Extending LCA Methodology for Assessing Liquid Biofuels by Phosphate Resource Depletion and Attributional Land Use/ Land Use Change

Heiko Keller, Horst Fehrenbach, Nils Rettenmaier, and Marie Hemmen

Abstract Many pathways towards reaching defossilization goals build on a substantially increased production of bio-based products and energy carriers including liquid biofuels. This is, amongst others, limited by land and phosphorous availability. However, it is challenging to adequately capture these limitations in LCA using state-of-the-art LCI and LCIA methods. We propose two new methods to overcome these challenges: (1) attributional land use and land use change (aLULUC) evenly attributes LU-/LUC-related burdens (emissions) occurring in a country to each hectare of cropland used in that country and (2) phosphate rock demand as a stand-alone resource indicator for a finite resource that cannot be replaced. Approach, calculations and used factors are described for both methods, and exemplary results for biofuels are presented. We conclude that both methods can yield additional insight and can support finding solutions for current challenges in agriculture.

1 Introduction

As for most bio-based products, replacing fossil fuels by biofuels mostly creates environmental advantages and disadvantages at the same time. Advantages typically relate to climate change mitigation and savings of fossil energy resources, and disadvantages of various kinds are usually caused by the required biomass production. This well-known pattern is reflected in standard LCA results in the field.

Public and scientific discussions more and more focus on environmental burdens and limitations of agriculture that are becoming important bottlenecks of agriculture on a global scale. These aspects include land use/biodiversity, water and increasingly also limited phosphate resources. These could also become limiting for currently discussed pathways for defossilization of the society, which often builds on using more bio-based products in general and biofuels of various kinds in particular.

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Results of state-of-the-art LCAs however often do not effectively support finding new solutions in these areas for various reasons. This paper focusses on the aspects land use/land use change (LUC) and phosphate resources. In the following chapters, limitations of current state-of-the-art LCA methods are discussed, and two new methods are proposed as solutions: (1) attributional land use and land use (aLU-LUC) change as new alternative to dLUC/iLUC and (2) phosphate rock demand as new stand-alone resource indicator.

2 Attributional Land Use and Land Use Change

2.1 Background

Land use change (LUC) describes the relative change in the use or management of an area compared to a previous use of the same area and the associated emissions (or emission avoidance). Which methodology is suitable for the quantification LUC-related burdens depends on the goal and scope of a study. This can include the overall greenhouse gas balance of a country, the traceable direct consequences of a specific product in its supply chain (dLUC, direct land use change) or the indirect consequences of a change in the market, e.g. triggered by the support of a specific product such as biofuels (iLUC, indirect land use change).

In theory, dLUC could accurately determine the actual LUC emissions from a product such as rapeseed diesel. However, this is not applicable in practice for several reasons: Firstly, existing data is not available and subject to data protection. Secondly, more biomass not associated with land use change is available than interested customers or regulated markets are demanding. Thus, dLUC is not useful to mitigate or stop continuing land use change.

iLUC factors are calculated by combining land use models with an economic equilibrium or partial system and are intended to estimate the overall impact of a targeted or shock-like increase in production on global land use. Fehrenbach [18], amongst others, analysed and described the wide range of results depending on the choice of model. The iLUC approach is therefore only of limited use for developing solutions based on life cycle assessments due to the disagreement amongst experts about the suitability and reliability of the various iLUC models. Moreover, iLUC always describes results of changes or measures, which is incompatible with attributional LCAs describing the status quo. Finkbeiner [19] also discussed these aspects in detail.

We propose a life cycle inventory approach termed attributional land use/land use change (aLULUC) to attribute existing and documented burdens caused by land use change and continuous burdens/emissions from using converted land to products [1]. Here we focus on climate impacts although further impact categories such as biodiversity [2, 3] can also be assessed using the life cycle inventory method aLULUC.

2.2 Approach

A decisive premise for aLULUC is that land use changes to arable land take place in reality. These land use changes are usually recorded and associated emissions are backed up with data. This includes one-time emissions from actual LUC and continuous emissions mainly from organic soils caused by LUC but occurring for many decades of land use (LU) that can only be stopped if land use is given up and appropriate protection measures are taken.

The aLULUC concept is independent of models of future land use change as it is the case for iLUC. In the same systematic way as real emissions are attributed to the processes of a life cycle, real LUC processes can be attributed to the associated processes, as it is also done applying the dLUC concept. However, even if actual land use changes can be clearly assigned to certain agricultural products, all agricultural products of a production area compete for limited availabilities on the local market for cropland. The reaction of the markets on, e.g. the EU biofuels policy, has shown that crops on and products from recently logged land (or from "LUC-free" land) can be flexibly allocated to customers according to their preferences. For that reason, a land-market-based attribution of aLULUC to products produced on that land following the aLULUC concept is a more consistent representation of the underlying processes than a direct attribution following the dLUC concept. For the majority of agricultural products, country borders are the most appropriate geographical reference areas for the aLULUC concept. Firstly, there are no internal trade barriers within national markets. More importantly, however, decisions and policies regarding the conservation of areas such as rainforests, wetlands and grasslands are made or influenced at the country level. A more specific attribution of LUC to individual crops within these markets would require economic assumptions and models that seek to establish causalities. These do not necessarily reflect the complex socio-economic and political processes that can cause, promote or prevent LUC.

Following the proposed aLULUC approach, the real land use changes that have been caused by agriculture (of a defined region) are allocated to all agricultural products in proportion to the land requirements. It is therefore an allocation according to the attribute land demand. aLULUC can be calculated for arable land as well as for other types of land such as grassland. The country- and year-specific aLULUC factor for arable land is determined as follows: All carbon stock changes in biomass and soils caused by net conversion from other types of land use to arable land in a country in a certain year are summed up and divided by the area of arable land used in that year. One-time changes in biomass and soil carbon stocks (LUC) are attributed to the year in which the LUC occurs although actual CO_2 emissions may be partially delayed by a few years. Continuous emissions of CO_2, CH_4 and N_2O from the cultivation of organic soils (LU) are counted in the year in which they occur. Averages of aLULUC factors over the last ten available years result in stable values that do not disregard medium- to long-term developments. Detailed calculation procedures and data sources are discussed in [1]. Current emission factors for the climate impact of land use and land use change according to the aLULUC concept for selected countries can be found in Table 1.

2.3 *Application Example: GHG Emissions Including aLULUC of European Rapeseed Biodiesel*

Biodiesel can achieve certain climate change mitigation if it replaces conventional diesel. This is however only the case if land use does not cause high additional greenhouse gas emissions. Usually, this problem is discussed for palm oil biodiesel and deforestation. However, depending on the used land and the methodological approach used to attribute emissions from LU and LUC to the fuel, also European rapeseed biodiesel can cause in total more greenhouse gas emissions than it saves (Fig. 1). Greenhouse gas emissions from LU and LUC in Europe mainly stem from conversion of grassland and from cultivation on organic soils, i.e. drained wetlands/peatland.

The cultivation of rapeseed on former grassland can lead to overall additional contributions to climate change following the dLUC approach if common time horizons of up to about 25 years are used. If organic soils/peatlands are used, an analogous direct attribution of LU to the product (termed dLU in the figure) could even lead to very high additional greenhouse gas emissions. Where such emissions have

Table 1 Exemplary country-specific aLULUC emission factors for annual crops cultivated on arable land selected from [1]

Country	Total aLULUC t CO_2eq/(ha year)	aLU t CO_2eq/(ha year)	aLUC t CO_2/(ha year)
France	0.90	0.41	0.50
Germany	1.44	1.22	0.21
Italy	0.26	0.14	0.12
Netherlands	4.50	4.08	0.41
Poland	1.60	1.59	0.01
Romania	0.17	0.14	0.03
Spain	0.04	0.04	0.01
United Kingdom	0.55	0.55	0.00
EU 28	1.05	0.85	0.20
Argentina	3.36	0.03	3.33
Colombia	52.3	0.00	52.3
Brazil	9.32	0.00	9.32
Malaysia	55.4	42.9	12.5
Indonesia	30.4	13.7	16.7
India	0.06	0.06	0.00
Russia	0.80	0.30	0.50
USA	0.52	0.52	0.00

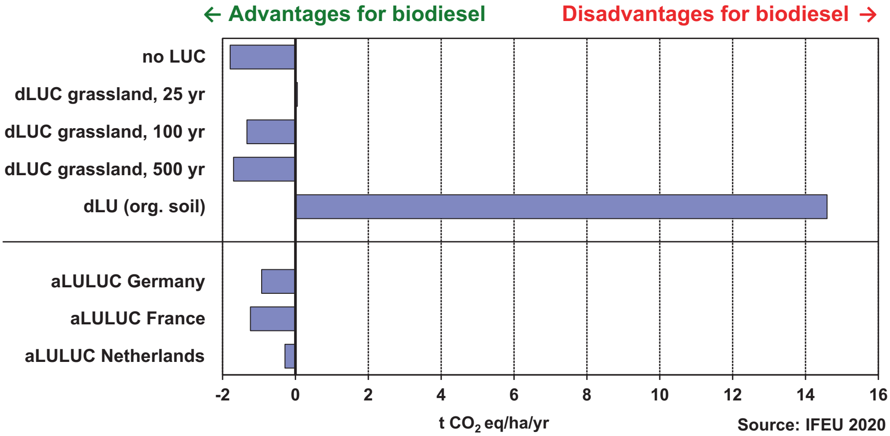

Fig. 1 Life cycle greenhouse gas emissions of European rapeseed biodiesel compared to conventional diesel. All results are based on the same life cycle comparison with differences only in the used land and the methodological approach to land use (LU) and land use change (LUC). The time horizons, over which one-time emissions are distributed, are specified where applicable

to be attributed to a fuel according to the European renewable energy directive [4], no farmer would of course cultivate crops for biofuels. Nevertheless, biofuel crops occupy land and increase the pressure to use former grassland and peatland for cultivation of crops in general. Following the aLULUC approach, LU- and LUC-related emissions are evenly distributed over all cropland of the respective country. This leads to somewhat reduced climate change mitigation for French rapeseed biodiesel. Especially emissions from cultivated organic soils in Germany and even more so in the Netherlands lead to a substantial reduction of greenhouse gas emission savings.

This application example shows that LU and LUC can make significant contributions to carbon footprints also in European countries. The aLULUC approach helps that these emissions are not neglected because direct attribution of these emissions to products does not take place in practice – neither in Europe nor overseas. Hardly anybody would, for example, consider that, e.g. his/her meat could stem from animals raised on corn grown on drained Northern European peatland.

3 Phosphate Rock Demand

3.1 Background

Phosphate rock is the basic raw material for the production of phosphoric acid, which is essential for the production of phosphate products such as fertilizers, animal feed, food and other industrial products. Ninety per cent of the global supply of phosphate is used as fertilizer in agriculture [5]. Eighty-five per cent of phosphate ore is extracted from marine sedimentary deposits and 15% from magmatic deposits, with phosphate ore chemically including iron and aluminium salts as hydrate complexes with very different phosphorous and phosphate contents. Deposits based on guano deposits are largely exhausted [6]. The main producing countries are currently China (52%), the USA (10%) and Morocco (12%) [7]. Marketable rock phosphate contains between 27% and 40% phosphate ([8] cited in [6]). Besides, recycled phosphate can be recovered from sewage sludge by several processes [9, 10].

As a mineral raw material, phosphate is a non-renewable resource. Depending on the source, the static lifetime of global phosphate reserves is only several decades to a few centuries [11–14] (see Fig. 2).

This shortage is further worsened by a growing world population and simultaneously changing consumption patterns [15], resulting in an increasing demand for phosphate.

Due to this growing importance, the impossibility of substitution by other raw materials in central applications and simultaneous limitation, we recommend integrating the resource “phosphate” in life cycle assessments using a separate indicator. We suggest using the indicator phosphate rock demand as proposed in [16] and presented below.

3.2 Approach

Various indicators can be used in LCA to address resource use. One indicator is the cumulative raw material demand (CRD), which is defined as the sum of all raw materials entering a system – except water and air – expressed in mass units. Other indicators also include weighting of the individual raw materials by, e.g. scarcity. These established indicators have in common that the mineral resource consumption of phosphate is not reported separately. This is not sufficient especially for LCAs with a strong focus on agriculture such as LCAs on biofuels because phosphate/phosphorus is a raw material that cannot be replaced by any other element in

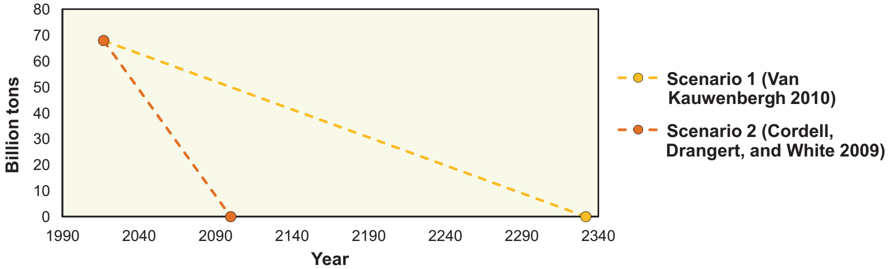

Fig. 2 Range of scenarios on the static lifetime of global phosphate reserves

its main application as a fertilizer. Therefore, the consumption of non-renewable phosphate rock needs to be addressed independently from other raw materials.

We propose a new indicator phosphate rock demand (informally also "phosphate rock footprint") following the concept of the CRD but only including phosphate rock. Phosphate rock demand is determined by the initial rock mass. The recommended unit for the life cycle inventory is "phosphate rock standard" [16]. The definition of a standard is necessary because phosphate rock can have significantly different phosphate contents. Based on [17], an average content of 25% of P_2O_5 is set for phosphate rock standard. P_2O_5 is the reference substance/unit commonly used in agriculture. This corresponds to 32% raw phosphate. This means that 1 kg of mineral P_2O_5 fertilizer corresponds to 4.0 kg of phosphate rock (std.) or 3.125 kg of raw phosphate (std.). This specification explicitly refers to mineral fertilizers. For organic fertilizers, a specific procedure must be derived depending on the goal and scope of the study. If consequential modelling is applied, for example, additional phosphate sources are taken into account, which can replace mineral phosphate without restrictions and which are available in limited quantities during the reference period of the study.

Results can be normalized to inhabitant equivalents by dividing them by the average annual resource consumption per inhabitant. The following normalization factors were derived for this purpose ([16] for details):

- For the reference area Germany: 16.1 kg phosphate rock (std.)/(inhabitant • year).
- For the reference area Europe: 23.1 kg phosphate rock (std.)/(inhabitant • year).

These factors refer to the 5-year average and thus remove short-term fluctuations in the statistics. Normalization factors for other regions can be derived accordingly.

3.3 Application Example: Phosphate Rock Demand of Different Biofuels

With the approach described in Chap. 3.2 outlining the definition and calculation of the indicator "phosphate rock demand", the resource phosphate can be integrated into life cycle assessments. In the following, the application of this approach is explained using an illustrative example. Several bio-based fuels were analysed: bioethanol, biomethane, biodiesel, fuel from vegetable oil and Fischer-Tropsch diesel. Figure 3 shows the ranges between minimum and maximum phosphate rock demand per biofuel.

The phosphate rock demand of different biofuels differs significantly. First-generation biofuels tend to perform much better than second-generation bioethanols with respect to phosphate rock depletion. Results also depend heavily on the biofuels' production schemes, co-product uses and their local conditions. This striking difference between first- and second-generation bioethanols mainly results from phosphate inputs into fermentation processes without subsequent productive

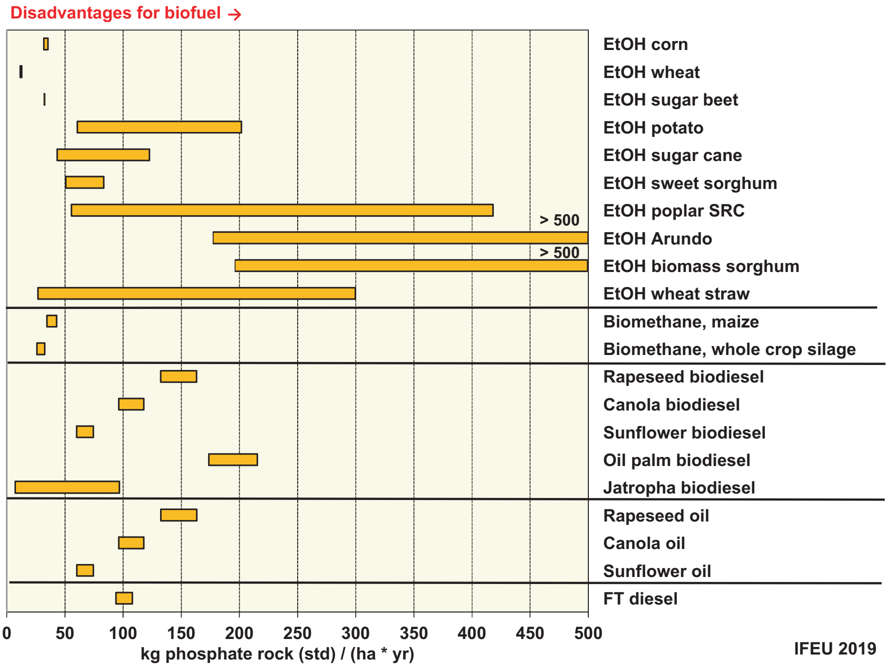

Fig. 3 Phosphate rock demand of different biofuels compared to the respective conventional fossil fuel. The ranges encompass conservatively and optimistically estimated phosphate rock demands for each fuel. EtOH stands for bioethanol, SRC for short rotation coppice and FT for Fischer-Tropsch

recovery. Based on the large range of results, it seems plausible that this aspect has not been optimized or not even been recognized as potential problem in the current state of process development and maturation. This underlines the importance of the indicator phosphate rock demand to support finding solutions to the problem of declining non-renewable phosphate resources.

4 Conclusions

In this paper, we presented two LCA extensions that intend to better address limitations of current agriculture in decision-making processes.

The life cycle inventory method attributional land use and land use change (aLULUC) evenly attributes impacts of deforestation, grassland conversion (both LUC) and organic soil use (LU) actually taking place in a country to each hectare of cropland used in that country. This has several advantages over commonly used dLUC or iLUC:

- Firstly, aLULUC is based on available data and does not require complex economic models or value-based choices of crucial parameters such as time horizons. This makes results more robust.
- Secondly, a comprehensive and regularly updated database is available based on the respective national inventory reports and FAOSTAT for LUC and LU.
- Thirdly, in contrast to iLUC, aLULUC is compatible to attributional LCA, because it attributes burdens/emissions to products and not to change processes. Finally, aLULUC factors on a country level can help to derive meaningful messages to politicians in charge for protection measures or to consumers.

The LCIA indicator phosphate rock demand was introduced as a stand-alone resource indicator because phosphate is a finite resource that cannot be replaced in its vital major application as fertilizer. Thus, phosphate consumption without recycling needs to be reduced which requires measures that are independent of other finite resources. The phosphate rock footprint was shown to be a valuable tool to identify such measures. For biofuels, for example, hot spots of phosphate use were found in various life cycle stages. This information can easily be lost in common evaluations of common aggregate resource indicators.

In summary, the LCI/LCIA methods aLULUC and phosphate rock demand are suitable to derive additional insights and recommendations for LCAs with a wide range of goals and scopes. In particular, both methods are designed to yield recommendations how to overcome crucial bottlenecks of agriculture that are solution-oriented and useful in practice. Therefore, these methods should be considered as an extension of or, if already addressed, alternative to methods nowadays routinely applied in LCA.

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The Environmental Assessment of Biomass Waste Conversion to Sustainable Energy in the Agricultural Biogas Plant

Magdalena Muradin

Abstract Operating an agricultural biogas plants offers the potential of stable, clean, renewable and diversified energy source. It is also a good opportunity to reduce the amount of organic waste. The objective of this study is to evaluate the main environmental hot spots of operating agricultural biogas plants using LCA methodology. This article presents the environmental impact assessment of two agricultural biogas plants with different type of feedstock provision. The environmental life cycle assessment was carried out from "cradle to gate" using the SimaPro software and the ILCD 2011 Midpoint+ methodology. The boundaries of the system included cultivation of maize, delivery of feedstock to the plant, energy production, storage and transport of digestate. The results show that transport of liquid manure induces the highest environmental impact.

1 Introduction

In 2019, the European Parliament assigned the resolution on the climate and environment emergency. Based on that, it is an urgent need to implement and develop many new technologies especially in energy sector, to prevent the further intensification of the crisis and reduce the global temperature growth.

It was expected that carbon dioxide produced by human activity would be absorbed by the oceans. Meanwhile, by warming the atmosphere, CO_2 is additionally released from the oceans and melting ice, so that its concentration may increase exponentially and cause more and more negative climatic phenomena. Food production and consumption account for as much as 35% of all greenhouse gases in the atmosphere, of which agriculture alone accounts for 10%.

Developed countries are struggling with ever-increasing amounts of waste, including the agri-food industry waste, due to overproduction and consumption of food. The issue of the generation of biodegradable waste is often marginalized, while animal production and the generated livestock manure contribute to 30% of

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the total emission of anthropogenic methane to the atmosphere. The global warming potential for methane is from 23, which means that the same amount of methane in the atmosphere as CO_2 will have a 23 more significant impact on climate warming. Technologies based on anaerobic digestion are very useful in reducing the amount of waste from agri-food industry and at the same time enable controlled methane capture and energy production in cogeneration systems.

Manure is a livestock residue that has little commercial value [1]. The slurry digestate which is a result of the anaerobic fermentation can be used as more bioavailable fertilizer form [2] and helps to reduce the number of pathogens entering the soil with direct application. Furthermore, storing animal manure in the open air results in methane and carbon dioxide emissions through the process of self-remediation [3]. Anaerobic digestion of animal manure reduces the environmental impacts caused by carbon dioxide, methane and nitrous oxide emissions from storage and reduces waste and odours [4]. For example, in Finland case, anaerobic fermentation on cattle farms contributes to the reduction at approximately 9% of the national agricultural GHG emission reduction goal during the 2005–2020 period [5].

However, animal manure has low biogas yield (9–36 m^3/Mg) compared with different feedstock especially maize silage. In this case, the co-digestion of different biodegradable substrates is often used at farms. The most effective in producing biogas is digesting liquid manure with maize silage, what is however economically unfavourable, and what even worse, maize cultivation for the energy production purpose stays against cultivation for feeding. The solution could be co-digestion with different waste from agri-food production. Such products have often relatively higher methane yield than manure, e.g. potato pulp or fruit pomace. Very favourable to use as a feedstock is also distillery waste. The methane yield for that waste is lower and similar to liquid manure but to manage with this waste is also very problematic and biogas plant can be a solution.

Anaerobic digestion seems to be a very efficient way to close the material and nutrient loop according to EU circular economy paradigm. The field application of digestate is also a part of nutrients' circularity. Digestated materials have advantages for their use as soil amendments which are microbial stability, hygiene and high amount of N present as ammonium. It improves also the total organic C concentration in soil [6, 7].

Biogas is a promising substitute for natural gas of fossil origin [8]. Published articles about environmental impact of biogas production analysed heat and energy production [9], biomethane purification [10] and domestic use [11]. Reviews also describe biogas LCA from manure in a global perspective, technological studies of biogas production and specific studies for specific countries or region. Studies also concern a transport of feedstock and indicate that it can play an important role in the environmental performance of biogas production [12]. The maximum transportation distance should not extend 10 km to make biogas environmentally viable for small-scale plants [9, 13], and for large-scale plants, it should be within 64 km [14]. However, mostly studies focus on electricity generation from biogas than on the possibility of biomass waste treatment.

The aim of this paper is to present the results of selected two biogas plants, which mostly differ with the type of feedstock, the way it is transported and the transportation distance, in order to highlight the most critical factors (hot spots) from the environmental point of view of operating those installations whose main purpose is the waste treatment.

2 Materials and Methods

The life cycle assessment (LCA) methodology was chosen for this study based on ISO 14040 and ISO 14044 as the most comprehensive evaluation of environmental impact. LCA analysis includes four steps: goal and scope definition, life cycle inventory analysis, life cycle impact assessment and interpretation of results [15, 16]. In this work, the ILCD 2011 Midpoint+ v.1.10 method was considered. The ILCD was developed by the Institute for Environment and Sustainability in the European Commission Joint Research Centre (JRC), in cooperation with the Environment DG which is widely used in Europe. In this method, 16 very detailed impact assessment categories are distinguished [17]. The inventory data for this study were taken directly from tested agricultural biogas plants located in Poland and from the ecoinvent database v. 3.3 and processed using the SimaPro calculation program.

Selected biogas plants were assessed in details from gate-to-gate perspective. Input data were collected for separate unit processes implemented under the modern mesophilic fermentation technology: maize cultivation, feedstock delivery, energy production and digestate storage and transport. All results were analysed relative to the reference unit, which is named as a functional unit (FU) and defined as "a delivery of 1000 Mg of feedstock designed to biogas conversion". The values of the eco-indicator were presented in impact categories, expressing the value of impact at environmental ecopoints (marked with the Pt symbol).

