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A quantitative and holistic circular economy assessment framework at the micro level

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ABSTRACT

Circular Economy (CE) aims to solve resource, waste, and emission challenges by creating a production-to-consumption supply chain that is restorative and environmentally benign. A variety of metrics has been developed with the focus mainly on the macro and meso levels. This work introduces a micro level CE assessment framework that provides i) a set of indicators and metrics with sector-specific dimensions, ii) quantitative and holistic CE overall and category-based metrics, iii) media for data visualization and analysis of CE indicators, and iv) an analytical tool to assess multi-national businesses and the multi-scale and interconnected CE supply chains. Using this quantitative tool, companies are able to track their transition towards CE, conduct temporal analysis, and benchmark their performance against their peers and industry's standards. The applicability and the capabilities of the developed CE assessment framework is demonstrated through three case studies, with the results demonstrating a clear trend towards circularity.

1. Introduction

The unprecedented economic development and the social advancement that occurred over the last centuries were inextricably linked to a "take-make-waste extractive" industrial model, which placed huge stresses on the natural resources and led to enormous negative environmental and socioeconomic impacts (MacArthur et al., 2013; Mukhi et al., 2020). The concept of Circular Economy (CE) has emerged as a potential solution to this issue, contributing to all dimensions of sustainable development (Suárez-Eiroa et al., 2019). It promotes the transition to renewable energy sources (Gallagher et al., 2019; Mathur et al., 2020; Hao et al., 2020), designs out waste and pollution (Lacy and Rutqvist, 2016; Malinauskaite et al., 2017; Jensen and Skelton, 2018; Zhang and Yeung, 2012), and focuses on improving recycling processes (Haas et al., 2015; Di Maio et al., 2015; Pagliaro and Meneguzzo, 2019). Moreover, it decouples growth from the consumption of natural resources (Stahel, 2016), and eventually leads to the regeneration of natural systems (MacArthur et al., 2013; Baratsas et al., 2021c). To this direction, the full exploitation of synergies among pioneering business models, revolutionary products' design and new systemic conditions is necessary (MacArthur et al., 2013; Nie et al., 2019; Baratsas et al., 2021b). In parallel, systematic and quantitative approaches are needed to identify, exploit and assess alternative pathways for production, distribution and recycling, ensuring that the CE goals related to the optimization of resources' consumption and minimization of the environmental burden are thoroughly captured and implemented (Saif et al., 2017; Mannan et al., 2018; Feng et al., 2020).

Despite the fact that CE has gained a lot of attention across various disciplines and it seems a rather straightforward concept, it still generates confusion among the involved parties. This is due to the vagueness of the definition, its extensive and universal nature as well as its lack of specificity in the implementation (Kirchherr et al., 2017; Reike et al., 2018). Therefore, and before proceeding with any further analysis, it is important to clarify this vagueness and specify the goals and objectives of CE.

CE was founded on the principles of the triple bottom line (TBL) (Elkington, 1997) as an intentionally designed restorative, regenerative and environmentally benign system that promotes the concepts of reduction, reuse, recycling

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and recovery. CE aims to attain sustainable development through innovation and disruption at the three systemic levels i.e. **micro level** (product, individual enterprises, consumers), **meso level** (industrial symbiosis, eco-industrial parks) and **macro level** (city, region, nation, globe) (MacArthur et al., 2013; Saidani et al., 2019; World Economic Forum, 2014). Ultimately, nature must be preserved and enhanced by optimizing the re-circulation of materials, resources and products, while improving the integration and efficiency of renewable resources. Any negative externalities should be eliminated (Bouton et al., 2016) and the material loops should be closed.

Furthermore, CE should be perceived as a roadmap or a toolbox to achieve sustainability. This can be done through the utilization of CE targeted practices and synergies towards the implementation of the majority of the sustainability goals (Schroeder et al., 2019). Geissdoerfer et al. (2017) concluded that academic researchers deem three relationships between CE and sustainability: 1) CE being a condition for sustainability, 2) CE and sustainability having a beneficial relationship, or 3) a trade-off relationship between CE and sustainability. This can lead to the inference that a subset relation between the two concepts is adequate, which also coincides with the general understanding of CE as a concept that entails two of the three dimensions of sustainability, while lacks social considerations (Kirchherr et al., 2017; Kravchenko et al., 2019). Recent literature reviews of CE metrics and indicators are also in agreement with this argument, claiming that the social dimension is the least covered one (Sassanelli et al., 2019; Saidani et al., 2019; De Pascale et al., 2020).

1.1. Key Contributions

The effective and the successful implementation of CE practices on a global scale requires systematic assessment of the alternative pathways and scenarios along with the development of holistic metrics to evaluate the different aspects of CE (Avraamidou et al., 2020; Silk et al., 2020). This presumes a clear and solid understanding of what needs to be measured and assessed, before considering how this will be measured, what are the metrics to be used and against what benchmarks the CE implementation should be evaluated and the CE targets must be set (Baratsas et al., 2021a).

To this respect, in this work a quantitative and holistic CE assessment framework for the micro level is presented. "MICRON" *(MIcro CirculaR ecOnomy iNdex)* is a Global Reporting Initiative (GRI) Standard based tool that takes into consideration all the goals and objectives of CE holistically while assessing the circularity of companies. Based on CE goals and objectives, a set of principal categories is defined so as to establish transparency and clarity in the scope and goal setting. Four sectors are introduced to classify the economic activity and to improve granularity. Then, sector specific indicators and metrics that are matched with GRI standards are used for each of the principal categories. This structure enables the assessment of circularity at the category's level, leading to the derivation of the Category-based Circularity Index (CCSI). The linear average of the category-based indices constitutes the Overall Circularity Index (OCI).

The framework provides i) a set of indicators and metrics with sector-specific dimensions, ii) quantitative, holistic and robust CE overall and category-based metrics, iii) media for data visualization and analysis of CE indicators, and iv) an analytical tool to assess multi-national businesses and interconnected CE supply chains.

The explicit incorporation of CE goals and objectives as assessment criteria, the classification of economic activity into distinct parent sectors, the conception of GRI matched, sector specific indicators and metrics are key contributions of the proposed framework to the literature. The metrics are normalized and standardized using sector specific relevant information, ensuring that assessments are up-to-date and dynamically adjusted. Overall, the high level of granularity covering all CE goals, the comprehensive nature of the framework and the enhanced interpretability are key features and important contributions of the framework.

The rest of the paper is organized as follows: A literature review is discussed in the second section, revealing key challenges for CE assessment at the micro level. Section 3 is divided into two subsections: the first one provides a detailed description of the proposed framework with an illustrative example, its structure, the selection of indicators and metrics as well as the procedure for the collection and analysis of data. The second subsection presents the case studies of multiple companies in three different sectors. The results along with extensive discussion of this analysis including comparison among the companies and sectors are presented in Section 4. Finally, conclusions and future work are discussed in Section 5.

2. Literature Review

A plethora of approaches and metrics have been proposed in the literature to measure different aspects of CE (Parchomenko et al., 2019; Roos Lindgreen et al., 2020; Elia et al., 2017; Cayzer et al., 2017a; Saidani et al., 2017), without consistency in their objectives, scopes, and potential applications (Saidani et al., 2019). Nevertheless, the CE assessment still lacks standardized methods (Vinante et al., 2020; Kristensen and Mosgaard, 2020; Sassanelli et al., 2019; De Pascale et al., 2020), while even the used terminology has not be formalized yet, i.e. metrics vs. indicators. Such a plethora of different approaches and metrics create confusion and ambiguity to the involved parties (Fiksel et al., 2012; Vinante et al., 2020), and set a barrier towards the prevalence of the CE concept (Åkerman, 2016). Undoubtedly, CE related measuring and assessment tools at the different systemic levels are necessary for the transition towards CE systems (Geng et al., 2012; Su et al., 2013; Ghisellini et al., 2016), and eventually sustainable development (Council, 2016; Saidani et al., 2019; Kristensen and Mosgaard, 2020). Despite that numerous CE indicators, metrics and assessment tools have been reviewed and proposed over the last years, the research and discussion is still ongoing at every level (De Pascale et al., 2020). Here, we briefly discuss some of the key outcomes from reviewing the recent literature.

Elia et al. (2017) highlighted a lack of CE indicators, measuring tools and standardized ways to assess circularity, especially in the micro level, which is in line with the findings of other researchers (Saidani et al., 2019; Howard et al., 2019; Kristensen and Mosgaard, 2020; Vinante et al., 2020). Elia et al. (2017) proposed a four level framework for CE assessment at the micro level, which did not capture all the CE characteristics, since the main focus was in the environmental evaluation. Saidani et al. (2019) categorized 55 indicators from the academic and business world into 10 groups based on the main CE features and characteristics as well as their potential usage i.e. level of implementation, performance, usage, degree of transversality etc. A CE indicator selection tool based on user's requirements was also presented. Parchomenko et al. (2019) analyzed 63 CE metrics based on 24 CE elements using a Multiple Correspondence Analysis (MCA). They assessed the interconnections of metrics and elements as well as the most and least frequently elements used, but their analysis did not recommend what CE characteristics need to be evaluated. Waste disposal, primary vs. secondary use of resources, resource efficiency/productivity and recycling efficiency were the most popular CE elements assessed, while preservation of value and product and system dynamic elements were poorly represented.

Moraga et al. (2019) developed a classification framework based on six CE strategies and three measuring scopes in line with the Life Cycle Thinking (LCT) by considering the CE as an umbrella concept without been limited by indicators' definitions. Nevertheless, the proposed framework cannot adequately capture the causality between CE and sustainability development, while it cannot support neither the distinction of CE indicators for inputs and outputs nor for the retention of functions. Sassanelli et al. (2019) presented another classification framework for CE assessment metrics using the product life-cycle stages, variables and circularity degree as criteria. Based on the results from its application in 45 papers, they proposed a framework for evaluating the circularity of companies under the TBL concept. The analysis revealed a lack of an overall CE evaluation with just half of the cases been analyzed under a mixed lifecycle stages perspective and a rather strong concentration on the environmental and material aspects. Similar findings were reported by Corona et al. (2019), with none of the assessed metrics been able to fully capture the CE or the three dimensions of sustainability, while little emphasis was put towards reviewing the scarcity and multi-functionality of materials or the importance of introducing new waste valorization techniques.

After reviewing 137 articles published over the last 20 years, De Pascale et al. (2020) identified 61 CE indicators using a double classification that takes into account the spatial dimensions of sustainability i.e. micro, meso, and macro, as well as the 3Rs core principles i.e. reduce, reuse, and recycle. The lack of systematic and standardized methodologies to evaluate and assess CE comprehensively at the different levels along with the known vagueness on what needs to be measured was reaffirmed. It was also shown that less than half of the indicators cover all the sustainability dimensions or all the 3Rs principles while none focus specifically on the social dimension. Also, just 13 CE indicators cover simultaneously all the sustainability dimensions and 3Rs core principles, with only one though been used at the micro level. Thus, it appears that the assessment and evaluation of CE and sustainable development at the company/product/consumer level is more challenging.

Concentrating the analysis at the micro level, Kristensen and Mosgaard (2020) reviewed 30 CE indicators and also inferred that the attention was directed mainly to the economic dimension of CE while the environmental and notably the social dimensions were considered to a lesser extent. The majority of the reviewed CE indicators, from single quantitative ones to more complex indicator sets, put emphasis on the recycling, end-of-life management, and re-manufacturing, with less focus towards life-time extension, waste management, disassembly and resource-efficiency. In addition, the CE indicators at the micro level primarily evaluate single products and materials, so they provide a unique decision-making tool for the companies (Masoud, 2020). At the same time, they introduce a challenge since the transition to circular solutions normally affects not just single products but rather the entire supply chain. A myopic approach could lead to sub-optimal solutions and therefore undermining the holistic CE viewpoint. To this respect, Pauliuk (2018) suggested the utilization of CE relevant information in conjunction with CE indicators so as to extent the CE coverage, although such a scheme would launch new challenges due to complexity issues and the inability for information disaggregation. An attractive suggestion by Kristensen and Mosgaard (2020) was the development of industry specific indicators, which will boost the prevalence of CE within the various industries and promote the respective indicators.

