Review of corporate environmental indicators

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abstract

This paper reviews a series of environmental indicators developed in the last years that were found suitable to be applied at corporate level for the evaluation of production processes and products. The indicators reviewed in this paper were classified into four main groups: 1) Indicators of Energy and Material Flows; 2) Indicators with a Territorial Dimension; 3) Indicators of Life-Cycle Assessment; 4) Indicators of Environmental Risk Assessment. Integrative and single index indicators such as the ecological footprint or carbon footprint were found as the most appealing for enterprises, although there is a need to advance in the field to combine the simplicity required at corporate level for tracking and reporting environmental data, and the scientific rigor and transparency necessary to make the scores reliable. Hence, for each of the indicators revised it was stated what they do and do not measure so that misleading information was not used for decision making at corporate level.

1. Introduction

Industry is recognized as one of the main sources of environmental pollution and resource depletion, both causing environmental degradation; nonetheless, its contribution to development and wealth creation is also acknowledged. Therefore, the identification of sustainable options in this area is a key factor (Azapagic and Perdan, 2000). In a sustainable production, the conservation of energy and natural resources is pursued, as well as the minimization of pollution. Economically viable, socially beneficial, safe and healthful are other desired characteristics for such processes and systems (Veleva and Ellenbecker, 2001).

In this respect, different attitudes have been adopted over the years (Sikdar, 2003a). At first, just corrective actions were carried out as a response to emerging environmental laws and regulations, but soon businesses realized that if pollution prevention and cleaner production policies were adopted, not only environmental improvements would take place, but also an increase in profits (Azapagic and Perdan, 2000). A change from a reactive to a more proactive attitude has succeeded thus avoiding or reducing human and ecological health impacts. In this respect, indicators can provide an early warning, sounding the alarm in time to prevent economic, social and environmental damage.

This paper aims to review the environmental indicators developed in the last years that are suitable to be applied under a process and product oriented approach. The former refers to the company activities, whereas the product-related information has a broader scope and, additionally to part of the company activities, it includes information from suppliers and customers, which is out of the company's control (Erlandsson and Tillman, 2009).

The search of related literature was mainly conducted using scientific search engines and, therefore, the works handled mostly corresponded to scientific papers from journals indexed in recognized databases (e.g. JCR). General search was also carried out using common engines from which interesting reports in the field were also extracted. The search was conducted based on the key words of the topic, i.e. environmental assessment under a product and process approach, indicating the specific indicators when convenient. A number of journals appeared to provide most of the contributions and, as a consequence, the search was refined within them.

It was observed that, commonly, authors focused their research in the application of a specific indicator in which they are specialized. In this respect, there are few works in which more than a methodology is applied to assess the environmental performance at corporate level. This brings a number of consequences: lack of an agreed classification of indicators; ignorance on similarities and differences among the existing indicators; lack of knowledge on how they can be used jointly to achieve meaningful and comprehensive evaluations. Some of the indicators have received more attention in the last years, as it is the case of the Ecological Footprint (EF). Abundant literature has been published both in favor or criticizing the application of such an integrate indicator, initiatives to improve the methodology have been proposed, but so far a broad agreement hast not been achieved (beyond practitioners involved in National Footprint Accounts), especially regarding its application at corporate level. The Carbon Footprint (CF) has also generated discussion because of the thin line existing with the global warming category of Life-Cycle Assessments (LCA) or the fossil energy category of EF. Similarly, the Water Footprint (WF) is considered as the third member of the so-called footprint family, although it represents material flows rather than an area based indicator.

The existence of a certain level of standardization of the methodologies underlying the indicators is usually the driving force to become popular. The support of an agreed framework and databases (as that provided by SETAC and ISO Standards for LCA or CF, or by National Footprint Accounts for EF) provides transparency, reliability and comparability to the indicators, characteristics well appreciated by corporations that, apart from measuring their environmental performance, are interested in reporting their results. In the case of EF, however, this is limited to national accounts and the availability of data necessary at corporate level is scarce.

The paper has been structured as follows. A first section deals with the reasons that explain the proliferation of indicators as a response to the emerging necessity to provide metrics of resources consumption and environmental impact. The indicators reviewed in this paper were classified into four main groups: 1) Indicators of Energy and Material Flows; 2) Indicators with a Territorial Dimension; 3) Indicators of Life-Cycle Assessment; 4) Indicators of Environmental Risk Assessment. They were treated in separate sections, including a description, discussing their usefulness and applicability, as well as their drawbacks. A last section provides a general discussion on the relationships existing among indicators and how can they better be applied to obtain the major benefit from their application.

2. Indicators: the necessary metric to track environmental performance and for decision making

2.1. Why are indicators necessary?

Sustainable development as a general concept results too vague and ambiguous to provide useful guidelines. Therefore, it results crucial the development and application of indicators, which provide metrics essential at the action level (Tibbs, 1999; Johnston et al., 2007).

Currently, sustainability is considered to comprise four dimensions: environmental, social, economic and institutional. For the former three, indicators have been developed in abundance, whereas for the institutional dimension indicator proposals are still quite rare (Spangenbergh, 2002). As stated in the introduction, this review is focused in the environmental dimension of sustainability.

The WCED (World Commission on Environment and Development) dissertation on sustainability considered the Planet Earth as a whole (WCED, 1987). However, there are different subsystems and levels at which sustainability can be addressed. Sikdar (2003a) found necessary the definition of concrete systems so that actions for progress became measurable and achievable. Thus, he defined four systems, namely the earth, the community (group of people sharing resources, more related with the urban level), business and technology. Meanwhile, Batterham (2006) considered 5 levels that comprised: global objectives, industry strategy, enterprise targets, specific projects and individual actions. In the context of production processes, it is a key issue to incorporate environmental aspects into process and product design, manufacturing and value chain management to prevent the consequences of unsustainable resource utilization and adverse environmental impacts. This is the perspective more strongly related to concepts such as industrial ecology, cleaner production or design for environment sustainability (Heijungs et al., 2010).

The ultimate purpose of any performance measurement scorecard is to change behavior (Hussey et al., 2001). Unfortunately, many companies appear to view reporting as an environmental strategy itself, rather than as a tool to measure progress towards environmental targets (Batterham, 2006). Nevertheless, when a metric is relevant, understandable and reliable, it can impact the consumer choice and ultimately influence legislative and regulatory action (MacLean, 2001; European Commission, 2003). For production processes and services, the availability of a set of indicators would allow comparing the environmental performance over time, highlighting optimization potentials, deriving and pursuing environmental targets, identifying market chances, benchmarking against other companies or communicating results in environmental reports (Jash, 2000; Azapagic and Perdan, 2000).