The allocation cut-off by classification model was used in this study, and the primary production of input of raw materials and pig slurry was allocated to the primary user/producer. It was also considered that the main product is electricity with 100% allocation, but the main purpose of those plants is the biomass waste management. Only the maize cultivation was taken into consideration as a dedicated tillage.

Two agricultural biogas plants A and B were taken into consideration with installed power 1.0 MW and 0.526 MW, respectively. In both cases, slurry digestate is not separated and used as a natural fertilizer on arable fields. The most important parameters of the tested plants are collected in Table 1. The construction and demolition of the biogas plant as well as the production of biomass waste feedstock and digestate application on fields were excluded from the scope of the study. The environmental impacts of the electricity production from biogas based on anaerobic co-digestion of pig slurry, silage maize and different feedstock from agri-food industry were determined (Table 2).

Table 1 The most important parameters of the tested biogas plants

Parameter	Biogas plant A	Biogas plant B
The amount of biogas [m^3/year]	4,169,760	1,725,155
The amount of electricity produced [MWh/ year]	786.1	300.7
The amount of heat produced [MWh/ year]	776.9	319.3
The amount of heat used [MWh/ year]	147.0	222.1
The amount of digestate [m^3/year]	35,515	19,744
Total efficiency [%]	51	69

Table 2 The feedstock input in relation to annual operations

Biogas plant	Type of feedstock	The amount of feedstock [Mg/year]	Biogas yield [m^3/Mg]	Maximum transport distance [km]
A	Pig slurry	14,824.0	232.0	5.0
	Maize silage	21,693.0	36.0	1.0
B	Maize silage	2,025.0	230.0	45.0
	Distillery residues	11,489.7	31.0	Gravity pipeline
	Carrot pomace	1,595.9	76.0	11.3
	Potato pomace	5,919.6	94.0	22.5
	Pig slurry	590.0	9.0	3.8
	Protein sediments	402.6	700.0	172.5

Liquid animal manure was transported by a farm tractor with a barrel. Maize harvested from the fields was transported to a biogas plant using heavy wheeled transport. The remaining raw materials from the agri-food industry were transported with a trailer or with different types of lorries. Only distillery residues in biogas plant B were delivered by a gravity pipeline.

3 Results and Discussion

The results were estimated by using the ILCD 2011+ method and the 16 midpoint categories. The results were described on two different levels of LCA methodology: characterization and weighting for four-unit processes – maize cultivation, feedstock delivery, energy production and digestate storage and transport. The feedstock delivery includes transport of agri-food residues, maize ensilaging on-site and delivery to the digester. In analysed biogas plants, we can distinguish six types of transport: (1) road transport of pig slurry to the plant, (2) road transport of raw materials to the plant, (3) pipeline transport to the plant, (4) internal transport on-site, (5) maize transport from the field and (6) digestate transport for final use as fertilizer.

The cumulative environmental impact of biogas plant B (1.48 kPt) is significantly lower than that of biogas plant A (42.66 kPt). The liquid feedstock with low organic mass content and biogas yield in plant B are provided by gravity pipeline. In an installation A, a feedstock is delivered by a tractor with a barrel (Table 3). The highest environmental burdens of biogas plant A stem from the delivery of a feedstock, whereas of plant B, it is related to the storage and transport of the digestate.

The highest value of eco-indicator for plant B concerns the digestate storage and transport. In this case, the transport of liquid digestate takes place using a tractor with a barrel. The storage of the digestate itself does not involve any energy consumption or emissions to the atmosphere. The digestate is stored in a sealed container, so transport in this process is the main contributor. Moreover, the fields for the application of the digestate are located in the vicinity of biogas plant B and the distance is 0.9616 km maximum. The transportation distance of a digestate to biogas plant A is almost twice longer (1,606 km), which can significantly affect the higher environmental impact. The area required for the spreading of the digestate and the maximum transportation distance were calculated as follows [18].

Biogas plant A exhibits a significant impact on almost all categories; however, the contribution of all categories for both biogas plants is almost equal (Table 4).

Only for the water resource depletion category for both biogas plants, the value is below zero. It means that in this category, the environmental impact can be positive. The lower is the value, the more positive is the impact. The reason for obtaining such results for this impact category is the temporary storage of the liquid digestate. It may provide a reservoir of water for field irrigation just next to the fertilization purpose.

Based on the results, three leading groups of factors with the highest environmental impact were separated: transport, electricity consumption and others. The factors were classified in terms of the value of environmental burdens and significance for the impact on climate change. In both biogas plants, transport is the main contributor and represents 99.9% and 98.1% of the total cumulative impact value, respectively (Fig. 1). Even electricity consumption, which in both cases comes from the grid, represents a negligible part of the total impact, 0.03% and 1.56%, respectively (Fig. 1).

Comparing all different types of transport as it was mentioned earlier in this article, for biogas plant A, the highest environmental impact is related to the transport of pig slurry (91%), while for biogas plant B, the impact mainly stems from the transport of the digestate (87%) (Fig. 2). The transport of raw materials to biogas plant B is characterized by a relatively low environmental impact, even though the distance from the production site to the biogas plant is up to 100 km. Raw materials from agri-food industry such as fruits and vegetable pomace have a higher organic mass content and a higher biogas yield per unit weight (Table 2). Then the

Table 3 The cumulative eco-indicator values for individual stages of operation

Biogas plant	Maize cultivation [kPt]	Feedstock delivery [kPt]	Energy production [kPt]	Digestate storage and transport [kPt]
A	0.58	38.68	0.01	3.39
B	0.01	0.18	0.02	1.27

Table 4 LCIA results of each biogas plant on the characterization level

Impact category	Unit	Plant A	Plant B
Climate change	kg CO_2 eq	1.93E+07	957E+05
Ozone depletion	kg CFC − 11 eq	2.30E+00	134E-01
Human toxicity, non-cancer effects	CTUh	5.82E+01	1.85E+00
Human toxicity, cancer effects	CTUh	2.12E+00	7.84E-02
Particulate matter	kg PM2.5 eq	1.82E+04	7.31E+02
Ionizing radiation HH	kBq U235 eq	1.26E+06	6.50E+04
Ionizing radiation E (interim)	CTUe	6.65E+00	3.67E-01
Photochemical ozone formation	kg NMVOC eq	1.59E+05	6.70E+03
Acidification	molc H+ eq	1.61E+05	6.86E+03
Terrestrial eutrophication	molc N eq	5.56E+05	2.36E+04
Freshwater eutrophication	kg P eq	5.93E+03	2.47E+02
Marine eutrophication	kg N eq	5.11E+04	2.17E+03
Freshwater ecotoxicity	CTUe	3.02E+08	1.14E+07
Land use	kg C deficit	1.35E+08	5.37E+06
Water resource depletion	m^3 water eq	−1.94E+06	−5.85E+04
Mineral, fossil and ren resource depletion	kg Sb eq	3.27E+03	1.27E+02

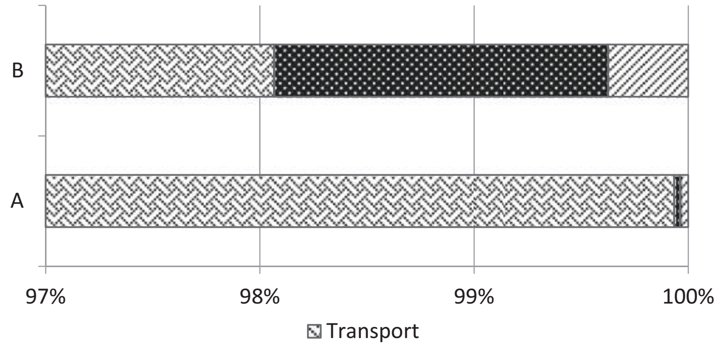

Fig. 1 The contribution of main critical factors in total environmental impact

transportation can be significantly extended obtaining the same results compared with the distance for pig slurry. In plant B, the distillery residues were transported by gravity pipeline what leads to negligible environmental impact at the exploitation stage. The impact can be visible at the construction or demolition stage when the input of metal used for pipelines is taken into account. However, in this study, these two stages were omitted.

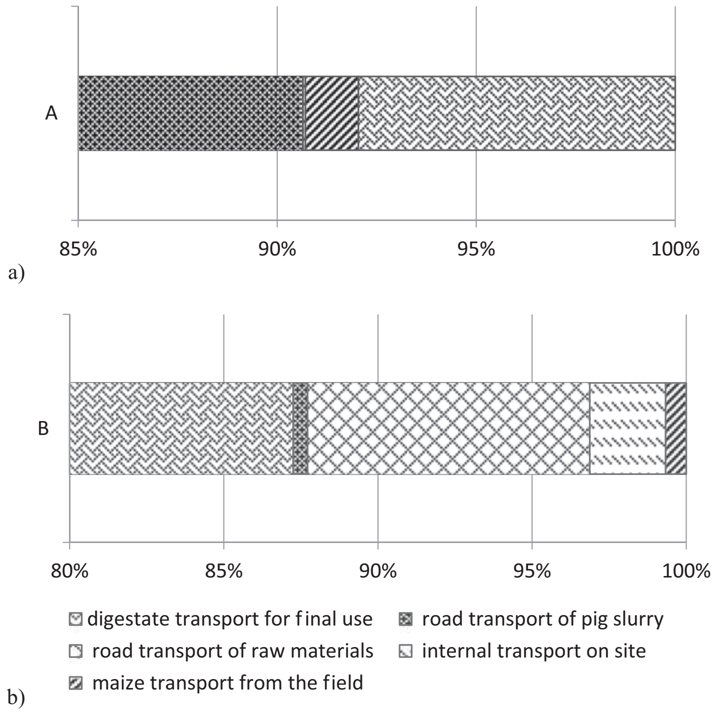

Fig. 2 The share of different types of transport in feedstock delivery process: (**a**) biogas plant A, (**b**) biogas plant B

4 Conclusions

The production of renewable energy from biogas is an unquestionably effective way to replace energy from conventional sources and reduce negative environmental impact and climate change. Biogas plants can also provide a solution to the problem of managing many agricultural and agri-food industry waste. However, taking into account many previous studies and this work, we can conclude that transport is the main contributor of the cumulative environmental impact of operating an agricultural biogas plant. Liquid raw materials with a low biogas yield should be transported by pipelines, and biogas plants using this type of raw materials should be located in the vicinity of feedstock sources. This is also confirmed by Cherubini et al. who claimed that keeping animals close to biogas plant provide the reduction of the environmental impact [19].

In the case of the ferment, the distance over which it is to be extracted should be limited or other solutions should be used to limit the quantity of the ferment that is needed to be used, e.g. by drying. The environmental impact of drying processes and the possible pelletization of the resulting biomass should be studied.

Undoubtedly, biomass waste is a key source of renewable energy (not only a biogas), but we have to be aware of the possible environmental impact.

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Life Cycle Assessment Benchmark for Wooden Buildings in Europe

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Abstract Climate change and other environmental problems from the production of raw materials, construction, and end of life of buildings are serious concerns that need to be solved urgently. Life cycle assessment (LCA) and the EU-recommended Environmental Footprint (EF) are well-known and accepted tools to measure a comprehensive set of environmental impacts throughout a product's life cycle. But to assess how good (or bad) a wooden building performs environmentally is still a challenge. In the EU Environmental Footprint [11] pilot phase from 2013 to 2018, an average benchmark for the different product groups was found to be very useful. Based upon the recommendations for a benchmark of all kinds of European dwellings, we developed a scenario of a typical European wooden building. The EU Environmental Footprint method covers 16 recommended impact categories and can be normalized and weighted into one single point for easy and quick comparisons. The results are presented as the average impact per one square meter (m^2) of floor area over 1 year. The developed benchmark for wooden buildings is a suitable comparison point for new wooden building designs. The benchmark can be used by architects and designers early in the planning stages when changes can still be made to improve the environmental performance of wooden buildings or the communication and interpretation of LCA results for customers and other stakeholders.

1 Introduction

According to the European Commission, the construction industry accounts for 15% of all greenhouse gas emissions [1]. During their use phase, buildings use 80% of the total energy consumption [2], which contributes significantly to air pollution and other environmental impacts stemming from energy sourcing, distribution, and transformation. While energy consumption during the use phase is predicted to decrease as efficient buildings, like zero and near zero energy buildings, become more common, climate change and other environmental problems from the production of raw materials, construction, and end of life remain serious concerns that

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need to be solved urgently. This calls for a life cycle-based approach for the assessment of the environmental impacts of a building.

In the EU Environmental Footprint [11] pilot phase from 2013 to 2018, an average benchmark for different product groups was found to be very useful [3–5] as a help for interpretation of the product's life cycle assessment results in scope of the product category.

Spirinckx et al. [6] give recommendations on benchmarks for office buildings, while Lavagna et al. [2] provide the average environmental impacts of existing dwellings in Europe. However, as the European Union has introduced a stricter policy for buildings' use of energy, a benchmark for new buildings to be built is needed. In this work, we provide an environmental benchmark for a near zero energy wooden residential buildings (nZEB) for new buildings in the future (after 2020). The typical (European average) wooden single-family house holds on average 2.36 inhabitants and, in this study, is set to be 100 m^2 large.

2 Data and Method

2.1 Background Data for a Typical (European Average) Wooden Single-Family House

Based on market-based statistics from Eurostat [7], supplemented with national data where necessarily [8], a prevision for where wood-based residential housing is found in Europe today is made (cf Table 1).

The apparent consumption is what is sold in each country and calculated based on production value – export + import (EUR). The apparent consumption is used for weighting the climate data and energy requirement data of the countries investigated to come to an average wooden residential building.

European countries have different climate and, therefore, different heating demand for residential buildings. We took the climatic conditions on a country level into account, represented by the degree heating days, which is a measurement for how much heating is necessary during a year [9, 10]. Table 1 also shows the heating degree days in the countries investigated. The weighted average heating degree days for the European countries according to Table 1 is 3500. We have used 10 years of data for the climate conditions, and not the usual 30 years, for two reasons: (1) prefabricated building statistics are not easily available for 30 years (for weighting the data), and, more importantly, (2) climate is changing to warmer conditions such that an increase in heating degree days can be observed. For example, the reference climate in Germany is 500 heating degree days less (i.e., warmer) in the period 2008–2017 than was used as a reference 20 years ago (3500 heating degree days).

The energy requirements for new residential buildings from 2021 are given in Table 2.

Table 1 Apparent consumption (million EUR) of prefabricated wooden buildings and climate expressed as heating degree days in different countries (average per year, 2008–2017)

Country	Consumption (million EUR)	Heating degree days per year	Country	Consumption (million EUR)	Heating degree days per year
Austria	583	3482	Latvia	5	4046
Belgium	56	2697	Lithuania	65	3854
Bulgaria	5	2494	Luxembourg	7	2906
Croatia	11	2281	Malta	0.1	468
Cyprus	1	691	Netherlands	150	2721
Czechia	27	3309	Norway	544	4113
Denmark	121	3244	Poland	4	3370
Estonia	23	4224	Portugal	14	1201
Finland	414	5466	Romania	30	2924
France	231	2380	Slovakia	10	3173
Germany	1658	3053	Slovenia	25	2785
Greece	2	1546	Spain	143	1742
Hungary	10	2668	Sweden	1126	5221
Ireland	42	2821	United Kingdom	1226	3033
Italy	615	1875	–	–	–

Source: [7–10]

Table 2 Energy requirement for new buildings (nZEB) from 2021

Country	Max kWh/(m^2 year)	Country	Max kWh/(m^2 year)	Country	Max kWh/(m^2 year)
Austria	160.0	Germany	48.3	Norway	97.5
Belgium	45.0	Greece	57.5	Poland	67.5
Bulgaria	40.0	Hungary	61.0	Portugal	57.5
Croatia	37.0	Ireland	45.0	Romania	155.0
Cyprus	100.0	Italy	57.5	Slovakia	43.0
Czechia	57.5	Latvia	95.0	Slovenia	47.5
Denmark	20.0	Lithuania	77.5	Spain	57.5
Estonia	75.0	Luxembourg	57.5	Sweden	52.5
Finland	130.0	Malta	40.0	United Kingdom	44.0
France	52.5	Netherlands	57.5	–	–

Source: Own calculations and estimates based on [12–15]

The weighted average maximum energy requirement (near zero energy building) is 67.5 kWh/(m^2 year).

2.2 *Design of a Typical (European Average) Wooden Single-Family House*

With the average climate (from Table 1, 3500 degree heating days, which corresponds to approximate climatic conditions in Austria, South Germany, Slovenia and Italy near the alps) and energy requirement, we started the design of the wooden single-family house that would serve as a benchmark; the shape of the house was made according to the most common plans and structures that we found offered from construction firms of prefabricated wooden houses in Austria. It contains three bedrooms, a living room, cabinet, toilet, utility, staircase, and bathroom. The outer measurements of the house are 9.6 m x 6.7 m, and maximum height is 7.72 m above ground floor level. The house has a pitched roof with 35° angle and 1.0 m overhang. Wooden windows (triple glazed) and doors have Uw = 0.8 W/m^2K. There is a 25-cm-thick concrete plate for the house's foundation. Walls are made of wooden profiles 16/8 cm and stone wood filling in-between, with additional 10 cm of stone wool on the outer side covered with finishing plaster. The roof structure is made of 16/8 wooden profiles as well, with mineral wool in-between and 10 cm on top. For roof cover, wave fiber cement roof tiles were used. Inner floors were covered with parquet on floating screed; ceramics were used in sanitary rooms. Figure 1 shows two profiles and Fig. 2 the schematic floor plan of the house.

After preliminary drawings were made, load-bearing construction of the building was calculated and drawings were updated; the layers for all building parts were precisely defined and U-values of the building's outer enclosure were calculated with diverse online tools. Afterward, the house's energy consumption was

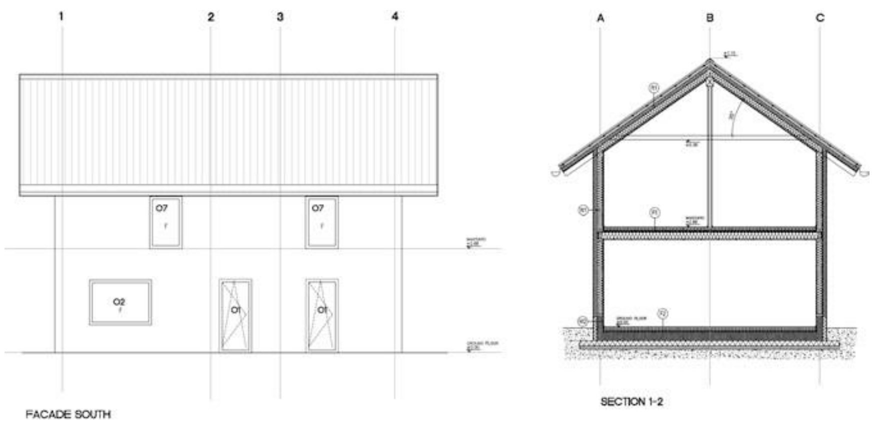

Fig. 1 Façade and section drawings of the house

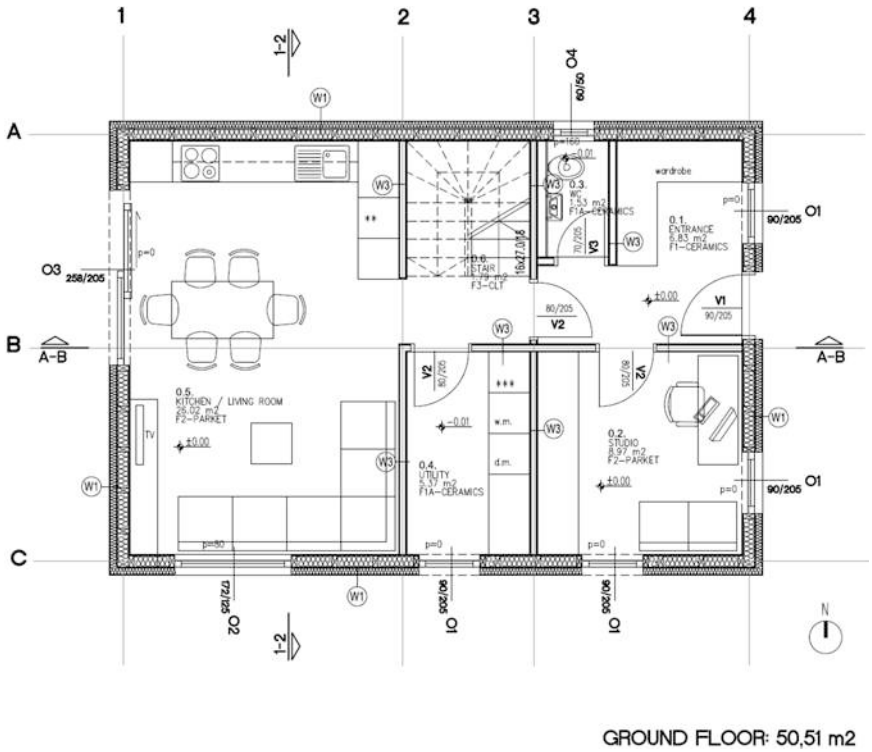

Fig. 2 Ground floor of the house

calculated using a simplified building energy calculation, the Preliminary Passive House Planning Package (PHVP) 2002 [16], which is suitable in the preliminary design phase. Since the shape of the building was made simple and compact, avoiding placement of widows on the northern façade, the energy consumption was calculated to be 26.9 kWh/m^{2}a. This corresponds to nZEB buildings for all countries in Table 2, except for Denmark where there is a stricter requirement.

3 Life Cycle Assessment of a Typical (European Average) Wooden Single-Family House

3.1 Goal and scope

The goal of the life cycle assessment (LCA) for the average wooden one family house is to have a benchmark for wooden buildings suitable as a comparison point for new wooden building designs. The benchmark should be of use for architects and designers early in the planning stages when changes to the building can be made to improve the environmental performance of wooden buildings. Further, a goal of the LCA is to facilitate the interpretation and communication of LCA results for customers and other stakeholders of wooden buildings, for example, when comparing environmental performance of different materials or building elements like the façade.

The functional unit is one dwelling with a 100-year lifetime. Our single-family house has a living area equal to 100 m^2; however, the results are given as per m^2 per year.

The impact categories selected are the EU-recommended Environmental Footprint methods [11], which include 16 impact indicators. Version 2.0 was the newest available at the time of the assessment.

3.2 Life Cycle Inventory

Data collection was based on the detailed architectural drawings of the house (cf. Figs. 1 and 2 for examples). Table 3 shows an example of data collection and calculations for one element of the house, the inner walls (W3).

Table 4 shows an overview of the materials for construction and maintenance of the house.

The life cycle inventory data and modeling follow closely the data and life cycle inventory modeling of the benchmark for environmental impact of housing in Europe – Basket of Products Consumer Footprint indicator for housing [2, 17], where the ecoinvent database is used. We used ecoinvent version 3.5 [18] with allocation, cutoff by classification, as implemented in SimaPro v 9.0 [19] for the background data.

4 Results

The characterized results (cf. Table 5) show that the energy for heating and water use in the operational stage (B6 and B7) of the house is dominating, expect for *land use* and *resource use, minerals, and metals* impact categories, where the product stages (A1–A3), respectively, and maintenance (B2 and B4–B5) are dominating. This is caused by high land use and land transformation for wood products (forest management areas) and high use of materials in the maintenance period, which is quite long (100 years). The *water scarcity* impact category is totally dominated by the operational water use during the use phase. However, both *water scarcity* and *resource use, minerals, and metals* are expected to decrease when the total life cycle, including water and other materials end of life, is included, as these can be cleaned and released into nature or, respectively, become recycled material.

The normalized results in Fig. 3 not only show high *water scarcity* from the use of water in the operational phase but also high *resource use, energy, particulate*

Table 3 Example of data collection, here for inner walls (W3)

W3 – inner walls	Quantity [m^2]	Volume [m^3]	Mass [kg]
Gypsum plasterboards 1.25 cm*2 = 2.5 cm	92.54	2.313	2082.1
Load-bearing construction profiles 6/10 cm – 10 cm	18.5	1.851	777.3
Stone wool (between wooden construction) – 10 cm	92.5	9.254	277.6
Gypsum plasterboards – 1.25 cm*2 = 2.5 cm	92.54	2.313	2082.1

Table 4 Material quantities for construction and maintenance

Material	Quantities for construction [kg]	Quantities for maintenance [kg]
Concrete	57621	0
Gypsum	9922	17186
Wood	12707	5354
Sawnwood	7419	821
Window frame, wood	1681	3122
Oriented strand board	1502	0
Fiberboard	423	987
Glued laminated timber	1258	0
Door, inner, wood	356	356
Door, outer, wood-glass	67	67
Insulation, stone wool	4355	10161
Cement	4342	2466
Gravel	5858	0
Ceramic	1439	1923
Glass	1019	1892
Plastic	660	806
Steel	1286	41
Insulation, polystyrene	288	673
Glue	395	547
Bitumen	591	0
Copper	23	23
Aluminum	12	0

matter, and *climate change*. Here, the use phase is still important, but so are the product stage (A1–A3) and maintenance (B2 and B4–B5) in these three impact categories.

The weighted results (cf. Figure 4) show that *water scarcity* and *climate change* are the most important, followed by *resource use, energy,* and *respiratory inorganics*. The impact category *ozone depletion* is less relevant.

