from various RE measures, for linking impacts to products/activities and assigning responsibilities to these (Barrett and Scott, 2012, EC et al., 2012), despite the utility of such measures being questioned (Allwood and Cullen, 2009, Ayres, 1995). Yet, impact indicators fail to capture the benefits of recovering material by-products, and summation of inputs across many processes makes it challenging to diagnose the cause of the loss for an single process.

Table 4: Review of impact-based resource efficiency metrics. Rep. stands for Replacement

Metric	Unit	Scope	Reference
Exergy Rep. Cost	GJ of exergy / tonne	From Global to Supply chain	(Valero et al., 2015)
Ecological Impact	Euros / Impact	From Global to Supply chain & Product	(Huysman et al., 2015)
Emissions Intensity	Tot. emissions / GJ energy	From Global to Plant & Product	(IEA, 2017)
Embodied Energy	Cum. GJ energy / tonne	From Global to Plant & Product	(Milford et al., 2013)
Emissions-Exergy Intensity	CO_2 emissions / GJ exergy	From Global to Site	(Eisenmenger et al., 2017)
Embodied Exergy	Cum. GJ exergy / tonne	From Global to Plant & Product	(Szargut et al., 1988)
Eco-costs	Euros / CO_2 eqv.	From Global to Supply Chain & Product	(Aghbashlo and Rosen, 2018)

The diversity of measured impacts makes it challenging to draw meaningful conclusions from impact-based indicators. Several options for aggregating these metrics have been proposed, including their weighting (Huppes et al., 2012), normalisation (Benini et al., 2014) and monetisation (Krieg et al., 2013). However, the process of combining multiple metrics is highly subjective and risks biasing one impact over another.

2.4 Metrics for further study

Three types of indicators were reviewed: economic, physical and impact metrics. Their relative advantages and disadvantages were investigated with the aim of assessing their suitability as indicators to measure and track resource efficiency in emission-intensive industries. As stated at the beginning of this paper, this study seeks to define a metric for RE that is able to appropriately capture the efficiency with which both energy and materials are transformed in production processes. This metric should help policymakers and industry firms make decisions on how to improve RE, and in doing so must: take account of resource interactions; be comparable across different processes and sectors; reflect both resource quantity and quality; be applicable at different spatial boundaries, and over varying temporal scales.

Based on this review, we conclude that economic indicators, although useful at tracking macro-level trends, provide only a limited understanding of the underlying physical flows involved in production. In practice, these are primarily used to inform high-level policy decisions. As a result, we support the view of Huysman et al. (2015) and IEA (2014*b*), who argue that to guarantee the transition to a resource-efficient industry it is necessary to complement economic indicators with market-independent ones. In fact, we believe that to conduct a sound economic analysis of an industrial system, there must first be an underlying understanding of its physical flows.

Impact-oriented metrics are designed for tracking upstream implications of resource use (e.g. emissions) and for assigning responsibilities to different products or materials. They are typically used to inform design decisions or to make comparisons between products at the downstream-end of the supply chain, where they can assist consumer choices. While essential to quantify achieved life-cycle emissions reductions of a product, impact metrics are not well-suited to stimulate and guide RE improvement actions at the operational level. Like economic metrics, impact-oriented indicators cannot directly measure the true distance to achieve RE goals because they fail to provide insights into process losses. Neither economic nor impact metrics reflect the real function of engineering systems, and understanding which is vital for identifying improvement opportunities.

We therefore conclude that physical, market-independent indicators are most appropriate to measure the RE of production processes in emissions-intensive industries. In fact, sound economic and impact-based analyses must be rooted on a detailed understanding of fully balanced physical flows. Physical indicators capture the underlying drivers of RE variations, can help producers “understand opportunities for action in a language that they are more comfortable with” and can drive the sector’s low-carbon transformation in a more targeted manner. This gives producers and policymakers increased confidence that targets are indeed achievable (IEA, 2014*a*).

To limit the scope of this analysis, a set of five physical-based metrics is selected for further analysis, as shown in Table 5. This selection includes metrics from each of the three physical categories: energy-, material- and exergy-efficiency. We selected the most-widely-used metrics from each category and avoided those narrowly measuring very specific measures, such as the material re-use rates or end-of-life-recycling indicator.

Table 5: Selected list of resource efficiency metrics for further evaluation.

Metric	Unit	Scope
Energy Efficiency	GJ of energy per GJ of energy	From Site to Unit
Energy Intensity	GJ of energy per tonne output	From Site to Unit
Circularity Index	Percentage (%)	Sector, Supply chain
Material Yield	Percentage (%)	Site, Plant, Process
Exergy Efficiency	Percentage (%)	From Global to Unit

2.5 What makes a good resource efficiency metric?

There are many ways of defining a ‘good’ metric. Neuhoff et al. (2009) define good indicators as “representations of quantitative or qualitative data, which can be used to understand the state of a problem, and illustrate the progress made towards obtaining a solution”. In most cases, whether a given metric is defined as ‘good’ or ‘appropriate’ depends on the specific application under consideration. No single metric will work for all purposes and across all existing applications, and equally no unique set of criteria will satisfy all opinions about what makes a good metric. Yet, a review of known criteria provides a basis to make an informed decision about which criteria to use.

The literature is a rich source of information about the criteria that companies, academics and policymakers deem useful. We reviewed eight studies to compile a list of the most popular criteria used for selecting and evaluating industrial performance metrics. Table 6 portrays the list of metric requirements (or criteria) which we thought were directly relevant to our study. This table is organised in terms of the banner criteria described in the RACER methodology (Best et al., 2008, EC, 2012), which we use to later evaluate the strengths and weaknesses of resource efficiency metrics. This method has been used to evaluate the criteria for RE metrics both within the context of industry applications (MORE, 2017) and that of policymaking (Best et al., 2008, EC, 2012).