2.2. Environmental indicators

According to the definition given by the European Environmental Agency (EEA), an environmental indicator is an observed value representative of a phenomenon under study (EEA, 1999). Indicators quantify information by aggregating different and multiple data (necessary to obtain reliable information); thus, they can be used to illustrate and communicate complex phenomena in a simpler way, including trends and progresses over a certain period of time (Roca et al., 2005; Herva et al., 2008b).

Indicators must provide information about the main characteristics that affect the suitability of products and processes from a sustainability viewpoint. These are: energy use per unit of economic value-added; intensity and type of energy used (renewable or non-renewable); materials use (or resource depletion); freshwater use; waste and pollutants production; environmental impacts of product/process/service; assessment of overall risk to human health and the environment (Sikdar, 2003b).

Next, a review of environmental indicators is presented, classified into the following categories: indicators of material and energy flows; indicators with a territorial dimension; indicators of environmental life-cycle assessment; indicators of environmental risk assessment (Fig. 1).

3. Indicators of material and energy flows

Flows of energy and material are valuable environmental indicators both at micro and macro scale. Actually, a key task of industrial ecology is to identify, trace and allocate energy and material flows throughout the system (Lou et al., 2004). Dematerialization is one of the mechanisms to deal with environmental sustainability, meaning the reduction of material flows and substitution, i.e. exchange of type/quality of flows and/or activities, that can be planned in parallel and on different scales, e.g. from changing amounts and types of fuel in the same process, through a more radical change of the whole process, to completely new and less resource demanding and more ecologically and socially sound ways of satisfying the same human need (Robèrt et al., 2002). Efficiency in resource use is directly related to the Factor X approach, i.e. by what factor can or should certain flows be reduced.

Thus, Energy and Material Flow Analysis (EMFA) is an assessment methodology of environmental issues and a decision-support method that can be defined as a systematic appraisal of the flows and stocks of energy and material within a system defined in space and time (Torres et al., 2008). The methodology comprises different steps that can be supported by computer tools like Umberto®, which offer versatility to model, calculate and visualize material and energy flow systems under particular specifications (Wohlgemuth et al., 2006). This is suitable, when applied to production processes, to pursue reductions in the consumption of energy, raw material, water and in the discharge of effluents, emissions or wastes.

3.1. Energy flow indicators

3.1.1. Energy analysis

Energy analysis is the process of determining the energy required directly and indirectly to allow a system to produce a specified good or service (Nilsson, 1997; Herendeen, 2004). It accounts for the different types of energy in the same analysis. A key concept is the embodied energy, which is the direct and indirect energy required to produce a good or a service (Herendeen, 2004). Therefore, the embodied energy incorporates the cradle to gate scope by accounting for all the energy invested in obtaining a product (Svensson et al., 2006). The literature also refers to the Cumulative Energy Demand (CED) of a product as the direct and indirect energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials (Huijbregts et al., 2005).

Energy indicators gained in relevance during the periods of crisis in the energy sector, being subjected to the societal and political context and, therefore, varying over time. Different studies have been conducted to assess energy consumption in production processes and energy embedded in products (Sakamoto et al., 1999; Bernard and Côté, 2005; Ramírez and Worrell, 2006; Neelis et al., 2007). Energy flows provide interesting information on the efficiency of energy use, but fails at describing the environmental impacts derived from the consumption of different energy sources, which include depletion of abiotic resources, land use, ozone depletion, global warming, toxicity, acidification, eutrophication, etc. In this respect, Huijbregts et al. (2005) found significant correlations between fossil CED and a series of mid-point impacts for products belonging to any of these categories: energy production, material production and transport. The existence of such relationships is common scientific knowledge, not only for fossil but also for renewable sources of energy. Hence, using CED as screening indicator can helpfully simplify environmental assessments, but it can hardly substitute exhaustive LCA when in depth analyses are required.

3.1.2. Exergy analysis

Exergy is an efficient indicator for decision making on energy concerns since it is a measure of quantity and quality of the energy sources, unlike energy which only informs about the quantity (Hovelius, 1997). From a thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a system or a flow of matter or energy as it comes to equilibrium with a reference environment (Rosen and Dincer, 2001). While seeking for this equilibrium changes in the environment may occur and, therefore, exergy may to some extend be considered as an indicator of environmental impact. Exergy analysis is useful in identifying the causes, locations and magnitudes of process inefficiencies, thus helping to identify more sustainable technologies (Rosen et al., 2008).

Its application in the environmental impact evaluation of industrial processes has been explored (Hau and Bakshi, 2004a; Zhu et al., 2005), as well as its usefulness to measure the optimal use of energy in processes (Banat and Jwaied, 2008) or in buildings (Torío et al., 2009). It has also been employed to measure water quality (Huang et al., 2007) or to assess the efficiency of resources use and losses of quality during recycling processes (Castro et al., 2007; Talens et al., 2008). As a thermodynamically founded indicator, its applicability is majorly focused on evaluating energy related techniques, such as thermal energy storage, heating equipment, power plants, and so on. Nevertheless, it has also successfully been applied in whole chain production processes, especially in the case of biofuel production (Dewulf et al., 2005; Talens et al., 2007; Ometto and Lopes Roma, 2010).

The application of exergy at process level implies transforming materials and energy consumed into exergetic units, for which a detailed knowledge of every single operation unit is required. On this basis, exergy of pure substances, mixtures or utilities is calculated. All these required data is not usually readily available; further, thermodynamics make the computation less intuitive than for other indicators for non-experts in the field. By comparing output to input flow exergy, an exergetic efficiency can be derived that informs of the irreversible losses occurred in the process.

3.1.3. Emergy analysis

Emergy, term introduced by H. Odum in the 1980's (Odum, 1988; Brown and Ulgiati, 2004), is defined as the solar energy directly or indirectly necessary to obtain a product in a process and it is expressed in solar emergy joules (seJ). To carry out the conversion into the solar equivalent, it is necessary to know the solar transformity, which is the emergy used to make a unit of available energy of a product or service and it is usually expressed in seJ/J (Herendeen, 2004; Pulselli et al., 2008). The calculations consider different energy qualities and take into account the losses of energy in the energy transformation processes. Emergy computations include renewable (eg. solar energy, rain, wind, tide) and non-renewable (e.g. fossil fuel) local resources, input purchase from market (e.g. electricity, equipment, service), the product to be sold to the market and the waste released from the system.