Likewise, Vinante et al. (2020) reviewed 365 CE metrics at the micro level and introduced a classification based on value chain framework, composed of 23 categories. This framework associates CE metrics with company's functions and structure, enabling the disaggregation of the CE assessment. Moreover, the generalized nature of most CE metrics, along with their applicability in evaluating CE procedures regardless of company's specific characteristics, offset any contingency factors. The extensive literature review uncovers also the fragmentation of the current CE assessment at the micro level, along with the diverging interpretations of CE's goals. The dominance of environmental metrics in comparison to the shortage of social metrics was reaffirmed, with the former demonstrating a more quantitative approach as opposed to the more qualitative approach of the latter.

3. Development of Circular Economy Assessment Framework for the Micro Level

The vast majority of CE and sustainability analyses focus on the macro and meso levels, creating a shortage of CE assessment methods and tools at the micro level (Elia et al., 2017; Saidani et al., 2019; Howard et al., 2019; Kristensen and Mosgaard, 2020; Linder et al., 2017; Lonca et al., 2018). This is attributed to some of the intrinsic characteristics of circularity assessment at micro level. In particular, Kristensen and Mosgaard (2020) pointed out that reuse, repair or maintenance dimensions of CE that are considered major contributors to TBL principles require greater consideration. Also, CE indicators frequently concentrate on just a subset of CE principles e.g. Material Circularity Indicators (MCI) (MacArthur and Design, 2015), Circular Economy Toolkit (CET) (Evans and Bocken, 2013), Circular Economy Indicator Prototype (CEIP) (Cayzer et al., 2017b), Product-level Circularity Metric (PLCM) (Linder et al., 2017), missing the bigger picture and leading to misleading results (Saidani et al., 2017; Niero and Kalbar, 2019). This further exacerbates the inherent issue of CE indicators at micro level which are mainly designed with a narrow focus to specific products and materials, leading again to sub-optimal solutions due to the lack of a systems perspective. The plethora of different aspects and types under CE consideration at the micro level, introduce extra obstacles for companies and organization who want to pursue CE, and thus potentially jeopardize the overall succession of CE concept. To this respect, we present "MICRON" *(MIcro CirculaR ecOnomy iNdex)* as a quantitative and holistic CE assessment framework for the micro level. This is an attempt to address the generic challenges related to the CE assessment as well as those arise from the application specifically to the micro level.

According to the (Gabrielsen and Bosch, 2003), a proper indicator should have the following features: i) communicate with simplicity complex and critical matters, ii) be interpretable and traceable, iii) be used as a point of reference, iv) provide a systems analysis perspective, v) reflect all causality relations and driving forces. On top of these features, CE indicators should equally reflect on material and energy aspects, with extra care for critical raw materials and resource efficiency (Council, 2016). They should also raise public awareness on local and global effects of human activities through the lens of TBL concept.

3.1. Structure of the framework

Figure 1 summarizes the key steps undertaken for the development of the proposed framework. The rest of this section discusses in detail each step outlined in Figure 1.

Step 1: Definition of CE Goals and Identification of Principal Categories

The first step in the development of MICRON was the introduction of five principal categories of indicators which were designed and matched with the goals and key characteristics of CE, as defined by (Reichel et al., 2016). Table 1 shows the correspondence between CE goals and key characteristics with principal categories of indicators. This is a necessary first step towards transparency in the scope and goal setting. Identifying and setting specific boundaries and targets of what must be measured and evaluated is crucial before establishing the indicators and metrics (Avraamidou et al., 2018). An extra principal category, named "Organization" is also used for providing general information about a company's business activity e.g. company's revenue, number of products sold etc.

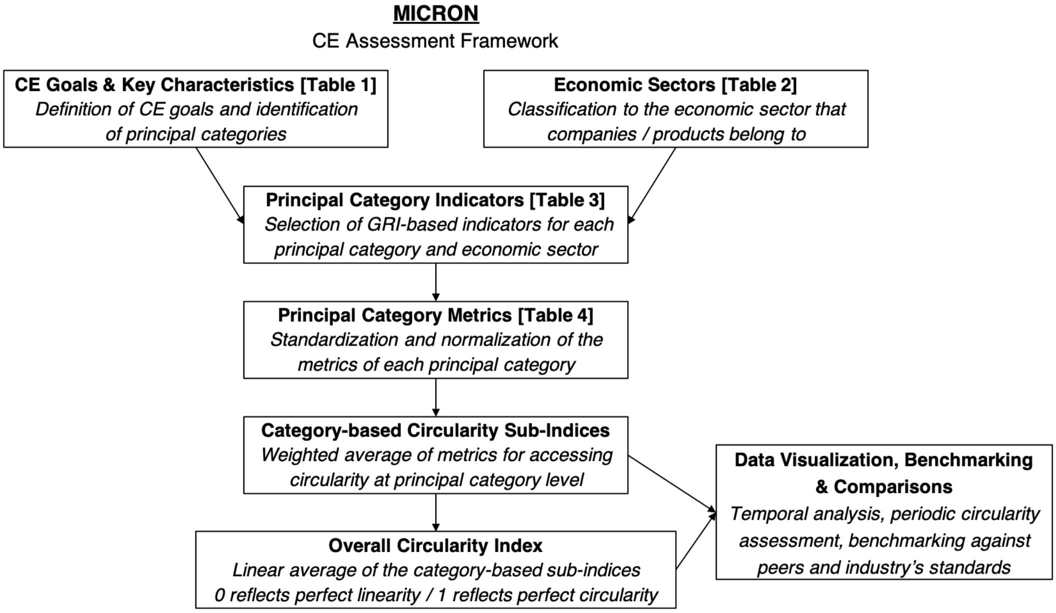

Figure 1: Step by step analysis of circularity assessment framework MICRON.

#	CE Goals & Key Characteristics		Principal Categories of Indicators
1	Reduction of material losses/residuals: Waste and pollutants minimization through the recovery and recycle of materials and products.	↔	Waste
2	Reduction of input and use of natural resources: The reduction of the stresses posed on natural resources through the efficient use of natural resources.	↔	Water, Procurement
3	Increase in the share of renewable resources and energy: Replacement of non-renewable resources with renewable ones, limiting the use of virgin materials.	↔	Energy
4	Reduction of emission levels: The reduction in direct and indirect emissions / pollutants.	↔	Emissions, Spillages
5	Increase the value durability of products: Extension of product lifetime through the redesign of products and high-quality recycling.	↔	Durability

Table 1: Matching of the Principal Categories with CE Goals.

Step 2: Classification of Economic Sectors

To increase the flexibility and the universal nature of the framework while improving the specificity in the implementation, different economic sectors are introduced, each one having its own set of indicators and metrics. The four parent sectors introduced to represent the economic activity are i) Energy and Utilities (EnU), ii) Services (SrV), iii) Manufacturing (MaN), and iv) Automotive (AuT). A series of industries are assigned to each of the parent sectors based on their primary business activity. For example, the industries Energy, Energy Utilities, Waste Management, and Waste Utilities are assigned to the Energy and Utilities sector. The list of industries is taken from the GRI sustainability Disclosure Database (Global Reporting Initiative, 2020). The breakdown of sectors and industries is shown in Table 2.

Step 3: Selection of Principal Category Indicators and Metrics

Each economic sector defined in the previous step consists of a number of industries (see Table 2) and should have its own unique assessment indicators and quantitative metrics, so as to capture the special characteristics of each company and the industry sector that it belongs to.

Energy & Utilities (EnU)	**Services (SrV)**	**Manufacturing (MaN)**	**Automotive (AuT)**
Energy	Aviation	Agriculture	Automotive
Energy Utilities	Commercial Services	Chemicals	
Waste Management	Financial Services	Computers	
Water Utilities	Healthcare Services	Conglomerates	
	Logistics	Construction	
	Media	Construction Materials	
	Non-Profit / Services	Consumer Durables	
	Public Agency	Equipment	
	Railroad	Food and Beverages Products	
	Real Estate	Forest and Paper Products	
	Retailers	Healthcare Products	
	Telecommunications	Household and Personal Products	
	Tourism / Leisure	Metals Products	
	Universities	Mining	
		Technology Hardware	
		Textiles and Apparel	
		Tobacco	
		Toys	

Table 2: Classification of the economic activity into parent sectors.

The terminology regarding indicators and metrics is not standardized in the literature and in order to maintain consistency throughout the document the terms are defined below.

Definition 3.1 (Indicator)**.** An *indicator* is the smallest unit of information that must be measured and evaluated under a CE goal, standard or principal category, e.g. total renewable energy consumed within the company.

Definition 3.2 (Metric)**.** A *metric* is the composite, normalized measure of an indicator to gauge company's level of business activity and productivity, e.g. total renewable energy consumed within the company over company's revenue.

This is essential to capture the progress and efficacy of a company's circularity year over year, as well as to conduct meaningful comparisons among companies (Herriott, 2016).

Definition 3.3 (Category)**.** The term *category* refers to the upper level grouping of indicators within the framework, e.g. Waste, Energy etc.

Definition 3.4 (Aspect)**.** If a category is broken down further so as to reflect a particular theme, e.g. environmental, economic etc., then the sub-categories will be called *aspects* (Herriott, 2016). Aspects may refer to a single indicator or a group of indicators depending on the scheme.

Indicators determine the type of information and data that must be collected and reviewed for each principle category over a specific period of time, normally one full year. Then *metrics* are defined to mathematically express and interpret the information and data that is stored in the indicators over the period of interest. For easy and objective comparison, metrics are normalized. The CE assessment of each principal category is based on the weighted average of its metrics, and is called *Category-based Circularity Sub-Index* (CCSI) of this particular principal category. For example, three different metrics are used to assess the circularity of principal category of Water on yearly basis. The annual Circularity Sub-Index of Water is calculated from the weighted average of the corresponding metrics (weights of metrics may not be equal). The varying levels of significance of the metrics are contemplated using weighted averages. The linear average of the category-based sub-indices determines the *Overall Circularity Index* (OCI) for each company, product or supply chain.

The selection of appropriate indicators and metrics for each principal category is critical since they must incorporate all the characteristics that were mentioned earlier, while successfully capturing the dynamics of companies and industries at different levels. For example, the indicators chosen for the principal category "Waste" include i) the weight of hazardous waste generated, ii) the weight of non-hazardous waste generated, and iii) the weight of waste diverted from disposal, as it can be seen in Table 3. The indicators chosen have been matched with the Global Reporting Initiative (GRI) Standards (Global Sustainability Standards Board, 2016), ensuring uniformity in the reported results while providing a reference guide for those who want to use the proposed index. Different indicators are used for the four different economic sectors. This increases the flexibility and the universal nature of the framework while improves the specificity in the implementation. Having specific indicators to measure over predetermined periods of time facilitates the data collection process and the comparisons among peers. Large companies with diversified activities in multiple countries may decide to split their CE assessment to individual business segments or regions for better benchmarking and accurate planning, which can be readily accommodated within the framework. As such, these companies will be able to measure the effectiveness of circular strategies deployed at international, national and regional levels or at each business segment individually. Table 3 illustrates the complete set of indicators for all principal categories and sectors considered. The sector specific indicators individually are shown in Supplementary Tables 1a-1d. While this set of indicators holistically addresses all CE goals identified in Table 1, the flexibility of the proposed framework allows for the introduction of further sector-specific indicators that might be needed to holistically capture the sector-specific circularity.

Similarly, one or more metrics are chosen to standardize the indicators of each principal category. Different metrics are determined for each principal category of each sector of the economy in an attempt to reflect accurately the specific features and attributes of each sector. As an example, three or four different metrics are utilized in GHG Emissions principal category depending on the economic sector (Table 4). The formulas used for each metric generate a number that lies between 0 and 1, with the target value of 1. For example, metric 1a that captures the percentage of hazardous waste over total waste generated shall be preferably 0, but since our target is 1 then the formula *100%-1a* is used. On the contrary, metric 1b that tracks the percentage of diverted waste over total waste generated shall preferably approaches 1, and thus the formula used is *1b*.

Table 4 illustrates the complete set of metrics and their formulas for all principal categories and sectors. The sector specific metrics individually are shown in Tables B.8 to B.11.