Table 5 Characterized results [per m^2 and year] broken down at different stages

Impact category (unit)	A1–A3 product stages	A4–A5 transport and construction	B2, B4, B5 maintenance	B6, B7 use – operational energy and water
Climate change (kg CO_2 eq)	2.99E+00	3.90E-01	3.73E+00	8.54E+00
Ozone depletion (kg CFC11 eq)	2.60E-07	5.31E-08	5.83E-07	6.52E-07
Ionizing rad. (kBq U-^{235} eq)	1.42E-01	5.04E-02	1.62E-01	9.40E-01
Photochem. Ozon form. (kg NMVOC eq)	1.24E-02	1.34E-03	1.45E-02	2.68E-02
Respiratory inorg. (disease inc.)	5.35E-07	1.60E-08	6.30E-07	9.76E-07
Non-cancer HH effects (CTUh)	5.09E-07	4.66E-08	5.31E-07	1.77E-06
Cancer HH effects (CTUh)	9.34E-08	3.40E-09	7.56E-08	1.33E-07
Acidification (mol H^+ eq)	1.95E-02	2.52E-03	2.71E-02	6.33E-02
Eutrophication – fresh w. (kg P eq)	1.95E-04	2.94E-05	2.26E-04	7.44E-04
Eutrophication – marine (kg N eq)	3.23E-03	4.38E-04	3.56E-03	8.36E-03
Eutrophication terr. (mol N eq)	4.34E-02	6.67E-03	5.24E-02	1.33E-01
Ecotoxicity freshwater (CTUe)	3.01E+00	3.90E-01	3.56E+00	4.21E+00
Land use (Pt)	7.97E+02	4.07E+00	3.55E+02	3.87E+02
Water scarcity (m3 depriv.)	1.06E+00	8.24E-02	1.34E+00	5.73E+01
Resource use, energy (MJ)	4.13E+01	7.11E+00	5.39E+01	1.41E+02
Resource use, mineral, and metals (kg Sb eq)	3.19E-05	7.82E-07	4.29E-05	9.35E-06

5 Discussion, Outlook, and Conclusion

This contribution shows how we designed an average European wooden residential building and used life cycle assessment (LCA) and, more specific, the EU-recommended Environmental Footprint (EF) to investigate the cradle to gate and use phase of the house suitable for a benchmark. Even with an improved design,

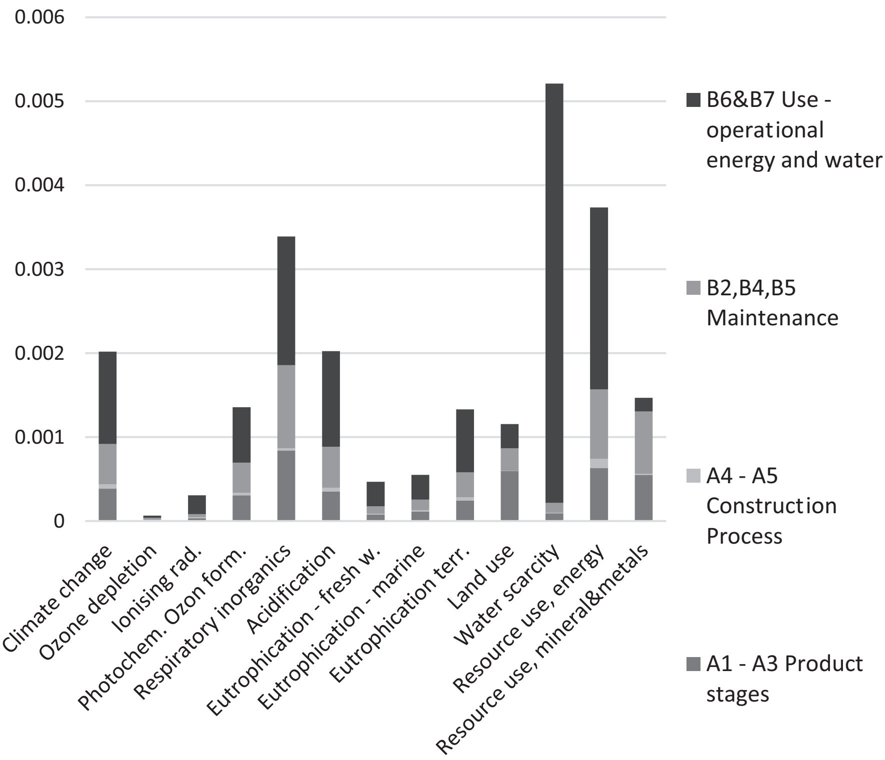

Fig. 3 Normalized results

like better insulation, the use phase is still a major contributor to the environmental impact categories investigated. Climate change, respiratory inorganics (particulate matter), water scarcity, and resource use and energy are the most important impact categories in this study. Waste scenarios, some that happen 100 years into the future, are left for future studies. However, these are believed to include lots of reuse and material recycling. Future studies should also apply the new EU Environmental Footprint method v.3, where the toxicity impact categories have been updated. However, this was not yet implemented in the software used at the time of impact assessment calculation.

The results will be used to compare to existing housing in the Basket of Products for a single-family house and establish and compare the reference houses in specific countries, like Spain. Other building types, like multifamily houses and other buildings made of wood, could be investigated based on the same concept.

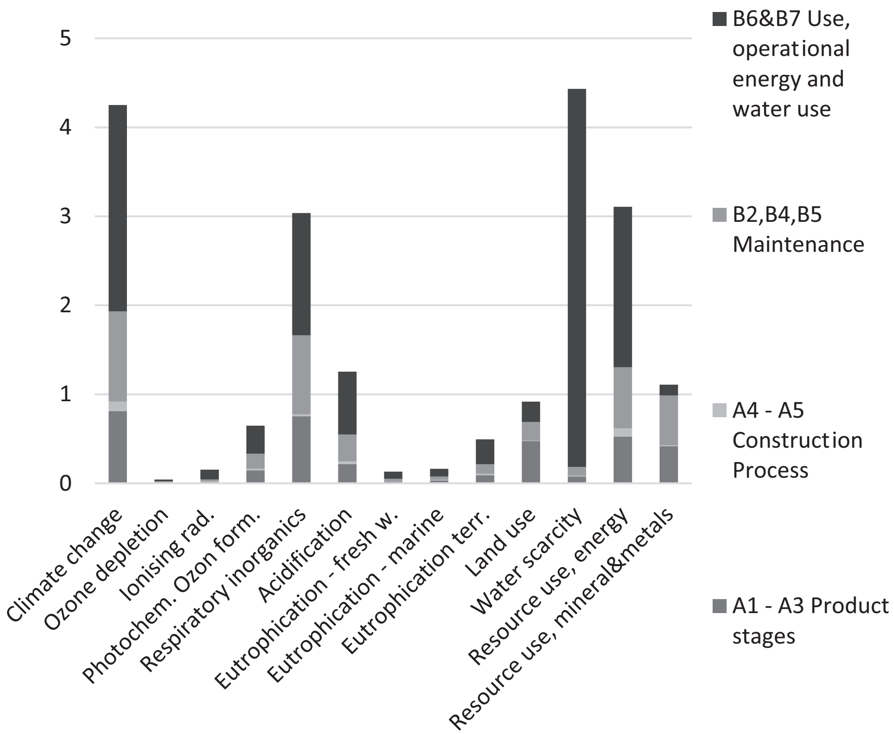

Fig. 4 Weighted results

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Importance of Building Energy Efficiency Towards National and Regional Energy Targets

Can B. Aktaş

Abstract The buildings sector in the EU consumes 40% of energy and is responsible for 36% of CO_2 emissions. With growing public interest on the subject, there have been several EU policies developed to curb impacts. Statistical analysis conducted in the case study indicates an increase in both total and buildings' energy consumption trends leading up to 2030, with total energy consumption having an expected value of 40% increase and building energy consumption having an expected value of 33% increase. Analysis results indicate that building energy consumption could be maintained at current levels if a proactive approach is embraced. Focusing solely on buildings' energy consumption does not solve national or regional energy problems, but neglecting them altogether prevents significant gains to be made. Building energy efficiency is not the solution by itself to achieve energy goals in EU, but is an important contributor toward the solution.

1 Introduction

In the EU, buildings are responsible for approximately 40% of energy consumption, and 36% of CO_2 emissions. Approximately 40% of residential buildings in EU are dated pre-1960, with another 45% from between 1960 and 1990 and did not undergo major renovation since then. Currently, almost 75% of the building stock in the EU is reported to be energy inefficient [1]. Building energy efficiency measures are known to generate economic, societal, and environmental benefits. They also stimulate the economy, in particular the construction industry which generates about 9% of EU's GDP and directly accounts for 18 million jobs. Especially SMEs are known to benefit from building energy efficiency measures as they contribute to more than 70% of the value added in the EU building sector [1].

Existing EU policies demonstrate the timeliness of the subject as successive EU policies regarding building energy efficiency have been put forth in recent years

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including the 2010 Energy Performance of Buildings Directive and the 2012 Energy Efficiency Directive. The former directive has a 2020 strategy of making new construction nearly zero-emission buildings [2]. Hence, there is urgency toward further action as goals are already set to curb energy consumption and associated emissions.

Sandberg et al. [3] demonstrate that the intended EU energy efficiency goals cannot be met if the best available energy efficiency measures are not applied when existing dwellings undergo renovation during their lifetime. While existing building energy codes and regulations are a step forward in the right direction, they have not proven to be sufficient to achieve desired efficiency gains. Furthermore, developers and consumers alike have been shown to interpret meeting the minimum requirements set by the code as sufficient warranty for the energy efficiency of the building, whereas the code rarely represents the optimal point of efficiency [4, 5]. There have been developments in numerous building efficiency technologies to reduce energy consumption in buildings, but their implementation has been lagging mostly due to a lack of knowledge or awareness of their potential impacts, which could be significant considering the extensive lifetime of residential buildings.

The goal of this study is to identify the extent building energy efficiency can play a role toward meeting national and regional energy targets. For that purpose, total energy consumption together with the building sector's share has been analyzed together with forecasts for the near future in line with EU Directives timeline.

Data on Turkey was analyzed as a case in point, as it is one of the fastest growing economies in the EU region as well as having one of the highest total energy demand in the region. Turkey's population grew from 56.5 million in 1990 to 71.5 million in 2008. In addition to population growth, Turkey's urbanization rate has also increased from 52.9% to 74.9% during those years. As a result of these population movements, the number of buildings and consequently energy consumption in buildings increased rapidly [6]. As a result of the developing economy and increasing urbanization rate, electricity consumption has tripled between 1990 and 2008 and reached 198 TWh. Furthermore, Turkey has experienced the highest increase in energy demand in the past 10 years among OECD countries, and only second after China globally. Current expectations are that the trend will continue in short and medium terms [6, 7].

2 Turkey's Total and Sectoral Energy Demand

Between 1972 and 2017, Turkey's total energy consumption rose from 20 million ton petrol equivalent (TPE) to 111 million TPE, indicating a 5.5-fold increase in total energy consumption within 45 years. Figure 1 presents total and sectoral energy consumption trends, both via historical data, as well as forecasted levels of consumption via a statistical analysis that has been carried out. It can be observed that exponential distribution provides the best fit to past data with the indicated R^2 values, as compared to a linear trend [8].

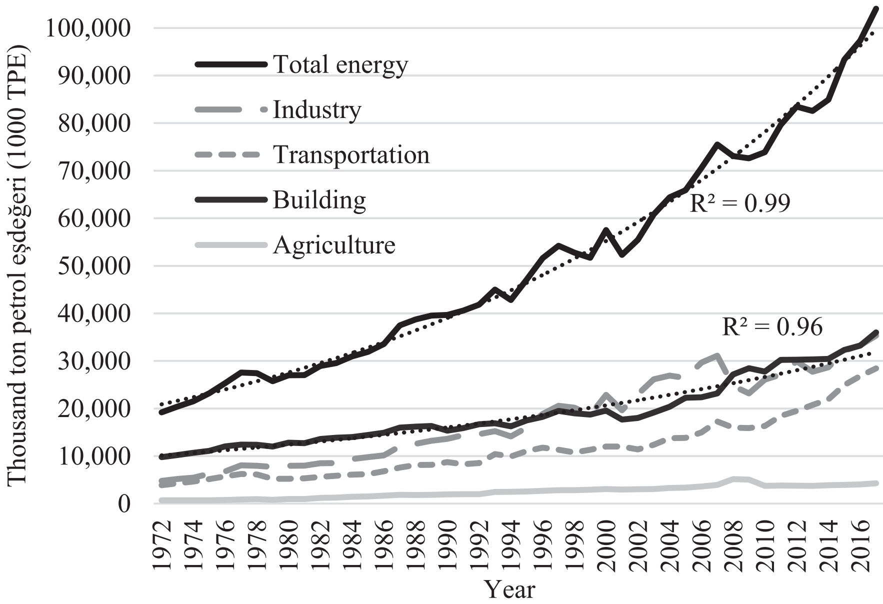

Fig. 1 Total and sectoral energy consumption in Turkey between 1972 and 2017 [8]

Forecasting methods up to the year 2030 have been carried out by using statistical methods. The tool of choice was "Crystal Ball" software. Forecast assessment carried out using the autoregressive integrated moving average (ARIMA) model provided a 95% confidence interval for the expected energy consumption level by 2030. In this context, total consumption and consumption in buildings are presented separately in Figs. 2 and 3 for closer examination of the range, and their implications.

The average value of expected total energy consumption in 2030 is 152 million TPE, and with 95% probability consumption is expected to be between 122 and 182 million TPE. The average value indicates an increase of 40% should be expected compared to 2017 levels. Considering the confidence interval, an increase of 10–65% may be expected by 2030 with a probability of 95%. What should also be emphasized is that it is very unlikely that total energy consumption will remain constant, let alone decrease, in the next decade in Turkey [8].

The average value of forecasted building energy consumption is 48 million TPE for 2030. The 95% confidence interval indicates that consumption may be expected to be in between 37 and 59 million TPE. These values indicate that the average consumption will increase by 33% from the 36 million TPE level in 2017, will remain flat in the best-case scenario, and will increase by 64% in case of a rapid increase.

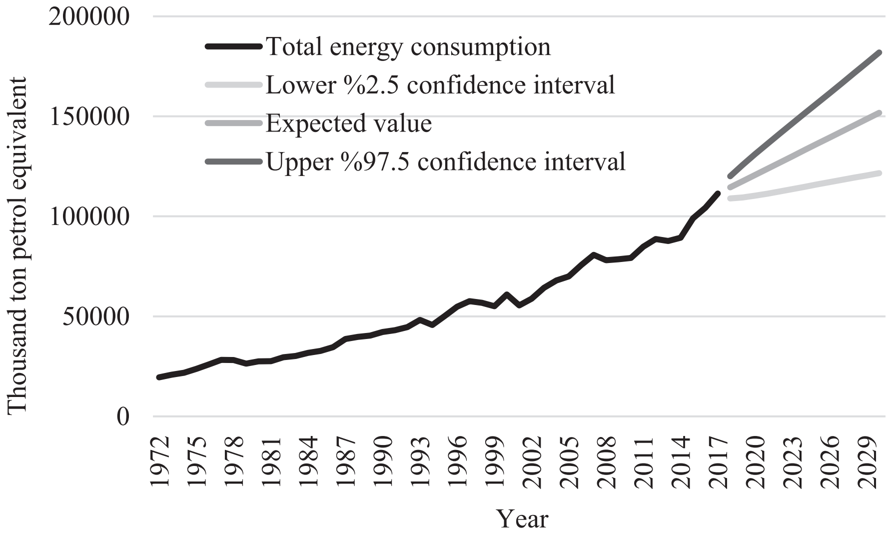

Fig. 2 Average estimated value of the total energy consumption forecasted for 2030 together with its 95% confidence interval [8]

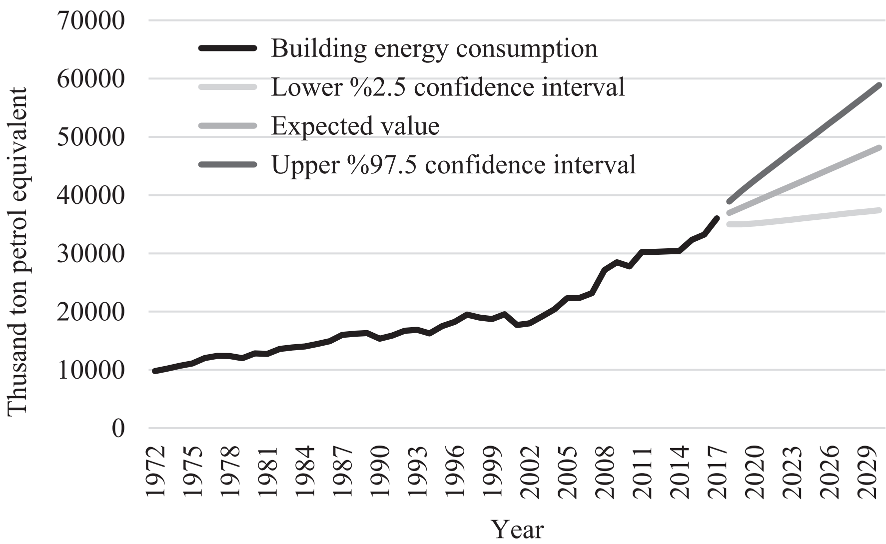

Fig. 3 Average estimated value of building energy consumption forecasted for 2030 together with its 95% confidence interval [8]

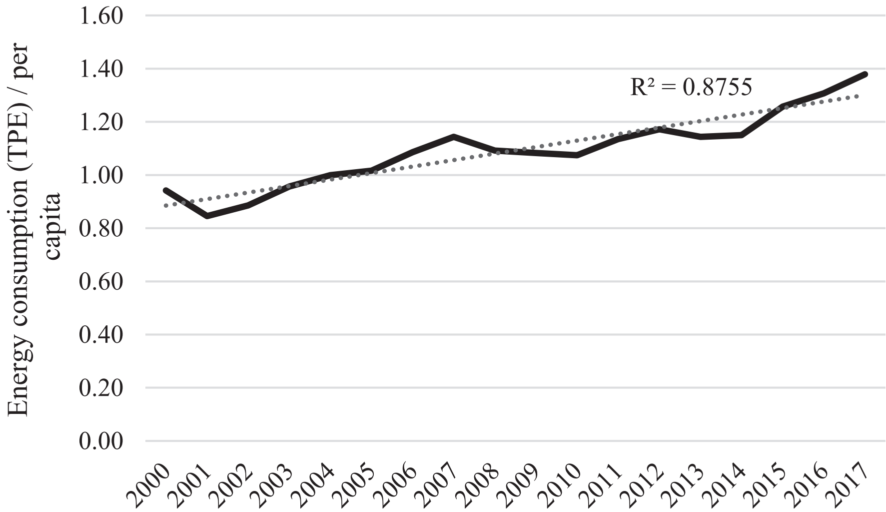

Fig. 4 Energy consumption per capita in Turkey between 2000 and 2017 in TPE [9–10]

2.1 Energy Consumption Per Capita

Energy consumption per capita is important both for forecasting energy consumption levels and for comparisons among countries. For this reason, per capita energy consumption was analyzed and presented in Fig. 4. Since annual population information could not be obtained from reliable sources before 2000, the evaluation was limited to 2000–2017. Results indicate that in addition to an increase in population in Turkey, per capita energy consumption has also increased consistently together, leading to an even more rapid increase in total energy consumption. This trend overlaps with those seen in other countries in the EU and elsewhere.

2.2 Factors that Contribute to Total and Building Energy Consumption

The most frequently studied factor looking into the causality of energy consumption of countries is economic activity or gross domestic product (GDP). There are several detailed studies on the subject in academic literature [11–12]. However, as part of the case study, it was deemed valuable to not only analyze GDP but also investigate the correlation between energy consumption and other pertinent factors. Among the factors analyzed were factors such as population, foreign exchange rate index, and oil price index.

The correlation between the above listed factors with energy consumption was evaluated using the Pearson correlation coefficient and results presented in Table 1.

Table 1 Correlation between total energy consumption and analyzed factors. Presented values are Pearson correlation coefficients [13–16]

	Total energy consumption	Building energy consumption
GDP index (1972 = 100)	0.989	0.985
Building energy consumption	0.979	–
Population	0.968	0.976
Foreign exchange index	0.924	0.912
Oil price index	0.747	0.780

The Pearson correlation coefficient is a statistical method frequently used to determine the linear correlation between two variables. Results are between −1 and 1, and as the values increase, it indicates a stronger correlation between the variables. A positive or negative result indicates direct or indirect correlation, respectively. Zero value indicates that no correlation was detected among the variables.

In agreement with existing literature, the case study also found GDP to be the main factor correlated with both total and building energy consumption. The fact that this analysis was based on a time span of 45 years may indicate that policies or studies aiming to forecast future energy consumption should pay close attention to GDP. Another outcome of the analysis is the revelation on the close correlation between total and building energy use. At least in the past 45 years, the two can be said to have moved together.

3 Role of Building Energy Efficiency Targets Towards National Goals

In order to maintain the current national energy consumption level, energy efficiency policies will need to be developed, enacted, and regulated in order to minimize a further increase in energy consumption. As was discussed in Sect. 2, the expected value of total energy consumption in 2030 is 152 million TPE with a 95% confidence interval of 122–182 million TPE. For buildings, the expected value was 48 million TPE with a 95% confidence interval of 37–59 million TPE.

The abovementioned statistical values were taken as a basis in determining the energy efficiency targets required for the residences to stabilize or reduce the national energy consumption. In this context, the aim is to reduce the energy consumption level as much as possible with effective policies and techniques. Existing data and assessment of Turkey's total energy levels to maintain the level of 2017 indicate that this goal is not achievable only through improving the energy efficiency of buildings. The expected increase in total energy consumption of 41 million TPE is higher than the entire energy consumed by buildings in 2017. Therefore, it seems unlikely that total energy consumption will stabilize or decrease in the short term. Increasing population and per capita energy consumption values also support this result. What needs to be done is to establish and implement effective policies toward these targets with the assumption that the environmental, social, and economic goals and priorities will be determined, and energy consumption will increase. While setting official goals and targets aiming for stabilizing or reducing total national energy consumption, statistical analysis of past policies and practices of the past 45 years indicates that such goals may be beyond reach at least for certain countries. They may still have motivational value, but lack a strong scientific basis unless drastic technological changes are mandated and implemented.

However, when energy consumption of buildings is examined, it seems possible that the increase may be reversed with a proactive approach. The stated expected value assumes that the methods and techniques applied to date will continue to change at the same rate moving forward. However, increasing energy consumption in buildings can be prevented with effective policies and methods. The numerical target determined for this purpose is an additional 25% energy efficiency in buildings based on their current state of energy consumption. However, this strategy should be applied not only to new buildings but also to existing ones, as failure to improve the performance of existing buildings mostly negates any significant gains that may be achieved through new buildings alone. It is not possible to reach the desired energy consumption target set by the EU Directive on buildings by 2030 with policies targeting only the construction of new buildings. Ultimately, even though focusing solely on buildings' energy consumption do not solve national or regional energy problems, due to the share of energy consumed in buildings, neglecting them altogether prevents significant gains to be made. Therefore, building energy efficiency is not the solution by itself to achieve regional energy goals, but is an important contributor toward the solution.

The analysis described herein was based on a case study of Turkey. The reasons for its selection were explained previously and include the fact that Turkey is one of the fastest growing economies in the region and has one of the highest energy demands. However, the conclusions from the analysis do not stay limited to one country, and similar results may be expected for the EU region in general as the underlying principles and factors that affect energy consumption remain the same. Therefore, the presented case study sheds light on the influence and potential impact of building energy use toward national and regional energy goals.

4 Conclusions

The buildings sector in the EU is significant when dealing with energy or environmental issues as buildings consume 40% of energy and are responsible for a comparable amount of greenhouse gas emissions. On the other hand, 85% of buildings in the EU are built before 1990, with 40% built before 1960. This is a problem as well as an advantage: energy-inefficient homes have led to higher than required energy consumption in the EU region; but potential gains to be made by employing efficiency measures are significant. With growing public interest on the subject, there have been several EU projects, guidelines, and policies developed to curb energy consumption and associated emissions.

Turkey is used as a case study in this study as the country has one of the fastest growing economies in the region, and also has a high energy demand growth, which is the central theme of the study. Both total energy consumption and building energy consumption in Turkey have increased exponentially in the past 45 years, although building energy consumption could possibly be represented by a linear trendline as well. This is positive as it indicates a certain degree of energy efficiency measures taking hold in the buildings sector.

Statistical analysis conducted in the analyzed case study indicates an increase in both total and buildings' energy consumption trends leading up to 2030, with total energy consumption having an expected value of 40% increase with a 95% confidence interval of 10–65%, and building energy consumption having an expected value of 33% and a 95% confidence interval of 3–64%. Analysis results indicate that total energy consumption should be expected to increase even in the best-case scenario, but building energy consumption could be maintained at current levels if a proactive approach is embraced.