Emergy has been applied as environmental indicator in different fields: electricity production systems (Brown and Ulgiati, 2002); comparison of horse and tractor traction (Rydberg and Jansén, 2002); evaluation of building materials (Pulselli et al., 2008) and their recycling options (Brownand Buranakarn, 2003); evaluation of a building (Meillaud et al., 2005); evaluation of eco-industrial park with power plant (Wang et al., 2005); production, processing and export of coffee (Cuadra and Rydberg, 2006); solar salt production process (Laganis and Debeljak, 2006); hydrogen production systems from biomass and natural gas (Feng et al., 2009).

3.1.4. Strengths and limitations of energy flow indicators

Many environmental issues are caused by or relate to the production, transformation and use of energy, e.g. ambient air quality, solid waste disposal, acid deposition, global climate change, etc. (Dincer, 2002). Thus, the minimization of energy flows is extremely important to increase sustainability of resources. Process energy analysis focuses on different processes and levels in the product life cycle and sums up the flows of energy use through each of the production process stages (Ness et al., 2007). But attention must also be paid to the quality of energy. Thus, it has been observed that exergy exhibits a potential usefulness in addressing and solving environmental problems as well as attaining sustainable development. Increased efficiency can help to achieve energy security in an environmentally acceptable way by reducing the emissions that might otherwise occur (Dincer, 2002). Emergy has also found a good acceptance as environmental indicator, although, as other holistic approaches, it has encountered certain criticism mainly stem from the difficulty in obtaining details about the underlying computations (Hau and Bakshi, 2004b).

Some studies have accomplished combinations of energy, emergy or exergy analyses of a studied system, most of them in the biomass production field (Nilsson, 1997; Hovelius, 1997; Hovelius and Hansson, 1999; Franzese et al., 2009). Nevertheless, the results provided by each of the energy related indicators significantly differ. Since they are based on so different theoretical features, comparisons among them are difficult if not impossible. Therefore, the analyst should be more concerned with the appropriate use of each method according to the goal of the investigation (Franzese et al., 2009).

3.2. Material flow indicators

Traditional material flow indicators relate to input and output flows within specific geographical or politic boundaries (countries, regions, etc.), e.g. Direct Material Input eDMI-, Physical Trade Balance ePTB- or Domestic Processed Output eDPO- (EUROSTAT, 2000). However, other indicators, such as rucksacks, Material Input Per unit Service (MIPS) or Substance Flow Analysis (SFA), are more suitable indicators at corporate level, which allow taking into account indirect flows that are often omitted (Sendra et al., 2007). Besides, the usefulness of Material Flow Analysis (MFA) in sustainable materials management has also been stated (Allen et al., 2009).

3.2.1. Ecological rucksack and MIPS

The Ecological Rucksack (ER), term coined by F. Schmidt-Bleek in 1993 in the Wuppertal Institute (Spangenbergh, 2002), represents the sum of all materials which are not physically included in the economic output under consideration, but have been necessary for production, use, recycling and disposal (including those consumed indirectly). Thus, by definition, the ER is the life-cycle-wide material input minus the mass of the product itself (Schmidt-Bleek, 2001; Spangenbergh, 2002). Economic, social and technical innovation is advocated such that population needs are satisfied using less natural resources -reduction of at least a factor 10 as established in the Brundtland Report (WCED, 1987)-, at the same time that the value and utility of goods produced are improved. This relation between material input and service obtained as an output is called MIPS (Material Input per Unit Service) and introduces the idea of resource-efficiency (Hille, 1997). The reference to an output flow provides a standardized reference and allows comparisons among different yet functionally equivalent products (Spangenbergh, 2002). Thus, MIPS is a resource-efficiency measurement for the micro level that helps in the design of industrial products and in the planning of environmentally friendly processes, facilities and infrastructures (Adriaanse et al., 1997; Hertwich et al., 1997). Sinivuori and Saari (2006) applied MIPS to analyze the natural resource consumption in two university buildings. The methodology showed a good potential to point out the measures that should be adopted to reduce natural resource consumption during the different phases of a building life cycle (namely planning, construction and usage).

3.2.2. Substance flow analysis. Water footprint

Substance Flow Analysis (SFA) focuses on specific substances, either within a region or from “cradle-to-grave”. Typical examples can include studies of nitrogen flows in a local area or flows of a specific metal in a regional scenario (Finnveden and Moberg, 2005). Albeit, it has also been applied to assess industrial processes (Antikainen et al., 2004) and in the waste management field (Brunner and Ma, 2008).

The Water Footprint (WF) is one of the more recently developed indicators, built on the concept of virtual water (Allan, 1998). Little or no reliable data on water usage is available in life cycle databases; moreover, an agreed impact assessment method does not exist (Finnveden et al., 2009; Kumar Jeswani and Azapagic, in press). Due to need of a standardized methodology in this field, the WF was introduced in 2002 in order to have a consumption based indicator of water use that could provide useful information in addition to the traditional production-sector-based indicators of water use (Hoekstra and Hung, 2002). Developed in analogy to the EF, although not expressed in area units (see subheading 3.2), the WF of a nation was defined as the total volume of freshwater that is used to produce the goods and services consumed by the people of the nation. Thus, it could be considered as a particular case of SFA. Since not all goods consumed in one particular country are produced in that country, WF consists of two parts: use of domestic water resources and use of water outside the borders of the country (Hoekstra and Chapagain, 2007). In any sense, this term complements the EF and supplies one of its limitations given that water consumption is not properly accounted for in EF estimates. At corporate level, the indicator can be estimated for a business or a product by calculating the total water used during the production of goods and services in the entire supply chain.

Water is a highly site-specific resource that also depends on seasonal conditions; as a consequence, it can hardly aim to be part of an integrated or globally expressed indicator. Besides, as it is expressed in volume units, it can be considered as a resource management indicator rather than as a measure of environmental impact.