Step 4: Development of Category-based Circularity Sub-Indices

Equal weights are used for the calculation of the Category-based Circularity Sub-Index of Waste, Water, Procurement, and Durability across the sectors. One metric with 100% weight is used for the Energy principal category in Energy and Utilities sector, while for the Manufacturing and Automotive sectors, higher weight (75%) is assigned to the metric related to the evaluation of renewables utilization, and lower weight (25%) is assigned to the metric related to the energy efficiency. In the Service sector, an extra metric is used to evaluate the performance and leadership of companies towards CE for their buildings and facilities, with an assigned weight of 25% (which is subtracted from the renewables utilization metric that becomes 50% for this sector). Furthermore, three plus one metrics are used within the GHG Emissions & Spillages principal categories in the Energy and Utilities, Manufacturing and Service sectors. The highest emphasis is put towards the Net Emissions Intensity (50-55%), followed by lower weights for the rest of the metrics i.e. 5% - 20%. In the Automotive sector, the Average Specific CO_2 Emissions metric is introduced, which gets the highest weight (40%), followed by the weight in the Net Emissions Intensity metric (35%), while for the rest of the metrics the weights range from 5% to 10%. The calculated values of all the sub-indices lie between 0 and 1, with the target value of circularity being 1. Thereby, a value of 1 for any of the sub-indices reflects perfect score in that category for the assessed company/product/supply chain while a value of 0 reflects the worst score in that category for the assessed company/product/supply chain.

Step 5: Development of the Overall Circularity Index

The Overall Circularity Index is calculated by a linear average of the Category-based Sub-Indices. Since the sub-indices lie between 0 and 1, the Overall Circularity Index also lies between 0 and 1. Thereby, a value of 1 for the Overall Circularity Index reflects perfect circularity on the assessed company while a value of 0 reflects perfect linearity on the assessed company.

3.2. Collection and analysis of data

A key advantage of the proposed framework originates from the explicit definition of the specific indicators and metrics that prevents vagueness and ambiguity on the data to be collected as well as on the type of data that are needed. The data are generally easily accessible from a variety of sources and trackable over a long period of time.

Principal Categories	**Indicators**	**GRI Standards Correspondence**	**Sectors Allocation**			
Organization	Revenues [million $]	GRI-201-1	EuN	MaN	AuT	SrV
	Total social investment for environmental sustainability and circular economy [million $]	GRI-203-1	EuN	MaN	AuT	SrV
	Products sold [weight or volume]	GRI-301-3		MaN		
	Number of products sold [# of products]	GRI-301-3			AuT	
	Full time employees (FTE) [# of people]	GRI-401-1			AuT	SrV
	Operational building/facilities space	GRI-302-3				SrV
Waste	Waste generated - Hazardous [weight]	GRI-306-3	EuN	MaN	AuT	SrV
	Waste generated - Non Hazardous [weight]	GRI-306-3	EuN	MaN	AuT	SrV
	Diverted waste from disposal (reused, recycled, recovered) [weight]	GRI-306-4	EuN	MaN	AuT	SrV
Water	Water withdrawal [volume]	GRI-303-3	EuN	MaN	AuT	SrV
	Fresh water discharge (<= 1,000mg/L TDS) [volume]	GRI-303-4	EuN	MaN	AuT	SrV
	Other water discharge (>= 1,000mg/L TDS) [volume]	GRI-303-4	EuN	MaN	AuT	SrV
	Water recycled or reused [volume]	GRI-303-3 (2016)	EuN	MaN	AuT	SrV
Procurement: Production & Packaging	Non-renewable material used [volume or weight]	GRI-301-1			AuT	SrV
	Non-renewable packaging material used [volume or weight]	GRI-301-1		MaN		
	Renewable material used [volume or weight]	GRI-301-1			AuT	SrV
	Renewable packaging material used [volume or weight]	GRI-301-1		MaN		
	Recycled input material used [volume or weight]	GRI-301-2			AuT	SrV
	Recycled packaging material used [volume or weight]	GRI-301-2		MaN		
	Reusable, compostable or recyclable material [%]	GRI-301-3			AuT	
	Reusable, compostable or recyclable packaging material [%]	GRI-301-3		MaN		
	Paper consumption [weight]	GRI-301-1				SrV
	Single-use plastics consumption [weight]	GRI-301-1				SrV
Energy	Total energy generated [joules or multiples]	GRI-302-1	EuN			
	Total non fossil fuel energy generated [joules or multiples]	GRI-302-1	EuN			
	Total energy consumed [joules or multiples]	GRI-302-1		MaN	AuT	SrV
	Renewable energy consumed [joules or multiples]	GRI-302-1		MaN	AuT	SrV
	Certified buildings and facilities i.e LEED [%]	GRI-302-3				SrV
GHG Emissions	Direct GHG emissions (Scope 1) [tCO2e]	GRI-305-1	EuN	MaN	AuT	SrV
	Energy indirect GHG emissions (Scope 2) [tCO2e]	GRI-305-2	EuN	MaN	AuT	SrV
	Total use of products (Scope 3) [metric tons CO2 equivalent (tCO2e)]	GRI-305-3	EuN	MaN	AuT	SrV
	Average specific CO2 emissions [gCO2/km]	GRI-305-4			AuT	
	Emissions neutralized by carbon offset projects [tCO2e]	GRI-305-5	EuN	MaN	AuT	SrV
	Emissions of ozone-depleting substances (ODS) [metric tons of CFC-11 equivalent]	GRI-305-6	EuN	MaN	AuT	SrV
	Nitrogen oxides [NOx], sulfur oxides [SOx] & other significant air emissions [kg or multiples]	GRI-305-7	EuN	MaN	AuT	SrV
Spillages & Discharges	Environmental fines [$]	GRI-307-1	EuN	MaN	AuT	SrV
	Volume of flared hydrocarbon [tCO2e]	GRI-306-3	EuN			
	Volume of vented hydrocarbon [tCO2e]	GRI-306-3	EuN			
Durability	Packaging Material to be reclaimed/recovered [# of products or %]	GRI-306-2		MaN		
	Material to be reclaimed/recovered [%]	GRI-306-2			AuT	
	Average lifespan of product or Warranty provided [years]	GRI-306-2			AuT	

Table 3: CE Indicators with sector allocation [EuN : Energy and Utilities, MaN : Manufacturing, AuT : Automotive], SrV : Service].

Here, each company's annual "Sustainability", "Environmental-Social-Governance (ESG)" and "Financial" reports are recommended as the main sources of data. Each company's data from multiple years are collected and analyzed based on the proposed indicators and metrics so as to calculate the annual "Category-based Circularity Sub-Index" and the annual "Overall Circularity Index" for each principal category e.g. 2019 "Circularity Index for Energy", "Circularity Index for Waste", 2019 "Overall Circularity Index" etc. Therefore, a company's Overall "Circularity" as well as its "Category-based Circularity" versus every CE goal can be tracked on annual basis and/or against its peers.

The metrics are generally expressed as percentages. When this is not the case, the metrics are normalized using an upper bound value that is 1.5 times higher than the average of the already collected data for this metric. This provides a reasonable and realistic upper bound for each principle category. The target value for the metrics is 1 or 100%, and thus the formulas have been defined in a corresponding way (see "Formula Used" tab in Table 4). As an example, metric 4d that captures the average specific CO2 emissions shall be preferably 0, but since our target is 1 then the formula *1-norm[metric]* is used. The only exception is metric 5c that reflects the average lifespan of product or warranty provided and shall preferably approaches 1. Thus, it is calculated based on the formula *norm[metric]*.

In case data for a metric are not available for a specific period of time, then the corresponding metric gets a value of 0 for this particular period, reflecting a linear behavior. Additionally, the upper bound value for each metric is a parameter of the framework that is updated once more data become available and more companies use the framework. For example, the upper bound of metric 4d that captures the average specific CO_2 emissions (gCO_2/km) of vehicles is set at 200 gCO_2/km based on analysis of data from various automotive manufactures. A hypothetical measurement of 100 gCO_2/km results to a 4d metric of 0.5. In case the value of a metric is higher than its upper bound and in order to avoid negative (when formula *1-norm[metric]* is used) or larger than 1 (when *norm[metric]* is used) index numbers, the final normalized metric is set to 0 or 1 respectively.

3.3. A holistic and robust CE assessment framework

The developed quantitative framework combines data and information from the academic and industrial literature along with a novel structure to effectively assess the circularity at the micro level in any sector of the economy. It provides media for data visualization and analysis at different levels of granularity and is an analytical tool to assess the multi-scale, multi-faceted and interconnected CE supply chains and business activities. This structure provides a holistic approach in capturing both the CE and sustainability attributes across the different sectors while it improves the interpretability and traceability of the integrated CE within the various aspects of a business. It also enhances the robustness of the framework allowing the successful treatment of outliers which is crucial for comparison among peers or among different industries and sectors as well as for tracking year over year performance. Specific CE targets and benchmarks can be set by taking advantage of the high level of granularity, having a positive impact on the decision-making at different operational levels and investment time horizons (short or long term).

Figure 2 demonstrates the schematic of the proposed CE assessment framework - MICRON. For demonstration purposes, arbitrary values are assigned to the Category-based Circularity Sub-Indices while the Overall Circularity Index is calculated as their linear average.

Illustrative Example

Let's assume that a company wants to assess its overall circularity performance, compare its performance against its competitors, track its progress over the years, and identify areas of potential improvement. First, the company is classified into one of the four economic sectors according to its business activities. For this example, let's assume that the company belongs to the Manufacturing sector. Next, the company provides annual data for a variety of indicators in 7 plus 1 principal categories. As such, the annual data of "Total energy consumed, in GJ" and "Renewable energy consumed, in GJ" must be provided for the Energy principal category, the "Waste generated - Hazardous, in metric tons", "Waste generated - Non Hazardous, in metric tons" and "Diverted waste from disposal, in metric tons" must be provided for the Waste principal category, and so on (Table 3). The data provided are then used for the calculation of the various standardized and normalized metrics of each principal category. The metrics are dimensionless, with values close to zero reflecting linear behavior while values close to one (or 100%) reflecting circular behavior. For the case of the Energy principal category, two metrics are calculated: "% of Renewable energy consumed over Total energy consumed", and "Total energy consumed over Products sold, in GJ per ton product". The first metric is a percentage so no further processing is required, but the second metric needs to be normalized, thus an upper bound value is used. Since this metric captures the energy consumption per unit sold, this implies that a value close to zero is preferable in circularity terms. Therefore, the normalized value is subtracted from 1. As indicative values for this example for the years 2018 and 2019, let's assume that the first metric has values of 0.20 and 0.25, and the second metric has values of 0.80 and 0.85 with an upper bound of 10 GJ per ton product. The same process is followed for the rest of the metrics in the remaining principal categories (Table 4). Having estimated the normalized metrics for all principal categories, then the Category-based Circularity Sub-Indices using weighted averages are calculated. In particular, for the Energy principal category, the first metric gets a 75% weight, while the second metric gets a 25%. Given the previous mentioned values, the 2018 "Circularity Index for Energy" is 0.35, which increased to 0.40 in 2019. Conducting the analogous process for the rest of the principal categories, the annual Circularity Sub-Index for each principal category is calculated. The linear average of all annual Circularity-based Sub-Indices leads to the Overall Circularity Index, in this case being 0.46 and 0.49 for 2018 and 2019 respectively. Finally, data visualization, benchmarking and various comparisons can be conducted and indicative analysis is shown in the next Section 4 Case Studies.