The largest number of criterion are found under the category of *Relevance*. This makes sense given the wide range of views on what makes a metric relevant; it means different things to the different stakeholders involved across the production chain. For this study, *relevant* criteria were chosen from the point of view of industry practitioners and managers. These should reflect the requirements, which can provide guidance for the daily operations of a site or a single process equipment. Table 6, under the *Description* column, details what we mean by each criterion and briefly explains why they were chosen.

Table 6: Selection of possible metric evaluation criteria. Sources: A (Beisheim et al., 2017), B (Sfez et al., 2017), C (Neuhoff et al., 2009), D (IEA, 2014*c*) , E (Best et al., 2008) , F (EC, 2012), G (IEA, 2014*a*), H (IEA, 2008)

Criteria	Description	Sources
Relevance		
Resource Coverage	Must cover all relevant resources from which improvements can be realised or which affect other improvement measures. This typically means multiple resources, e.g. energy, materials, water and emissions if possible.	A, B
Scope, granularity	Should be applicable and multiple spatial and temporal scales, and should cover a substantial section of system (e.g. at least an entire facility)	A, B, C ,D
Sensitiveness	Indicator outputs should be affected by input parameters to pick up relevant changes, detect non-linearities, discontinuities, thresholds.	A, D, E
Stimulus	Indicator should incentivise the entire gamut of RE measures and incentivise improvements in the right direction. In this case, this means it must incentivise reductions in both resource use and emission generation.	B, E
Policy support Strategy support Operations support	Disaggregation – either spatial, by product, industry – must be possible as these are required for effective policy. For example, if decisions are made at local level, does the indicator provide required local information?	A, D, E
Target setting	Decision makers should be able to use indicator to track progress towards established climate objectives (e.g. GHG emission reductions). The metric should directly reflect RE and be related to the overall goal (e.g. resource or GHG emissions reduction). Must be able to define baseline.	A, E, G
Applicability	Indicator should be applicable to different process, equipment and sectors. It should allow meaningful comparisons across these systems.	A, C
Trends	It should allow for RE performance to be traced and tracked across time (i.e. using time series data).	E
Forecasting & modelling	Should be used in predictions to forecast future emissions and resource use or for modelling where impacts of different potential policies or technology progress and/or consumption patterns can be simulated.	E
Acceptance		
Policy makers Industry technical Industry financial Industry manager Academics	Underlying rationale and meaning of indicator should be accepted by multiple stakeholders (including academics, policy makers, corporate managers and technical staff). For effectiveness in communication, it should resonate with widely-held values and pains to motivate stakeholders to calculate or provide data and accept interpretations.	C, E, F
Credibility		
Easy interpretation	Message must be easily understood by decision-makers and practitioners. It should inform any RE action or decision.	C, E, G
Transparency	Underlying data and methods must be fully disclosed and reproducible.	F
Ambiguity	Should convey clear, unambiguous message, and should allow for clear conclusions to guide political & corporate action.	C, E
Easiness		
Data collection effort	Does not require data that are overly expensive or onerous to collect, or that cannot be properly measured; ideally based on data already collected & electronically available.	C, D, F
Complementary	Should complement other indicators collected and assessed by decision-makers to provide richer insights.	B, C, E
Technical feasibility	Methodology is simple enough to be deployed using software and expertise appropriate to application. Calculation methodology is clearly defined to avoid ambiguity and implementation errors.	C, D, E
Robustness		
Level of Subjectivity	Indicator should avoid use of subjective factors to weight components. If used, must at least be explicit and justified.	C, D, E, H
Theory soundness	Based on sound theory; avoids double-counting or omissions; is consistent; relies on clearly-stated assumptions, not require ill-defined parameters.	C, E
Accuracy	Should accurately depict function of the process under study and the mechanisms taking place (e.g. chemical conversions).	F
Completeness	Indicator should avoid shifting of burdens among single problem types.	D, F

The *Acceptance* category can include any of the stakeholders involved in the industrial sector. In this study, industrial technical, financial and managerial roles were selected as the most important, alongside policymakers and academics – both of which have the ability to influence industrial decisions. For the categories of *Credibility*, *Easiness* and *Robustness*, the choice of criterion were relatively consistent across the studies reviewed irrespective of the context in which they were applied. Overall, industry practitioners seek a metric that they can feasibly measure (i.e. that they have data for), understand and which they trust will take them in the right direction.

3 Methodology: the RACER evaluation

The methodology outlines the process undertaken to select the most appropriate RE metric available to support decarbonisation strategies. This process involves the selection of both relevant RE metrics from the literature and appropriate evaluation criteria. This section is divided into two. First, Section 3.1 where we define what we mean by resource efficiency. Second, Section 3.2 where we describe the evaluation methodology used and the choice of evaluation criteria.

3.1 Resource efficiency definition

Described generally, an efficiency provides a measure that relates the effect obtained from a process (output) to the effect supplied (input). Resource efficiency considers a broader picture than either energy efficiency or material efficiency by themselves. The multi-dimensional nature of resource efficiency (resource can mean many different things) results in the existence of many definitions of resource efficiency. To provide clarity for this paper, we define being resource-efficient as:

less resource inputs are required to produce a given output, be it a product or a service.