Applications of WF are mostly related to agricultural activities and energy crops: water footprint of worldwide cotton consumption (Chapagain et al., 2006), tomato production in Spain (Chapagain and Orr, 2009) and biofuels (Domínguez-Faus et al., 2009). Applications to energy crops aim to determine the secondary effects of exchanging traditional fossil energy sources by biofuels to decrease the emission of carbon dioxide. These studies reveal the increasing demand of water that can reach unsustainable rates in those regions suffering from water scarcity.

A comparison among indicators related to the environmental impact associated to the consumption of materials flows is presented in Table 1.

4. Land-based indicators

In 1965, Borgström explained the apparent excess in own resources (particularly referring to food) appropriation by alluding to the fact that nations had drawn upon on an “invisible” carrying capacity (i.e., located elsewhere on the planet). In opposition to the “visible acreage” (farm and pasture land within the nation’s borders), this was named as “ghost acreage” and divided into two components: “trade acreage” (fraction that comes from net imports of food) and “fish acreage” (food obtained from the sea) (Borgström, 1965). This was the first precedent to the idea of providing flows of natural resources with a territorial dimension (Hornborg, 2006). It was during the 90’s that these ideas were further developed. Within this context, concepts like Environmental Space (ES) or the Ecological Footprint (EF) emerged. The notion of ES was first introduced by Horst Sieber in 1982 (Bührs, 2007), although further developed by J.B. Opschoor in the early 1990s (Opschoor and Reinders, 1991). It is based on the establishment of ecological limits that, if exceeded, would cause irreversible damage to ecosystems. This limited space must be distributed among stocks of resources and sinks to absorb waste and pollution (Hille, 1997). ES usually uses a range of indicators for different resources, in contrast to the single-scored ecological footprint (Bührs, 2007). The ES has been used in urban sustainability and policy guidance, rather than to evaluate the environmental performance of production processes (Mittler, 1999). Therefore, it is not treated in further detail in this section, but focuses on the more widely applied EF and the Dissipation Area Index (DAI) which is considered to be a modified version of the EF.

Table 2 collects the referred indicators in chronological order of appearance.

4.1. Ecological footprint

The EF indicator was mainly founded on the carrying capacity concept, which refers to the number of individuals who can be supported in a given area within natural resource limits, and without degrading the natural, social, cultural and economic environment for present and future generations (Kratena, 2008; CCN, 2010). Originally, the EF was advocated to assess the level of sustainability of the urban development, lifestyles or regions. A more appropriate definition for the corporate level is that the EF determines the space required to support an activity by means of the area needed to provide the resources consumed and to absorb the wastes generated (Wackernagel and Rees,1996; Monfreda et al., 2004; Kitzes et al., 2007; Venetoulis and Talberth, 2008). Major land use types in EF accounting are: cropland, grazing land, fishing grounds, forest area, built-up land and carbon land (Kitzes et al., 2007). In contrast, biocapacity is the capacity of ecosystems to produce useful biological materials and to absorb waste materials generated by humans using current management schemes and extraction technologies (Kitzes et al., 2007). A comparison between the EF and the biocapacity reveals whether existing natural capital is sufficient to support consumption and production patterns (Monfreda et al., 2004). The ecological deficit occurs when the EF exceeds the available biocapacity.

The European Union has showed particular interest in evaluating the EF capability to measure sustainable use of resources (ECOTEC, 2001; EUROSTAT, 2006; Best et al., 2008). Currently, there are also a wide range of applications in the environmental evaluation of production processes and products (Herva et al., 2008c; Kratena, 2008; Mamouni Limnios et al., 2009), like in aquaculture processes (Kautsky et al., 1997; Muir, 2005), a water supplier company (Lenzen et al., 2003), mobile phones (Frey et al., 2006), textile industry (Herva et al., 2008a) or wine production (Niccolucci et al., 2008).

4.2. Dissipation area index

The DAI originates from the concept of assimilation capacity: a certain part or compartment of the ecosphere can absorb only limited output flows from the anthroposphere without suffering irreversible damage. Instead of estimating the output flows of human activities that can be tolerated with a given assimilation capacity, the assimilation capacity that would be necessary to cope with given output flows is calculated (Eder and Narodoslawsky, 1999). Narodoslawsky and Krotscheck (1995) developed a method to estimate the dissipation areas of output flows. Then, a Sustainable Process Index (SPI) is appraised as a result of aggregating all the areas implied in a process: material resources, energy, personnel, process installation (e.g. machines for the production process), product dissipation (assessment of the waste quality and quantity of different material and energy flows) and emissions (Narodoslawsky and Krotscheck, 1996; Stoeglehner and Narosdoslawsky, 2009).

An important difference between EF and DAI is that the latter considers the absorption of certain kind of substances excluded from EF because they are considered unsustainable and not belonging to closed cycles in nature (e.g. heavy metals). For carbon dioxide a dissipation area is considered only if the emissions stem from fossil sources. The DAI can be disaggregated for the different key production sectors in a region. Thus, the production activities with the highest potential of contributing to a steering process towards sustainability can be identified (Eder and Narodoslawsky, 1999). The relation between assimilation capacity and dissipation area is equivalent to that between the ecological footprint and the carrying capacity. Thus, DAI could be considered as a modified version of EF.

4.3. Strengths and drawbacks of the EF

The most appealing characteristic of the EF is its integrative nature. Expressing all environmental aspects in a single score facilitates the understanding and communication of results (Ferguson, 1999). Further, the comparison with the available biocapacity is quite straightforward; hence, the EF is often regarded as an indicator of sustainability since it states limits for the consumption of resources (materials and energy). Besides, the physical areas considered in EF accounting are weighted according to their relative productivity to obtain a final figure expressed in global hectares. Hence, aggregation is conducted using weighting coefficients based on the relative productivity of the different area types (Kitzes and Wackernagel, 2009) rather than on the relative importance derived from the subjective opinion of experts or decision makers.

However, some limitations were acknowledged for this methodology, even though active development on EF methodology poses to continuous new proposals to overcome core critiques (Venetoulis and Talberth, 2008; Kitzes et al., 2009; Herva et al., 2010). Van den Bergh and Verbruggen (1999) were pioneers in publishing an evaluation of the

EF, but many of the ideas they exposed were further debated by different authors during the last decade (Fiala, 2008; Kitzes et al., 2009; Wiedmann and Barrett, 2010). The main critiques refer to the fact that there is no distinction between sustainable and unsustainable use of land (intensive production increases waste, land depletion and soil degradation), the measure refers to virtual land area and therefore it cannot be compared to real biocapacity, it does not reflect neither relative scarcity changes over time nor variation over space, the quality and quantity of renewable resource use is missed, the evaluation of energy use is focused on emissions and not in the effects of the consumption of resources and the aggregation using physical weight is considered unfair (it refers to world average technology).