Principal Categories	Metric		Upper Bound	Formula Used	Sectors Allocation			
Waste	1a	% of Hazardous waste over Total waste generated	100%	100%-1a	EuN	MaN	AuT	SrV
	1b	% of Diverted waste over Total waste generated	100%	1b	EuN	MaN	AuT	SrV
	1ca	Waste generated over Products sold [kg waste over tons of product]	200	1-norm[1ca]		MaN		
	1cb	Waste generated over Number of products sold [kg waste over # of products]	1500	1-norm[1cb]			AuT	
	1cc	Waste generated over Full Time Employees [kg waste over # of FTE]	1000	1-norm[1cc]				SrV
Water	2a	% of Recycled/reused water over Total water withdrawal	100%	2a	EuN	MaN	AuT	SrV
	2b	% of Other water discharge over Total water discharge	100%	100%-2b	EuN	MaN	AuT	SrV
	2c	% of Water consumed over Total water withdrawal	100%	100%-2c	EuN	MaN	AuT	SrV
	2da	Water withdrawal over Products sold [m3 water over tons of product]	10	1-norm[2da]		MaN		
	2db	Water consumption over Number of products sold [m3 water over # of products]	30	1-norm[2db]			AuT	
	2dc	Water consumption over Full Time Employees [m3 water over # of FTE]	100	1-norm[2dc]				SrV
Procurement: Production & Packaging	2paa	% of Recycled input material used	100%	2paa			AuT	SrV
	2pab	% of Recycled packaging material used	100%	2pab		MaN		
	2pba	% of Renewable material used	100%	2pba			AuT	
	2pbb	% of Renewable packaging material used	100%	2pbb		MaN		
	2pca	% of Reusable, compostable or recyclable material used	100%	2pca			AuT	
	2pcb	% of Reusable, compostable or recyclable packaging material used	100%	2pcb		MaN		
	2pd	Paper consumption over Full Time Employees [kg over # of FTE]	365	1-norm[2pd]				SrV
	2pe	Single-use plastics consumption over Full Time Employees [kg plastic over # of FTE]	50	1-norm[2pe]				SrV
Energy	3aa	% of Non fossil fuel energy generated over Total energy generated	100%	3aa	EuN			
	3ab	% of Renewable energy consumed over Total energy consumed	100%	3ab		MaN	AuT	SrV
	3ba	Total energy consumed over Products sold [joules or multiples over tons of product]	10	1-norm[3ba]		MaN		
	3bb	Total energy consumed over Number of products sold [joules or multiples over # of products]	15	1-norm[3bb]			AuT	
	3bc	Total energy consumed over Operational space [joules or multiples over surface area]	1	1-norm[3bc]				SrV
	3bd	% of Certified buildings and facilities i.e LEED	100%	3bd				SrV
GHG Emissions	4aa	Net total emissions over Total energy delivered [tCO2e over joules or multiples]	600	1-norm[4aa]	EuN			
	4ab	Net total emissions over Products sold [tCO2e over tons of product]	500	1-norm[4ab]		MaN		
	4ac	Net total emissions over Number of products sold [tCO2e over # of products]	2,000	1-norm[4ac]			AuT	
	4ad	Net total emissions over Operational space [tCO2e over surface area]	300	1-norm[4ad]				SrV
	4ba	Emissions of ODS over Total energy delivered [metric tons of CFC-11 eq. over joules or multiples]	0.1	1-norm[4ba]	EuN			
	4bb	Emissions of ODS over Products sold [metric tons of CFC-11 eq. over tons of product]	0.1	1-norm[4bb]		MaN		
	4bc	Emissions of ODS over Number of products sold [metric tons of CFC-11 eq. over # of products]	0.1	1-norm[4bc]			AuT	
	4bd	Emissions of ODS over Operational space [metric tons of CFC-11 eq. over surface area]	1	1-norm[4bd]				SrV
	4ca	NOx, SOx, and other significant air emissions over Total energy delivered [metric tons over joules or multiples]	1.0	1-norm[4ca]	EuN			
	4cb	NOx, SOx, and other significant air emissions over Products sold [metric tons over tons of product]	1	1-norm[4cb]		MaN		
	4cc	NOx, SOx, and other significant air emissions over Number of products sold [metric tons over # of products]	10	1-norm[4cc]			AuT	
	4cd	NOx, SOx, and other significant air emissions over Operational space [metric tons over surface area]	0.05	1-norm[4cd]				SrV
	4d	Average specific CO2 emissions [gCO2/km]	200	1-norm[4d]			AuT	
Spillages & Discharges	4da	Environmental fines over Total energy delivered [$ over joules or multiples]	1.0	1-norm[4da]	EuN			
	4db	Environmental fines over Products sold [$ over tons of product]	10	1-norm[4db]		MaN		
	4dc	Environmental fines over Number of products sold [$ over # of products]	10	1-norm[4dc]			AuT	
	4dd	Environmental fines over Operational space [$ over surface area]	0.5	1-norm[4dd]				SrV
Durability	5a	% of Packaging material to be reclaimed/recovered	100%	5a		MaN		
	5b	% of Material to be reclaimed/recovered	100%	5b			AuT	
	5c	Average lifespan of product or Warranty provided [years]	20	norm[5c]			AuT	

Table 4: CE Metrics with sector allocation [EuN: Energy and Utilities, MaN: Manufacturing, AuT: Automotive], SrV: Service].

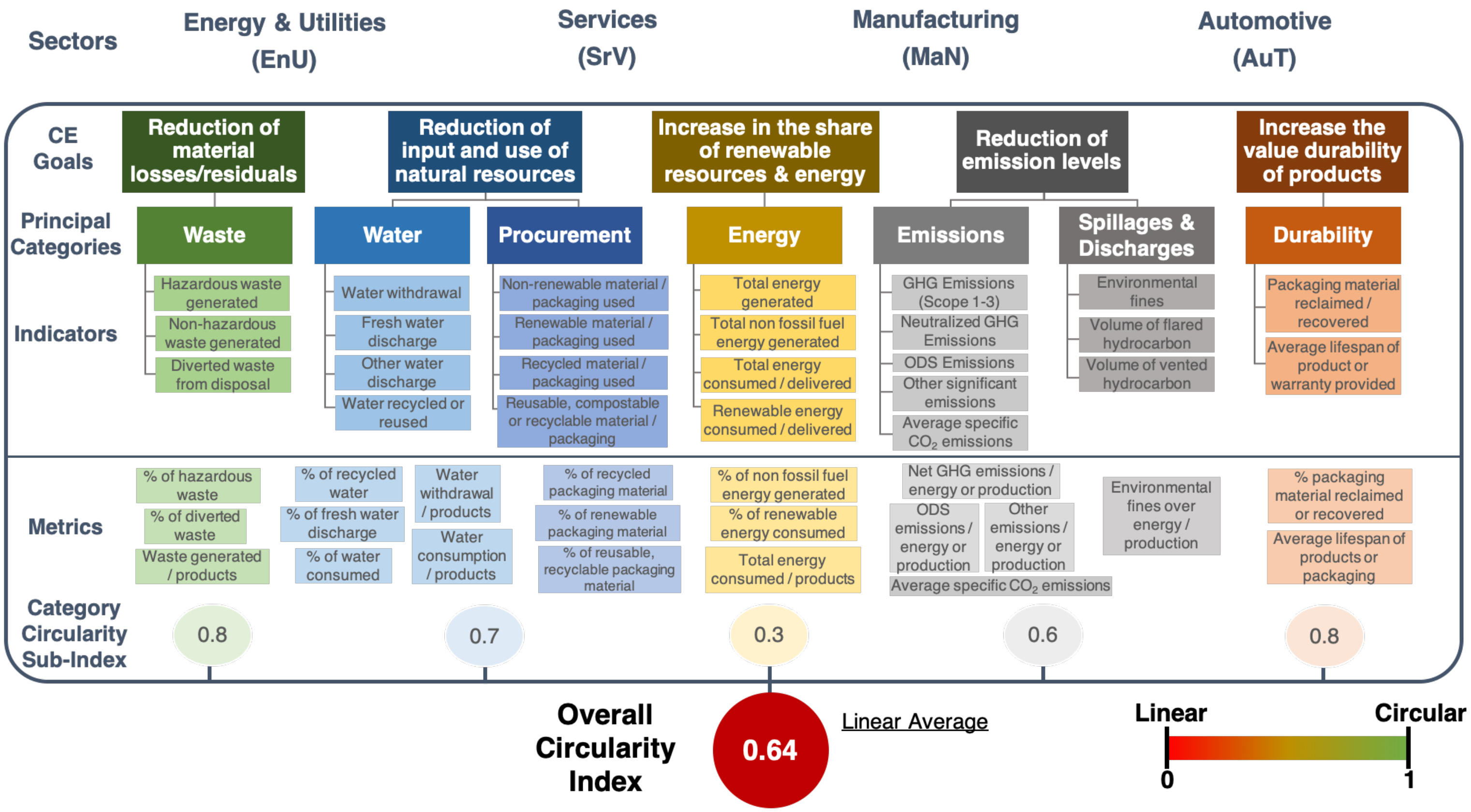

Figure 2: Schematic of MICRON CE assessment framework, with arbitrary values on Category-based Circularity Sub-Indices.

4. Case Studies

Leading companies from the Energy and Utilities, Manufacturing, and Automotive sectors are used as working examples to illustrate the extent, use and applicability of the proposed framework.

4.1. MICRON applied in Energy and Utilities (EnU) sector

We start first by applying the developed CE assessment framework to Energy Utilities companies which operate in Energy and Utilities sector so as to estimate their Overall Circularity Index as well as their Category-based Circularity Sub-Indices. In particular, we evaluate the circularity of the following companies over the a number of years: **PG&E** (2014-2019), **NextEra** (2016-2019) and **Uniper** (2016-2019). The data used for the subject calculations and analysis are taken from the following sources: PG&E: "Corporate Responsibility and Sustainability" reports (2015-2020), NextEra: "Environmental, Social and Governance" report (2020) and "Sustainability: By the Numbers" report (2014-2018), Uniper: "Sustainability" reports (2017-2019) and "2019 Annual Report - Financial Results" (PG&E, 2015-2020; NextEra, 2020, 2014-2018; Uniper, 2017-2019, 2019). First, the annual metrics of each indicator are calculated using the methodology described in sections 3.1 and 3.2, and are summarized in Table A.5.

PG&E scores almost the maximum (100%) with regards to the water preservation metric (2c - percentage of water consumed over water withdrawal), but data for the other two Water metrics are not available. One of the environmental GHG emissions intensity metrics (4ca - NOx, SOx, and other significant air emissions over Total energy delivered) demonstrates almost perfect score (100%) over this period, while no data are available for the third environmental GHG emissions intensity metric (4ba - Emissions of ODS over Total energy delivered). The spillages intensity metric (4da - Environmental fines over Total energy delivered) fluctuates dramatically over this period.

The majority of the required data are not available for NextEra in 2016. NextEra is the only one of the three companies which reports recycled water values, although the reported values are close to 0. It does not report any values for the spillages and discharges (4da), percentage of other water discharges (2b), and ODS emissions (4ba). NextEra scores almost 100% in the Waste principal category, the water preservation metric (2c), and one of the environmental GHG emissions intensity metrics (4ca). Finally, despite the increase in Energy and Net emissions intensity (4aa) metrics in 2017, both metrics did not improve over the years.

Data availability for Uniper is similar to PG&E, with the only difference that spillages and discharges are also not available. The company performs poorly in multiple metrics, including diverted waste (1b), Energy (3aa) and GHG emissions (4aa, 4ca).

4.2. MICRON applied in Manufacturing (MaN) sector

The second application of MICRON framework is at the Food and Beverages industry which is classified under the Manufacturing sector. Here, we assess the category-based and overall circularity of the following companies from 2010-2019: **Nestle** (2010-2019), **General Mills** (2010-2019), **Tyson** (2015-2019) and **Ferrero** (2016-2019).

The following sources are used for collecting data for the analysis: Nestle: "Progress Report" (2018-2019) and "Consolidated Nestle Environmental Performance Indicators" (2019), General Mills: "Global Responsibility" report (2016-2020) and "Annual Report to Shareholders" (2020), Tyson: "Sustainability" reports (2012-2019), and Ferrero: "Sustainability" reports (2017-2019) (Nestle, 2018-2019, 2019; Mills, 2016-2019, 2020; Tyson, 2012-2019; Ferrero, 2017-2019). The annual metrics of each indicator are calculated using the methodology described in sections 3.1 and 3.2, and are summarized in Table A.6.

Nestle demonstrates a continuous improvement with regards to circularity in almost all principal categories. Waste is the best performing category, with close to perfect scores. As an example, the company reports on average 30 kg of total waste per ton of product produced (1ca) over the decade. The metrics for GHG Emissions & Spillages also reveal an upward trend, with about 35% decrease in the net emissions per ton of product sold metric (4ab), and even higher reductions in the ODS and other significant emissions per ton of product sold (4bb, 4cb) during the same period. The environmental fines are constantly minimal in comparison to the level of production. On the contrary, and despite the advancements over the years, there are significant opportunities for improving circularity in the Energy principal category, since just 20% of the energy consumed comes from renewable resources.

Similar findings are observed from the circularity assessment of General Mills. The introduction of recycling and reusing initiatives for the waste handling (1b) in 2015 resulted in a substantial improvement in the corresponding category. There are enormous enhancement possibilities for the rest of the principal categories, since for example less than 5% of energy consumed comes from renewable resources (3ab), or the water withdrawal per product sold has raised by 22% without any provision for recycling or reusing initiatives (2da).