We are interested in assessing the effectiveness of the use of resources in production processes and the effect of resource efficiency on carbon emissions specifically. As such, we do not intend to advocate for a metric that quantifies associated environmental impacts.

3.2 Indicator evaluation methodology

When faced with a wide choice of possible metrics, it is valuable to have a framework that can assist in classifying the different metrics and providing nomenclature. This gives structure to information and allows the evaluation of the strengths and weaknesses of the considered indicators. In this study, we use the RACER methodology (Beisheim et al., 2017, Best et al., 2008, EC, 2012). RACER is an evaluation framework, which is applied to assess the effectiveness of indicators. It is normally applied in policy making, but can be equally insightful when assessing metrics at the more local levels, such as corporate or operational.

RACER is an acronym of the key criteria groupings in the method: Relevance, Acceptance, Credibility, Easiness and Robustness:

- **Relevance** – should be closely linked to the objectives to be reached;
- **Acceptance** – by process engineers, plant managers, policy makers, other stakeholders;
- **Credibility** – unambiguous, transparent and easy to interpret;
- **Easy** – monitoring and calculation of the metric should be feasible (e.g. data collection should be possible at low cost and reasonable level of expertise should be required);
- **Robust** – based on a sound theory and not susceptible to manipulation (e.g. subjective assumptions or allocations).

Figure 1 depicts the methodology followed in this study. It begins with a review in Section 2, where we evaluated the wide portfolio of resource efficiency metrics proposed in the literature, and provided a list of important criteria for industry practitioners and policymakers – as described in previous studies. Based on these two reviews, we propose a final selection of metrics and criteria to use in the evaluation process.

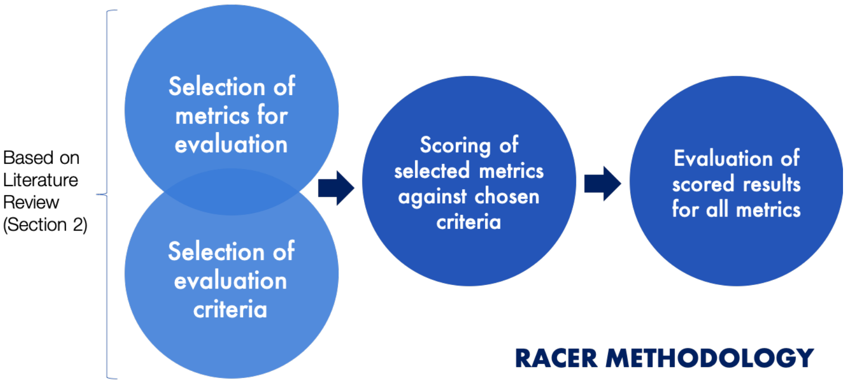

Figure 1: Implementation of RACER methodology.

For the selected metrics and criteria, a point-system is used to weigh the degree to which these criteria are met. This provides us with a score for each criterion. Three scores are used, corresponding to the level of success (2 = fully, 1 = partially or 0 = not achieved). A score of two points is allocated to a criterion if this is fully achieved, one point is given if it is partially achieved, and zero points if it is not achieved. It is only possible to provide one answer for each of the criterion.

The framework is designed to help us discern the strengths and weaknesses of the indicators under consideration. For this reason, it is helpful to treat the criteria as independent variables. The more suitable RE metrics should have good or acceptable scores in all five dimensions, with special emphasis on both its relevance and industrial acceptance. It is worth noting that there is a subjective dimension in this evaluation process. Two potential sources of subjectivity arise from: (1) the chosen list of criteria and (2) the different rankings for each criterion, based on the opinions of the various assessors. We have striven to reduce this subjectivity by reviewing the literature for suitable criteria and by allowing several assessors to score each metric.

4 Results

The results of the metric evaluation are presented in Table 7. The five chosen resource efficiency metrics are scored—0 (not achieved), 1 (partially), 2 (fully)—against 34 criteria grouped in five RACER sub-categories. The scores are presented in their raw form, without summation, to avoid any bias between sub-categories.

Figure 2 shows the breakdown of scores for each metric, with 0 (not achieved) in light blue, 1 (partially) mid-blue, and 2 (fully) in dark blue—with darker colours indicating a more effective metric.

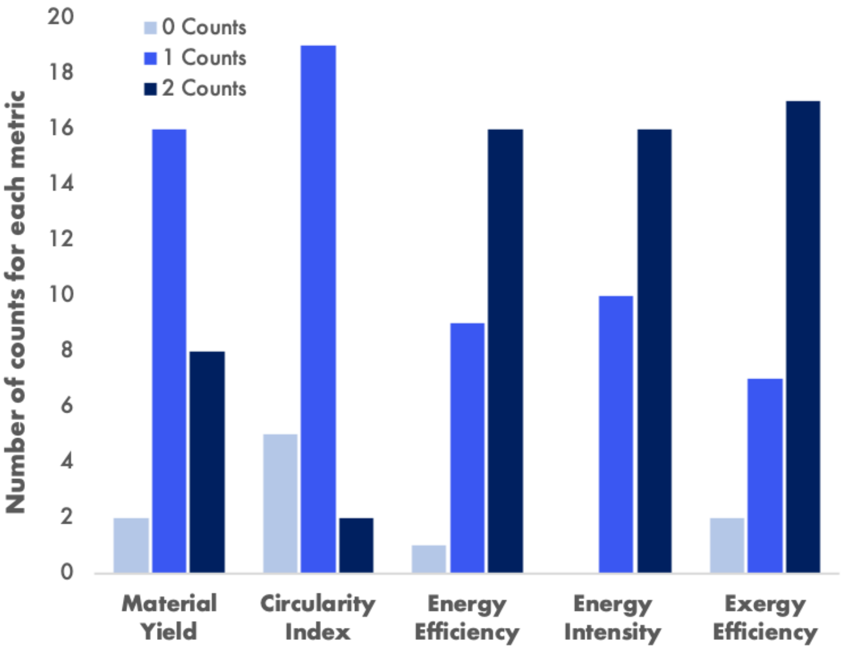

Figure 2: RACER evaluation results showing the number of counts for all the chosen metrics.