Not differentiating between sustainable and unsustainable agricultural activities is a consequence of using world average yields. Niccolucci et al. (2008) compared a conventional and an organic wine production system and, by including local productivities, the EF proved to be sensitive enough to differentiate between the two processes. Besides, the product EF methodology developed by Mamouni Limnios et al. (2009) introduced a disturbance factor accounting both for current and potential land disturbance, thus considering the effects of unsustainable activities (mainly in agriculture). Although the idea of computing such effects is very appealing, the scale defined by the authors seems to suffer from certain subjectivity as it occurs with other weighting schemes (e.g. multi-criteria analysis). Along the three calculation stages proposed by the authors, accuracy on estimates increases as dependency on national average is replaced by directly collected data. Actually, realistic, reliable and decision-guiding results are only expected from the latter and the use of specific data should be pursued and preferred at corporate level.

It is also questioned the suitability of employing administrative or historical boundaries to calculate ecological deficits. The problem gains relevance at corporate level: what is the biocapacity available for an industry? Or, is it meaningful to compare the EF of a product to its size as it is done by Frey et al. (2006) in the case of a mobile phone? This makes the EF lose its capacity to establish resource consumption limits. Another key point when the EF is applied to evaluate production processes or products is that it does not capture most of the impact categories derived from waste and emission flows. Only CO2 emissions are specifically appraised by the EF. The argument is that for CO2 emissions, a sufficiently sound method is available for calculating the land area required to absorb them, while this is not the case with other greenhouse gases. It has been proposed to aggregate greenhouse gases by means of global warming factors (Global Footprint Network, 2009) and then to estimate the area require to absorb such CO2 equivalent emissions; nevertheless, the rigor of such appraisal is arguable since there is not a relation between the absorption capacity by nature and the global warming effect of emissions. In addition, the same discussion as for agricultural productivities should be conducted on the adequacy of employing world average carbon absorption factors when a production process placed in a specific region is being evaluated (Herva et al., in press). But there are many other pollutants released to different compartments (soil, water, air) that are systematically excluded from EF estimates because their small or null assimilation capacity that would result in too large EF figures, but this is unacceptable when evaluating a production process. The method developed by Mamouni Limnios et al. (2009) is opened to incorporating waste flows by means of pollution absorption rates when available, as it was also explored by Herva et al. (2008, in press) for a textile and a ceramic factory. The difficulty arises at finding such rates for all streams that can be found in industry. In this respect, in the case of DAI a list of relative factors is available for a variety of substances for different compartments: e.g. carbon dioxide, ammonia, methane, sulfur oxide or lead in air, or nitrate, phosphate, copper or iron in water (Eder and Narodoslawsky,1999).

Herva et al. (in press) also proposed a method to evaluate the EF of wastes, including hazardous ones, by considering a closed cycle modeled through a plasma process – a phenomenon that naturally occurs in stars and volcanoes. The application of this methodology would allow evaluating the impact of waste streams currently discarded from EF estimates, which may become relevant in most production processes. Nevertheless, this methodology does not take into account the degree of hazardousness of the wastes and other important environmental effects should be evaluated with other methodologies such as risk assessment.

5. Indicators of environmental life-cycle assessment

This framework is based on a life cycle approach which considers the full supply chains of materials and energy. The conventional philosophy underlying in environmental life cycle approach refers to a cradle to grave framework, although in recent years a cradle to cradle perspective has been introduced (McDonough and Braungart, 2002); however, when analyzing particular systems or production processes, a specific-boundary approach can be defined and a gate to gate assessment carried out. The main phases in Life-Cycle Assessment (LCA) studies are: 1) Goal and Scope definition; 2) Inventory analysis; 3) Impact assessment; 4) Interpretation (ISO, 2006). Indicators usually originate from the impact assessment phase (Guineé, 2001). After the classification phase characterization factors are employed to aggregate substances within a specific impact category (Eq. (1)).

$$C_j = \Sigma\, C_{ij} = \Sigma\, A_i \,.W_{ij} \qquad (1)$$

Where Ai is the amount of emission i released, W_{ij} is the characterization factor for the emission i within the category j, C_{ij} is the contribution of the emission i to the category j and C_j is the characterized value of the category j. Some of the impacts have a local effect on the environment (e.g., photochemical smog and eutrophication) while the others are of a more global nature (e.g., global warming and ozone depletion) (Azapagic and Perdan, 2000; Batterham, 2006). The use of software tools like SIMAPRO®, GaBi® or Umberto® can assist the appraisals.

Apart from the above mentioned impact categories, which relate to a mid-point perspective in LCA -e.g. the methodology by the Institute of Environmental Sciences (CML) of the Leiden University (CML, 2000)-, other indicators correspond to a higher level of aggregation, like the Ecoindicator 99, oriented towards damage estimation. In this case, three types of environmental damages (endpoints), namely human health, ecosystem quality and resources, are weighted to obtain a final single score (ecoindicator) (Goedkoop and Spriensma, 2001).

LCA has largely been applied in the environmental appraisal of processes (Bartonet al., 1996; Burgess and Brennan, 2001; Wood et al., 2006;Cherubini et al.,2009) and products (Milà et al.,1998; Nieminen et al., 2007; Roy et al., 2009). Styles et al. (2009) developed the Environmental Emission Index (EEI) based on LCA methodology. This index provides an integrated measure of the environmental significance of various emissions reported by industrial installations and sectors licensed under the EU Integrated Pollution Prevention and Control (IPPC) Directive (European Union, 2008).

Issues of global warming and greenhouse gas emissions are increasingly becoming one of the major technological as well as important societal and political challenges. Although several carbon-related indicators have emerged to this respect, the Carbon Footprint (CF) is the most popular and widely used to raise awareness on this environmental impact (Hoffmann and Busch, 2008). Next, the CF is described in further detail.