Multiple factors were analyzed to test correlation with energy consumption. Among the variables analyzed, GDP was found to be highly correlated with energy consumption both for total and for building energy consumption with a Pearson correlation coefficient of 0.99 for both. This fact could provide a quick way of estimating future changes in energy consumption in other countries and regions as well.

Results of the study indicate that it is not possible to reach the desired energy consumption target set by the EU Directive on buildings by 2030 with policies targeting only the construction of new buildings. Ultimately, even though focusing solely on buildings' energy consumption does not by themselves solve national or regional energy problems, due to the share of energy consumed in buildings, neglecting them altogether prevents significant gains to be made. Therefore, building energy efficiency is not the solution by itself to achieve regional energy goals, but is an important contributor toward the solution.

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Part III
Sustainable Organisations

Enhancing Social-Environmental-Economical Systemic Vision: Applying OLCA in a NGO

José Manuel Gil-Valle and Juan Pablo Chargoy-Amador

Abstract Emmaüs International a non-governmental organization (NGO) in the social and environmental sector had practiced, since its foundation – now more than 60 years – the recuperation of objects that others consider as waste. This activity had allowed collecting the funds to help the needy giving them the means to find their dignity that society had taken. Nowadays, the modes had changed, and these recovery activities had made of Emmaüs movement a well-known actor against the non-controlled waste "an environmental actor" working in the reuse and recycling. Given its environmental focus, Emmaüs has interest in assessing the environmental impacts of its own activities throughout the whole value chain. Therefore, an organizational life cycle assessment (O-LCA) study had been conducted as a test in one Emmaüs community. The study was realized in the framework of the road testing of the UNEP/SETAC Guidance on Organizational Life Cycle Assessment. It is important to mention that the avoided burdens assessment is not part of the O-LCA method.

1 Introduction

The Emmaüs community Etagnières, as a non-governmental organization (NGO) in the social and environmental sector, is interested in assessing the environmental impacts of its own activities throughout the whole value chain. Therefore, an organizational life cycle assessment (O-LCA) study was conducted. The study was performed in the framework of the road testing of the UNEP/SETAC Guidance on Organizational Life Cycle Assessment [1, 2].

Emmaüs' goals are of analytical, managerial and societal nature. The O-LCA study offer insights in internal operations as well as in other steps of the value chain, with a focus on wood board recycling. The results allow identifying environmental

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hotspots and set a reference for performance tracking over time. In a parallel study, the avoided burdens originated by the nature of the organization (recycling) will be analysed and compared with the results of the O-LCA. It is important to mention that the avoided burdens assessment is not part of O-LCA.

The study delivers the basis for environmental communications with stakeholders and reporting and allows showing environmental awareness with marketing purposes.

In general, the results of the study were analysed as an outcome of the road-testing phase of the Flagship initiative "LCA of Organizations" in the framework of the UNEP/SETAC Life Cycle Initiative and are publically available.

2 Materials and Methods

Using life cycle assessment (LCA) to quantify the environmental performance of products has become a global trend, since a comprehensive evaluation is achieved, considering all stages of the life cycle, as well as the different environmental problems, including the carbon footprint. The advantages and potential of LCA are not limited to a product application, and although the methodology was originally developed with this approach, its application at the organizational level is possible and is increasingly relevant.

The technical specification ISO/TS 14072:2014 Environmental management – Life cycle assessment – Requirements and guidelines for organizational life cycle assessment [3] describes the application of LCA with an organizational approach. In this way, it extends the application of ISO 14040 [4] and ISO 14044 [5] for all the activities of the organization, which means that the system evaluated covers the life cycle of the different products and operations within the same study.

O-LCA consists of the collection and evaluation of inputs, outputs and potential environmental impacts of the activities associated with an organization considered as a whole or portions of it, adopting a life cycle perspective.

ISO/TS 14072: 2014 provides details on:

- The application of LCA principles and methodology to organizations.
- The benefits that LCA can provide to the organization, using the methodology at the organizational level such as defining environmental aspects in the Environmental Management Systems ISO 14001: 2015, quantifying the environmental impact in an integral way and helping in strategic decision-making and prioritizing the actions that must be carried out to reduce the environmental impact of the organization.

O-LCA quantifies potential environmental impacts through a reporting flow, which is equivalent to the functional unit in a traditional LCA and is used as a reference. The system limits are defined by one of the following consolidation methodologies:

- Operational control
- Financial control
- Participation in shares (percentage of ownership)

In addition, O-LCA proposes two ways to perform data collection: the bottom-up approach and the top-down approach. In the first, the impact of the organization will be calculated with the sum of the LCA of each of the products it manufactures. This implies a collection of data broken down by product, which can be extremely complex for organizations with large portfolios. In the case of the top-down approach, the inputs and outputs of the system can be collected as a whole, by production plant (site) or even by business group. This approach eases the collection of information and allows disaggregation of the results according to the information needs of the organization.

O-LCA can be used as an input for environmental communication, especially for monitoring the environmental performance of the organization over time (performance tracking).

3 Results

3.1 Goal and Scope

The assessed organization was a local Emmaüs community, located in Etagnières, Switzerland, during 1 year from January 2015 to December 2015. The reporting flow was the annual sales expressed in mass (kg).

The system boundary considered a cradle-to-gate approach for the inputs and outputs necessary for each of the activities included, extended by considering the transport of sold goods by the costumers. The production and first use of products are not considered, as well as the use and end of life of the sold recycled materials. The activities considered are categorized into indirect upstream activities and direct activities. Supporting activities like the organization's buildings and employee commuting were considered. System boundary is depicted in Fig. 1.

3.2 Inventory Analysis

A top-down screening approach was used as first approximation to obtain a basis for future studies. Transport data is collected with higher granularity and disaggregated into trucks transport, direct donor transport and customer transport.

Energy data was disaggregated in energy production on site and electrical – solar.

Both generic and specific data were used. The source is on-site, from literature, statistics and databases. A data quality scheme was used with the following criteria:

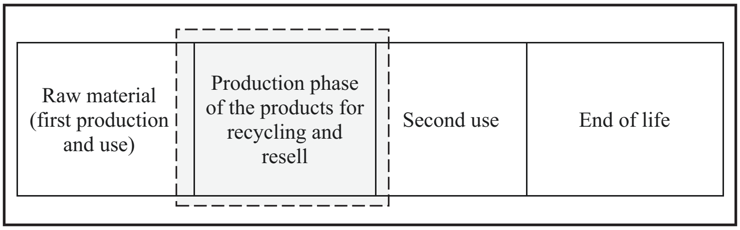

Fig. 1 Emmaüs community system boundary

Table 1 Impact assessment results

Damage (Pt)	Direct activities	Indirect activities	Total
Climate change, human health	2294	11,594	13,888
Ozone depletion	0,000	0,004	0,004
Human toxicity	0,073	1513	1586
Photochemical oxidant formation	0,000	0,000	0,000
Particulate matter formation	0,543	1704	2247
Ionizing radiation	0,000	0,145	0,145
Climate change, ecosystems	1451	7336	8788
Terrestrial acidification	0,004	0,009	0,014
Freshwater eutrophication	0,000	0,008	0,008
Terrestrial ecotoxicity	0,003	0,021	0,025
Freshwater ecotoxicity	0,000	0,042	0,042
Marine ecotoxicity	0,000	0,008	0,008
Agricultural land occupation	0,000	0,493	0,494
Urban land occupation	0,000	0,095	0,095
Natural land transformation	0,000	0,409	0,409
Metal depletion	0,003	0,950	0,953
Fossil depletion	0,003	11,615	11,618
Total	4378	35,953	40,331

reliability, completeness, temporal correlations, geographical correlation and further technological correlation.

3.3 Impact Assessment

The impact assessment method ReCiPe Endpoint (H) [6] was applied. The main impacts have been detected in the categories climate change, human health and ecosystem followed by fossil depletion and particle matter formation. The impacts related to the transportation of sold materials represent an overall contribution of 41%. Impact assessment results are depicted in Table 1.

4 Discussion

The assessment with the ReCiPe Endpoint method allowed identifying environmental hotspots in the impact categories climate change, human health and ecosystem, followed by fossil depletion and particle matter formation. Electricity production, organization's buildings and transport of purchased goods are found being relevant activities. Actions to reduce transport-related impacts, such as selling points next to potential customers and online sales, are recommended.

The main limitations of the study consist in the exclusion of certain capital goods such as trucks and the boiler. The same applies for cleaning products, medicines, gardening products and personal care products that could be analysed in the future because of the potential effects of micropollutants. Facilities as kitchen, green and gardening areas were not included since they were already targeted in the framework of our food recuperation programme. Moreover, the use and end-of-life phase of the sold recycled products are not considered in this study.

Through O-LCA study, the hotspots could be detected. This could help improving the image of the community as a main actor regarding environmental activities. Emmaüs' study was a pilot and serves as example for other Emmaüs communities around the world. As first application in an NGO, Emmaüs' O-LCA experience has the great potential of being a landmark for environmental assessment activities among charitable organization.

5 Conclusions

O-LCA is useful in detection of the main environmental impact categories and their contribution concerning indirect and direct activities. A performance tracking of the mentioned activities could be established from this study on.

The study delivers the basis for the communication of "Sustainable Development Issues" with stakeholders (customer, services providers and partners) and reporting.

A basic model to apply the O-LCA methodology had been established in an Emmaüs recycling community that could be applied in other Emmaüs communities in the future.

The tools developed to apply this methodology were designed with the aim of supporting recycling communities around the world and the whole Emmaüs organization to evaluate and to reduce their environmental impacts in their own communities but also in the regions where they operate, thus positively affecting local development.

Further applications of the study are being considered. First, the data collected could be used in the future as environmental data basis for a formal Environmental Management System (EMS). Second, the Emmaüs community could serve as a pilot project as O-LCA is concerned. In fact, further recycling communities worldwide could apply the methodology in the future, thus enabling an assessment of the whole organization or a broader part of it.

From this perspective, Emmaüs is a first mover in the NGO sector.

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LCA in the Field of Safety at Work: A New Engineering Study Subject

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Abstract Life cycle assessment (LCA) is a standardised and comprehensive approach for evaluation of environmental impacts within the material and energy flows associated with various human activities and through the life cycle stages. Besides environmental impact evaluation, with LCA, costs, social impacts, impacts on workers, organisations and others can also be assessed. This paper focuses on development of educational framework for evaluation of occupational safety based on LCA. The goal is to develop a new study subject "LCA in the field of safety at work" for the occupational safety engineering master study programme at the Faculty of Technical Sciences in Novi Sad. New study subject is based on LCA approaches that evaluate the occupational safety and impact on workers. Based on the previous research of LCA in the field of occupational safety, the goal, outcome, content and realisation are defined for the new study subject.

1 Introduction

Life cycle assessment (LCA) has been in education process at the University of Novi Sad for more than 20 years, since the foundation of the Department of Environmental Engineering at the Faculty of Technical Sciences. The starting point was a teaching topic within the environmental engineering study programme, the subject mechanical engineering in environmental protection. Today, LCA is studied in several courses at bachelor, master and PhD levels of environmental, occupational safety, mechanical and civil engineering study programmes. The result is a growing number of bachelor, master and PhD theses in the field of LCA, eco-labelling and eco-design. Considering the importance of occupational safety in engineering and aiming to fulfil the expectations of organisations operating on the labour market, besides the environmental engineering, since 2010 occupational safety engineering study programme has been established at the Faculty of Technical Sciences.

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Besides environmental LCA, life cycle costing and social LCA (S-LCA) emerge in order to provide sustainable LCA, where S-LCA is the youngest methodology. Within the S-LCA [1], impact on workers' health and safety during the life cycle is a group of stakeholder impact categories that can provide information on accident rates at workplace (non-fatal and fatal), occurrence of various diseases and injuries, disability-adjusted life years (DALYs), presence of safety measures, etc. Working environment LCA (WE-LCA) [2] aim to compile and evaluate potential working environmental impacts on humans of a product system throughout its life cycle. The impact categories in WE-LCA can be expressed through evaluation of potential accidents and diseases: fatal accidents, total number of accidents, central nervous system function disorder, hearing damages, cancer, musculoskeletal disorders, airway diseases (allergic and non-allergic), skin diseases and psychosocial diseases. Furthermore, damage to human health attributable to the work environment can be assessed as DALYs [3].

Table 1 provides several approaches for WE-LCA. Schmidt et al. [2] developed one of the first WE-LCA approaches. This WE-LCA approach is based on EDIP life cycle impact assessment method and contains a small life cycle inventory (LCI) database with more than 80 activities. Pettersen and Hertwich [4] focused on evaluation of safety issues related to offshore crane lifts working environment. Kim and Hur [5] developed two working environment indicators in context of LCA: occupational health and occupational safety. One of the first S-LCA case studies that followed the UNEP/SETAC S-LCA guidelines [1] was presented transparently and in detail was realised by Ciroth and Franze [6]. Group of authors [3, 7] provided two papers published in 2013 and 2014 and used national occupational safety and health industry statistics for United States of America to express the impact on working environment through the WE-DALY units. For WE-DALY indicator, they [3] provided 127 working environment characterisation factors linked with various industry sectors. Kijko et al. [8] also used DALY units to assess health impacts from occupational exposure to chemicals. Khakzad et al. [9] used LCA and quantitative risk assessment methods in parallel to obtain the environmental and safety assessment. Monetary valuation, Canadian dollar (CAD) units were used for both methods in order to have comparable outputs from LCA and quantitative risk assessment.

It can be noted that all approaches in Table 1 have the following common characteristics:

- Compatible with ISO 14040 LCA phases and environmental LCA.
- National statistic records of safety issues through the industrial sectors are used to evaluate safety at work, or to assess the risk of injuries and illness.
- Although developed on national level, all approaches have the potential for universal worldwide use.

Considering that the working environment indicators are relatively new topic in LCA, and that research in the field of S-LCA is an actual topic nowadays, this paper focuses on development of educational framework for LCA in the field of safety at work and working environment in LCA. The goal of this paper is to develop a new study subject on a master study programme of occupational safety engineering at

Table 1 LCA approaches to evaluate safety at work

Approach	Working environment in life cycle assessment	Human health impact indicator for offshore crane lifts	Hybrid input-output analysis
Acronym	WE-LCA	–	Hybrid IOA
Reference	[2]	[4]	[5]
Developing basis	EDIP[b] method	LCA and DALY[d] units	LCA and IOA method
Problem-solving	Impacts on workers/universal	Development of a human health impact indicator for offshore crane lifts	Assessment of occupational health and safety
Geography	Denmark	United Kingdom	Korea
Characterisation	Based on statistics on work-related accidents and reported diseases from the Danish Labour Inspectorate and Statistics on the amounts of produced goods in Denmark	Based on number of crane lift incident injuries and expressed in DALY per crane lift	Linking the LCI[a] data with 28 basic industrial sectors classified by the Bank of Korea for occupational health and Korea Occupational Safety and Health Agency for occupational safety
No. of impact categories	10 – fatal accidents, total number of accidents, hearing damages, cancer, musculoskeletal disorders, airway diseases (allergic), airway diseases (non-allergic), skin diseases, psychosocial diseases, CNS function disorder	1 – health burden per crane lift	2 – occupational health (number of workers affected by certain hazardous items) and occupational safety (number of workers at certain magnitude of disability)
Normalisation	Yes – 2 sets: Danish population (person equivalents) and Danish work force (worker equivalents)	Yes – number of lifts performed per hour	Yes – total national lost work days from the occupational diseases by hazardous items during the given period of time divided by the total number of the workers
Developed and provided LCI[a] database	Yes – more than 80 activities based on DB93[c] industry sectors	No	No

[a]LCI, life cycle inventory
[b]EDIP, Danish Environmental Agency
[c]DB93, Danish nomenclature for industry sectors (identical to the EU NACE-code system)
[d]*DALY* disability-adjusted life years

the Faculty of Technical Sciences in Novi Sad in order to produce occupational safety engineers that will be able to assess the impacts on workers' health and safety with LCA approach.

2 Methodology

The study programme of the graduate master academic studies in Occupational Safety Engineering presents the continuation of the undergraduate academic studies of Occupational Safety Engineering at the Faculty of Technical Sciences, University of Novi Sad [10]. Engineering and technical disciplines are incorporated into the realisation of the curriculum of the undergraduate and graduate academic studies of Occupational Safety Engineering, thus representing a highly multidisciplinary and interdisciplinary programme. The study programme prerequisites for the enrolment are completed undergraduate studies with at least 240 ECTS and the passed enrolment examination. General information on Master in Occupational Safety Engineering study programme are provided in Tables 2 and 3.

Distribution of ECTS points in master academic studies in occupational safety engineering is provided in Fig. 1. The other study subjects (curriculum) on occupational safety engineering study programme tackle topics such as hazardous materials and hazardous waste, occupational risk assessment, statistical advanced models, occupational medicine, chemical risk assessment of fire and explosion, system regulations and EU practice in occupational health and safety, occupational noise and human vibration in industry, accidental risk management and the environment, product safety and user/consumer protection and sociological and legal aspects of occupational safety. On the other side, none of the current subjects cover the safety at work from life cycle perspective.

According to the previously defined study subject topic, the goal, outcome, content and realisation of new study subject will be defined in results section.

3 Results

Based on the previous literature, the new study subject LCA in the field of safety at work has to cover the following topics (Fig. 2):

- LCA according to ISO 14040 and 14044 international standards
- Relationship between WE-LCA and other LCA approaches: the environmental LCA, S-LCA, life cycle costing organisational LCA and sustainability LCA
- S-LCA for workers stakeholder group: goal and scope definition, S-LCI, social life cycle impact assessment methods and interpretation
- Software support for S-LCA: S-LCA software and S-LCI databases
- Evaluation of products life cycle impact on workers through WE-DALY approach

Table 2 LCA approaches to assess safety at work (continued)

Approach	Social life cycle assessment	Work environment disability adjusted life year	Occupational LCA	Accident risk-based life cycle assessment
Acronym	S-LCA	WE-DALY	–	ARBLCA
Reference	[6]	[3, 7]	[8]	[9]
Developing basis	LCA	LCA and DALY units	LCA and DALY	LCA and quantitative risk assessment
Problem-solving	Evaluation of social impacts through the product's life cycle	Waste management – landfilling and incineration	Assessment of health impacts from occupational exposure to chemicals	Green and safe fossil fuel selection
Geography	Worldwide	United States of America	North American	Canada/ potentially worldwide
Characterisation	Assessment of the performance of the sectors and companies, respectively, based on the status of the indicators taking the performance of the sector/company in relation to the situation in the country/region into account	Characterisation factors are obtained from US industry-level occupational safety and health data (work-related fatal and non-fatal injuries and illnesses) and the physical quantities of goods produced by these industries	Based on labour hours and indoor intake concentration	IPCC[d]
No. of impact categories/ indicators	8 – within workers' stakeholder category, the subcategories are the following: freedom of association and collective bargaining, child labour, forced labour, fair salary, working time, discrimination, health and safety, social benefits/ social security	1 – work environment DALY[b] (WE-DALY)	1 – occupational exposure to chemicals expressed in DALY/h	2 – GHG[e] (CO_2) emissions converted to CAD[f] by carbon tax for LCA, and 5 risk loss categories in CAD[f]

(continued)

Table 2 (continued)

Approach	Social life cycle assessment	Work environment disability adjusted life year	Occupational LCA	Accident risk-based life cycle assessment
Normalisation	Yes – each subcategory is assessed twice with a colour system ranging from very good performance to very poor performance and very negative impacts to positive impacts	No	No	British Colombia province carbon tax (30 CAD[f] per metric ton of CO_2 equivalent)
Developed and provided LCI[a] database	LCI database is not provided in the particular study; however, S-LCA databases exist	Yes – 127 WE characterisation factors linked with NAICS[c] industry sectors	Yes – for various NAICS [c] industry sectors, characterisation factors have been developed for 19069 organic chemical/sector combinations	None

[a]LCI, life cycle inventory
[b]*DALY* disability-adjusted life years
[c]*NAIC*, North American Industry Classification System
[d]*IPCC* Intergovernmental Panel on Climate Change
[e]*GHG* greenhouse gases
[f]*CAD* Canadian dollar

Table 3 General information on master in occupational safety engineering study programme [10]

Type of studies	Master academic studies
Academic degree	Master in Occupational Safety Engineering (M. Occ.Saf.Eng.)
Educational field	Technical-Technological Science
Scientific, professional or art field	Environmental and Occupational Safety Engineering
Duration (year/sem)	1 year/2 semesters
Total European Credit Transfer System (ECTS) points	60
Web address containing study programme information	http://www.ftn.uns.ac.rs

Fig. 1 Distribution of ECTS points in master academic studies in occupational safety engineering

Fig. 2 Topics in study subject LCA in the field of occupational safety

- Evaluation of products life cycle impact on workers through the WE-LCA approach

Fundamentals for teaching will certainly include recommendations for LCA from ISO 14040 and 14044. These standards provide basics for environmental LCA and are nowadays incorporated in other LCA approaches. Historical development, similarities and differences between the various LCA approaches are interesting starting point for better understanding of LCA in the field of safety at work. Within S-LCA, besides other social issues, evaluation of occupational safety is expressed through the workers stakeholder impact category. Software support for S-LCA enables practical calculations of social impacts, supply chain modelling and connection between the industry sectors and countries. Therefore, S-LCA software can be used for performing exercises in computer classrooms with students. WE-DALY and WE-LCA approaches have their LCI database which also can be used for exercises in computer classrooms with students.

The new subject LCA in the field of safety at work on a master study programme of occupational safety engineering at the Faculty of Technical Sciences in Novi Sad has been developed and applied for the accreditation programme for the new 2020/2021 academic year. Goal, outcome, content and realisation of this subject are provided in the following part:

- Goal: Acquisition of knowledge, competences and academic skills in field of safety at work and product's life cycle. Development of creative capabilities, academic and practical skills for implementation of life cycle assessment of processes and products from aspect of impact on the worker;

- Outcome: Ability to solve real problems in the field of life cycle assessment of product's impact on worker. Mastering methods and procedures for life cycle assessment of product's impact on worker. Development of skills for life cycle assessment of product's impact on worker with respecting the sustainable development principles. Ability to critically and self-critically think within interpretation of product's and process's life cycle assessment results.
- Content: Product's life cycle. Life cycle assessment in the field of environmental protection and safety at work. Sustainable development, economic, social and environmental dimension within the life cycle assessment. Defining goal and scope of study. Life cycle inventory. Life cycle inventory databases. Life cycle impact assessment on worker. Methods for life cycle impact assessment of products and processes on worker. Interpretation of results.
- Realisation: Lectures are interactive in the form of lectures, auditory, laboratory and computer practice. During the lectures, theoretical part of the course is presented followed by typical examples for better understanding. During the auditory practice, typical problems are solved and the knowledge is deepened. During the computer practice, information communication technologies are applied in order to master the knowledge of the observed field. Besides lectures and practice, consultations are held on a regular basis.

Besides the lectures, this study subject is based on exercises where students can obtain practical knowledge. The exercises have to be based on interactive relationship between the lecturer and students and use of modern educational equipment, computers and the Internet. Mastering methods from this study subject will enable students to perform and develop skills for LCA of product's and process's impact on worker health and safety.

4 Conclusions

Although the environmental LCA is well known, the social LCA and LCA in the field of safety at work are starting to gain their momentum in scientific community. The new study subject LCA in the field of safety at work on a master study programme of occupational safety engineering at the Faculty of Technical Sciences in Novi Sad aims to enable students to master these methods and to perform and develop skills for LCA of product's and process's impact on worker health and safety. The objective is to achieve student's scientific competencies and academic skills in the field of LCA and occupational safety. One of the specific objectives is to develop students' awareness of the need for continuous education in the field of occupational safety and the development of a society in general.

The educational framework in this paper is developed for the purposes of occupational safety engineering study programme at the Faculty of Technical Sciences in Novi Sad. However, this framework can be applied at other study programmes and universities with certain modifications according to their specific needs. Further development directions will be detected after implementation of LCA in the field of safety at work study subject.

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Setting Internal Price of Environmental Criteria, the Good Way to Transform Organization?

Stéphane Morel, Nabila Iken, and Franck Aggeri

Abstract In this communication, we present some lessons learned on the construction of an internal carbon price by businesses, based on the four-dimensional framework of the Carbon Disclosure Project. We illustrate the scheme with the example of a car manufacturer. Based on grey literature and the conclusions of exchanges with various companies, we discuss the different dimensions of the CDP framework within the scope of the automotive sector. We also analyse the various risk and success factors associated with the carbon pricing tool at organizational, tooling, business and cultural levels within a car manufacturer. We conclude that the carbon pricing tool requires many design choices and a reflection on the company's objective regarding climate change mitigation.

1 Introduction

Whether in the form of taxes, emissions trading systems or other mechanisms, there are currently 57 carbon pricing initiatives implemented or scheduled for implementation worldwide, covering 46 national jurisdictions [1]. However, the carbon prices emanating from them are very disparate and often not commensurate with the issues at stake. Indeed, they vary from less than US1$/tCO2e (Poland carbon tax) to 127US$/tCO2e (Sweden carbon tax), with 51% of emissions priced less than 10 US$/tCO2e. Therefore, some companies are proactively adopting non-regulatory (so-called internal) carbon prices. Even though this practice involved more than 1300 companies in 2017 [2], there is little research on how this price is constructed in practice and deployed internally by companies, which will be the subject of this communication.