The Circularity Index scores the highest number of 'not achieved' criterion. From Table 7 we can see that this arises mainly from its lack of acceptance across stakeholders and its limited robustness. This makes sense given that the development of circularity-type metrics is in at embryonic stage. The circular economy, as is the case for RE, is a multi-faceted concept and this complicates the design of appropriate metrics to measure its progress. Circularity indices perform weakly under the *Relevance* banner. This is because most circularity metrics focus on measuring the mass ratio of recycled materials at the level of entire economies (Ellen MacArthur Foundation, 2015). They have limited scale-ability, to lower scales such as industrial processes, equipment or products, and fail to consider the energy-impacts of closing material loops (Cullen, 2017). Today, it is still early to determine whether they can provide the right type of stimulus and whether they are sensitive to changes experienced.

Table 7: Results from RACER evaluation for a selection of resource efficiency metrics. Scores: 0 (not achieved), 1 (partially), 2 (fully)

	Relevance											**Acceptance**					**Credibility**			**Easiness**			**Robustness**			
	Resource Coverage	Scope / granularity	Sensitiveness	Stimulus	Policy support	Strategy support	Operations support	Target setting	Applicability	Trends	Forecasting / modelling	Policy makers	Technical industry staff	Financial industry staff	Industry managers	Academics	Interpretation	Transparency	Ambiguity	Data collection effort	Complementary	Technical feasibility	Subjectivity	Theory soundness	Accuracy	Completeness
Material Yield	0	1	1	1	0	1	2	1	2	1	1	1	2	2	2	2	1	1	1	2	2	1	1	1	1	1
Circularity Index	1	1	1	1	1	1	0	1	2	1	1	1	0	0	0	1	1	1	1	1	2	1	1	1	0	1
Energy Efficiency	0	2	1	1	1	1	1	2	2	1	2	2	2	2	2	1	2	2	2	2	2	2	2	2	1	1
Energy Intensity	1	2	1	1	1	1	1	2	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	1	1
Exergy Efficiency	2	2	2	2	1	2	2	2	2	2	2	0	1	0	1	1	1	2	2	1	2	1	2	2	2	2

Material Yield, a mass-based ratio, is ranked as the second weakest metric, with mainly 1 (partially) scores. The metric is well accepted among stakeholders, especially so in industry (and academia) where it has been widely-adopted to measure the material efficiency of specific processes (Milford et al., 2011). It scores highly on *Easiness*—precisely because companies have been collecting material yield data for a long time. However, it scores much lower in the *Credibility* category because yield rates are defined in multiple different ways, dependent on the materials involved and the choice of system boundaries (worldsteel, 2009). There is no unique, established method with which all industries, or even facilities within a given industry, measure their yield rates. This makes the metric suitable for targeting improvements at the process level, but not for comparison between processes or analysis at wider scales.

Energy Efficiency, Energy Intensity and Exergy Efficiency all score highly, with many 2 (fully) scores. This reflects their overall effectiveness as performance metrics in industry. Given the subjectivity of the scoring, it is difficult to discern which of these metrics constitutes a better metric of resource efficiency. For now, Energy Efficiency, Energy Intensity and Exergy Efficiency are taken forward as preferred metrics for further analysis.

In Figure 3 we explore the comparison between metrics in more detail. Here the scores in each of the five sub-category are summed and plotted by metric to explore how each metric scores within the five sub-categories.

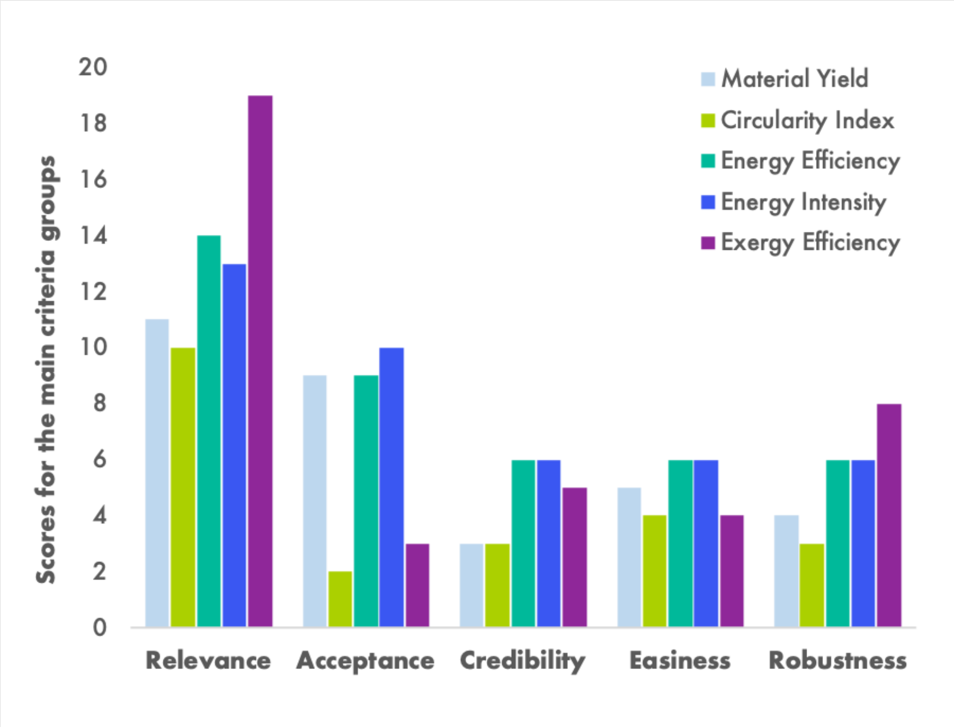

Figure 3: RACER evaluation results showing the scores of each metric under the five banner criteria.