5.1. Carbon footprint

The largest single contributor to climate change is carbon dioxide, although other greenhouse gases have higher global warming potential (IPCC, 2007). Hence, a CF measures the total set of greenhouse gas emissions caused directly and indirectly by an individual, event, organization or product and is expressed in carbon dioxide equivalent. Consequently, this indicator results particularly useful for energy planning scenarios. The carbon footprint is measured in mass units. Therefore, in spite of the "footprint" term, the CF is equivalent to the global warming characterized category in LCA studies, and it does not measure land requirement as in the case of the EF. A further step of transformation from mass to area units is required. However, the difficulty and controversy arises when trying to identify an average assimilation rate for the different substances. Albeit, when biofuel systems are considered in energy planning, not only reduction of CO2 should be considered but also land availability constraints, especially when agricultural resources need to be used for both food and energy production (Foo et al., 2008). In this sense, Stöglehner (2003) has also proposed a modified model of EF, which does not only account for energy savings but also for the substitution of fossil through renewable energy carriers, to be used for energy planning.

Business can use carbon footprints to inform their internal environmental management. Furthermore, carbon labels are a way to communicate a summary of the carbon footprints (which is strongly related to the supply chain) of a product to the final consumers (Edwards-Jones et al., 2009). Carbon Trust, a British not for- profit company, was a pioneer in the development of a carbon label for products. They were also involved, alongside the British Department for Environment, Food and Rural Affairs (DEFRA) and the British Standard Institute (BSI), in the launching of PAS 2050:2008 Standards (Specification for the assessment of the life cycle greenhouse gas emissions of goods and services). Currently, there is also an ISO standard under development (ISO/WD 14067-1, Carbon footprint of products - Part 1: Quantification).

The CF is generally applied in energy-related studies (Johnson, 2008; Perry et al., 2008; Foo et al., 2008) but, unlike energy flow indicators, it provides limited information on the environmental impacts associated to energy consumption. Besides, by using the CF as single indicator, much relevant information is being missed. Table 3 collects all the indicators reviewed in this paper that account for energy related impacts.

5.2. Bottlenecks in life-cycle indicators

LCA is commonly regarded as the only methodology that provides a comprehensive assessment of the environmental impacts associated to an activity or product. However, this broad perspective is a consequence of the inventory compiled (which usually refers to the system boundary from cradle to grave, but that could also be limited to a gate to gate) rather than to the methodology itself.

The whole set of indicators that can be derived from the impact assessment stage widely depict the environmental effects of a process or product, but at the same time makes the analysis more complex and less intuitive. Nevertheless, the impact categories considered are frequently limited according to the interests of the study. This simplification relies on the subjective criteria of LCA practitioners and could lead to discard relevant impact categories. Applying exclusively the CF is an extreme example of this simplification.

Besides, from LCA it is difficult to derive the significance of the measured environmental impacts; i.e., a number of indicators are obtained that can serve to compare operational options, products, companies, etc. or to analyze time series. Impact categories can be compared if the normalization stage is conducted, but the factors necessary for this step are scarce and refer to general geographical areas, thus limiting the accuracy of results.

Further, the information provided regarding human and ecosystem toxicity, is more incomplete than desirable. This means that it has a limited capacity to predict toxicity effects given that the fate of pollutants is usually not considered, so that the calculated impacts are potential rather than actual (Azapagic and Perdan, 2000; Finnveden et al., 2009).

6. Indicators of environmental risk assessment

Over the last decades there has been an exponential increase in the level of pollution and in the quantity of toxic substances released to the environment. This circumstance has awakened awareness about potential exposure to contaminants and a considerable activity in the field of Environmental Risk Assessment (ERA) has been going on. This has mainly taken place in international bodies such as the Organization for Economic Co-operation and Development (OECD) or the World Health Organization (WHO). In this context, the REACH deserves a special remark as a recent European Community Regulation on chemicals and their safe use (EC 1907/2006) which entered into force on 1 June 2007. It deals with the Registration, Evaluation, Authorization and Restriction of Chemical substances and aims at improving the protection of human health and the environment through the better and earlier identification of the intrinsic properties of chemical substances.

Historically, risk assessments have primarily focused on risks to human beings. It has gradually become apparent, however, that the ecological implications of large-scale environmental pollution should also receive attention (Van Leeuwen, 2007). ERA takes many different forms, depending on its intended scope and purpose, the available data and resources, and other factors. Hence, the scope and nature of risk assessments can range from national to site specific findings concerning the same chemicals. Besides, some assessments are retrospective, focusing on injury after the fact, while others seek to predict possible future harm to human health or the environment (Patton, 1993).

ERA is a standardized process for the estimation of the magnitude, probability and uncertainty of adverse effects on health derived from the exposure to substances present in the environment (US EPA, 2009; ORNL, 2009). Risk assessment comprises hazard identification, exposure assessment and risk characterization (Van Leeuwen, 2007).

From this, two relevant indicators (Hazard Quotient HQ and the Cancer Risk factor CR) can be obtained as indicated in Eq. (2) and Eq. (3).

$$HQ = Dose/RfDs \qquad (2)$$

$$CR = Dose \,.\, SF \qquad (3)$$

Where RfDs and SF are Reference Doses for non-carcinogenic effects and Slope Factors for carcinogenic effects, respectively (US EPA, 2009; ORNL, 2009).

There are a great variety of models of a diversity degree of complexity for the assessment of distribution and exposition to hundreds of pollutants. These models are particularly useful to obtain a quick preliminary result providing information about the scenario. ChemCAN (Trent University, 2003), EUSES (European Union System for the Evaluation of Substances, European Commission, 2009), Cal-TOX (McKoneand Enoch, 2002) and ACCHuman (Czuband McLachlan, 2004) are, among others, some of the most representative ones.

Risk assessment studies cover different areas related to the corporate field, such as waste reuse scenarios (Franco et al., 2006; Muñoz et al., 2009); release of hazardous substances from products (Babich et al., 2004; Franco et al., 2007) or occupational and home exposure to chemicals (Ling and Hoang, 2000; Tsai et al., 2001; Hellweg et al., 2005).

6.1. Strengths and weaknesses

Unlike LCA, risk assessments provide an established methodology based on the assessment of different scenarios and events, distribution and transfer routs, exposure pathways, duration and frequency of the events that allows for a more rigorous and exhaustive evaluation. Albeit this level of accuracy is required when it comes to likely damages to human (and ecosystems) health, this also requires very exhaustive toxicological studies that analyze the hazardousness of a variety of substances and the safety limits that should be allowed (e.g. RfDs and SF).