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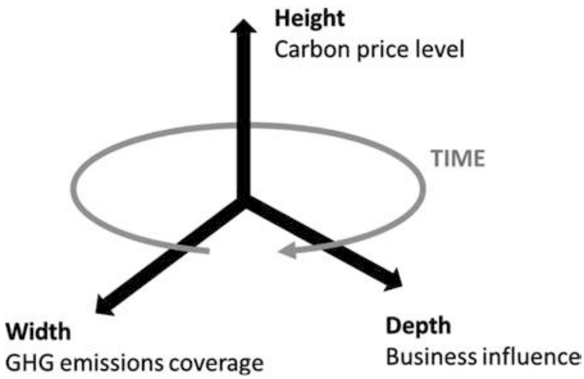


Fig. 1 Four dimensions of internal carbon pricing

2 Method

In order to grasp the implications of setting an internal carbon price in a company, we based our analysis on the Carbone Disclosure Project four-dimensional framework [3], illustrated in Fig. 1. Indeed, we considered that the integration of an ICP[1] by a company is determined by its (i) height, the carbon price level adopted; (ii) width, the emissions coverage in terms of indirect and/or direct greenhouse gas emissions and company's activities concerned; (iii) time, evolution of carbon pricing strategy through time; and (iv) depth. the business influence (informative or decisional ICP? In which form?). In the following, we describe our findings on each of the dimensions described above, in the case of a car manufacturer.

3 Results

Through our study of the grey literature as well as corporate practices in the private sector, our objective is to strengthen managerial knowledge about carbon pricing. Our results therefore make it possible to move a little further towards putting carbon pricing into practice, by highlighting various avenues for reflection in the case of a car manufacturer.

3.1 Height: Carbon Price Level

To reflect the cost of greenhouse gas emission-related externalities in the economic system, the monetary valuation of carbon has been the subject of concern among economists, public authorities and scientists [4]. This has given rise to a multitude of possible forms and values of carbon, which is reflected in the current regulatory

[1] Internal carbon price.

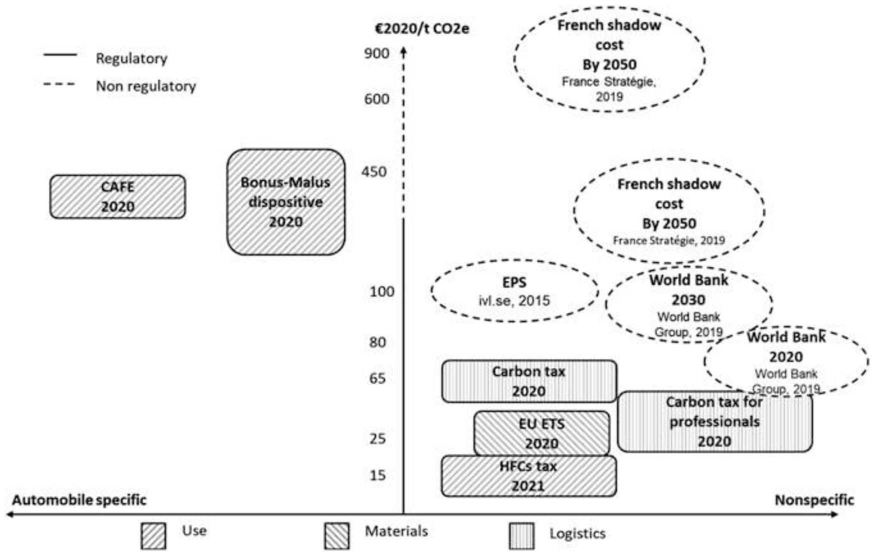


Fig. 2 Regulatory carbon pricing initiatives affecting carmakers in France and other carbon prices

landscape. Because the automotive sector is one of the largest sources of greenhouse gas emissions in Europe (72% of transport CO_2 emissions [5]), some regulatory measures directly target this industry. Figure 2 presents the French regulatory context, where the dates in bold represent the date of application of the measure for regulatory prices, or the time horizon within which the prices should be applied (for non-regulatory prices).

The choice of the carbon price therefore comes down to a positioning in relation to regulations (a degree of anticipation), but also to the company's ambition in terms of the objectives to be achieved (alignment with best market practice, alignment with the 2 °C objective or another company-specific objective). There is also a whole dimension related to internal feasibility, depending on whether the carbon pricing initiative comes from top management, in which case it is a question of deployment, or elsewhere in the company, where it is more of a negotiation process with the decision-makers.

3.2 Width: Emissions Coverage

Figure 2 shows that the carbon pricing regulatory initiatives tend to reduce CO_2 emissions on the use phase of vehicles, much less the emissions in the upstream stages of the vehicle's life cycle. This can lead to a transfer of pollution to phases of the life cycle that are not covered by these regulations, in particular materials production. For this reason, the use of an internal carbon price makes sense within the scope of materials, whether to anticipate regulatory changes or to prevent the transfer of pollution.

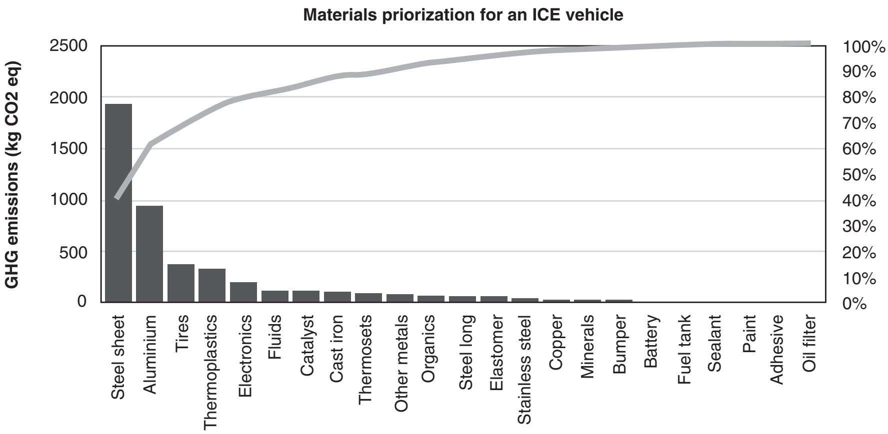


Fig. 3 Materials production greenhouse gas emissions in an ICE vehicle

In order to prioritize relevant perimeters of carbon pricing of materials for a car manufacturer, we based ourselves on vehicles' LCA results. Figure 3 illustrates the greenhouse gas emissions due to the production of different materials for an electric vehicle, without the Li-ion battery. Figure 3 shows the same for an ICE vehicle.

On this basis, we have selected the following priority perimeters.

Besides, LCAs are conducted with a scope 3 perimeter, which means that both direct and indirect emissions are considered through the whole life span of the vehicles.

3.3 *Depth: Business Influence*

For the carbon price to play the role of a transformative tool, it must be embedded in the company's decision-making processes. This raises the question of making it consistent with existing tools and calls for examples of possible use.

For this reason, we conducted a survey with 13 companies that disclose their use of management tools involving monetary valuation of environmental externalities (including carbon). This allowed us to identify the following four categories of tools:

3.3.1 Assessing the Environmental P&L[2]

In the natural capital valuation movement pioneered by PUMA [6], several companies have calculated and communicated their Environmental P&L or Integrated P&L (including social externalities). It is a company's monetary valuation of its

[2] Profit and loss.

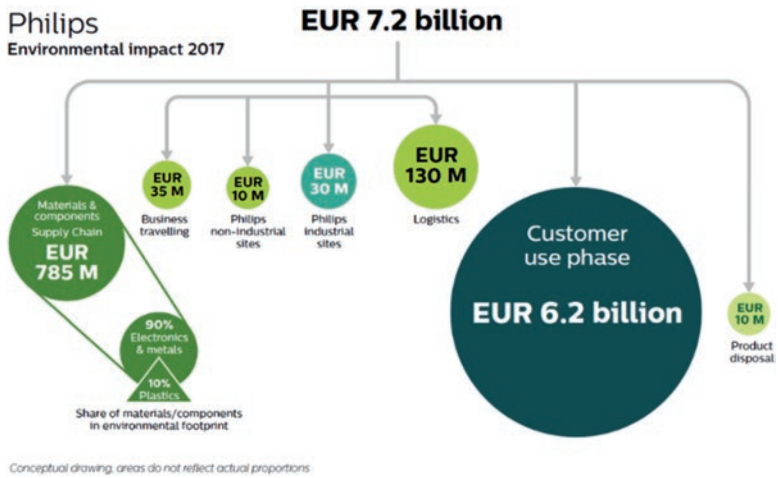


Fig. 4 Philips' 2017 Environmental Profit and Loss accounting

environmental impacts to see their magnitude, disclose them to stakeholders and possibly guide the company's strategy. Figure 4 shows the result of the EP&L calculation made by Philips in 2017 [7].

3.3.2 Including the Cost of Externalities in the TCO[3]

One way to consider the price of carbon in business decisions is to integrate it into cost indicators, such as TCO. Volvo Bus company applied this method to compare between electric and diesel buses in Sweden (Fig. 5), by including environmental and social externalities in the TCO calculation [8].

3.3.3 Including a Shadow Price in the NPV

Another method identified is the integration of a shadow price in the calculation of indicators for investment choices such as the net present value (NPV). This is a way of applying a pricing scenario on a resource or pollutant (in this case carbon). For example, Dow Chemical used this approach to introduce the hidden cost of water into their infrastructure investment choices [9].

[3] Total cost of ownership.

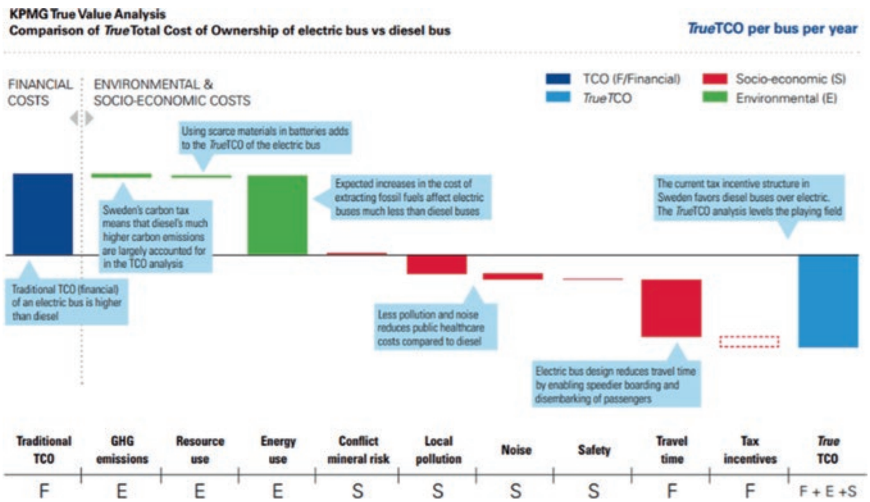


Fig. 5 Volvo Bus' true TCO of electric buses compared with diesel buses

3.3.4 Integrating the External Costs in the Portfolio Strategy

It is also possible to introduce external costs in general – or carbon price in particular – into business strategy through a portfolio management tool, in order to gradually eliminate the most impactful products from the portfolio and replace them with the most virtuous ones. Such a product-oriented approach has been developed by the chemical company Solvay [10] under the name of Sustainable Portfolio Management. Figure 6 shows how the SPM allows mapping the different PACs[4] in the portfolio in two dimensions: (i) market alignment, which is a qualitative estimation of market early signals related to sustainability in the chemical industry, and (ii) operations vulnerability, which is the ratio of the external cost related to the product and its sales value. The blue colour scale represents the turnover associated with the PAC.

Based on the available materials in grey literature and our discussions with the companies, we classified the previous tools typical use according to these two axes:

- **External *versus* Internal**: indeed, some tools are rather designed for communication purposes with external stakeholders and are often mobilized as a means of enriching the sustainability report. On the contrary, some tools are rather intended to guide corporate strategy, investment or portfolio choices. However, it doesn't prevent a tool from playing both roles at the same time.
- **Prospective *versus* Retrospective**: if the tools use data from past activities, they are retrospective and therefore allow an a posteriori evaluation of the company's

[4] Product in an application.

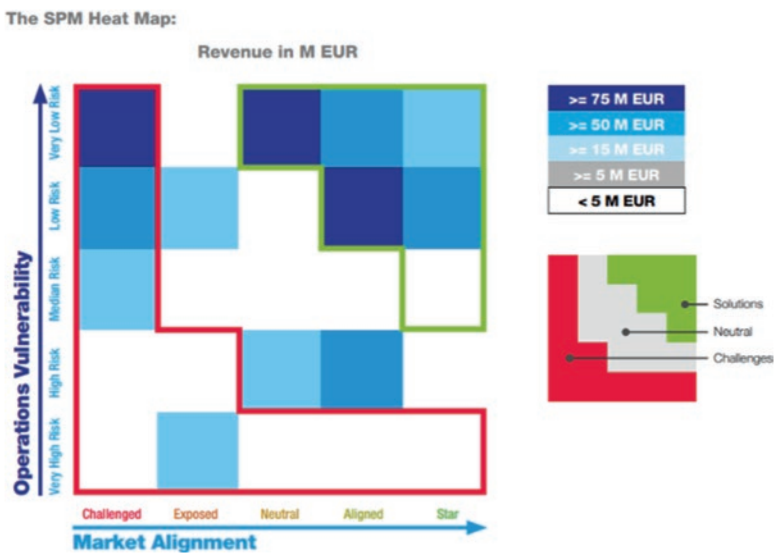


Fig. 6 Solvay's Sustainable Portfolio Management

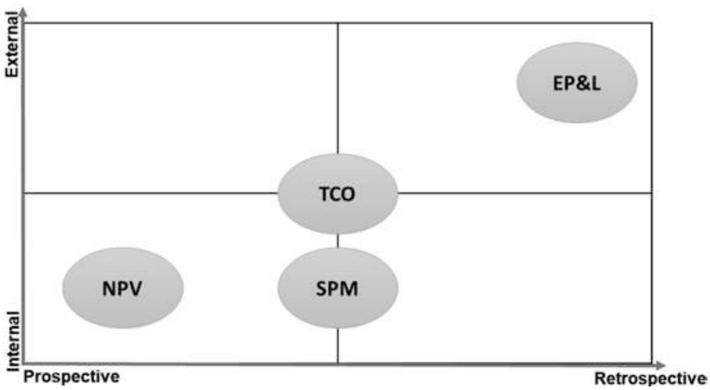


Fig. 7 Typical tools' use by businesses

activities. Similarly, if they are based on future projections (e.g. cost forecasts or future technological developments), then they are prospective.

Figure 7 shows the position of each tool described according to their typical use by the companies.

3.4 Time

The time dimension highlights the dynamic nature of the carbon pricing process in a company. Indeed, this makes it possible to envisage the construction of a roadmap for the implementation of an internal price in a progressive way, starting, for example, with a low price to minimize internal oppositions at the beginning and increasing it progressively. It is also more realistic to test the tool in a reduced scope (pilot project) to identify risks and opportunities and refine the tool's design choices before considering its generalization in the organization.

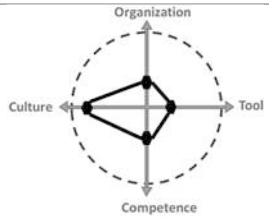
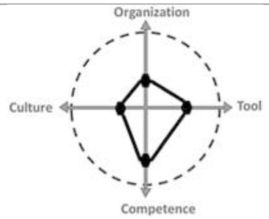
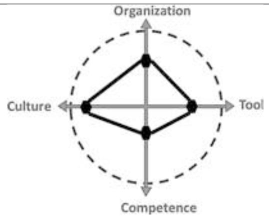
4 Discussion

To illustrate the potential oppositions to the implementation of an internal carbon price within a car manufacturer, we used the following framework as a reading grid. We considered that an induced change in the routines of an actor – or a category of actors – can be subdivided into changes in its (i) culture, (ii) competences, (iii) organization and (iv) tools. This allows identifying the possible oppositions and adapting the proposed solutions to each category of actors.

In our analysis, we considered the following categories of actors based on their influence on materials use: materials buyers, materials experts and environmental experts. Our conclusions concern the introduction of an internal carbon price in the form of an NPV and are shown in Table 1.

Table 1 indicates that introducing an internal carbon price requires the development of an often new expertise to understand this concept of environmental economics and to determine the price level in line with the company's objectives. However, moving from theory to practice means for different actors accepting to change the time horizon of decisions, by incorporating a hidden cost that is a kind of anticipation of future risks. This may conflict with immediate financial objectives, hence the need to reflect on both the relevant perimeter (e.g. considering that R&D and innovation gives more latitude to include the long term in decisions) and also the discourse and rhetoric that accompanies this tool.

Table 1 Analysis of the change due to the integration of an internal carbon price in the form of a NPV

Materials buyers		Familiar with the NPV tool NPV is already a decision criterion Difficulty to consider a shadow cost on the same level with internal costs (cultural gap)
Environmental experts		Already aware of environmental issues Familiar with environmental impact assessment tools Need for learning in the field of carbon pricing
Materials experts		Are used to favouring materials with the best technical-economic performance Need to be more in touch with environmental experts

5 Conclusion

In this communication, we exposed some learnings about the practice of internal carbon pricing, and its potential application in the automotive sector. We showed that the choice of the height of the price was ultimately a choice of target concerning the reduction of CO_2 emissions over a given time horizon. We also demonstrated that the perimeter of materials was a relevant field of application for a car manufacturer and proposed different forms of integration based on companies' practices. However, we have also illustrated the potential difficulties in implementing this tool in a company, especially if it is not a top management initiative. This is why this tool must be an element of a more global approach involving the dissemination of long-term strategic thinking with regard to sustainability issues.

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Part IV
Sustainable Markets and Policy

Metal and Plastic Recycling Flows in a Circular Value Chain

Sasha Shahbazi, Patricia van Loon, Martin Kurdve, and Mats Johansson

Abstract Material efficiency in manufacturing is an enabler of circular economy and captures value in industry through decreasing the amount of material used to produce one unit of output, generating less waste per output and improving waste segregation and management. However, material types and fractions play an important role in successfulness of recycling initiatives. This study investigates two main fractions in automotive industry, namely, metal and plastic. For both material flows, information availability and standards and regulations are pivotal to increase segregation, optimize the collection and obtain the highest possible circulation rates with high quality of recyclables. This paper presents and compares the current information flows and standards and regulations of metals and plastics in the automotive value chain.

1 Introduction

In today's value chain, where production rate and correlated resource and energy consumption constantly increase, efficient and effective use of resources is imperative. In addition, recent concerns regarding non-renewable resources and environmental burden of extracting and producing products from virgin raw materials have been published in several reports and scientific publications such as [1–4]. Material efficiency is an approach within circular economy and resource efficiency to regain

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the original material value via reduction in industrial waste volumes and decrease of the total virgin raw material production per one unit of output, in addition to increasing the homogeneity of wasted material with better waste segregation [5]. The latter enables moving from landfill and waste incineration towards recycling, remanufacturing, reuse and repair (reverse material flow).

The importance of the production phase in the value chain is essential in sustainable development and circular economy as it currently accounts for 33% of total global energy consumption and 38% of direct and indirect carbon dioxide emission [6]. In addition, the production phase contributes to different environmental effects including increased (virgin) raw material and energy consumption, great industrial waste volumes and airborne emissions.

The automotive industry is of particular interest to study, due to the fact that it negatively contributes to the majority of environmental effects. According to the European Automobile Manufacturers Association [7], the production phase in automotive industry in 2017 contributed to 38.8 million MWh energy consumption, 9.47 million-ton CO_2 emission, 56.89 million cubic metre water consumption, 1.4 million-ton waste generation and 38.6 thousand-tons of volatile organic compounds emission. Considering material flows, automotive industry is of interest since metal is used as the primary product material, while several other material fractions such as plastics, chemicals, cardboard, wood and combustible are consumed as auxiliary materials. Furthermore, the generated waste from automotive industry are common residuals mainly including scraped aluminium and steel, chemicals and hazardous waste and packaging materials such as plastics, cardboard, wood and combustible waste. Figure 1 shows the common material flows in automotive industry using a framework presented by [8].

This paper presents and compares the current flows of metals and plastics in the automotive value chain by two criteria, namely, information flow and standards and regulations. An underlying reason is to learn from the relatively better working metal recycling when improving plastic recycling and highlight common needs in both loops. This contributes to the material circular flow knowledge by pinpointing

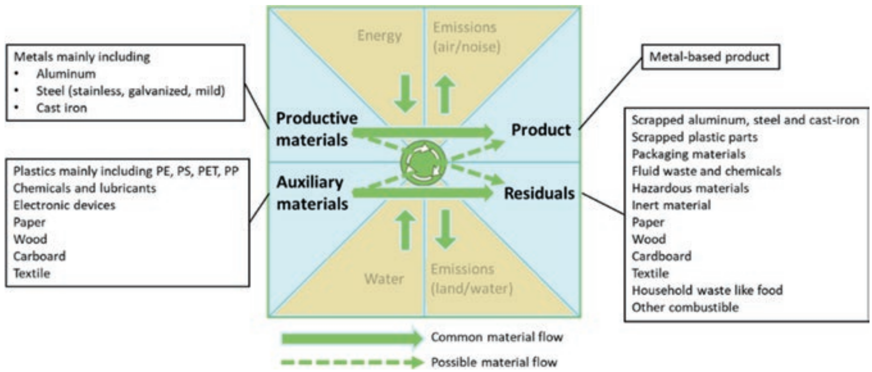

Fig. 1 Common material flows in automotive industry

the gaps, similarities and differences of two material flows as well as extending the collaboration in recycling loops. It is also a help for improving the overall material efficiency and industrial waste management practice.

2 Research Methodology

Research presented in this paper was carried out as a part of an ongoing Swedish research project called "Circular Models for Mixed and multi Material Recycling in manufacturing extended Loops" (CiMMRec), and with an extension pre-study on plastic loops in a research called "Sustainable plastic use by managing uncertainties for the market actors". The project aims to explore opportunities for extended collaboration in recycling loops, especially studying knowledge transfer, information flows, incentives, standards and regulations and business models for improved material recycling, and contributes to the area of circular economy [9] and sustainable supply chains [10]. With limited understanding and lack of empirical studies on characteristics of metal and plastic flows in an automotive value chain, a case study methodology was adopted to fulfil the research objective, consisting of real-time empirical data from different companies within the automotive value chain and a limited literature review. The studied companies are all value chain actors within the automotive industry but in the two separated metal and plastic loops. Studied companies range from primary production of raw materials, product manufacturers, foundry and waste management entrepreneurs to recycling companies.

Although the metal and plastic flows are generally different, the information flows and communication, incentives, business models and standards and regulations for these flows should not differ to a very large extent in order to have a successful recycling flow. Lack of recycling initiatives in any of these flows causes losing material values captured during the linear production processes of materials and products (linear production process as opposed to reverse processes of reusing, repairing, remanufacturing and recycling). As a result, multiple case design with embedded unit of analysis [11] was used, where one case represents metal value chain and the other represents plastic value chain (see Fig. 2). The product manufacturers in both cases are multinational manufacturing companies with global footprints in the automotive industry that use metals as primary production material (productive material) and plastics as auxiliary materials (see [5] for definitions). The selection of companies was mainly based on their close collaboration and project connections, which in turn was primarily based on their enthusiasm in improving their current systems for achieving sustainability and circularity in their materials flows. This close co-research connection facilitated accessing and data collection, arranging semi-structured interviews [12], direct observation by visiting operation sites [11], reviewing relevant documents and monitoring material and waste flows. In the first set of interviews, a total of eight people was interviewed, although some (waste management entrepreneurs) answered two sets of questions related to both metal and plastics. Each semi-structured interview lasted between 30 and 90

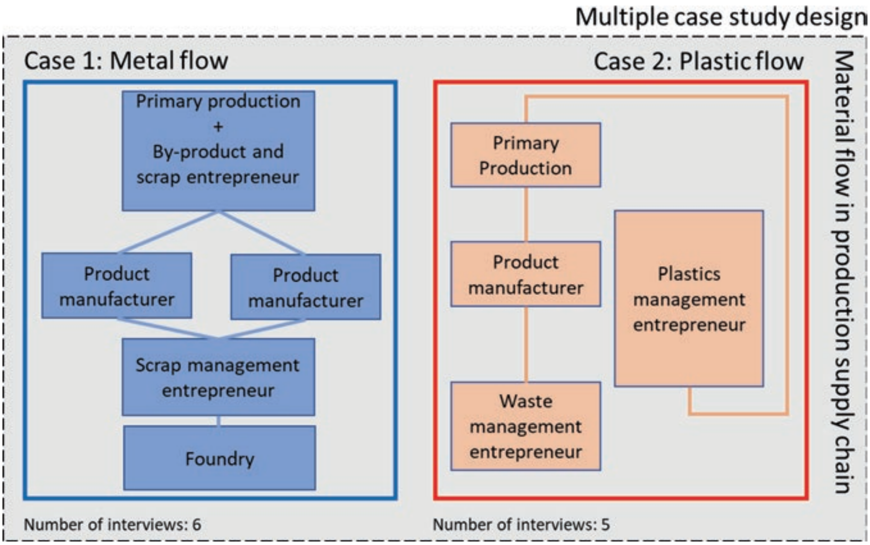

Fig. 2 Case study design

minutes and incorporated predefined questions regarding metal and plastic flows in value chain with several criteria such as information flow, regulation and business models. A second set of interviews included four interviews with six people from the same plastic flows as the first set of interviews. Considering these ongoing market changes, the supplier - user requirements were further elaborated. Data analysis and interpretation was performed within a very short time interval after data collection, as suggested by [11]. Consistency between interviews and for both material flows was maintained throughout the data collection and analysis, by continuously reviewing, comparing and discussing the results with project members including practitioners from the studied companies.