Tyson is the least circular from the assessed companies in the Food and Beverages industry. As an example, the total waste generated per ton of product sold (1ca) more than doubled within five years while the GHG emissions per product sold (4ab) grew by more than 7% over this period. The portion of renewable energy in company's portfolio is less than 1% (3ab), and the energy efficiency (3ba) has deteriorated by almost 60% since 2015.

Ferrero illustrated a slightly better circular performance in comparison to Tyson. Despite the significant increase of 91% in the share of renewables sources (3ab), renewables still provide less than 20% of the total energy requirements, while GHG emissions intensity (4ab) grew by more than 30% over the last four years. The water consumed as a percentage of water withdrawal (2c) and the water withdrawal per product sold (2da) increased by almost 40% and 20% respectively.

Finally, it is worth highlighting that none of the reviewed companies in this sector reported data related to the Durability. This will be another contribution of the proposed framework towards enhancing the awareness of companies with regards to specific overlooked or under-reviewed categories, that are inextricably linked with the CE concept.

4.3. MICRON applied in Automotive (AuT) sector

The Automotive industry has some unique characteristics that differentiate it from the rest of the industries and require its classification into a separate sector, the Automotive sector. These characteristics refer to the output of the industry which is counted in vehicles with distinct features and as such affects all the intensity metrics, the environmental aspects of the produced vehicles, and the lifespan or the warranty that is provided by the automotive companies for their vehicles. Here, we evaluate the category-based circularity sub-indices and the overall circularity index of the following companies from 2012-2019: **Daimler** (2012-2019), **Ferrari** (2016-2019), **Audi** (2014-2019) and **BMW** (2015-2019).

The sources of data and information for our analysis are as follows: Daimler: "sustainability" reports (2012-2019) and "GRI" (2017-2019), Ferrari: "Sustainability" reports (2017-2019) and "Annual" reports (2017-2019), Audi: "Sustainability" reports (2014-2019), and BMW: "Sustainability Value" reports (2015-2019) and "GRI" (2017-2019) (Daimler, 2012-2019, 2017-2019; Ferrari, 2017-2019b,-; Audi, 2014-2019; BMW, 2015-2019, 2017-2019). The annual metrics of each indicator are calculated using the methodology described in sections 3.1 and 3.2, and are summarized in Table A.7.

Waste and Durability are the top performing circularity principal categories for Daimler over a period from 2012 to 2019, followed by Emissions & Spillages and Water & Procurement, with Energy being the worst performing category. The amount of waste that is diverted from disposal (1b) continued to increase over the years, while the hazardous waste remained minimal as a percentage of the total waste (1a). Both metrics of Durability remain constant over the years, which is also the case for the rest of the automotive companies considered, with the exception of Audi, which started reporting information for the percentage of the material that is reclaimed and/or recovered (5a) in 2015. Emissions demonstrate a mix picture since the net total GHG emissions per vehicle sold (4ac) are reduced by 33% while on the other hand, the NOx, SOx and other significant air emissions per vehicle sold (4cc) have increased by 52% over the same period. The water consumption per vehicle sold (2db) declined by 22%. The company did not report any total renewable energy consumption.

With the exception of Durability metrics, the rest of Ferrari's circularity principal categories reveal room for substantial improvement. Energy is by far the worst performing circular category, with the energy consumption per vehicle sold (3bb) being 11x to 25x times higher than the other three companies. Similar results are reported for Emissions, with Ferrari's GHG emissions per vehicle sold (4ac) being between 10x to 33x times higher than the other three companies. Water & Procurement and Waste categories have slowly progressed over the years, but further improvements towards circularity are required.

Audi scores close to the maximum with regards to the Waste metrics, followed by Durability and Emission & Spillages. A significant improvement in Durability category occurs after 2016, once the company reported that 95% of the materials used are reclaimed and/or recovered (5b). The share of renewable energy in the total mix of consumed energy (3ab) has grown to almost 36%, while the energy efficiency in vehicle production (3bb) remains the highest in the sector. Water & Procurement is the worst performing circularity category despite the improvement caused by the reported high percentages of reusable and/or recyclable materials (2pca) after 2016.

BMW reveals a very similar circular behavior with Daimler, scoring almost excellent in Waste metrics. GHG Emissions per vehicle sold (4ac) decreased by more than 42%, while 30% was the reduction in the NOx, SOx and other air emissions per vessel sold (4cc) over the same period. On the contrary, Water & Procurement metrics remain rather unchanged since 2015. Renewable energy remains a minor percent of the total energy consumed (3ab), while the energy efficiency in vehicles' production (3bb) has increased by 8%.

5. Results and Discussion

Having considered the individual metrics of each principal category in the previous section, here we compute and assess the Category-based Circularity Sub-Index and the Overall Circularity Index for each company in the three sectors. Initially, the analysis is performed per sector, estimating the Category-based Circularity Sub-Index for the companies within the sector and conducting a comparison between peers. Then, the Overall Circularity Index of each company within the same sector is calculated, and a comparison between peers at this higher level is presented, enabling the identification of areas that require improvement. As it was discussed earlier, this is an advantage of the proposed framework that allows the CE assessment at different operational and structural levels and monitoring the progress towards CE goals in due time. Also, benchmarking against peers from the same industry and/or sector, or even from different sectors can be conducted.

5.1. Category-based and Overall Circularity Indices for Energy and Utilities (EnU) Sector

The following figures illustrate the annual Category-based Circularity Sub-Indices (Figure 3) and annual Overall Circularity Index (Figure 4) for three companies that operate in the Energy & Utilities sector from 2016 to 2019, using the weights described in previous sections. According to Figure 3, PG&E scores higher than the other two companies in circularity in the Energy and Emissions principal categories over the years, in comparison to Waste category in which NextEra is by far the best performing company. All three companies reveal the same steady performance in Water category. PG&E scores on average 62% and 30% higher than NextEra, and 309% and 362% higher than Uniper in the Energy and Emissions categories respectively. Conversely, NextEra outperforms on average Uniper and PG&E by 68% and 159% respectively in the Waste category between 2017-2019, while no data are available for NextEra in 2016. Supplementary Figures 1a-1c present Category-based Circularity Sub-indices for the three Energy Utilities companies for multiple years, while Supplementary Figure 1d highlights the Category-based Circularity Sub-indices for the Energy & Utilities sector for 2019.

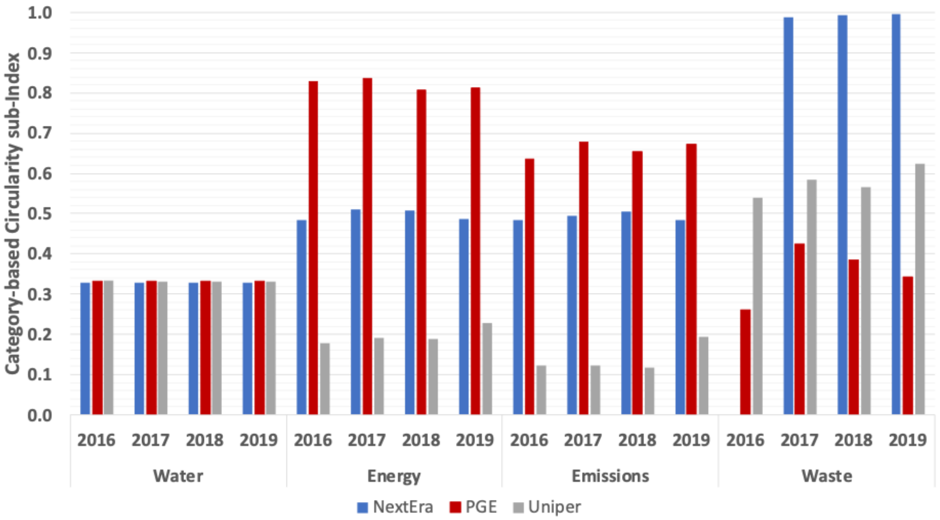

Figure 3: Category-based Circularity Sub-Indices in the Energy & Utilities sector (2016-2019).

The annual Overall Circularity Index for each company represents an aggregate of the annual category-based circularity metrics. As it is shown in Figure 4, NextEra's improvement in 2017 places the company in the top of the comparison among industry peers, with an Overall Circularity Index just below 60% of the target. The significantly lower price of NextEra's overall index in 2016 is attributed to the non availability of data for the Waste principal category that resulted in zeroing of the corresponding category. On the contrary, Uniper is the least circular company from the three under consideration. With the exception of NextEra in the Waste category, there are opportunities for enhancement in all aspects of CE for these companies.

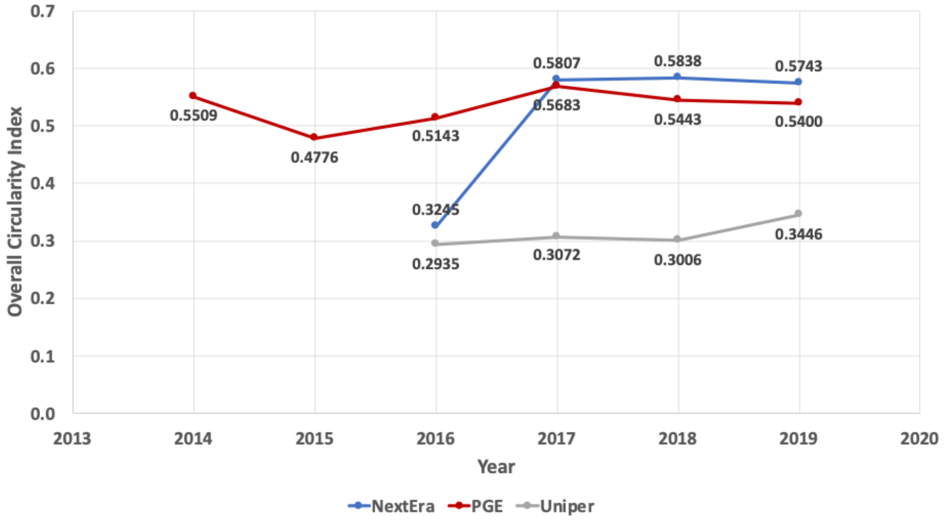

Figure 4: Overall Circularity Indices in the Energy & Utilities sector (2016-2019).

5.2. Category-based and Overall Circularity Indices for Manufacturing (MaN) Sector

Figure 5 and Figure 6 highlight the category-based circularity sub-indices and the overall circularity indices of four companies from the Food and Beverages industry, which is classified within the Manufacturing sector. Figure 5 displays only the period from 2016-2019, due to the non-availability of data for two of the assessed companies for the previous period. An interesting finding is that none of the companies report any information or data that can be used to assess Durability. Thus, the Durability metrics for these companies are zero. Similar to the Energy & Utilities sector, companies score very well in the Waste category, with Nestle and General Mills been very close to each other and around 0.9. Ferrero achieved a major improvement the last two years with a 62% jump in this category. This is mainly attributed to the reporting of excellent handling of hazardous wastes over this period. On the contrary, Tyson's performance with regards to Waste shows a declining pattern with a 37% decrease in just four years, as a result of the deterioration of the waste generated per ton of product sold (1ca), which has more than double in such a short period of time.

Emissions & Spillages and Energy categories reveal similar trends. More specifically, Nestle is the leading company in both categories, achieving more than 0.8 in the Emissions & Spillages category, and being 143% higher than the second company of the list. Tyson performs slightly better than Ferrero in these two categories. In the Energy category, the gap between the first two companies is much smaller around 51%. Tyson and Ferrero demonstrate opposite paths in circularity in this category, with the former declining and the later increasing in values, and eventually managing to cover the initial 100% difference in just four years. In the Water & Procurement category, Ferrero has the lead, followed by Nestle, General Mills, and then Tyson. Ferrero's improvement in the last two years is attributed to the high percentage of recyclable, reusable and compostable packaging materials that was reported. A similar finding is observed also for Nestle in 2019. Supplementary Figures 2a-2d display the Category-based Circularity Sub-indices for the four Food and Beverages companies for multiple years, while Supplementary Figure 2e shows the Category-based Circularity Sub-indices for the Manufacturing sector for 2019.