Nevertheless, assessments may need to integrate the risks from the entire life cycle of the chemical or product (Van Leeuwen, 2007). Therefore, LCA and ERA are complementary tools that can be integrated (Leet Socolof and Geibig, 2006). Hence, LCA can identify "hot spots" that require the additional detail and level of certainty provided by ERA.

7. Relationships and trade-offs between indicators

Material and energy flow scan be considered as the basis on which all indicators are founded. They reflect the consumption of resources from nature and thee mission of pollutants to the environment. These flows can be considered separately expressing resource use in original units, certainly providing more detailed information, or aggregated, thus reducing the number of indicators to be handled. To this respect, bulk-MFAs are material flow analysis in which all materials flows are summed to generate single indicators of mass flow within an industrial economy. MIPS is bulk-MFA applied to a specific product or service, and could be considered as a simplified LCA in which the mass flows (including hidden flows) are used as an indicator of the environmental impact of a product or service (Kleijn, 2001).

Therefore, a strong link exists between EMFA and LCA, since inventories used for EMFA are generally based on a life-cycle perspective. However, EMFA fails at including all the information necessary to assess potential impacts on human health and the environment or energy and water consumption (Allen et al., 2009). MIPS is a useful indicator of material efficiency but it does not differentiate between a ton of inert material and a ton of highly hazardous material, and does not include the environmental impacts of the life-cycle of each material (Lilja, 2009). Thus, EMFA and LCA indicators are not completely exchangeable but are likely to be integrated (Azapagic et al., 2007).

On the other hand, composite indicators like EF allow synthesizing in a single score the great amount of information handled in environmental studies. Moreover, indicators expressed in territorial dimensions are easier to be interpreted by all the stakeholders, given that the documented ecological demand can be compared to the biosphere's regenerative capacity (Wackernagel and Yount, 2000). Consequently, indicators like EF result particularly appealing for communication purposes. Moreover, the EF has proved suitable to effectively assess the environmental performance of different competing management and manufacturing options that may be considered in an industrial production process (Herva et al., 2008a; Niccolucci et al., 2008). Therefore, it could also be helpful in determining the ability of an industrial system to adapt to the local natural limiting factors (Kratena, 2008).

In contrast, according to Bührs (2007), general EF analyses appear less fruitful in terms of providing specific policy guidance: whereas environmental space indicators can be used as a basis for formulating specific objectives and targets, EF lose this capacity when aggregating different forms of resource use and environmental impacts. Consequently, it is more difficult to identify or obtain clues to advance sustainability and it could be thought that mitigating climate change by afforestation, for instance, could compensate any other impact generated in the environment. However, the contribution of the different categories to the EF can be disaggregated and studied separately, thus helping to identify the key issues where action should be taken first (Herva et al., 2008a).

Emergy or exergy indicators also tend to express all input and output flows as a single score; however, the units in which the results are expressed are less intuitive and makes it difficult to transfer these more scientific concepts to industries and other stakeholders. As a consequence, they result more suitable at the design of facilities, processes and products than for measuring the environmental performance of and operating factory.

Nowadays, popularity seems to be the main driver to select indicators at corporate level. The CF has been launched in the last years as indispensable indicator for corporations and it has found a very good reception by the markets, mostly because of its relationship with global warming and the Kyoto protocol. The good point is that, given the simplicity of the CF, it is encouraging enterprises to report environmental information, although steps forward to include other relevant impact indicators are still required.

Finally, none of the resource (material or energy) accounting methodologies properly assess the effects of toxic or hazardous substances, although some attempts to include the likelihood of risk have been conducted, as in the proposal to evaluate the footprint of nuclear energy made by Stoeglehner et al. (2005). Therefore, when these compounds are present in a production process or a product, an ERA should always be conducted, regardless of the indicator being employed to record the environmental performance, to ensure safety conditions. Toxicity impact categories in LCA could be used as preliminary screening information about the potential contributions to actual impacts or risks, but not as definite results, given that other sources of exposure and background conditions are not being considered (Finnveden et al., 2009).

8. Conclusions

In the present paper, indicators of different nature have been reviewed under a corporate approach, from those with a territorial dimension to the more generic material and energy flows, life-cycle or risk assessment indicators. The importance and usefulness of each of them have been highlighted, as well as the similarities among them and complementary characteristics.

Environmental performance indicators measure the current or past environmental performance of an organization, depicting the vast quantity of environmental data in a comprehensive and concise manner, and compare it to the targets set. Frequently, only data readily available are employed, since they do not aim to offer a comprehensive analysis but rather to represent the key characteristics of a business. Hence, the single index indicators reviewed in this paper, such as energy flows or the ecological footprint were considered to be more useful for the corporate level. In spite of the difficulty of a land-based indicator to measure all kinds of anthropogenic impacts, the EF is one of the most promising indicators since it does not only account for the environmental impacts derived from energy consumption but also from other material resources. Nevertheless, to make its application to products and production processes completely fair and reliable, there is a need to jointly standardize the different proposals to improve the methodology published in the last years and to develop reliable databases that provide all factors necessary for calculations. Once this is done, the EF could allow for consistent measurement, labeling and comparative evaluation across products and industries.

In spite of the appealing idea of using one single score to express all the environmental information, there are certain aspects that can hardly be ever part of such an indicator. When applied to assess the environmental performance of a production process, a more comprehensive analysis of all environmental burdens is required; otherwise, the results reported could be misleading and useless when comparing two production processes or products from an environmental point of view. Hence, the evaluation of production processes or products that imply the presence of toxic pollutants should always be accompanied by risk assessments. Also, when a more detailed analysis is required LCA may be necessary, although this can be substituted by any of the energy or material single indicators when the problem being studied is particularly concerned with any of these issues.