3 Empirical Findings and Discussions

The empirical findings and following discussions presented in this section are based on performed interviews of actors in the value chain shown in Fig. 2, reviewed documents and also direct observation in operation sites (where possible). This section is divided into the main material flows in automotive industry, i.e. metal and plastic. For each material flow, the two main criteria, i.e. information flow and regulations and standards, are discussed.

3.1 Metal Flow

Several different types of information and data are communicated between different actors within the value chain. However, our focus was on information that helps circulating the metal flow (mainly metal scrap in order to close the loop) for recycling and reuse. That being said, the main information flow within this value chain includes material type and fraction, sorting degree, physical shape and dimension, amount in terms of weight in kg, chemical composition and price. There has been a general consensus among the actors (interviewees) that currently sufficient amount and type of information is available (e.g. exact chemical composition of the waste), and there is no need to dig deeper to find the information. However, the problem is mainly information sharing, communication and transparency. It is also the matter of actors' ambitions to ask for more information and to put more effort and time in obtaining necessary information and analyse them for improvement. For instance, the communication between the scrap management entrepreneur and product manufacturers (and also right department, in particular purchasing who buys materials) could be improved; in a specific example, changing the material and/or supplier of components was not clearly communicated with scrap management entrepreneur. The main reason for this was that the product manufacturers were not aware that changing alloy or chemical content of materials and components would have serious consequential effects in end-of-life management and recycling. This issue does not require any regulation or legal intervention, but better information sharing and communication between the actors. Another issue related to information is variability. The majority of metal scraps and waste are generated due to deviations, errors and mistakes in production (see also [8, 13]); therefore, types, physical shapes and weights differ significantly from one to another. This variation negatively affects the number of transportations where sometimes half-full trucks are transporting the waste. There have been some unsuccessful attempts to solve this issue such as using sensors in the metal bin, but it did not work as good as for fluids. In another example, a camera was placed to monitor the content of the metal bin, but sharing this type of data between companies was problematic due to IT regulations. Nevertheless, it could be concluded that improvement actions should start from the product manufacturer, for instance, with better sorting or better communication of information with other actors.

Taking regulation and standards into consideration, there was an agreement among the actors that quality standards for secondary material (metal) would not only ease pricing based on value but also help improve waste segregation and recycling. However, there was also consensus that forced additional standards may disturb the market and distort the competition. The metal primary production actors believed that having more standardized fractions would lead to more complexity and therefore more cost would relate to type of scrap, handling systems and storage. According to metal primary production actors, European standards bring difficulties due to import and export regulations between different countries which take a lot of time and knowledge to fulfil those requirements. The interviewee from a foundry company also asserts "I don't see any need for additional standards on iron and steel, but how well one manages to follow the standards is important … we don't need any further pressure or temptation". In Sweden, companies also follow the national iron standard (Järnbok), which does not always align with standards from other countries, e.g. when buying iron from Germany. Hence, in the long term, an international iron standard is needed to facilitate recycling. There was also difference of opinions on whether regulations and standards should be material or industry specific.

To summarize our empirical results on metal, information flow, actors' role, technology development, market, regulation and standards, product design and behaviours work quite fine with the current infrastructure of metal flow, although several minor improvements (such as given in the examples above) can be made.

3.2 Plastic Flow

The main information flow within the reverse plastic value chain (mainly recycling and reusing) includes plastic type, fraction and prime material, sorting degree and cleanness, shape and dimension, volume in terms of weight in kg, chemical composition and price. Unlike the metal flow, the general consensus among the actors was that more and better information and communication are needed, particularly on exact sorting degree and exact type of plastic and fraction, including details on risk of contamination with unwanted substances. The information flow from the plastic supplier to product manufacturer seems to be working better than the information flow to the waste management and also further back to the plastic management entrepreneur (see Fig. 2). In spite of this, also the information required and given from the supplier has gaps. For instance, it is now the product manufacturer that almost solely decides on the selection of supplier and also type and material of the plastic packaging of purchased components. This decision is mainly based on requirements on the products' protection during transport, due to legal issues (the one who determines the packaging is responsible for parts broken during transport), and until just recently, the footprint of the packaging material has not been in requirements. However, such decisions could involve waste management entrepreneur to explore and discuss opportunities to exclude plastic packaging to a certain possible level and use less additive to ease recycling.

According to the interviews with actors in the plastic value chain, there are several issues with the plastic recycling, including the following:

(1) Recycled plastic does not always have the exact same quality/properties as specified in current parts.
(2) Price of recycled plastic has often been more expensive compared with the relative low prices of plastics made of virgin material, although recently virgin prices have been perceived as more volatile according to the second sets of interviews.

(3) The reverse value chain is not as smooth and steady as the forward value chain and has lots of interruptions, delays and bottlenecks due to unevenness of availability of recycled plastics and variable lead time in collection of plastic waste and recycling. Within the automotive industry, manufacturing companies have the obligation to produce the exact same product for several years, e.g. 10 years, and hence, they need a guarantee that the recycled plastic with the same properties and quality is available for the next 10 years and can be delivered steadily in order to be able to produce the same product with the same properties and quality.

(4) There has not been a customer requirement on the share of recycled plastic in the products. Increasing the share of recycled plastic without the customers' requirement and with current higher prices of recycled plastic compared to virgin plastic would make the product more expensive and hence less competitive.

(5) The interviewees also highlighted issues with the plastic recycling process itself, including lack of plastic sorting. Increase in the number of bins to better segregate plastics into more fractions is a great challenge because usually there is not enough space inside and outside the factories. In addition, managing five to eight different plastic fractions would be time-consuming and expensive for the product manufacturer considering the relatively low market prices. There are also more combustible bins on the shop floor with less walking distance than a specific plastics bin. Consequently, with intrinsic indolence of human being and weariness and exhaustion from work, plastics are usually discarded in combustible bins. One potential solution would be to somehow achieve higher market price for the sorted recycled plastics.

(6) Unlike the household plastic waste that is separated after collection by the waste management entrepreneur in exchange of a small fee, in the industrial system, the product manufacturer is not willing to pay the waste management entrepreneur for segregation, which substantially limits the segregation. At the same time, factory workers do not understand the need for sorting plastics in multiple fractions as just one bin for plastics is used for households. Therefore, a behavioural change or education/training in industry is needed for further waste segregation of plastics.

(7) Low volume fractions are not economically viable for separation and recycling. According to the interviewees and our previously published study [14], polyethylene (PE) account for 40–74% of total plastic waste from automotive manufacturing, which can and must be separately segregated for recycling. However, the remaining fractions (such as polypropylene – PP) have relatively low volumes, and hence, efforts for separation are perceived not to be economically viable.

(8) There is a transportation efficiency issue with correlated high costs that trucks need to be full for economic and environmental reasons. A sufficient volume for each transport can be 3–4 tons for PA (polyamide) and 5 tons for PP, a relatively high amount compared to the general low volumes of sorted plastic waste in many automotive plants.

(9) Separation should be based on polymer which is difficult for operators to distinguish the type of plastic; hence, environmental education as well as plastic labelling is important as unmarked plastics cannot be segregated.
(10) Segregated plastics should not be contaminated with dirt, sand, metal chips, etc.
(11) There is a lack of information, e.g. precise volume, sorting degree and type of material for transportation. Not all companies provide the necessary information to the waste management or plastic management entrepreneur. Sometimes, the information provided is also wrong. Therefore, extra time and cost have to be put in testing the fractions randomly by the waste management or plastic management entrepreneur.
(12) Current technologies for plastic segregation and recycling (e.g. segregation machine based on plastics colour shade) are inefficient and expensive, and also the process is time-consuming, which neither the customer nor the product manufacturer willing to pay for that.
(13) Demand for recycled plastics has been low and separation is being done manually; hence, there is a high associated cost.
(14) It is simply too expensive to recycle plastics, compared to incinerating it. However, this issue is related to Sweden where it is relatively cheap to incinerate to produce household heat; hence, little incentive exists for industry to recycle more. Government intervention or tax is needed to solve this problem and gives motivation to make changes, for example, by looking into other countries such as France where it is rather expensive to incinerate or the Netherlands where it is forbidden to incinerate certain materials.

Taking regulation and standards into consideration, in general it was believed that more regulation would be helpful to close the plastic loops; however, the so-called carrot approach was more favourable than the stick approach. During the interviews, several regulation suggestions were proposed including the following:

- Better suited industrial waste fractions standards (not necessarily regulated), adapted for how to sort to reach marketable fractions and material properties.
- Regulations and standards that take away tax on recycled material to lower costs for using recycled plastics. Maybe also subsidies to start demand for recycled plastics will help. Likewise, shifting tax from labour to tax on virgin materials might help sort and recycle plastics better.
- Regulations and standards on having the same type of plastic for all packaging to reduce diversity and ease sorting. Purchasers can make demands on suppliers to use only a certain type of plastic.
- Regulations and standards on number of polymers allowed in a single product. Many products include several types of plastics which are difficult to separate. Shredding or incinerating those products is the only current possibility. Perhaps some legislation on not mixing several types of plastics might be helpful.
- Regulations and standards on labelling the plastics. Unmarked plastics cannot be segregated into plastic fraction and hence are thrown in combustible bins without any recycling. Companies could demand suppliers to mark their plastics.

Although label is mainly for end-customers, it might lead to OEM wanting a higher share of recycled materials in their parts.
- Regulations and standards to force product manufacturing companies to take responsibilities for their plastic waste and segregate it (e.g. PE as mentioned earlier).
- Tax on waste incineration; alternatively, prohibiting incineration of recyclable materials.
- Regulations and standards to put requirements on sorting and recycling waste; alternatively, tax on unsorted waste.
- Regulations and standards to put requirements for manufacturers to use a certain level of recycled material.

Nevertheless, some concerns regarding regulations were also expressed including limiting regulation from European Union that hinder the plastic recycler and recycled plastic seller to purchase and import from non-EU countries, which exacerbate the abovementioned issue of insufficient volume. It was of concern that having strict legal requirements only in Sweden might lead to a shift to other countries outside Sweden to stay competitive in the market; therefore, regulations and standards must aim at EU and/or global level. Furthermore, waste management entrepreneurs were concerned about standardization that would also mean increased logistics and increased requirements of more bins and space. Plastics have a large volume compared to weight. Therefore, for efficiency transportation, a shredder is needed to make plastic more compact to increase the volume for each transportation.

There was difference of opinions on whether regulations and standards should be material or industry specific. One example of industry-specific regulations and standards was to have a simple guideline for automotive industry to pinpoint few possible improvement steps for better plastic segregation and recycling. An example of material-specific regulations and standards was to put tax on certain virgin materials. However, this proposition was argued to be counterproductive in a way that it might decrease the use of virgin plastic but not necessarily increase the recycled plastics. Tax cut could improve the situation, but the price of recycled plastic is much higher than the tax on it and therefore would only have a very limited effect.

There is some sort of circular business model in the studied product manufacturing company to reuse some plastic components where slightly lower properties are required and also some variations are possible. Nevertheless, proper reuse and remanufacturing of plastic parts is not possible. There is not much commodity between parts and it is much easier to melt down plastic and recycle it. However, it would be still very costly to have an additional flow of used plastic parts in production. This requires a big design change in the automotive industry, e.g. less durability requirement in vehicles for carpooling.

4 Conclusion

There has been a consensus among interviewees that competition for recycled material will increase and more manufacturing companies will ask for recycled material. Hence, waste management need to be integrated in daily operations, to effectively meet the increased demand. According to our empirical study and performed interviews, metal waste is segregated to a high degree and with low level of errors, while mostly the exact chemical composition of the metal scrap is known. For instance, to get the best recycling option, steel is not mixed with non-ferrous metals like aluminium or copper. The demand for recycled metals is also relatively good and current standards are fine. However, there are still some improvement potentials in metal flow management such as better communication and information sharing among actors which could positively affect the number of transportations and incoming material selection for better recycling options at the end-of-life. These issues are apparent also in the small plastic recycling flows. On the other hand, the major problem for plastic recycling is that plastic waste has low level of segregation with high level of errors in the segregation process. The full chemical composition is usually not known either. As a result, the plastic waste needs to be regularly checked, which implies additional waste handling and administration. With such low level of separation (due to several reasons discussed earlier) and correlated low volumes, inefficient transportation, quality errors and contaminations, technological issues and top of all insufficient demand for recycled plastics and low price of virgin plastics, recycling were commonly not regarded as economically interesting for companies in the value chain. There is a rather great requirement for more standardized fractions, and legal requirement as well as an economic or regulatory motivation.

As it can be perceived from literature and our empirical study among actors in the value chain, the metal flow is more matured than the plastic flow. This can be argued with the long history of metal industry development since the 1850s, and even far back earlier in the prehistory where human used metal to build tools and weapons. On the other hand, plastic industry development is relatively new, started in almost the 1950s. While the plastic manufacturing and use in a variety of applications expanded exponentially, little thought and research has been given to the impact of such quick growth and to develop proper waste management system for plastics. In addition, this can be reasoned with the fact that the metallurgical properties of metals allow them to be recycled repeatedly with no or neglectable degradation in performance and quality, and from one product to another. Deteriorating, plastic recycling is challenging, thanks to the variety of additives and blends used in manufacturing, low demand of recycled plastics and cheap price of virgin plastic.

With such underdeveloped plastic waste management and the sudden decision of China in 2016 to terminate importing plastic waste for recycling, we need to create the motivation in developed countries to develop an effective domestic recycling infrastructure, expand domestic market for recycled plastics, change the product design for better recycling and reuse and make the business model economically more interesting for actors in the value chain. A developed market and competition can be enablers for self-imposing regulation in increasing the share of recycled material in the products, increasing tax on virgin materials and reducing tax on recycled materials, subsidies, etc., which will happen gradually and naturally over time.

Our studies were carried out in automotive industry where metal is the dominant material, and circulation (recycling in this case) of the dominant materials is of most importance due to volume and value. However, this should not justify the low circulation/recycling rate of other materials, particularly plastics.

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Social Life Cycle Indicators Towards a Sustainability Label of a Natural Stone for Coverings

Elisabetta Palumbo and Marzia Traverso

Abstract The stone industry plays an important economic role in Italy as well as worldwide, and its products are part of the construction sector for hard coverings. The relevance of these products led the European Commission to develop specific criteria for natural stone within the Ecolabel scheme for hard coverings. In order to provide environmental information and to establish and maintain their comparability, the eco-labelling schemes recognized the life cycle assessment (LCA) as a scientific method to be employed when describing the environmental performance of the products. In its current form, the European Ecolabel scheme only considers environmental impacts and overlooks significant social impacts, especially for the category of stakeholders most affected during the extraction and manufacturing phases: workers. The main purpose of this study is to define a set of social criteria to be added to the revised version of the European Ecolabel with reference to issues concerning natural stone covering products. In particular, according to the updated guidelines for the social life cycle assessment by UNEP/SETAC Life Cycle Initiative (2019), we have identified that the "health and safety" impact category as it relates to workers during the extraction and manufacturing phases of the products must be considered a priority. The results provide a set of criteria for the S-LCA inventory which should be added to the Ecolabel guidelines when assessing the natural stone covering sector. Integration of the social sphere with the results obtained from the LCA study would provide reliable and more complete information on the sustainability of the natural stone product.

This represents a first step towards the inclusion of similar criteria for other covering products.

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1 Introduction

The stone industry plays an important economic role in Italy and worldwide. In fact, the stone and marble industry is a sector that in certain geographical areas contributes to the local production and employment capacity.

In the global trade of natural stone (marble, granite, stone, travertine) in 2015, Italy ranked second worldwide (13.5%) after China, which holds the largest market share with 35.8% (Japan and other countries in the region are among its most important partners) (Table 1) [1, 2]. Italy, with its production areas covering highly specialized activities and extracted rock types, still plays a strategic role in the production and exportation of stone materials. In 2018, marble, travertine and alabaster products achieved high exports of around 402,685 tonnes [3, 4].

Natural stone is widely employed in the building and construction sector, in particular as a wall cladding material due to its attractiveness, durability and versatility [5].

Nevertheless, this sector has a negative impact on the environment and society as a result of the large amount of waste generated by extraction and processing (30–50% of the extracted gross quantity) [6], dust pollution linked to the extraction process and water pollution caused by cutting processes [7].

By the twentieth century, the location of mining sites had shifted from developed to developing countries, with two important consequences: firstly, the provision of less expensive raw materials from non-European Union countries led Europe to rely more on imports; secondly, the environmental and social impacts shifted to countries that are major producers where attention to sustainability issues is lacking, making sustainability assessment necessary.

The interest in social and ethical issues raised by a product along its life cycle is increasing, particularly in sectors such as raw material extraction and mining where there are potentially high health and safety risks for workers.

As far as natural stone is concerned, the Italian ornamental stone industry is one of the main producers worldwide.

In Italy, in 2015 alone, approximately 5.3 million tonnes of ornamental stone were produced; the regions with the highest number of quarries (20 or more) are Tuscany, Lombardy, Apulia and Veneto [8]. The quarries of Carrara in Tuscany, for

Table 1 Quarry productions and processing wastes in the world (readapted by [3])

Leading stone countries	Quarry production	Processing waste	
	(kt)	(kt)	(%)
China	45,000	22,768	50.6
India	21,000	6285	29.9
Turkey	10,500	2493	23.7
Brazil	8200	2990	36.5
Italy	6500	2485	38.2
Spain	4750	1641	34.5
Portugal	2700	812	30.1

example, provide most of the marble used in Italy and Europe for sculpture and other ornamental work, along with a large number of blocks, which are sent in raw or finished form to all parts of the world [9].

Given the importance of this sector, the social impact issue cannot be ignored. Data from the Italian National Institute for the Prevention of Accidents at Work (INAIL) [10] shows that the number of accidents and occupational diseases in the "Quarrying of ornamental and building stone, limestone, gypsum, chalk and slate (NACE 08.11) sector" is not insignificant.

Starting with statistical data collected on accidents at work in this sector from the INAIL database, this study aims to highlight the integration of social aspects of sustainability regarding natural stone within the Ecolabel scheme (ISO 14024:2018) into the current revision of the criteria for the Ecolabels of hard floor coverings (Commission Decision 2009/607/EC).

The main goal of this study is to identify the social hotspots and social impacts that should be added as assessment criteria in the revised Ecolabel scheme for natural stone coverings.

In order to achieve the above-mentioned aim, this study is divided into three parts:

(1) Background of the social criteria considered in official documents, in literature and in the existing Ecolabel schemes (e.g. European Ecoflower) with particular attention to stone and hard surfacing and the field limitations of this study
(2) Identification of the weaknesses of the natural stone sector as regards health risks and injuries to workers during quarrying and manufacturing processes, based on a review of the literature on work medicine and a survey of the statistical data relating to workers' health – taking the database developed by the Italian National Institute for the Prevention of Accidents at Work (INAIL) as a reference and based on an investigation of the Social Hotspots Database (SHDB), which provides social risk data at sector and country level, focusing on the global risk to health and safety in both stone quarrying and manufacturing processes
(3) Proposal of a set of criteria for S-LCA inventory for natural stone coverings

The social indicator set developed can serve both as a proposal for the Ecolabel criteria revision with a view to social considerations and as a guide on how to determine the sustainability performance of the hard coverings. Furthermore, a list of challenges and benefits for social life cycle assessment (S-LCA) implementation can be identified and presented to support the current revision of the Guidelines on Social Life Cycle Assessment [11].

2 Aims of the Study and Assumptions

The main reference in the social life cycle assessment (S-LCA) is represented by two important guidelines: those developed by UNEP [11] which define the S-LCA as a complementary method of life cycle assessment (ISO 14040, 2006) and the

Handbook for Product Social Impact Assessment [12], which was developed over 3 years of work by the Roundtable for Product Social Metrics. Both methodologies – the second derived from the first – identify the main stakeholder groups: workers, users/consumers and local communities. For each of them, a set of impact categories and its relative indictors was proposed. According to the UNEP guidelines, few case studies can be identified, and one of the first concerns natural stone products [13, 14].

The literature review conducted some years ago by Hosseinijou et al. [15] on the integration of social aspects into a life cycle format for building materials counts nine papers as the most remarkable: O'Brien et al. (1996), Schmidt et al. (2004), Dreyer et al. (2006), Hunkeler (2006), Norris (2006), Weidema (2006), Reitinger et al. (2011), and Lagarde and Macombe (2013) and Jørgensen et al. (2008), which reviewed most of the current S-LCA literature.

Based on an overview of the social aspects identified in 12 major S-LCA sources of the literature, and in accordance with the social impact categories proposed in the UNEP guidelines, Siebert A. et al. [16] in a recent study applicable to wood-based production systems in Germany identified a set of 15 social aspects. Of these 15 aspects identified, it was estimated that the most used indicators in the 12 case studies are discrimination/equal opportunities, fair salary/wages, health conditions/health and safety, freedom of association and collective bargaining (Fig. 1).

Social impacts in the mining sector appear to have been discussed for over 10 years. Mancini et al. [17, 18] deal with this type of problem by combining the Social Hotspots Database (SHDB), a global database that eases the data collection burden in S-LCA studies [19], with the social impacts in the mining sector documented in 12 references (9 scientific papers and 4 reports from international organizations). The SHDB, following the UNEP S-LCA guidelines, indicates the social risk of the main countries and sectors in the world. Not all the data from impact subcategories is contained in the SHDB, but there is enough to provide a good overview. The study divides the social impacts into positive and negative and checks which impacts are included in the Social Hotspots Database. Therefore, as a first step of the research, taking into account all the impacts considered, we selected only the negative ones dealt with by both multiple sources of literature and the SHDB, and specifically "negative health and safety impacts on workers" and "environmental impacts affecting social conditions and health".

The Global Ecolabelling Network (GEN), established in 1995, is a non-profit association of Type I Ecolabel organizations and has members in several countries. To improve, promote and develop the Ecolabels of products and services globally and to enhance mutual trust and recognition among various reputable Type I Ecolabelling programmes in accordance with ISO 14024, the GENIUS framework was developed which, in addition to verifying that each programme "abides by ISO 14024 principles and is robust and trustworthy, the process can inspire your employees around a shared societal goal" (The Global Ecolabelling Network, 2017).

An analysis focused on the ecolabelling programme for hard coverings within GEN showed that a very small percentage of schemes evaluate the social issues and adopt social indicators related to the health and safety of workers.

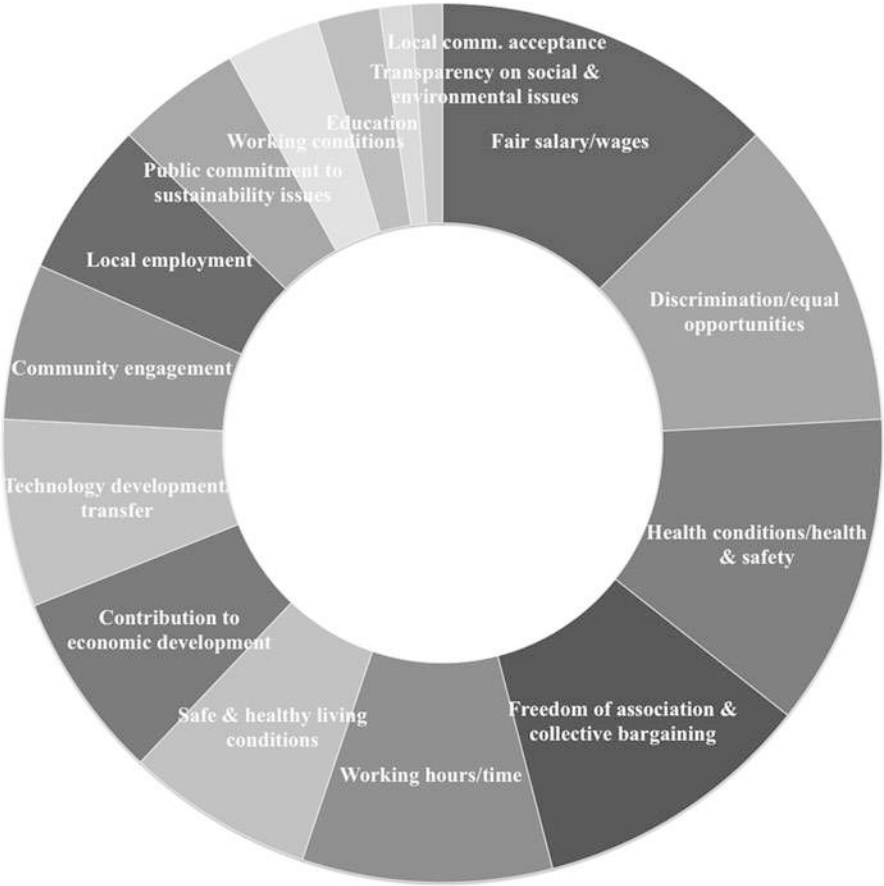

Fig. 1 Set of social aspects applied in S-LCA case studies identified by [12]

One of the most pertinent Ecolabel schemes in this sense is Australia's Good Environmental Choice Australia (GECA) for hard surfacing, which with the introduction of Section 10 on "social and legal requirements" includes criteria linked to aspects such as equal opportunities and the safety and protection of workers.