Figure 6 summarizes the overall circularity assessment of the four companies since 2010. Three out of four companies demonstrate an improving upward trend in their overall circularity, with Tyson being the only one whose performance has deteriorated. More specifically, Nestle and General Mills achieved a 47% and 37% increase in their overall circularity respectively over the decade. Ferrero improved even more (up to 60%) almost reaching General Mills, while Tyson dropped by 17%. Despite the difference between the top two performing companies which is 47%

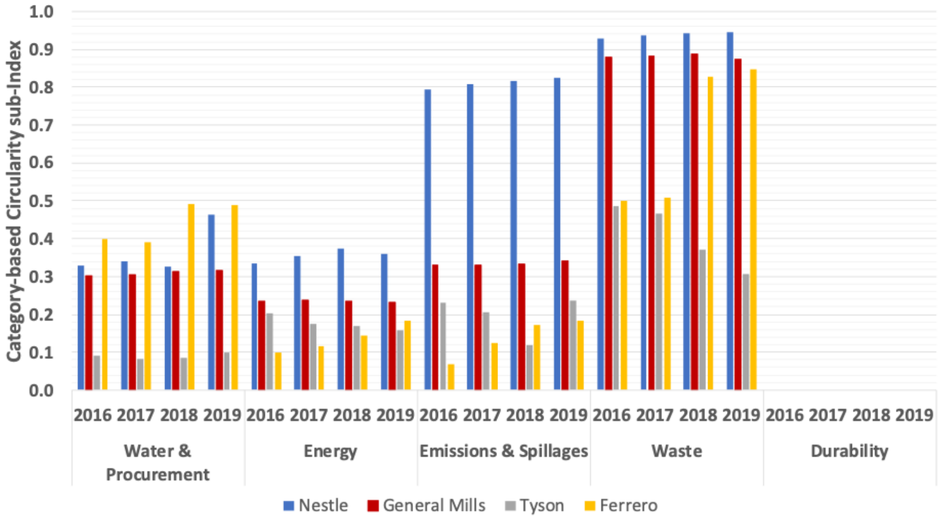

Figure 5: Category-based Circularity Sub-Indices in the Manufacturing sector (2016-2019).

in 2019, and the rising trend of CE performance over the years, there is still big room for CE improvement for all companies, as it was also observed for the Energy & Utilities sector.

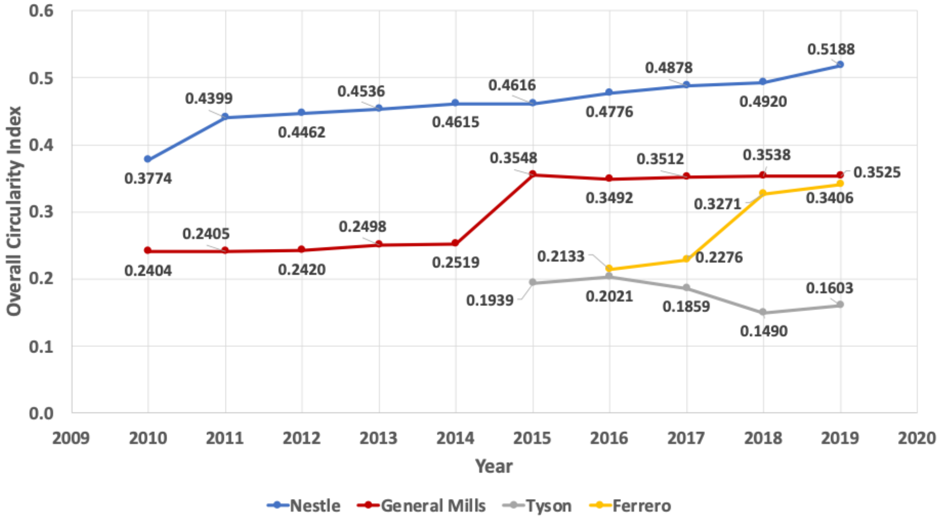

Figure 6: Overall Circularity Indices in the Manufacturing sector (2010-2019).

5.3. Category-based and Overall Circularity Indices for Automotive (AuT) Sector

Waste is the best performing circularity sub-index for three of the assessed companies, having reached and maintained values close to 0.9, as it can be seen in Figure 7. Audi and BMW lead the category, followed by Daimler, while Ferrari despite the improvement over the last two years, still scores almost 75% less than Daimler. However, Ferrari scores 0.85 in Durability sub-index, 17% more than Audi which comes second, and 31% higher than Daimler and BMW. This is attributed to the fact that Ferrari's vehicles have longer lifespan and they are considered collectibles. Audi and BMW are also the top performers in the GHG Emissions & Spillages category, scoring almost 50% higher than Daimler. Audi scores 71% and 72.5% higher than Daimler in net total GHG emissions per vehicle sold (4ac) and NOx, SOx, and other significant air emissions per vehicle sold (4cc) respectively. The average specific CO_2 emissions of Audi vehicles are also about 10% lower than those of Daimler. Even though Audi scores less than 0.5 in Energy sub-index, nevertheless its difference with the second in line is around 0.24.

Daimler's lack to report total renewable energy sources resulted in poor performance in this category, while Ferrari scores on average less than 0.05 due to its minimal exposure to renewable energy sources (3ab), as well as its energy intensive production (3bb). Thus, even a minor increase in both companies renewable energy footprint will boost their circularity. Water & Procurement sub-indices demonstrate a rather stable profile for all companies, with the difference gap among them being minimal. Supplementary Figures 3a-3d present the Category-based Circularity Sub-indices for the four automotive companies for multiple years, while Supplementary Figure 3e features the Category-based Circularity Sub-indices for the Automotive sector for 2019.

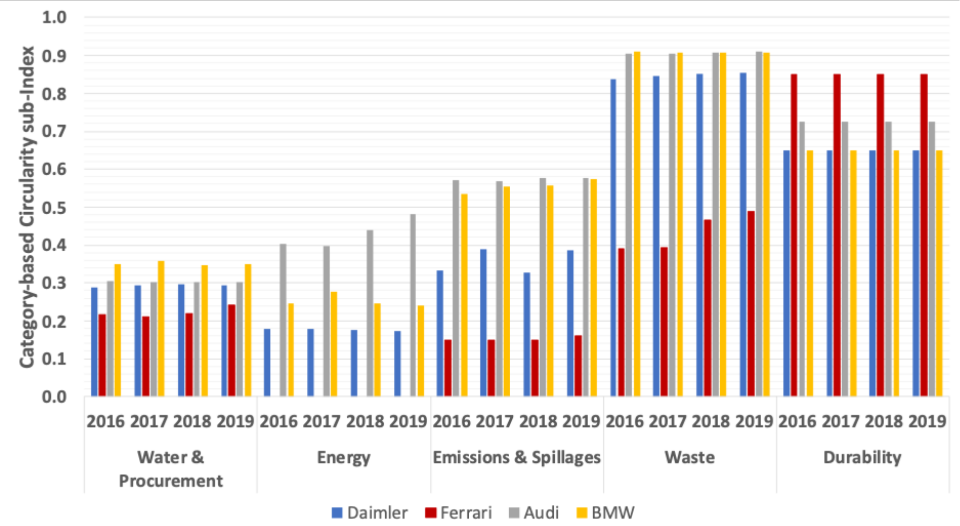

Figure 7: Category-based Circularity Sub-Indices in the Automotive sector (2016-2019).

The Overall Circularity Indices in the Automotive sector are displayed in Figure 8, revealing an upward pattern over the years. As expected from the previous analysis, Audi demonstrates the highest Overall Circularity Index the last four years, following a 26% rise in 2016 which is attributed to the improvement in Durability and Procurement principal categories. BMW and Daimler rank second and third with an increase of just 2% and 10% respectively. Ferrari is the least circular automotive company from the ones evaluated over this period.

6. Conclusions

MICRON has been developed as a quantitative CE framework for assessing circularity at the micro level, in an effort to accurately measure the various aspects of CE and identify potential areas of improvement towards the transition to a CE economic model. First, principal categories are designed based on the goals and key characteristics of CE. Then, clearly specified indicators and readily measurable metrics are selected for each of these principal categories so as to provide accurate CE assessment at different operational and structural levels, along the different CE goals. This is achieved through weighted average Category-based Circularity Indices that are calculated to evaluate the CE performance of companies at each of the principal categories. The linear average of these indices constitutes the Overall Circularity Index of each company that is a numeric value between 0 and 1, with 0 representing perfect linearity and 1 representing perfect circularity. It is a holistic approach that utilizes various sector specific indicators and metrics so as to effectively capture all CE aspects across different business segments. Its structure enables better interpretability and traceability of the integrated CE characteristics, while identifying key areas that require improvement. Moreover, it is a robust framework that allows the effective capture and fair evaluation of extreme cases e.g. Ferrari, easy comparison among peers, benchmarking within business segments/industries/sectors, and tracking of CE performance on year-over-year basis. As such, it can be utilized as a decision-making tool at different operational levels and investment time horizons.

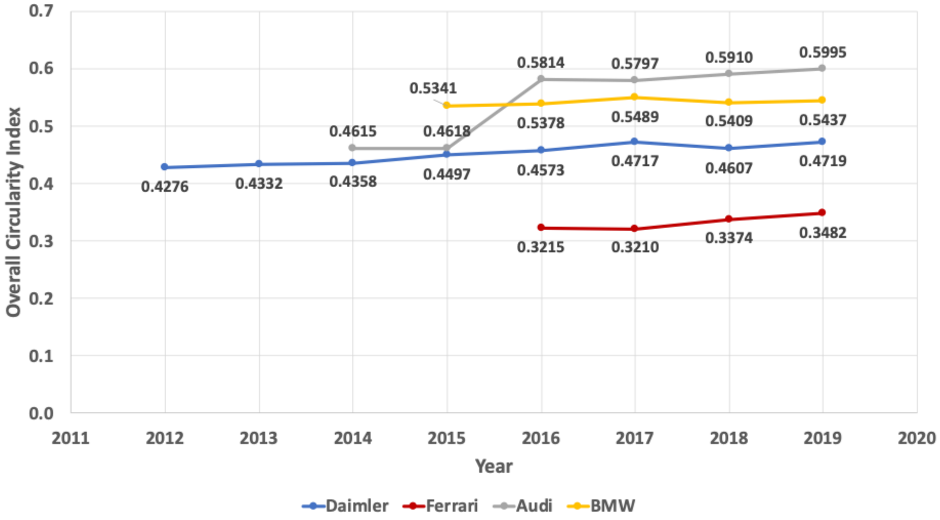

Figure 8: Overall Circularity Indices in the Automotive sector (2012-2019).

The capabilities and applicability of the subject framework are demonstrated through case studies in three sectors, namely Energy & Utilities, Manufacturing and Automotive. An upward trend is observed in most of the assessed companies, reaffirming the progress of CE across different industries and sectors of the economy. It is also evident that the aggregate prevalence of the CE concept is still far away, but important steps have already been made, and accurate assessment tools are critical to this direction. The proposed framework can act as an organization's internal CE and sustainability assessment tool, providing information about company's Category-based and Overall Circularity Indices, along with visualization mechanisms for tracking periodic progress, benchmarking against peers, and identification of areas for improvement.

The classification of industries into certain sectors, and the introduction of sector specific indicators and metrics that are matched with GRI standards are key features and contributions to the literature from the proposed framework. Furthermore, the normalization and standardization of metrics utilizing upper bounds which are derived from the statistical analysis of the given data, underline essential contributions and differentiating factors of the methodology, providing also a dynamic perspective. Ultimately, the metrics will evolve once more data become available and more CE initiatives and strategies are realized. Additionally, high level of granularity covering all CE goals, the wide range of parameters assessed, the simplicity of metrics with values ranging from 0 to 1, and the conception of the Category-based and the Overall Circularity Indices are also important contributions of the framework.

However, the non-availability or non-reporting of data complicates the evaluation process, potentially routing to misleading results. Also, social aspects are not directly captured in the current form of the framework, but can be incorporated in the future. Conglomerates or companies with diverse operations may not accurately assessed due to the extensive nature of their businesses. In such case, it might be more appropriate to assess individual segments of the company, matching their activities with the proposed classification. Future work could introduce a new sector that would reflect and capture the special characteristics of this type of companies. Similarly, sub-sectors can be added, focusing for example on the food, technology or aviation sub-sectors, with the introduction of sector specific indicators and normalization functions. In addition, future research should focus on conducting similar analysis at the meso and macro levels, especially in relation to the alignment between CE indicators and the three dimensions of sustainability. This can be done by investigating the interconnections of these dimensions with indicators and metrics at the meso and macro level.