Energy Efficiency and Energy Intensity score almost identically across all categories, reflecting their similarity as metrics in scope and coverage. Energy Efficiency measures the output product in units of Joules when it is applied to energy-transforming processes (e.g. motors, pumps), whereas Energy Intensity measures the output product in units of mass as it is used to quantify the performance of material-transforming processes (e.g. reactors, metal furnaces etc.). Both metrics have been widely employed industry, which explains their high scores within the *Acceptance* and *Easiness* categories. In contrast to Material Yield metrics, Energy Efficiency and Energy Intensity have been widely standardised within industry sectors (UNIDO, 2010, Worrell et al., 2008), reducing the scope for manipulation and ambiguity.

Energy Efficiency and Energy Intensity can be applied at multiple temporal scales and scopes, as shown in Table 7. Both metrics are often used for setting targets at at varying system levels, from national objectives to corporate or operational benchmarks. Policymakers and industry managers use such metrics to help close the emissions gap (IEA, 2017) by targeting energy reduction. They are partially successful in incentivising resource efficiency, but miss most material-related interventions (e.g. reducing yields, increasing re-use, recycle, recovering material by-products). This is because the metrics omit materials from their resource coverage, beyond the product output in mass in the case of Energy Intensity. As such, they score weakly for supporting policy, strategy and operational decisions.

The last of the preferred metrics to evaluate is Exergy Efficiency. Figure 3 shows that Exergy Efficiency scores higher than the other metrics in the category of *Relevance*. This reflects its ability to cover a wider range of resources and its capacity to scale across temporal and spatial levels (Gonzalez Hernandez, Lupton, Williams and Cullen, 2018, Gonzalez Hernandez, Paoli and Cullen, 2018, Masini and Ayres, 1996). Whereas, Energy Efficiency and Energy Intensity score higher for *Acceptance*, the slower uptake of Exergy Efficiency as an accepted and widely used metric is revealed. Exergy Efficiency is slightly weaker across *Credibility* and *Easiness*, reflecting two considerations: (1) it requires additional data to be collected, which affects its technical feasibility; (2) it is poorly understood among practitioners.

These results show that, although the preferred three metrics have a similar score profile across all the criteria (Figure 2), there are clear disparities at the sub-category level. Here Exergy Efficiency is scored as having the highest *Relevance* and *Robustness*, traits which are inherent to the metric and cannot be changed, but scores much lower for *Acceptance*, *Credibility* and *Easiness* in areas which could be improved with better education and dissemination (Viglietta, 1990). This would suggest that Exergy Efficiency may still have unrealised potential as a measure of resource efficiency.

5 Discussion

From the metrics reviewed, Exergy Efficiency is the only one which covers both energy and materials in a single indicator. It has been shown to rank highly as an effective metric for measuring Resource Efficiency, specifically in the areas of Robustness and Relevance – both of which are inherent traits that are key in the deployment of effective metrics at all management levels. This suggests that Exergy Efficiency could be a potential lever to drive the decarbonisation transition of resource-intensive industries.

The benefits of using exergy as a measure of RE can be summarised as follows:

- Exergy makes it possible to characterise energy and material-transforming processes more easily and to neatly combine measures of energy and material use in a single metric. Both mass and energy balances alone fail to show the upgrade in material quality that is enabled through the degrading of high-value fuels into low-value heat.
- Exergy allows energy and material to be integrated into a single value. This enables a dimensionless efficiency metric to be defined and allows comparison of efficiencies between industry sectors.
- Exergy reflects the *quality* of a resource, giving insight into *which* material or energy streams are worth recovering: streams with high exergy content have more potential for value extraction. Its foundation on the second law of thermodynamics provides an engineering understanding of the irreversibilities generated during production.
- Exergy captures the benefits associated with improving the recovery of material by-products, such as slag or slurry, which cannot be achieved using energy-based metrics.
- Exergy studies are common in literature demonstrating that a well-established procedure exists to quantify exergy efficiency. This ensures the traceability and repeatability of exergy analysis measurements.

Tables 8 and 9 provide further evidence to support the final choice of Exergy Efficiency as the most suitable Resource Efficiency metric for both policymakers and industry practitioners. The evidence is comprised of academic papers where specific criterion for the Exergy Efficiency metric have been met. These tables also show the scoring for the Exergy Efficiency metric as presented in Table 7 (under the heading RE) and specify a description for each criterion. Based on these results, the remainder of this section explores, in more detail, the implications of using exergy as a measure of Resource Efficiency in industry.