In light of the above and in accordance with the stakeholder categories and subcategories suggested by UNEP "Guidelines for Social Life Cycle Assessment of Products", this study focuses on workers' health and safety: "negative health and safety impacts on workers".

3 Weaknesses of Natural Stone Sector

The natural stone extraction, transportation and manufacturing sector produces relevant environmental, social and economic impacts internally, locally and globally.

Guidelines for the safety of human health in the extraction industries were developed by the European Commission in Directive 2006/21/EC together with measures and procedures to reduce any adverse effects on the environment (in particular water, air, soil, fauna, flora and the landscape) within waste management.

References in literature show that non-European stone quarrying processes release elements into the environment such as dust, sludge or other industrial waste that may be toxic and constitute a health risk to humans: substances that are hazardous to the cardiorespiratory system, physical fitness and the body as measured at stone quarries [20, 21], pulmonary problems [22], skin dermatoses [23] and ocular health hazards [24], and in general the health of employees and their productivity and efficiency [25].

An analysis of occupational accidents in the mining sector in Spain, based on data from the Spanish Ministry of Employment and Social Safety between 2005 and 2015, shows that the most typical accidents are body movement involving physical effort or overexertion and, in underground mines, fractures, slips, falls or collapse. Moreover, it highlights that the lack of safety education and training is one of the most influential factors leading to mining injuries [26].

The INAIL database on reported work-related injuries in the quarrying of ornamental and building stone sector in Italy shows a fairly stable trend. In particular, this data shows that in the last 4 years, accidents at work have decreased by about 10%, while professional illnesses have increased by approx. 6% (Fig. 2).

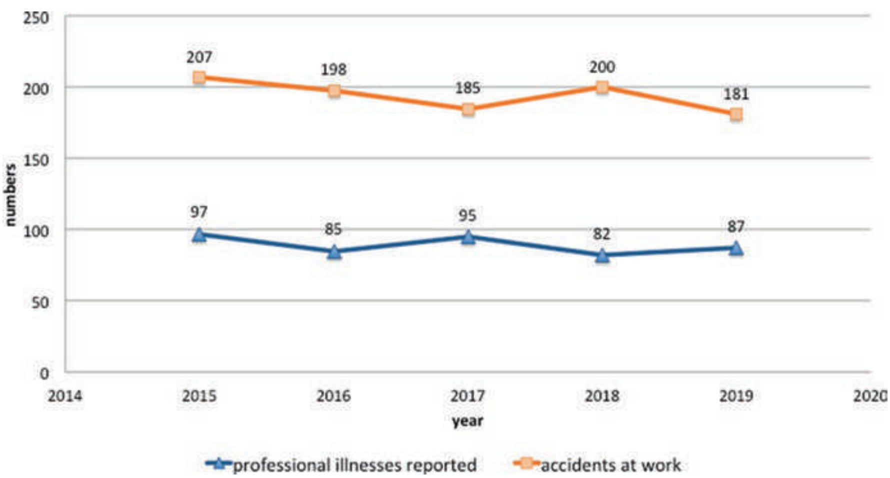

Fig. 2 Numbers of professional illnesses reported and accidents at work in the extraction of ornamental stone sector from 2015 to 2019 in Italy (elaborated by the authors from [10])

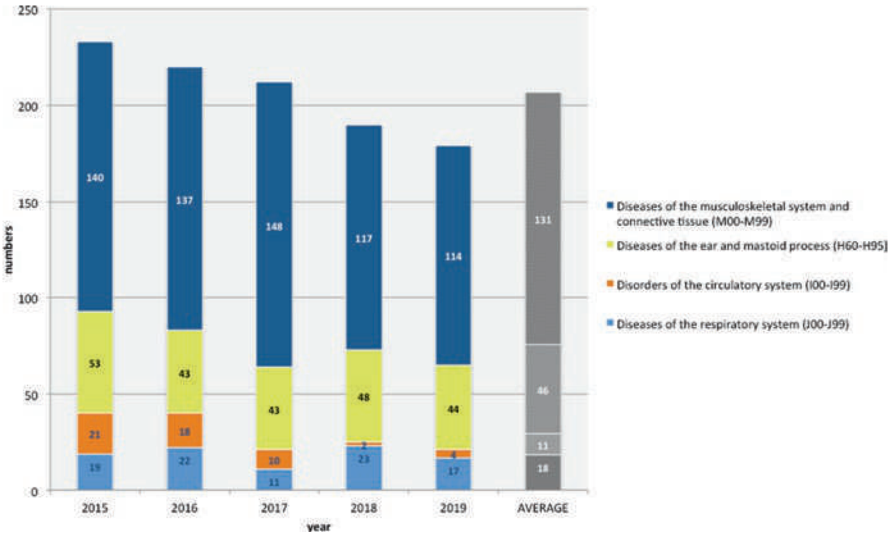

Fig. 3 Number of workers with the diseases classified according to ICD-10 from 2015 to 2019 in Italy (elaborated by the authors from [10])

A more detailed analysis of the professional diseases classified according to the International Statistical Classification of Diseases and Related Health Problems, version 2010 (ICD-10), indicates that the four main burdens of disease are respectively diseases of the musculoskeletal system and connective tissue (M00-M99), diseases of the ear and mastoid process (H60-H95), disorders of the circulatory system (I00-I99) and diseases of the respiratory system (J00-J99). Specifically, Fig. 3 shows the number of workers with the diseases recorded from 2015 to 2019 and the average for each of the four main illness types.

4 Outcomes

This study, which aimed to identify a set of social criteria to be added to the revised version of the European Ecolabel for natural stone covering products, has identified critical issues related to the social dimension through the following steps.

Starting with the screening of the five main stakeholder category groups (workers/employees, local community, society, consumers and value chain actors) to be considered in the social impact assessment in accordance with the UNEP guidelines (2009) and the revised version (2020) [11], we identified the priority of taking into account the health and safety aspects of workers who seem to be the most affected due to the intrinsic risks of the activities they perform during the extraction and manufacturing phases and their exposure to dust.

An initial review of work medicine literature relating to the issues arising in the natural stone industry was carried out, and we identified some recurrent and emerging diseases in addition to discomfort arising from occupational accidents and injuries.

Subsequently, we reviewed the social criteria already used in the flower scheme for products other than natural stone, and the results obtained from surveys on LCA studies filled in by companies in the natural stone sector.

We collected and analysed statistical data relating to workers' health and injuries in the natural stone industry, limiting our study to Italian data. This survey showed that the principal issues are linked to the effect of the dust released into the workers' environment during stone quarrying processes or within stone manufacturing phases, sludge production or other industrial waste processes workers come in contact with.

Finally, in order to highlight social hotspots in the mineral stone sector, we explored the SHDB in line with the outcomes highlighted by the last survey on the global risk to health and safety in both stone quarrying and manufacturing processes, and evaluated the risk levels related to chronic obstructive pulmonary disease due to airborne particulates in the workplace.

In conclusion, considering the results produced by this investigation from both work medicine literature and a survey of statistical data from the National Institute for the Prevention of Accidents at Work (INAIL), the main impacts are due to:

- Dust emission with consequences for pulmonary and cardiorespiratory functions, as well as dermatologic and ocular diseases
- The risk of accidents at work
- The risk of accidents at work caused by contact with water and sludge which may be harmful to human health

In addition to these aspects, the outcomes from the INAIL statistics database show that the major cause of accidents is movements in the workplace that can result in muscular problems (Fig. 3).

On the basis of these observations, it is important to define and integrate social criteria related to workers' health and safety in the natural stone coverings industry, to be added to the Ecolabel of these products. This would provide reliable and more complete information on their sustainable performance, as a first step towards the inclusion of similar criteria for other covering products.

5 Conclusion and Recommendations

These studies reveal the strong association between the environmental and social dimensions of the manufacturing processes. While the environmental dimension has been broached by voluntary methods to certify and label environmental performances, such as the Type 1 label (Ecolabel), social aspects were left out. Furthermore, no consideration was given to the fact that data and indicators to estimate local environmental impacts can also support the assessment of the social impacts related to health and safety. It should be noted that national regulations on the health and safety of workers are in place, but they are not included in product labelling.

The study we conducted shows that Type I Ecolabel statements should contain a more complete assessment and documentation of product sustainability. Our suggestion is that the inclusion of social criteria in the Ecolabel scheme is clearly necessary to avoid an incomplete assessment of the impact of the natural stone manufacturing process.

This work can be considered a first step in the process of identifying a set of social criteria related to the workers' stakeholder category. The limitations of the study lie in the fact that we only analysed one of the important stakeholders closely involved in the social issue.

Therefore, future work should broaden the field of analysis for this proposal and investigation, first and foremost to the impacts of subcategories on "local communities".

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A Life Cycle-Based Scenario Analysis Framework for Municipal Solid Waste Management

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Abstract A framework for the systematic analysis of the material flows and the life cycle environmental performance of municipal solid waste (MSW) management scenarios is described in this article. This framework is capable of predicting the response of waste treatment processes to the changes in waste streams composition that inevitably arise in MSW management systems. The fundamental idea is that the inputs (raw materials and energy) and outputs (final products, emissions, etc.) into/from treatment processes are previously allocated to the specific waste materials contained in the input waste stream. Aggregated indicators like life cycle environmental impacts can then be allocated to waste materials, allowing systematic scenario analyses. The framework is generic and flexible, and can easily be adapted to other types of assessments, such as economic analysis and optimization.

1 Introduction

Municipal solid waste (MSW) is generally defined as that generated in households and from commercial, institutional, and street cleaning activities with similar composition to the household waste. MSW contains a wide variety of potentially valuable materials (e.g., food waste, paper, cardboard, plastic, and metals) but whose increased generation and inappropriate management cause negative environmental and human health consequences as well as the loss of resources [1]. Decision-makers are under increasing pressure to adopt MSW management strategies aiming to maximize resource and energy recovery and minimize environmental and human health risks and usually under constrained budget. In Europe, the implementation of

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waste strategies to meet MSW targets is mandatory for the Member States. Reuse and recycling of MSW shall reach 65% by 2035 (Directive 2018/851/EC), while the Circular Economy Package refers to a maximum of 10% landfilling by 2035. However, only 30% of the MSW generated in 2017 in Europe was recycled while the average landfill rate was 23%, even though half of the Member States landfilled more than 50% of their MSW [2].

Handling the complexity of the MSW management system, which encompasses a large number of interconnected processes, remains the main challenge to the development of sustainable MSW management strategies. The waste streams derived from MSW collection and the intermediate waste streams present a heterogeneous composition of a wide variety of waste materials with different physicochemical and biological properties (Fig. 1). The resource and energy recovery rates and the technical, economic, and environmental performance of treatment processes depend to a large extent on the composition and properties of the input waste stream [3]. For example, the global warming impact of landfilling the residual waste stream depends on its content on biodegradable waste materials (food waste, paper, etc.), whereas the global warming impact of its incineration depends on its content on fossil-based waste materials (plastic).

Systems analysis techniques are required to tackle the complexity of the MSW management system and support the design of sustainable waste strategies [4]. Life cycle assessment (LCA) has emerged as the most popular, and there are a number of waste LCA tools available. The ability of linking the life cycle inventory (LCI) of treatment processes (i.e., emissions and resource consumption/recovery) to the composition and properties of the input waste stream was recognized as the key feature of a waste-specific LCA tool [5]. However, most of these tools have been developed with black-box models of treatment processes where inputs and outputs are only linked by unrealistic ratios to total mass of input waste. Recently, increased attention is being devoted to the development of modeling frameworks that allow linking input waste composition, treatment process operation, and outputs through a more appropriate approach to physicochemical and biological mechanistic models [6]. This is achieved by adopting a material flow analysis (MFA) perspective for the modeling of the LCIs of treatment processes [7].

MFA is the central methodology of the industrial ecology, and its goal is to provide a comprehensive and systematic inventory of the input-output flows of

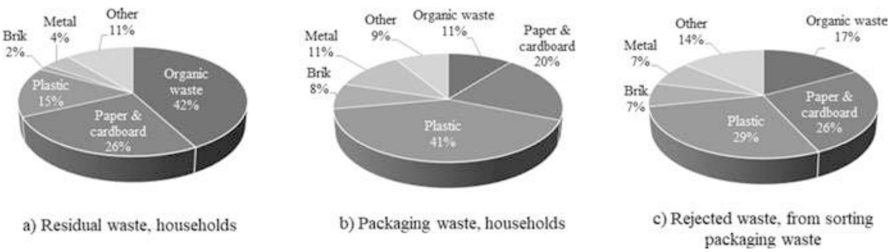

Fig. 1 Composition of municipal solid waste streams generated in Madrid (2017)

materials and substances in a system. Mass conservation is the fundamental principle of MFA, i.e., the quantity of input flows has to be equal to the quantity of output flows plus stocks [8]. Thus, MFA provides the appropriate mathematical relationships that describe the mass balance of waste materials and their chemical elements in a specific treatment process as well as the parameters required.

In addition to LCA and MFA, numerous optimization models for MSW management have also been developed. Mathematical programming techniques can provide a powerful framework that considers all the feasible configurations of the MSW management system and identify the best solution according to one or multiple objectives and considering the system's constraints. Typically, optimization models focused on economic objectives, e.g., the minimization of the system's annual cost. Also, the additional consideration of environmental objectives (based on LCA) and resource recovery objectives (based on MFA) has emerged as a recent trend [9]. In order to provide reliable results, optimization models should, as in the case of LCA tools, be able to capture the response of treatment processes to changes in the composition of the input waste stream [10, 11]. However, the incorporation of this feature leads to complex nonlinear optimization models, and therefore this issue remains little explored so far.

In this article, we describe a framework for the systematic analysis of the material flows and the life cycle environmental performance of MSW management scenarios. The framework is capable of predicting the response of treatment processes to the changes in waste composition that inevitably arise in MSW management systems. Furthermore, the framework is sufficiently generic and flexible to allow incorporating other methods into the assessment, such as economic analysis and optimization. Section 2 describes the framework. Section 3 includes an illustrative example of its application. Section 4 draws the main conclusions and the future work.

2 Framework Description

2.1 Scope and System Boundaries

Figure 1 illustrates the scope and system boundaries of the framework. Based on the definition of MSW given in the Waste Framework Directive, we considered the waste generated by three sectors: households, commercial activities, and street cleaning. Waste collection at each sector can be defined by combining the five waste streams that could be found in Spanish municipalities: residual, packaging, paper and cardboard, glass, and organic wastes (Fig. 2a). These streams need to be defined in terms of quantity and composition. Waste streams composition is disaggregated into 15 materials: food waste, green waste, mix paper, cardboard, polyethylene terephthalate (PET), high-density polyethylene (HDPE), low-density polyethylene (LDPE), mix plastic, cartons and alike, glass, ferrous metal, nonferrous metal, textile, wood, and other. Furthermore, each waste material is characterized by 83

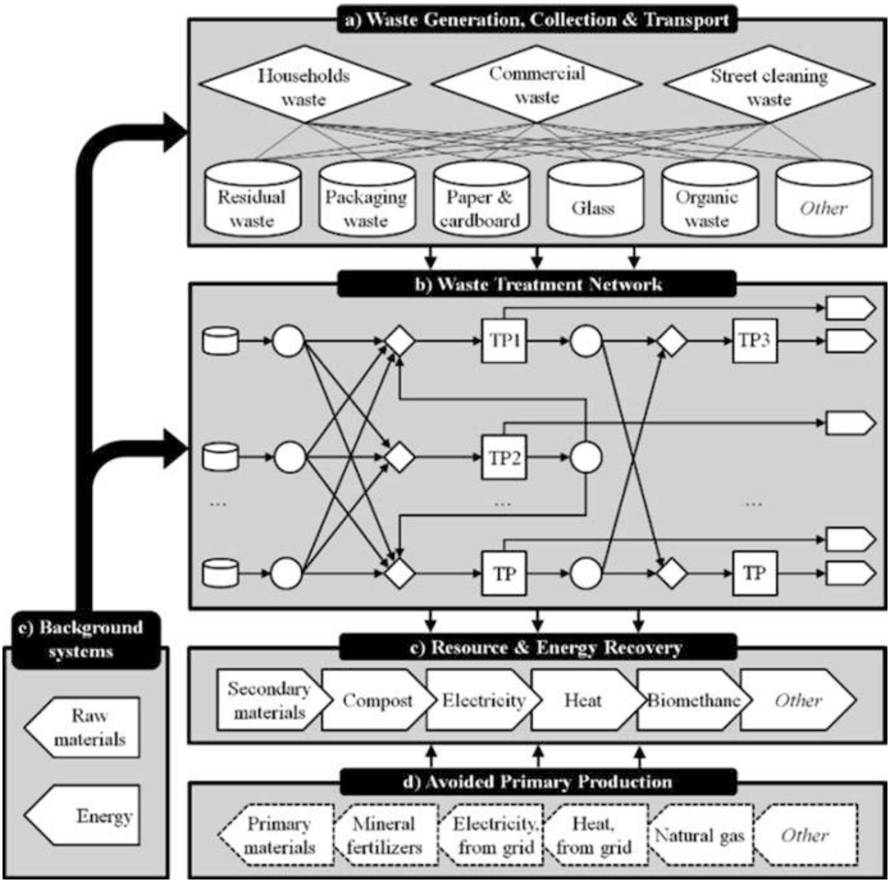

Fig. 2 Scope and system boundaries of the framework

physicochemical and biological properties (e.g., moisture content, lower heating value, biochemical methane potential, chemical elements, etc.).

Collected waste streams are processed in a network of interconnected treatment processes (material recovery facilities, composting, incineration, landfill, etc.) that generate intermediate waste streams (rejected waste, recyclable materials, etc.) and/or final products (secondary materials, compost, electricity, etc.) (Fig. 2b). While intermediate waste streams need further processing, final products are introduced into the market, thus avoiding primary production (Fig. 2c–d). Additionally, the MSW management system interacts with the background systems that supply raw materials and energy (Fig. 2e). Further details about network structure are provided in Sect. 2.3.

2.2 Modular Modeling

We adopted a modular approach so that the MSW management system was disaggregated into many modules that describe treatment processes [12]. This approach has the advantage that allows combining many technological alternatives. For example, anaerobic digestion (AD) was disaggregated into one module that includes the pre-treatment, reactor, dewatering, and post-treatment unit processes and other four modules for each unit process for the use of the biogas (flare, boiler, combined heat and power, and upgrading). Thus, AD can be combined with any alternative for biogas utilization.

Modules consist of the mathematical equations that describe mass and energy balances as a function of the properties of the input waste stream and the process operation conditions. The inputs (raw materials and energy for operation) and outputs (intermediate waste streams, final products, emissions, etc.) are allocated to the specific waste materials contained in the input waste stream (Fig. 3a), as explained below.

In LCA terminology, modules aim at performing a multi-input allocation of the LCI between the waste materials contained in the input waste stream. According to the ISO 14040/14044 standards recommendations, the allocation of process inputs and outputs should be based on natural causal relationships. We follow the MFA principles to perform the allocation. For example, transfer coefficients are used to model the transfer of input waste materials into the rejected waste stream and the recyclable materials stream in a sorting process. Emissions are allocated based on the physicochemical and biological properties of the waste material. For example, biogenic CO_2 emissions from waste materials incineration are linked to their biogenic carbon content. Electricity production is calculated for each waste material based on its lower heating value and the process electricity conversion efficiency. For those environmental exchanges where there is no obvious mathematical relationships, allocation is done on a mass basis.

Once allocated the inputs and outputs, aggregated indicators, such as life cycle environmental impacts (i.e., global warming, human toxicity, etc.) or the economic costs (i.e., operation costs, revenues, etc.), can also be allocated to each specific waste material. Therefore, instead of calculating the global warming impact associated with the incineration of 1 tonne of residual waste with a fixed composition, the module calculates the global warming impact associated with the incineration of 1 tonne of each waste material that may constitute the residual waste. Allocated inputs, outputs, and indicators are stored in non-square matrixes that represent in rows the 15 waste materials considered and in columns the inputs, outputs, and indicators given per tonne of waste material (Fig. 3b).

This approach has the advantage that translates the complex nonlinear mathematical models that describe mass and energy balances in treatment processes (e.g., methane generation in landfill is given by a time-dependent first-order decay equation) into a parametrized model (i.e., linear) that can be used for scenario analysis or optimization (Fig. 3c).

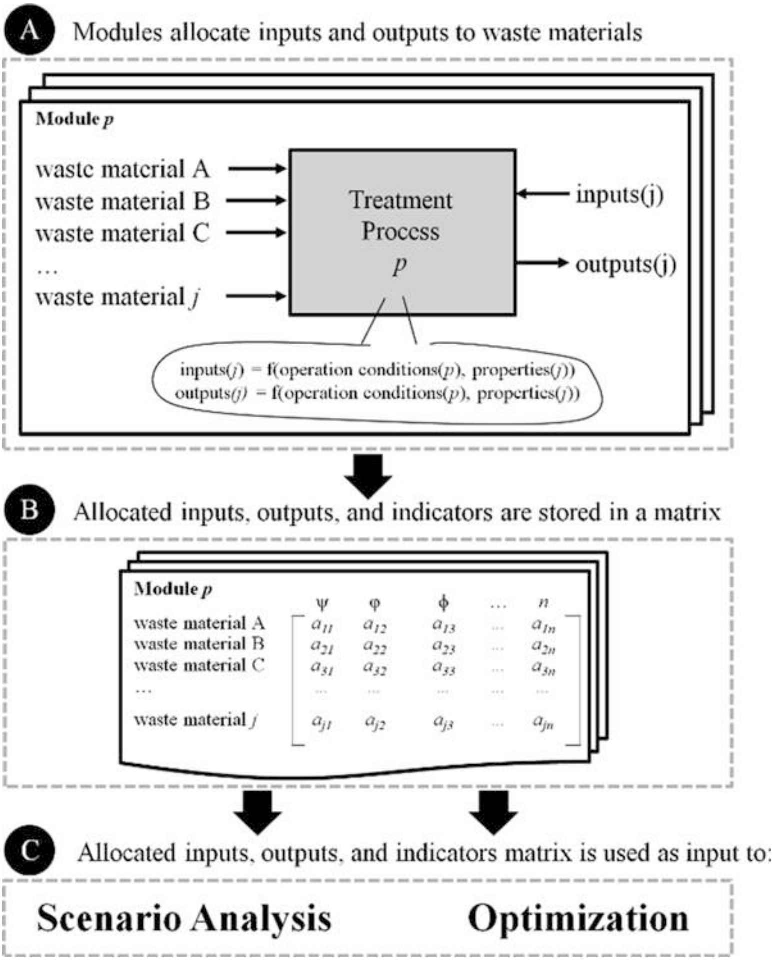

Fig. 3 Modular modeling of treatment processes

2.3 Scenario Analysis Modeling

The modules' matrixes of inputs, outputs, and indicators can be used for scenario analysis. All feasible modules combinations for treating household, commercial, and street cleaning waste streams as well as the intermediate waste streams are embedded in a mathematical network (Fig. 2b). The network consists of splitters (circles), mixers (diamonds), modules (boxes), and all their interconnections (arrows).

Splitters are located after each waste stream and assign the waste stream to the linked modules. The partitioning of a waste stream in a splitter between the modules linked is represented by user-defined mass fractions. For example, the mass fractions of a splitter for residual waste could be 20% to incineration and 80% to landfilling. Note that the waste streams leaving the splitter have the same composition as the input stream because splitters do not involve transformation. Therefore, the mass fraction introduced is applied equally to all the waste materials contained in the waste stream.

Mixers are located after splitters and prior each module. Since modules can receive several waste streams with different composition, the function of mixers is to sum over materials of the same type contained in different waste streams. Mixers do not require input data. Finally, modules performance, for example, the global warming impact of incinerating 20% of the residual waste, results by multiplying the array of input waste materials by the array of global warming impact contained in the matrix of inputs, outputs, and indicators obtained in Sect. 2.2. The performance of the overall MSW management system is obtained by addition of the performance of all modules. Note that, once the allocated inputs, outputs, and indicators for all modules are obtained, the only requirement to build a scenario is to introduce the mass and composition of the initial waste streams and to fill the mass fractions of all splitters in the network.