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8. Appendix A. Summary of CE Indicators & Metrics

Principal Categories / Year	**Waste**		**Water**			**Energy**	**GHG Emissions**			**Spillages and Discharges**
	1a	**1b**	**2a**	**2b**	**2c**	**3aa**	**4aa**	**4ba**	**4ca**	**4da**
Weights	***50%***	***50%***	***33.33%***	***33.33%***	***33.33%***	***100%***	***50%***	***20%***	***20%***	***10%***
Company	**PG&E**									
2014	0.4104	0.4630	0.0000	0.0000	0.9999	0.7893	0.6952	0.0000	0.9883	0.9893
2015	0.2072	0.2712	0.0000	0.0000	0.9997	0.7621	0.6799	0.0000	0.9872	0.3866
2016	0.2466	0.2741	0.0000	0.0000	0.9997	0.8294	0.7539	0.0000	0.9894	0.5954
2017	0.4166	0.4343	0.0000	0.0000	0.9997	0.8361	0.7777	0.0000	0.9890	0.9187
2018	0.3225	0.4452	0.0000	0.0000	0.9997	0.8068	0.7674	0.0000	0.9900	0.7160
2019	0.3519	0.3328	0.0000	0.0000	0.9996	0.8133	0.7745	0.0000	0.9901	0.8611
Company	**NextEra**									
2016	0.0000	0.0000	0.0032	0.0000	0.9855	0.4838	0.6028	0.0000	0.9167	0.0000
2017	0.9972	0.9797	0.0022	0.0000	0.9851	0.5103	0.6211	0.0000	0.9219	0.0000
2018	0.9985	0.9879	0.0027	0.0000	0.9850	0.5066	0.6366	0.0000	0.9392	0.0000
2019	0.9990	0.9934	0.0035	0.0000	0.9819	0.4871	0.5985	0.0000	0.9300	0.0000
Company	**Uniper**									
2016	0.9516	0.1252	0.0000	0.0000	0.9983	0.1788	0.1113	0.0000	0.3410	0.0000
2017	0.9072	0.2597	0.0000	0.0000	0.9940	0.1912	0.1210	0.0000	0.3121	0.0000
2018	0.9716	0.1600	0.0000	0.0000	0.9917	0.1896	0.1048	0.0000	0.3207	0.0000
2019	0.9330	0.3164	0.0000	0.0000	0.9934	0.2288	0.2216	0.0000	0.4151	0.0000

Table A.5: CE Metrics of Energy Utilities Companies (2014-2019) - Energy and Utilities Sector.

Principal Categories / Year	Waste			Water				Procurement: Production and Packaging			Energy		GHG Emissions			Spillages and Discharges	Durability
	1a	1b	1ca	2a	2b	2c	2da	2pab	2pbb	2pcb	3ab	3ba	4ab	4bb	4cb	4db	5a
Weights	33.33%	33.33%	33.33%	25%	25%	25%	25%	33.33%	33.33%	33.33%	75%	25%	50%	20%	20%	10%	100%
Company	**Nestle**																
2010	0.9951	0.7140	0.8454	0.0339	0.6178	0.6555	0.6685	0.0000	0.0000	0.0000	0.1190	0.7959	0.6746	0.2112	0.6036	0.0000	0.0000
2011	0.9967	0.7631	0.8414	0.0335	0.6172	0.6530	0.6818	0.2710	0.2801	0.0000	0.1200	0.8001	0.6778	0.6887	0.6331	0.9929	0.0000
2012	0.9972	0.7757	0.8500	0.0341	0.5759	0.6106	0.7105	0.2710	0.2801	0.0000	0.1250	0.8108	0.6973	0.7223	0.6705	0.9986	0.0000
2013	0.9979	0.8273	0.8551	0.0337	0.6133	0.5958	0.7084	0.2710	0.2801	0.0000	0.1340	0.8099	0.6966	0.8052	0.6446	0.9781	0.0000
2014	0.9984	0.8511	0.8549	0.0374	0.5899	0.6019	0.7244	0.2680	0.2837	0.0000	0.1450	0.8186	0.7148	0.8197	0.6837	0.9853	0.0000
2015	0.9986	0.8954	0.8534	0.0390	0.5817	0.5835	0.7426	0.2810	0.2769	0.0000	0.1530	0.8275	0.7280	0.6491	0.7091	0.9853	0.0000
2016	0.9996	0.9352	0.8504	0.0370	0.5657	0.5759	0.7520	0.2740	0.2587	0.0000	0.1690	0.8328	0.7546	0.8813	0.7157	0.9757	0.0000
2017	0.9998	0.9620	0.8503	0.0476	0.5624	0.5907	0.7633	0.2870	0.2821	0.0000	0.1930	0.8357	0.7764	0.8714	0.7303	0.9911	0.0000
2018	0.9998	0.9790	0.8472	0.0463	0.5618	0.5939	0.7668	0.2360	0.2504	0.0000	0.2190	0.8372	0.7826	0.8883	0.7505	0.9844	0.0000
2019	0.9998	0.9913	0.8424	0.0397	0.4765	0.5585	0.7718	0.2600	0.2701	0.8700	0.2020	0.8341	0.7886	0.8935	0.7631	0.9951	0.0000
Company	**General Mills**																
2010	1.0000	0.0000	0.8163	0.0000	0.0000	0.0000	0.7832	0.0000	0.0000	0.0000	0.0008	0.8080	0.5917	0.0000	0.0000	0.0000	0.0000
2011	1.0000	0.0000	0.8176	0.0000	0.0000	0.0000	0.7889	0.0000	0.0000	0.0000	0.0031	0.8080	0.5872	0.0000	0.0000	0.0000	0.0000
2012	1.0000	0.0000	0.8298	0.0000	0.0000	0.0000	0.7859	0.0000	0.0000	0.0000	0.0076	0.8100	0.5872	0.0000	0.0000	0.0000	0.0000
2013	1.0000	0.0000	0.8296	0.0000	0.0000	0.0000	0.7094	0.0000	0.0000	0.0000	0.0501	0.8110	0.6208	0.0000	0.0000	0.0000	0.0000
2014	1.0000	0.0000	0.8339	0.0000	0.0000	0.0000	0.7178	0.0000	0.0000	0.0000	0.0488	0.8120	0.6381	0.0000	0.0000	0.0000	0.0000
2015	1.0000	0.8800	0.8258	0.0000	0.0000	0.0000	0.7148	0.4900	0.0000	0.8400	0.0494	0.8130	0.6415	0.0000	0.0000	0.0000	0.0000
2016	1.0000	0.8500	0.7860	0.0000	0.0000	0.0000	0.6803	0.4200	0.0000	0.8800	0.0418	0.8140	0.6616	0.0000	0.0000	0.0000	0.0000
2017	1.0000	0.8700	0.7775	0.0000	0.0000	0.0000	0.7053	0.4300	0.0000	0.8800	0.0468	0.8090	0.6593	0.0000	0.0000	0.0000	0.0000
2018	1.0000	0.9000	0.7601	0.0000	0.0000	0.0000	0.7154	0.4500	0.0000	0.8900	0.0445	0.8120	0.6664	0.0000	0.0000	0.0000	0.0000
2019	1.0000	0.9200	0.7029	0.0000	0.0000	0.0000	0.7365	0.4700	0.0000	0.8800	0.0376	0.8110	0.6805	0.0000	0.0000	0.0000	0.0000
Company	**Tyson**																
2015	0.0000	0.9055	0.5594	0.0000	0.0000	0.0000	0.3031	0.0000	0.0000	0.0000	0.0166	0.7581	0.3320	0.0000	0.0000	0.7547	0.0000
2016	0.0000	0.8976	0.5604	0.0638	0.0000	0.0000	0.2555	0.3000	0.0000	0.0000	0.0215	0.7453	0.2760	0.0000	0.0000	0.9405	0.0000
2017	0.0000	0.8879	0.5077	0.0627	0.0000	0.0000	0.2022	0.3000	0.0000	0.0000	0.0135	0.6585	0.2400	0.0000	0.0000	0.8625	0.0000
2018	0.0000	0.8111	0.2993	0.0634	0.0000	0.0000	0.2240	0.2990	0.0000	0.0000	0.0075	0.6542	0.2400	0.0000	0.0000	0.0000	0.0000
2019	0.0000	0.8675	0.0505	0.0637	0.0000	0.0000	0.2537	0.3550	0.0000	0.0000	0.0077	0.6135	0.2800	0.0000	0.0000	0.9772	0.0000
Company	**Ferrero**																
2016	0.0000	0.9500	0.5535	0.7406	0.0620	0.7406	0.6279	0.3900	0.3700	0.0000	0.0994	0.1000	0.0326	0.2580	0.0000	0.0000	0.0000
2017	0.0000	0.9500	0.5727	0.7319	0.0590	0.7319	0.6319	0.3600	0.3700	0.0000	0.1202	0.1000	0.0851	0.4076	0.0000	0.0000	0.0000
2018	0.9877	0.9465	0.5503	0.6385	0.0510	0.6385	0.5697	0.3390	0.3690	0.8170	0.1371	0.1600	0.0000	0.8661	0.0000	0.0000	0.0000
2019	0.9854	0.9677	0.5892	0.6318	0.0530	0.6318	0.5620	0.3420	0.3690	0.8170	0.1900	0.1600	0.0000	0.9178	0.0000	0.0000	0.0000

Table A.6: CE Metrics of Food and Beverages Companies (2010-2019) - Manufacturing Sector.