5.1 Integrating energy and materials

Historically, efforts to reduce industry's carbon emissions (and energy use) have been limited to energy efficiency measures, i.e. reducing the direct use of fuels and recovering waste heat. In recent years, insights into the links between efficient material use, and energy and emissions, have been created several new fields including: material efficiency (ME), resource efficiency (RE), life-cycle thinking and circular economy (CE). Yet, none of these concepts in practice deal with the interactions between energy and materials found in industry. The production of materials involves a myriad of processes, constituting a complex network of interactions between energy and materials. Savings in energy and emissions are not only possible through reductions in fuel use or recovery of waste heat (energy efficiency options), but are also available through reductions in material use (material efficiency options). Energy and materials should be considered together.

Table 8: Evidence of criteria fulfilment from the literature

Criteria	RE	Description	Proven in, for example...
Relevance			
Resource Coverage	2	Quantifies and captures energy, materials and water flows, can also account for emissions.	(Costa et al., 2001, Gonzalez Hernandez, Paoli and Cullen, 2018, Valero et al., 2015, Wu, Wang, Pu and Qi, 2016)
Scope and granularity	2	Is applicable to measure performance at all system levels, from global analysis to equipment-level assessments.	(Costa et al., 2001, Luis and Van der Bruggen, 2014, Wu, Wang, Pu and Qi, 2016)
Sensitiveness	2	It is sensitive to changes in input variables. It will reflect a change if a relevant variable is modified.	(Costa et al., 2001, Flórez-Orrego and de Oliveira Junior, 2016)
Stimulus	2	It incentivises the entire gamut of RE measures, and allows material efficiency to be placed on equal footing to energy efficiency.	(Finnveden and Östlund, 1997, Wu, Qi and Wang, 2016)
Policy support	1	Disaggregation is possible to the required system boundary. The metric provides the required information at the level at which the decision needs to be taken. It can be used at the global, regional level at a level of years and months.	(Eisenmenger et al., 2017, Gonzalez Hernandez, Cooper-Searle, Skelton and Cullen, 2018, Valero et al., 2015)
Strategy support	2	It can be used at the yearly, monthly, weekly for sites and plants, which would be the appropriate level for strategy planning.	(Khattak, 2016, Luis and Van der Bruggen, 2014)
Operations support	2	It can be used at the daily, hourly and real-time level for plants, processes and units, which would be required for operational support.	(Flórez-Orrego and de Oliveira Junior, 2016, Ostrovski and Zhang, 2005, Wu, Wang, Pu and Qi, 2016)
Target setting	2	Decision makers can use it to track progress towards established emission reductions. There is link between RE and emissions, and can be quantified for different sectors. Baseline can be defined.	(Valero et al., 2015, Wu, Wang, Pu and Qi, 2016)
Applicability	2	Can be applied to any resource-intensive industry, and across any type of physical or chemical conversion process.	(Luis and Van der Bruggen, 2014, Masini and Ayres, 1996, Szargut, 2005, Szargut et al., 1988)
Trends	2	This metric can track resource efficiency across time and relative to other production systems. It can do so at multiple temporal scales.	(Costa et al., 2001, Gonzalez Hernandez, Lupton, Williams and Cullen, 2018, Valero et al., 2015, Wu, Wang, Pu and Qi, 2016)
Forecasting & modelling	2	Predictions of future resource efficiency can be made using this metric. CO2 emissions can then be calculated based on these. Information on specific measures improving efficiency may be needed to do this.	(Flórez-Orrego and de Oliveira Junior, 2016, **?**, **?**)
Acceptance			
Policy makers	0	Little awareness and some resistance, it does however resonate with many other values on circular economy and decarbonisation	(Ayres et al., 2011, Gonzalez Hernandez, Cooper-Searle, Skelton and Cullen, 2018)
Technical industry staff	1	Relatively well accepted and understood	(Gonzalez Hernandez, Lupton, Williams and Cullen, 2018)
Financial industry staff	0	Little awareness and some resistance. Yet, it mirrors value more closely than conventional energy analyses.	No evidence that of use to support financial decisions
Industry managers	1	Some awareness and relatively well accepted	
Academics	2	Widely accepted even with different interpretations & applications	(Costa et al., 2001, Masini and Ayres, 1996, Valero et al., 2015, Wu, Wang, Pu and Qi, 2016)

Table 9: Evidence of criteria fulfilment from the literature cntd.

Criteria	RE	Description	Proven in, for example...
Credibility			
Easy interpretation	1	Exergy remains an esoteric concept for non-experts (including industry practitioners and policymakers), still requires some explanation, although many academics are focusing lots of efforts into socialising the concept.	(Dincer and Rosen, 2007, Gaudreau et al., 2009, Khattak, 2016)
Transparency	2	Calculation methods have been documented by many academics and many tools are available to support it (e.g. exergy calculators). Well established method.	(Bakshi et al., 2011, Brodyansky et al., 1994, Dincer and Rosen, 2007, Szargut, 2005)
Ambiguity	2	Calculation methodology is clearly defined to avoid ambiguity, although some dispute exists around how metric may be interpreted.	(Brodyansky et al., 1994, Dincer and Rosen, 2007, Szargut, 2005, Szargut et al., 1988)
Easiness			
Data collection effort	1	Requires more effort than conventional energy efficiency analysis; we require additional material flow data, temperature, pressure and composition information. A lot of this is often already measured by production plants. It does, however, require greater data integration efforts as energy and material data quality can be very different.	(Flórez-Orrego and de Oliveira Junior, 2016, Gonzalez Hernandez, Paoli and Cullen, 2018, Wu, Wang, Pu and Qi, 2016)
Complementary	2	Provides richer insights into performance of production systems. Captures interactions between resources and provides more realistic account of functionality than conventional energy or material metrics.	(Duflou et al., 2012, Masini and Ayres, 1996, Valero et al., 2015, Wall, 1988)
Technical feasibility	1	Calculation methodology is clearly defined and documented. May require additional expertise.	(Costa et al., 2001, Khattak, 2016)
Robustness			
Level of Subjectivity	2	Subjectivity often arises when allocations are required. This is not the case with this metric, as we are not assigned responsibility to downstream processes (as is the case with impact-oriented metrics)	(Bakshi et al., 2011)
Theory soundness	2	It is based on well-established thermodynamic concepts, which are market-independent	(Masini and Ayres, 1996, Szargut, 2005, Valero et al., 2015, Wall, 1988)
Accuracy	2	It offers a more realistic representation of the functionality of processes because: it is based on the 2nd law of thermodynamics; it incorporates materials into the same metric, and it captures the quality as well as the quantity of resources.	(Gaudreau et al., 2009, Khattak, 2016, Szargut et al., 1988)
Completeness	2	By virtue of covering more resource types and being applicable across many system levels and industry sectors, it helps avoid burden shifting	(Bakshi et al., 2011, Masini and Ayres, 1996, Szargut, 1986)