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Appendix

Abbreviations

BSI	British Standard Institute
CCN	Carrying Capacity Network
CED	Cumulative Energy Demand
CF	Carbon Footprint
CML	Institute of Environmental Sciences, Leiden University
CR	Cancer Risk
DAI	Dissipation Area Index

DEFRA British Department for Environment, Food and Rural Affairs

DMI Direct Material Input

DPO Domestic Processed Output

EEA European Environmental Agency

EEI Environmental Emission Index

EF Ecological Footprint

EMFA Energy and Material Flow Analysis

ER Ecological Rucksack

ERA Environmental Risk Assessment

ES Environmental Space

EUSES European Union System for the Evaluation of Substances

HANPP Human Appropriation of Net Primary Production

HQ Hazard Quotient

IPCC Intergovernmental Panel on Climate Change

IPPC Integrated Pollution Prevention and Control

ISO International Organization for Standardization

LCA Life-Cycle Assessment

MFA Material Flow Analysis

MIPS Material Input Per unit Service

OECD Organization for Economic Co-operation and Development

ORNL Oak Ridge National Laboratory

PAS Publicly Available Specifications

PTB Physical Trade Balance

RAIS Risk Assessment Information System

REACH Registration, Evaluation, Authorization and Restriction of Chemicals

RfD Reference Dose

SF Slope Factor

SFA Substance Flow Analysis

SPI Sustainable Process Index

TBL Triple Bottom Line

US EPA United States Environmental Protection Agency

WCED World Commission on Environment and Development

WF Water Footprint

WHO World Health Organization

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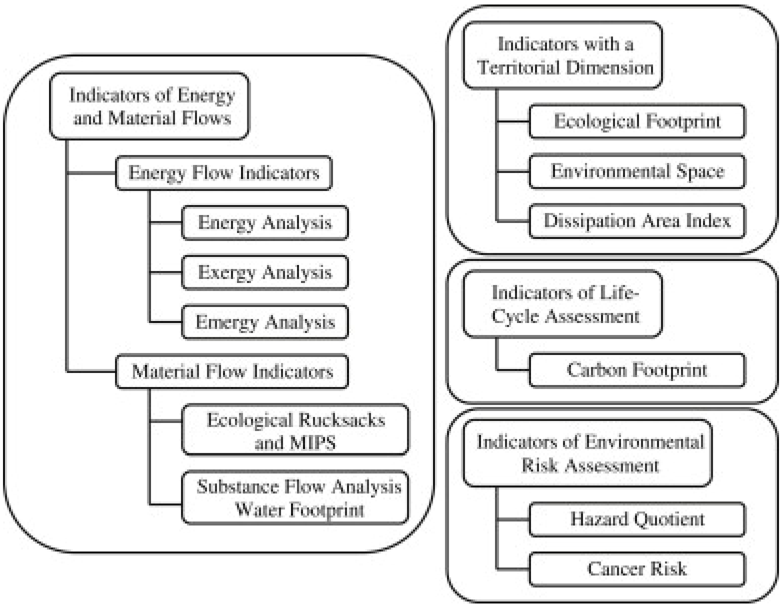

Fig. 1. Indicators of the environmental dimension of sustainability reviewed in this paper.

Table 1. Comparison among indicators accounting for materials consumption impacts.

Indicator	What is measured?	Strengths	Weaknesses
Ecological Rucksack and MIPS	Sum of all materials necessary for production, use, recycling and disposal of a product	Resource-efficiency measurement Allows to compare products	Uncommon metric at corporate level No much information on how to compute it
Water footprint	Total volume of freshwater that is used to produce the goods and services	Necessary standardized methodology to account for water (green, grey and blue) consumption	Only informs about water consumption
		Expressed in	Need to track water

Indicator	What is measured?	Strengths	Weaknesses
		original units, more easy to track resources consumption	consumption along the whole supply chain
Ecological Footprint	Primary products by means of natural productivity and manufactured products by means of embodied energy	Single index indicator Expressed in units easy to be interpreted Comparable to the available area to produce goods	Difficulties in distinguishing sustainable and unsustainable production processes For not primary products the impact is restricted to embodied energy
LCA	Biotic and abiotic resources depletion and other impact categories associated with the extraction of materials and manufacture of goods	Exhaustive analysis Considers the different perspectives and consequences of materials consumption	Extensive databases requirement Time consuming Not at small or medium enterprises reach More difficult interpretation

Table 2. Indicators with a territorial dimension in chronological order of appearance in the literature.

Indicator	Date	Author/s	Country	Reference
Ghost Acreage	1965	G. Borgström	U.S.A.	Borgström, 1965

Indicator	Date	Author/s	Country	Reference
Environmental Space	1980’s	H. Siebert and J.B. Opschoor	The Netherlands	Opschoor and Reinders, 1991
Ecological Footprint	1990’s	W. Rees and M. Wackernagel	Canada	Rees, 1992; Wackernagel and Rees 1996
Dissipation Area Index	1995	M. Narodoslawsky and C. Krotscheck	Austria	Narodoslawsky and Krotscheck, 1995

Table 3. Comparison among indicators accounting for energy consumption impacts.

Indicator	What is measured?	Strengths	Weaknesses	Includes other impacts?
Embodied energy	Energy invested in obtaining a product in a cradle to gate scope	Broad perspective in the production chain	Difficulty in compiling all energy flows through the life-cycle	No
		Single score	Does not inform about the type of energy employed nor the final environmental impacts	
CED	Direct and indirect energy use throughout the life cycle	Broad perspective in the production chain	Difficulty in compiling all energy flows through the life-cycle	No

Indicator	What is measured?	Strengths	Weaknesses	Includes other impacts?
		Single score	Does not inform about the type of energy employed nor the final environmental impacts	
Exergy	Measure of the quantity and quality of the energy sources	Identifies the causes, locations and magnitudes of process inefficiencies Helps to identify more sustainable technologies	Not intuitive for enterprises Lack of readily available databases with exergy values for all substances Complexity in calculations	Indirectly
Emergy	Solar energy directly or indirectly necessary to obtain a product in a process, expressed in seJ	Considers different energy qualities and takes into account the losses of energy in the energy transformation processes	Not intuitive for enterprises Lack of readily available databases with transformities	No
Ecological Footprint	CO_2 emissions from energy	Single index indicator	Need to select the appropriate	Yes

Indicator	What is measured?	Strengths	Weaknesses	Includes other impacts?
	consumed and embodied energy in products transformed into the area required for their absorption	Expressed in units easy to be interpreted Comparable to available capacity to absorb emissions Guidance to establish measures to mitigate effects (e.g. afforestation)	absorption factor to conduct estimates (global or regional) Part of aggregate index; the effect can be shadowed by other components of the indicator	
LCA	Whole set of environmental impact categories derived from resource consumption and emissions released	Exhaustive analysis Considers the different perspectives and consequences of energy consumption	Extensive databases requirement Time consuming Not at small or medium enterprises reach More difficult interpretation	Yes
Carbon Footprint	Global warming gases expressed as CO_2 equivalent	Simple and intuitive Attractive for enterprises	Misses other important environmental impacts	No