Principal Categories / Year	Waste			Water				Procurement: Production and Packaging			Energy		GHG Emissions				Spillages and Discharges	Durability	
	1a	1b	1cb	2a	2b	2c	2db	2paa	2pba	2pca	3ab	3bb	4ac	4bc	4cc	4d	4dc	5a	5b
Weights	33.33%	33.33%	33.33%	25%	25%	25%	25%	33.33%	33.33%	33.33%	75%	25%	35%	10%	10%	40%	5%	50%	50%
Company	**Daimler**																		
2012	0.9257	0.9266	0.6406	0.0000	0.0000	0.0000	0.7674	0.0000	0.0000	0.8500	0.0000	0.6734	0.2411	0.0000	0.6989	0.2415	0.0000	0.9500	0.3500
2013	0.9104	0.9055	0.6525	0.0000	0.0000	0.0000	0.7847	0.0000	0.0000	0.8500	0.0000	0.6868	0.2871	0.0000	0.7065	0.2770	0.0000	0.9500	0.3500
2014	0.8623	0.8542	0.6426	0.0000	0.0000	0.0000	0.8062	0.0000	0.0000	0.8500	0.0000	0.7159	0.3576	0.0000	0.7429	0.3039	0.0000	0.9500	0.3500
2015	0.9111	0.9088	0.6456	0.0000	0.0000	0.3816	0.8001	0.0000	0.0000	0.8500	0.0000	0.7078	0.3527	0.0000	0.5382	0.3328	0.0000	0.9500	0.3500
2016	0.9251	0.9129	0.6780	0.0000	0.0000	0.3608	0.8022	0.0000	0.0000	0.8500	0.0000	0.7146	0.4227	0.0000	0.5171	0.3305	0.0000	0.9500	0.3500
2017	0.9291	0.9236	0.6825	0.0000	0.0000	0.3921	0.8247	0.0000	0.0000	0.8500	0.0000	0.7163	0.4456	0.0000	0.5749	0.3175	1.0000	0.9500	0.3500
2018	0.9307	0.9623	0.6652	0.0000	0.0000	0.4111	0.8186	0.0000	0.0000	0.8500	0.0000	0.7072	0.4448	0.0000	0.5558	0.2927	0.0000	0.9500	0.3500
2019	0.9288	0.9696	0.6636	0.0000	0.0000	0.4079	0.8185	0.0000	0.0000	0.8500	0.0000	0.6962	0.4923	0.0000	0.5428	0.2742	1.0000	0.9500	0.3500
Company	**Ferrari**																		
2016	0.6765	0.4148	0.0828	0.0000	0.0000	0.5382	0.0000	0.0000	0.0430	0.8500	0.0468	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.9500	0.7500
2017	0.7204	0.4325	0.0260	0.0000	0.0000	0.5041	0.0000	0.0000	0.0430	0.8500	0.0517	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.9500	0.7500
2018	0.7497	0.4583	0.1912	0.0000	0.0000	0.5742	0.0000	0.0000	0.0430	0.8500	0.0541	0.0000	0.0000	1.0000	0.0000	0.0000	1.0000	0.9500	0.7500
2019	0.7605	0.4429	0.2646	0.0000	0.0000	0.5899	0.1550	0.0000	0.0380	0.8500	0.0655	0.0000	0.0000	1.0000	0.1056	0.0000	1.0000	0.9500	0.7500
Company	**Audi**																		
2014	0.8979	0.9674	0.8424	0.0000	0.0000	0.4058	0.9295	0.0000	0.0000	0.0000	0.2747	0.8715	0.8233	0.0000	0.8794	0.3450	1.0000	0.0000	0.5000
2015	0.9023	0.9683	0.8390	0.0000	0.0000	0.4012	0.9272	0.0000	0.0000	0.0000	0.2646	0.8644	0.8237	0.0000	0.8887	0.3700	1.0000	0.0000	0.5000
2016	0.9040	0.9766	0.8309	0.0000	0.0000	0.3731	0.9269	0.0000	0.0000	0.8500	0.2493	0.8592	0.8143	0.0000	0.8948	0.3700	1.0000	0.9500	0.5000
2017	0.9031	0.9773	0.8327	0.0000	0.0000	0.3510	0.9267	0.0000	0.0000	0.8500	0.2456	0.8558	0.8078	0.0000	0.9098	0.3650	1.0000	0.9500	0.5000
2018	0.9033	0.9838	0.8393	0.0000	0.0000	0.3656	0.9271	0.0000	0.0000	0.8500	0.2993	0.8643	0.8357	0.0000	0.9286	0.3550	1.0000	0.9500	0.5000
2019	0.8973	0.9913	0.8423	0.0000	0.0000	0.3541	0.9378	0.0000	0.0000	0.8500	0.3553	0.8636	0.8422	0.0000	0.9366	0.3450	1.0000	0.9500	0.5000
Company	**BMW**																		
2015	0.9515	0.9884	0.7772	0.0000	0.0000	0.6450	0.9747	0.0000	0.0200	0.8500	0.0449	0.8508	0.6780	0.0000	0.8780	0.3650	1.0000	0.9500	0.3500
2016	0.9540	0.9896	0.7839	0.0000	0.0000	0.6602	0.9758	0.0000	0.0200	0.8500	0.0447	0.8490	0.6971	0.0000	0.8860	0.3800	1.0000	0.9500	0.3500
2017	0.9473	0.9885	0.7880	0.0000	0.0000	0.7162	0.9806	0.0000	0.0200	0.8500	0.0830	0.8552	0.7713	0.0000	0.8970	0.3600	1.0000	0.9500	0.3500
2018	0.9469	0.9875	0.7880	0.0000	0.0000	0.6328	0.9733	0.0000	0.0200	0.8500	0.0400	0.8612	0.7757	0.0000	0.9070	0.3600	1.0000	0.9500	0.3500
2019	0.9367	0.9875	0.7949	0.0000	0.0000	0.6606	0.9759	0.0000	0.0200	0.8500	0.0319	0.8627	0.8151	0.0000	0.9150	0.3650	1.0000	0.9500	0.3500

Table A.7: CE Metrics of Automotive Companies (2012-2019) - Automotive Sector.

9. Appendix B. Calculation of CE Metrics

Principal Categories	Metrics		Upper Bound	Formula Used
Waste	1a	% of Hazardous waste over Total waste generated	100%	100%-1a
	1b	% of Diverted waste over Total waste generated	100%	1b
Water	2a	% of Recycled/reused water over Total water withdrawal	100%	2a
	2b	% of Other water discharge over Total water discharge	100%	100%-2b
	2c	% of Water consumed over Total water withdrawal	100%	100%-2c
Energy	3aa	% of Non fossil fuel energy generated over Total energy generated	100%	3aa
GHG Emissions	4aa	Net total emissions over Total energy delivered [tCO2e over joules or multiples]	600	1-norm[4aa]
	4ba	Emissions of ODS over Total energy delivered [metric tons of CFC-11 eq. over joules or multiples]	0.1	1-norm[4ba]
	4ca	NOx, SOx, and other significant air emissions over Total energy delivered [metric tons over joules or multiples]	1.0	1-norm[4ca]
Spillages and Discharges	4da	Environmental fines over Total energy delivered [$ over joules or multiples]	1.0	1-norm[4da]

Table B.8: CE Metrics for the Energy and Utilities Sector.

Principal Categories	Metrics		Upper Bound	Formula Used
Waste	1a	% of Hazardous waste over Total waste generated	100%	100%-1a
	1b	% of Diverted waste over Total waste generated	100%	1b
	1ca	Waste generated over Products sold [kg waste over tons of product]	200	1-norm[1ca]
Water	2a	% of Recycled/reused water over Total water withdrawal	100%	2a
	2b	% of Other water discharge over Total water discharge	100%	100%-2b
	2c	% of Water consumed over Total water withdrawal	100%	100%-2c
	2da	Water withdrawal over Products sold [m3 water over tons of product]	10	1-norm[2da]
Procurement: Production and Packaging	2pab	% of Recycled packaging material used	100%	2pab
	2pbb	% of Renewable packaging material used	100%	2pbb
	2pcb	% of Reusable, compostable or recyclable packaging material used	100%	2pcb
Energy	3ab	% of Renewable energy consumed over Total energy consumed	100%	3ab
	3ba	Total energy consumed over Products sold [joules or multiples over tons of product]	10	1-norm[3ba]
GHG Emissions	4ab	Net total emissions over Products sold [tCO2e over tons of product]	500	1-norm[4ab]
	4bb	Emissions of ODS over Products sold [metric tons of CFC-11 eq. over tons of product]	0.1	1-norm[4bb]
	4cb	NOx, SOx, and other significant air emissions over Products sold [metric tons over tons of product]	1	1-norm[4cb]
Spillages and Discharges	4db	Environmental fines over Products sold [$ over tons of product]	10	1-norm[4db]
Durability	5a	% of Packaging material to be reclaimed/recovered	100%	5a

Table B.9: CE Metrics for the Manufacturing Sector.

Principal Categories	Metrics		Upper Bound	Formula Used
Waste	1a	% of Hazardous waste over Total waste generated	100%	100%-1a
	1b	% of Diverted waste over Total waste generated	100%	1b
	1cb	Waste generated over Number of products sold [kg waste over # of products]	1500	1-norm[1cb]
Water	2a	% of Recycled/reused water over Total water withdrawal	100%	2a
	2b	% of Other water discharge over Total water discharge	100%	100%-2b
	2c	% of Water consumed over Total water withdrawal	100%	100%-2c
	2db	Water consumption over Number of products sold [m3 water over # of products]	30	1-norm[2db]
Procurement: Production and Packaging	2paa	% of Recycled input material used	100%	2paa
	2pba	% of Renewable material used	100%	2pba
	2pca	% of Reusable, compostable or recyclable material used	100%	2pca
Energy	3ab	% of Renewable energy consumed over Total energy consumed	100%	3ab
	3bb	Total energy consumed over Number of products sold [joules or multiples over # of products]	15	1-norm[3bb]
GHG Emissions	4ac	Net total emissions over Number of products sold [tCO2e over # of products]	2,000	1-norm[4ac]
	4bc	Emissions of ODS over Number of products sold [metric tons of CFC-11 eq. over # of products]	0.1	1-norm[4bc]
	4cc	NOx, SOx, and other significant air emissions over Number of products sold [metric tons over # of products]	10	1-norm[4cc]
	4d	Average specific CO2 emissions [gCO2/km]	200	1-norm[4d]
Spillages and Discharges	4dc	Environmental fines over Number of products sold [$ over # of products]	10	1-norm[4dc]
Durability	5b	% of Material to be reclaimed/recovered	100%	5b
	5c	Average lifespan of product or Warranty provided [years]	20	norm[5c]

Table B.10: CE Metrics for the Automotive Sector.

Principal Categories	Metric		Upper Bound	Formula Used
Waste	1a	% of Hazardous waste over Total waste generated	100%	100%-1a
	1b	% of Diverted waste over Total waste generated	100%	1b
	1cc	Waste generated over Full Time Employees [kg waste over # of FTE]	1000	1-norm[1cc]
Water	2a	% of Recycled/reused water over Total water withdrawal	100%	2a
	2b	% of Other water discharge over Total water discharge	100%	100%-2b
	2c	% of Water consumed over Total water withdrawal	100%	100%-2c
	2dc	Water consumption over Full Time Employees [m3 water over # of FTE]	100	1-norm[2dc]
Procurement: Production & Packaging	2paa	% of Recycled input material used	100%	2paa
	2pd	Paper consumption over Full Time Employees [kg over # of FTE]	365	1-norm[2pd]
	2pe	Single-use plastics consumption over Full Time Employees [kg plastic over # of FTE]	50	1-norm[2pe]
Energy	3ab	% of Renewable energy consumed over Total energy consumed	100%	3ab
	3bc	Total energy consumed over Operational space [joules or multiples over surface area]	1	1-norm[3bc]
	3bd	% of Certified buildings and facilities i.e LEED	100%	3bd
GHG Emissions	4ad	Net total emissions over Operational space [tCO2e over surface area]	300	1-norm[4ad]
	4bd	Emissions of ODS over Operational space [metric tons of CFC-11 eq. over surface area]	1	1-norm[4bd]
	4cd	NOx, SOx, and other significant air emissions over Operational space [metric tons over surface area]	0.05	1-norm[4cd]
Spillages & Discharges	4dd	Environmental fines over Operational space [$ over surface area]	0.5	1-norm[4dd]

Table B.11: CE Metrics for the Service Sector.

10. Appendix D. Templates for Data Acquisition

Templates for data acquisition can be found online at https://

CRediT authorship contribution statement

Stefanos G. Baratsas: Conceptualization, Methodology, Software, Validation, Formal Analysis, Data curation, Writing - original draft, Writing - review & editing, Visualization. **Efstratios N. Pistikopoulos:** Writing - review & editing, Supervision, Project administration, Funding acquisition. **Styliani Avraamidou:** Conceptualization, Methodology, Formal analysis, Writing - review & editing, Visualization, Supervision, Project administration.

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Graphical Abstract

A quantitative and holistic circular economy assessment framework at the micro level

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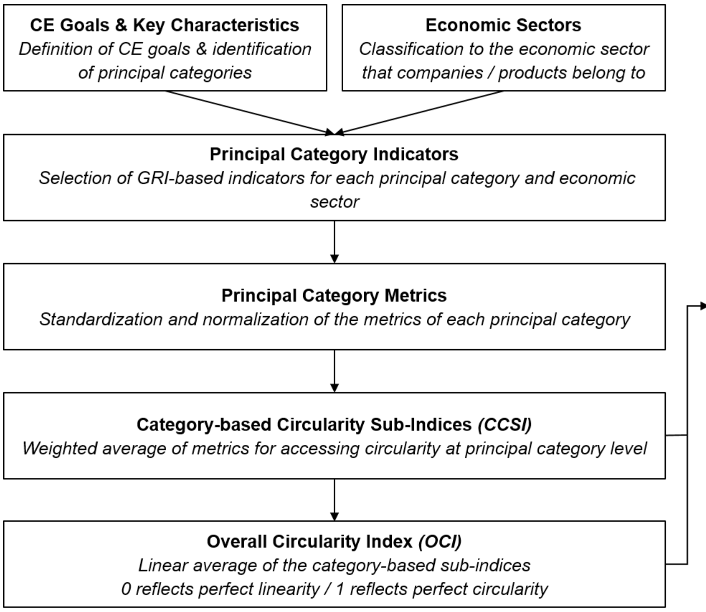

CE Goals & Key Characteristics
Definition of CE goals & identification of principal categories

Economic Sectors
Classification to the economic sector that companies / products belong to

Principal Category Indicators
Selection of GRI-based indicators for each principal category and economic sector

Principal Category Metrics
Standardization and normalization of the metrics of each principal category

Category-based Circularity Sub-Indices *(CCSI)*
Weighted average of metrics for accessing circularity at principal category level

Overall Circularity Index *(OCI)*
Linear average of the category-based sub-indices
0 reflects perfect linearity / 1 reflects perfect circularity

Data Visualization, Benchmarking & Comparisons
Temporal analysis, periodic circularity assessment, benchmarking against peers and industry's standards