A common analytical framework is the first step towards a unified resource efficiency narrative. Yet this is in fact hindered by the current widespread use of Energy Efficiency, Energy Intensity and Material Yield metrics. Among the physical-based indicators, energy-intensity metrics ignore the value of material by-products and material inputs, fail to reflect upgrades in material quality and are difficult to compare across different processes and industries. Material Efficiency and Circular Economy indicators focus solely on tracking materials and the effectiveness of specific material improvement strategies (i,e. waste reduction, recycling or reuse). The measurement of efficiency in mass units fails to capture changes in resource quality along process chains. Furthermore, their failure to consider the energy or emissions impacts of such strategies, can lead to the unintended consequences: recycling of some materials can lead to even more emissions than virgin production (Cullen, 2017).

Many practitioners from industry, academia and policy fields have come to the conclusion that an integrated metric to measure both energy and materials is required. Gonzalez Hernandez, Cooper-Searle, Skelton and Cullen (2018) undertook in-depth interviews with industry practitioners and policymakers, with almost all agreeing that it is either necessary or beneficial to integrate the analyses of energy and materials into a single metric. One explained: *"I'm totally bought into the idea that [...] you need a balance[d] understanding of what's the energy and material implications or consequence of a decision that's made"*. Another interviewee explained that it is necessary to *"broaden out the understanding that energy is just one resource input that goes into the broader industrial production process; that there are other materials and inputs that are associated with that and there the efficiency which with they use and through which the waste of those resources is reduced is also very important"*.

Additional evidence of industry's acceptance of exergy as a tool to measure resource efficiency can be found in Khattak and Greenough (n.d.). The author also interviewed many industry practitioners, and their responses can be found in the Appendix.

An exergy-based RE metric offers a solution to resolve these issues. Exergy allows energy and material flows to be consolidated into a single metric, based on well-known thermodynamic principles. Using one single number to track resource efficiency may seem overly simplistic, but in this case, an appropriately-designed number can become an enhancement. Collapsing energy and materials into a single measure reduces the number of variables to be tracked while at the same time providing a more complete and nuanced picture of a system's RE.

5.2 Spatial and temporal scalability

There are many advantages in having a single RE metric which can be applied across different spatial boundaries and temporal scales. Currently, there is frequently a mismatch between the indicators used at the equipment and process scale (i.e. energy efficiency and material yield, calculated in real-time) and those used at the national and global scale (i.e. resource productivity and circularity, calculated annually). This creates a need for expert translators, who can gather bottom-up data from company surveys and convert these into high-level indicators, and much effort is expended in sorting out the discrepancies that result.

When it comes to metrics, it is often said that what gets measured gets done. Yet, industrial process systems are complicated, requiring the reinterpretation of metrics at each stage of the management chain. Highly aggregated data (at a level of weeks, months or years) is commonly used at high-management levels to understand general trends and the overall amount of savings available. Whereas, engineering staff, typically work with detailed data at time-scales of minutes, hours or days to solve safety, stability and reliability issues. If the operators at the plant floor lose sight of the overall objectives of resource efficiency and decarbonisation, then improving RE globally can become a challenge. Having a fully scalable RE metric is no small accomplishment, as it requires complete line of sight along the management chain and gives full visibility to operators at the plant floor.

Exergy efficiency provides a universal metric which can be applied at all spatial and temporal scales. Exergy analysis is commonly used in across the full range of spatial scales, from global analysis (Cullen and Allwood, 2010), to nations (Eisenmenger et al., 2017, Serrenho et al., 2014), sectors (Wu, Wang, Pu and Qi, 2016), and processes (Liu et al., 2015). In addition, it is simple to aggregate exergy data along the temporal scale, from seconds to years.

As bottom-up real-time data from equipment and devices becomes more prevalent, there is an opportunity to gather raw data and aggregate this up through the spatial and temporal scales for higher-level analysis. This would allow companies to see the RE of their entire fleet of plants, or annual RE accounts to be collated and compared between countries. In addition, any discrepancy discovered at a higher spatial or temporal scale could in turn be investigated at a more granular level. In this way, the flexibility and transparency of financial metrics, which can scale from individual purchase transactions to long-run economic trends, could be similarly applied to resource efficiency. This using the scalable properties of exergy.

5.3 Driving industrial decarbonisation

Evidence suggests that the decarbonisation potential of resource efficiency measures is vast (Allwood et al., 2010, Circle Economy, 2019). For the energy-intensive industry sectors alone, the potential contribution of material efficiency is predicted to provide 10-12% of the carbon emission savings required to prevent 1.5° average temperature rise (IEA, 2017). To unlock this potential, however, current energy efficiency and ME metrics must be reconciled into a single production performance metric.

It is commonly understood that reducing energy use results in emissions savings, for fossil-fuel-based energy supplies. However, less obvious is the emissions savings resulting from improving material efficiency. Neglecting the impact of material use in emission mitigation efforts gives only partial insight into the emission savings. Furthermore, energy efficiency and material efficiency interventions should be assessed together to avoid trading one against the other. Energy-intensive industries must therefore be equipped with actionable metrics that allow the leveraging of the full gamut of RE options.

While tracking emissions is essential for understanding measuring progress against targets and holding actors to account, they provide only limited insight into the most effective actions required to decarbonise industrial production systems. Emission-based metrics—such as total annual GHG emissions, GHG per unit of gross domestic product (GDP) or production—indicate how well an economy, sector or plant is doing, but fail to reveal which actions have influenced the results or where to focus next. The linking of exergy efficiency metrics to carbon emissions, can reveal the potential impact of interventions which aim at improving resource efficiency, thus closing this missing gap in understanding.

Our belief is that focused RE metrics are more effective at catalysing change for multiple reasons. They can:

- Help producers understand opportunities for action in a language that they are more comfortable with;
- Reframe the decarbonisation challenge positively, as an opportunity to be seized as opposed to a burden to be carried;
- Drive sector transformation in a more targeted manner and in doing so, provide producers and policy makers with increased confidence that targets can be achieved.
- Provide deeper insight into the underlying drivers of change and can track interventions with long-term as well as short-term impacts.

Tracking exergy efficiency allows the impacts of changes in energy use, on material inputs and material by-products to be quantified, and vice-versa for the impact material changes have on energy use. Furthermore, exergy can still be compared as ratios to other economic or impact variables, such as resource cost or carbon emissions, but halves the number of indicators required to do so. This opens up hitherto neglected opportunities to reduce overall energy use and emissions.

5.4 Improving accessibility and uptake

There is little doubt that exergy metrics can be made more accessible to non-expert audiences (Sousa et al., 2017). Once a metric has been mainstreamed, people are comfortable using it even if they do not understand the intricacies behind it. The metrics of gross domestic product (GDP) or internal rate of return (IRR) are just two examples where metrics have been widely adopted despite the limited understanding of how they are calculated.

One option for improving the accessibility of exergy analysis and efficiency to non-expert audiences is the use of Sankey diagrams. Presenting mass-flow, energy-flow and exergy-flow diagrams for the same process system, helps show how exergy is calculated and interpreted in practice. Recent efforts to translate the principles of exergy analysis into software solutions, with databases of exergy conversion factors and Sankey visualisation tools, shows much promise (Gonzalez Hernandez, Lupton, Williams and Cullen, 2018, Gonzalez Hernandez, Paoli and Cullen, 2018). These have the potential to extract large quantities of data from industrial process control systems and produce real-time resource flow maps for plant managers. Automation of data collection and analysis could soon make integrated exergy analyses a feasible practice in industry firms. If combined with appropriate resource efficiency methodologies, the access to more and higher-quality, bottom-up data has the potential to help companies and governments make better-informed decisions about how to reduce industrial resource use.

Other pursuits that would facilitate the socialisation of exergy metrics in industry and policy-making practices include: (1) the development of internal training programmes for engineers, plant managers and industry practitioners in general, so that they are comfortable with implementing exergy methodologies and interpreting exergy metrics; (2) the development of a standard exergy efficiency and exergy auditing methodology for industry practitioners endorsed by international standardisation bodies, so that there is a universal language among practitioners (like with LCA today); (3) the support (and endorsement) from industry trade associations (such as worldsteel or worldaluminium) and other influential international organisations such as the International Energy Agency.

Academic papers on their own do not make a metric popular. For an exergy-based Resource Efficiency metric to be socialised, a broader consensus across policy makers, scientific experts and industrial communities is necessary. However, making an informed proposal which champions the RE metric is a prerequisite to achieve such consensus. This is especially important at a time where it is increasingly urgent to develop more appropriate RE tools to support decarbonisation strategies.

6 Conclusions

Providing industry firms with the necessary tools to measure and improve resource efficiency is crucial. This paper provides a review and evaluation of metrics that might be used to measure resource efficiency and drive industrial decarbonisation. Results suggest that an exergy-based metric can offer a more complete and universal measure of resource efficiency.

We find Exergy Efficiency to be: *holistic*, because it covers entire systems; *flexible*, because it can be applied at any system level; *integrated*, because exergy consolidates energy and materials into a single framework, capturing the interactions between these; *transparent*, because all physical resources are included, thereby preventing burden-shifting. Furthermore, Exergy Efficiency provides a basis for incentivising the reduction of raw-material inputs and the recovery of material by-products, neither of which is captured in conventional energy metrics. It is also useful for driving industrial decarbonisation, as the efficient use of energy and materials directly impacts carbon emissions.

What is clear from the results, is that Exergy Efficiency requires further advocacy if it is to be accepted as a mainstream measure of resource efficiency. The metric, in our view, is no more complex to calculate that many common industrial and financial KPIs (Key Performance Indicators). However, more work is required to provide simple guides, training and software tools, to facilitate wider use of Exergy Efficiency. We hope that this paper, is a first step towards demystifying Exergy Efficiency and will spur further discussion about the use of Exergy Efficiency metrics for measuring Resource Efficiency.

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