3 Illustrative Scenario Analysis Case Study

In order to illustrate the applicability of the framework, a streamlined example addressing the global warming consequences of MSW incineration phasing out in Madrid (Spain) is presented. In 2017, about 313,697 t of rejected waste from sorting residual and packaging waste stream at material recovery facilities have been incinerated in Madrid [13]. The new waste strategy of the city aims at phasing out the incineration plant by 2025, which can led to the diversion of huge amounts of waste toward landfilling. In this example, we assess the life cycle global warming impact associated with the management of 1 tonne of rejected waste in Madrid considering different incineration rates. Four scenarios were formulated. S1 considers that 100% of the rejected waste is incinerated. S2 considers that 75% is incinerated and 25% landfilled. S3 considers that 50% is incinerated and 50% landfilled. Finally, S4 considers that 100% is landfilled. The ILCD-recommended characterization factors were used for the assessment [14]. Emissions of biogenic CO_2 and the biogenic carbon that remains sequestered in landfill after 100 years were assumed with a characterization factor of 0.

Table 1 shows the life cycle global warming impact allocated to waste materials as obtained from the incineration and landfilling modules. Incineration was disaggregated into emissions to air (INC [UP_1]), resource consumption (INC [UP_2]), and avoided impacts due to the substitution of electricity from the Spanish mix (INC [UP_3]). Landfilling was disaggregated into dispersive emissions (LAND [UP_1]), resource consumption (LAND [UP_2]), and avoided impacts due to the substitution of electricity from the Spanish mix (LAND [UP_3]). Note that values in Table 1 were computed using technology and operation conditions from Madrid.

Table 1 Life cycle global warming impact allocated to waste materials for incineration (INC) and landfilling (LAND) for the case study of Madrid (kg $CO_{2\text{-eq}}$ t^{-1} wet waste material)

Waste material	INC [UP_1]	INC [UP_2]	INC [UP_3]	LAND [UP_1]	LAND [UP_2]	LAND [UP_3]
Food waste	24	12	−76	733	0.07	−110
Green waste	21	6	−48	301	0.07	−43
Mix paper	11	5	−143	1615	0.07	−149
Cardboard	9	4	−111	1045	0.07	−72
PET	2326	6	−307	0	0.07	0
HDPE	2499	7	−417	0	0.07	0
LDPE	1448	8	−218	0	0.07	0
Mix plastic	2692	22	−417	0	0.07	0
Cartons and alike	140	6	−128	810	0.07	−56
Glass	0	0	0	0	0.07	0
Ferrous metal	0	0	0	0	0.07	0
Nonferrous metal	0	0	0	0	0.07	0
Textile	440	46	−223	240	0.07	−22
Wood	38	9	−206	71	0.07	−4
Other	217	8	−30	0	0.07	0

Table 1 reveals the large differences that exist with respect to the environmental impacts of waste materials. The global warming impact of incinerating plastic is largely higher than other waste materials due to the higher content on fossil carbon. Avoided impacts due to electricity substitution are also higher for plastic due to the higher energy content. Dispersive greenhouse gas emissions from landfill are significantly higher for mix paper, cardboard, and cartons and alike compared to food and green waste. Note that values in Table 1 are expressed per tonne of wet waste material. Although food and green waste have a higher degradation rate compared to paper and cardboard, the former have also higher moisture content. Finally, the global warming impact of resource consumption in landfill (electricity and diesel for landfill operation) is the same for all waste materials. This reflects that energy consumption was allocated on a mass basis because energy is used for waste movement. Consequently, the same impact is obtained per tonne of each waste material.

Figure 4 shows the procedure to build scenarios S1–S4 and how the global warming impact of each scenario is calculated. Quantity (Q) and composition (c) are required as input data in order to define the rejected waste stream. The quantity was assumed 1 wet tonne (functional unit), and the composition is as follows: 13.91% food waste, 3.52% green waste, 26.48% mix paper, 8.46% cardboard, 2.54% PET, 1.30% HDPE, 10% LDPE, 7.65% mix plastic, 3.71% cartons and alike, 3.57% glass, 1.49% ferrous metal, 1.11% nonferrous metal, 10.98% textile, 5.29% wood, and 0% other. The input data into the splitter are the mass fractions of the rejected waste stream to incineration (σ) and landfilling (ω). The allocated global warming impact of incineration INC(GW) and landfilling LAND(GW) were calculated by

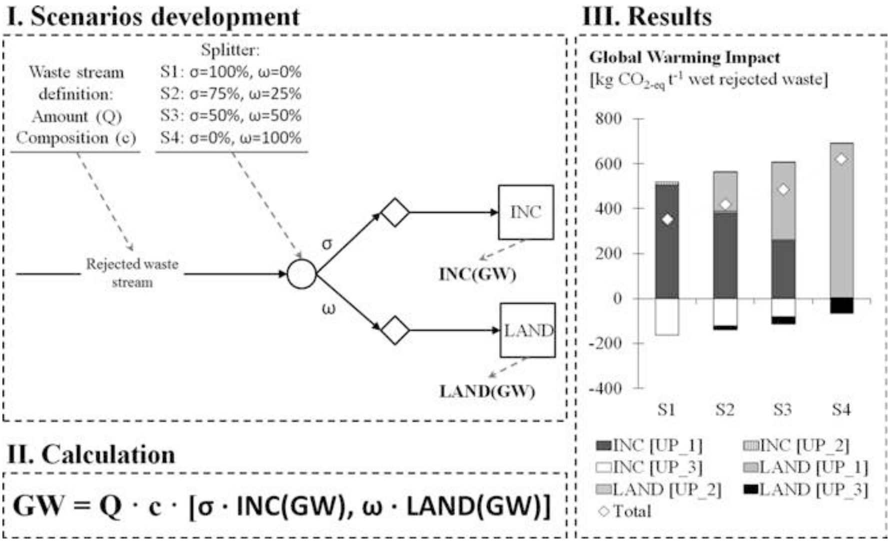

Fig. 4 Scenarios development (I), calculation (I), and global warming impact results (III) for the scenarios addressed

the framework (Table 1). Thus, the global warming impact of each scenario disaggregated by unit processes can be easily obtained.

For this case study, increasing the landfilling of rejected waste at the expense of reducing incineration entails an increase in the global warming impact. The increase is related to the dispersive emissions of methane from landfill. Note that the mix paper and cardboard contained in the rejected waste are significant: 26.48% and 8.46%, respectively. These waste materials have the highest global warming impact on landfilling. In contrast, their impact on incineration is negligible because biogenic CO_2 emissions were considered not to contribute to the global warming impact (Table 1).

Figure 5 shows the global warming impact of S1–S4 as a function of a gradual decrease on mix paper and cardboard content at the expense of an increase on plastic content. The results highlight the key role of waste composition when assessing MSW management systems. In fact, if the rejected waste did not contain mix paper and cardboard but a higher proportion of plastic, landfilling would be a better option than incineration. This is because the global warming impact of plastic in landfill is negligible (Table 1).

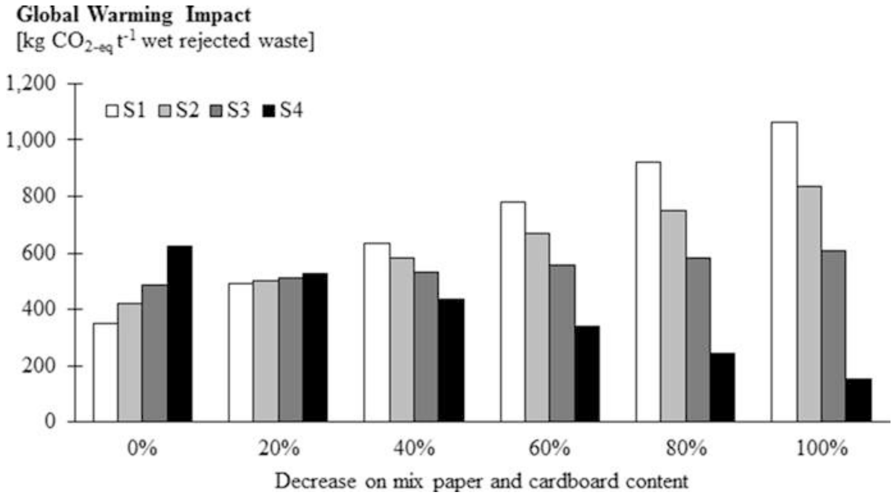

Fig. 5 Global warming impact of S1–S4 as a function of a gradual decrease on mix paper and cardboard content at the expense of an increase on plastic content. (S1, 100% incineration; S2, 75% incineration and 25% landfill; S3, 50% incineration and 50% landfill; S4, 100% landfill)

4 Conclusions and Future Work

A framework for the systematic analysis of the material flows and the life cycle environmental performance of municipal solid waste (MSW) management scenarios has been proposed and described in this article. The framework addresses the collection, treatment, and final disposal of household, commercial, and street cleaning waste streams generated in a given region. System boundaries include the network of interconnected treatment processes, the recovery of resource and energy that avoid primary production, as well as other background systems that supply raw materials and energy to the MSW management system.

The framework is based on a modular modeling approach so that the MSW management system was disaggregated into many modules that describe treatment processes (or even stages of treatment processes). All feasible modules combinations are embedded in a network, and therefore any (feasible) MSW management scenario can be addressed. A key feature of the framework is its capability of tackling the assessment of the complex response of treatment processes to the changes in waste streams composition that inevitably arise in MSW management. The fundamental idea is that inputs (raw materials and energy for operation), outputs (final products, emissions, etc.), and aggregated indicators (life cycle environmental impacts, economic costs, etc.) of treatment processes are previously allocated to the specific waste materials contained in the input waste stream.

The framework is generic and flexible to the incorporation of other types of assessments. The allocated inputs, outputs, and indicators can be used as input parameters into an optimization model. This represents an enormous advantage since the response of treatment processes to changes in waste composition can be easily evaluated with fixed parameters. There is no need to formulate a mathematical program based on the complex nonlinear models that describe mass and energy balances in waste treatments. The only requirement is to consider as optimization variables the flow of each waste material contained in waste streams. While the modeling approach based on the flow of multi-components has been typically applied in wastewater networks optimization problems, this remains unexplored in the field of MSW management.

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The Life Cycle Sustainability Indicators for Electricity Generation in Chile: Challenges in the Use of Primary Information

Mabel Vega-Coloma and Claudio Zaror

Abstract The need to get an appropriate quantification of the sustainability indicators involves the use of site-specific information that could come from several sources, affecting its quality. This study analyses the quality and sources to build eight environmental, seven social and four economic indicators for eight electricity generation technologies in 2005, 2009 and 2015 as reference years, following the ISO 14.040-44:2006 life cycle assessment approach. The results show for the three dimensions important differences among the periods, reaching over 400% of reduction in 2015 in case of acidification for coal power plants, thanks to environmental regulations. For levelized electricity cost and corruption index, the variations reach around 40% and 30%, mainly for fossil fuel-based power plants. These changes support the need to have a centralized, reliable and accurate data system of registration, in order to contribute to the sustainability of the electricity system in Chile.

1 Introduction

The need to get an appropriate quantification of the sustainability indicators involves the use of site-specific information [1]. This information could come from several sources and sometimes is barely systematized and highly heterogonous, being its quality and consistency a matter of concern [2]. Due to the increasing environmental, economic and social requirements, more data are available to model the potential impacts profile. In particular, the power plants of electricity generation in Chile report continuously their air and water emissions, as well as the hazardous waste

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generated from their process, and from those were developed several accurate reports assessing the environmental performance [3–6]. Nevertheless, the results could be a source of more questions about the data quality, such as the traceability or the methodological approach to measure mass fluxes [1, 2, 7]. In the same way, the economic profile is well-known data for experts and investors, but is not always open and available for researchers. The social indicators are still under development and the data is usually scattered. For these reasons, just a few studies had covered jointly the environmental, economic and social dimensions [8–12].

As was reported by Laurent and Espinosa [13] is relevant to study the variability of the environmental performance at the country level, exploring the opportunity to analyse the annual environmental, economic and social performance, just in case to have enough reliable information. This analysis could bring information about the data sources, the quality needed and the potential effect of the assumptions. Moreover, in the case of developing countries, this analysis could be helpful to policy-makers to evidence the legal and regulatory needs to improve the current report of projects.

2 Goal and Scope

The aim of this work is to contribute to the discussion about the use of primary information reported directly from electricity generation power plants, to get an appropriate pool of environmental, economic and social indicators for the electricity generation in Chile. The scope of this work is cradle to gate for the environmental aspects, while for social and economic are covered the direct processes, due to the lack of information.

For environmental issues was included the whole electricity generation process, from the materials and fuel extraction from natural sources to the decommission stage, including the transport, infrastructure and operation specific for each year assessed (see Fig. 1). Economic indicators were developed based on local information for technologies investments, for each year, and reported as "blackbox", without the possibility of disaggregating by stage. In the same sense, the social

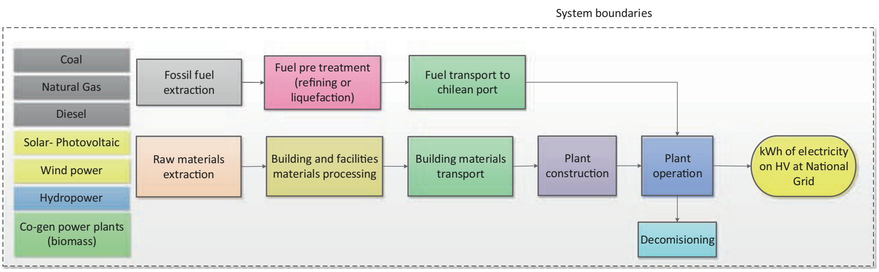

Fig. 1 System boundaries of the electricity generation in Chile considered in this work

information was obtained from several sources and represents different stages of the process (e.g. employment is associated with infrastructure and operation, while import dependency is associated with the whole process).

3 Methodological Procedure

This work was developed following the ISO 14.040-44:2006 [14, 15] approach for life cycle assessment. The electricity generation power plants covered in this work were selected to build a set of eight environmental, four economic and seven social indicators, following a life cycle approach applied to eight electricity generation technologies, coal, diesel, natural gas, biomass, wind power, solar photovoltaic (PV), run of river and reservoir, in Chile. The temporal coverage includes 10 years, using specific data for 2005, 2009 and 2015. The technologies assessed cover more than 99.5% of the current installed capacity in Chile, and the geographical coverage only includes the continental territory, excluding Patagonia. The electricity generation produced by technology for the period analysed is presented in Table 1.

3.1 Definition of Environmental, Economic and Social Indicators

The environmental indicators have been calculated from CML 2000 mid-point impact model. Several studies have worked with this impact model to represent the damage over different categories. Some categories are associated with environmental impacts and another with social impacts, as is detailed in respective subsection.

Eight environmental indicators, namely, ozone layer depletion potential (ODP), photochemical oxidation potential (POP), global warming potential (GWP), acidification potential (AP), eutrophication potential (EP), freshwater aquatic ecotoxicity

Table 1 Electricity generation in Chile in 2005, 2009 and 2015

	Electricity generation by source (GWh/y)		
Technology	2005	2009	2015
Coal	8813	15,625	28,613
Diesel	1113	1395	2862
Natural gas	14,681	1,444,038	10,807
Biomass	518	968	1931
Wind power	–	61	2103
Solar PV	–	–	1373
Reservoir	14,801	13,921	11,616
Run of river	10,673	10,633	12,283
Total	50,599	56,641	71,588

potential (FAEP), marine aquatic ecotoxicity potential (MAETP) and terrestrial ecotoxicity potential (TEP) impacts were assessed in this study, on the basis of previous work [3, 4]. These indicators were calculated following the ISO 14.040-44:2006 standards for life cycle assessment [14, 15], using the CML 2000 v.2.05 mid-point impact models [16], with the computational support of SimaPro v.7.3.3 software [17].

On the other hand, four indicators were used to address economic issues, namely, total capital cost (TCC), levelized electricity cost (LEC) and fuel sensitivity price (FSP) as proposed by [18], while total annualized cost (TAC) was considered from the definition brought by [9]. Finally, seven indicators related to social issues were estimated. These issues were addressed by [18] and categorized as follows:

- Energy security, measured as import dependency (ID), imported fuels potentially avoided (IFPA) and diversity of fuel supply (DFS)
- Provision of employment (PE)
- Intergenerational issues, measured as human toxicity (HT) and abiotic depletion (ADP)
- Local community impacts measured as corruption index (CI)

Every indicator was estimated by technology and by year totalizing 399 indicators specific for Chilean electricity situation.

3.2 Data Sources, Quality and Assumptions

The data were obtained mainly from primary open sources. They were several governmental offices and institutions, which have been implemented a transparency system of data registration, mainly driven by environmental control regulations. In this sense, was possible to get reliable data from these sources to build the most part the indicators reported [19–24]. Some others were obtained from studies [25], international reports [26] and assumptions.

The most part of the assumptions were addressed to economic and social indicators. Particularly, all the costs were corrected to 2015 value, considering the inflation, in order to compare the decade's values. Due the lack of data for cost of renewables investment in Chile, they were assumed from international values for the same technology [26]. For corruption index, the data were considered using the perception index for the respective year, and the mix of imported fuels.

3.3 Variation on Indicator Values

For every indicator, the variation with respect to the 2015 value was estimated, in order to represent a better or worst situation in the past compared with the current. To quantify this, the use of a percentage of variation is proposed defined by Equation 1.

$$\%variation = \left(\frac{Indic.value_{2005} - Indic.value_{2015}}{Indic.value_{2015}} \right) * 100 \quad (1)$$

This percentage represents the pathway that every single indicator has followed during this last decade. Depending of the accuracy and representability of the information reported for each indicator, this variation could be relevant or null.

This variation does not apply to solar PV during 2005 and 2009, as well as for wind power during 2005 due the lack of contribution to the electricity generation from these sources in those years.

4 Results and Discussion

The results are presented in terms of a general analysis of the data quality followed by the main variation of the environmental, economic and social indicators among the period covered between 2005 and 2015.

4.1 Analysis of Data Quality and Sources

The analysis of the data quality is based on the description of the five aspects included in the pedigree matrix. The description is presented in Table 2.

From the table above, it is possible to identify that only reliability could be a source of uncertainty, while the rest are well covered. However, the data

Table 2 Description of data quality based on pedigree matrix aspects

Pedigree aspects	Description
Reliability	The most part of environmental, economic and social data were obtained from primary source, with exception of infrastructure of run of river, diesel and solar PV, which were complemented with ecoinvent data. For the economic indicator, only the costs for biomass were obtained from foreign source in 2005 and 2009
Completeness	All the process stages were covered in the simulation and there are no missing data
Temporal coverage	Each environmental, economic and social data was specific for each year and not average was used covering more than 1 year
Geographical coverage	The continental territory in Chile was completely covered with the exception of Patagonia. The overseas territory was not included
Technological coverage	The 99.5% of installed capacity of each year was covered in this study, upgrading annually the electricity generation, the conversion efficiency, air emissions, prices and corruption and perception index

assumptions are based on verified information, becoming the main constrains the source and its location instead of the availability of data.

In this case, the location of data process for the environmental profile by technology was based on sources from the Environmental and Energy Ministry and official agencies. This information must be reported because it is mandated by law. On the contrary, the information for the economic profile were obtained from different and heterogeneous sources, such as official agencies, international reports and specific studies, avoiding the systematization of the consultancy and the respective updating. The Economic Ministry has no data about these issues and the Energy Ministry has only information about the cost of investment just for some years and not enough disaggregated to be consistent with the life cycle approach. In fact, this information could be really well-known by investors but still unknown by the researchers. More dramatic is the availability of the social information, with no official institution or agency controlling these aspects and main part of the information obtained from sources related with environmental issues. Currently, scatter and spot information are available determining the capacity to include more and better social indicators.

Everything was possible only thanks to a very detailed and continuously updated knowledge about current instruments of central information report, which has been very dynamic and improved. For this reason, the development of a detailed work like this could be a field of close relation with the central authorities, in order to have a constant validation and evidence the future needs.

4.2 Environmental Indicators

The environmental indicators had important changes during the period, mainly due to changes for conversion efficiency by technology and changes in the environmental regulations. The effect of the conversion efficiency is shown in Fig. 2, for natural gas mainly, where in 2005 and 2009 the acidification potential (ACP) was 10% and 22% higher than in 2015, respectively. On the other hand, the effect of new environmental regulations over the environmental profile of the thermal technologies is clearly exposed in the behaviour of acidification for coal power plants in 2005 and 2015. The reduction of this indicator was over 400%, thanks to a specific regulation for thermoelectric plants, due to its high emission levels and poor abatement systems.

The rest of the environmental indicators present changes like that representing the specific annual situation of each technology [3]. Since these relevant changes in each indicators, it worth to keep constantly evaluated the process data reported in the environmental system, in order to validate them and contribute with a more accurate and transparent central information repository.

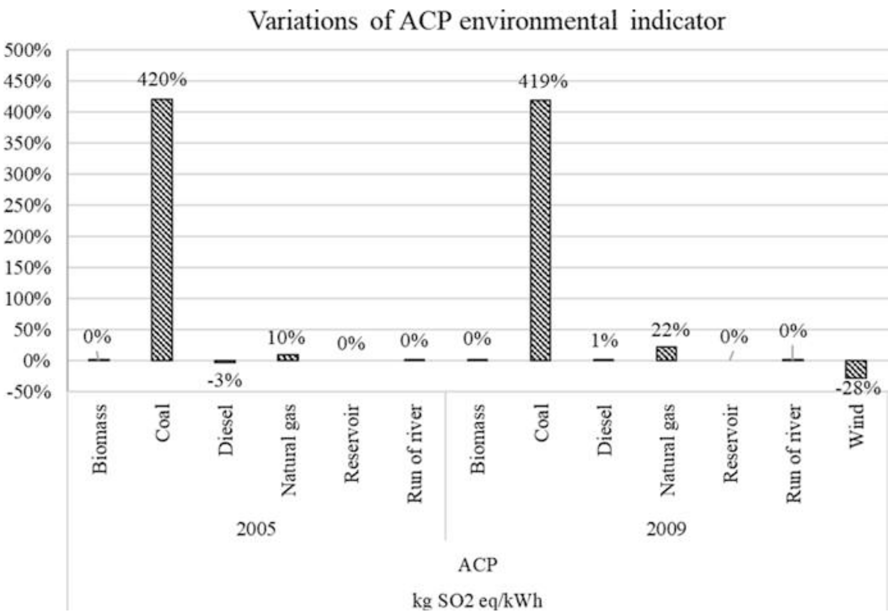

Fig. 2 Variation percentage of acidification environmental indicator in 2005 and 2009 in relation to 2015

4.3 Economic Indicators

Economic indicators are very sensitive with market constrains; for this reason, the need to count with updated information is vital. As is possible to see from Fig. 3, the levelized electricity cost presents a relevant variation in 2005 and 2009 relative to 2015 for all technologies. In fact, thermal power plants present higher values in 2015 than in 2005 and 2009, reaching for coal −36% and −30%, respectively. Due to the uncertainty related to the cost of investment for biomass, the fluctuations are very wide. The reduction of the LEC of wind power among 2009 and 2015 presents the trends in the international markets, where the cost of this technology has decreased.

The important changes in the economic indicators reflect the need to have an updated source of information based on local restrictions, where it could be systematized in order to contribute to an accurate economic analysis. The use of average values from other countries are too vague, for the same reason that is not convenient to consider the economic allocation for the environmental burdens [14, 15].

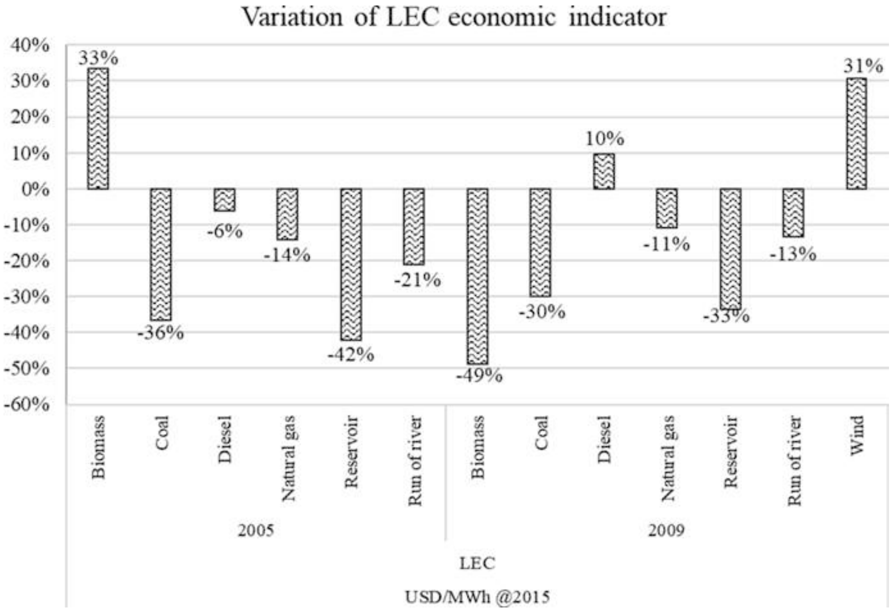

Fig. 3 Variation percentage of levelized electricity cost economic indicator in 2005 and 2009 in relation to 2015

4.4 Social Indicators

The social indicators present an important variation among the period. In Fig. 4 is shown the corruption index (CI) performance, which is very sensitive for coal, natural gas, diesel and biomass, mainly due to the importance of fuel. In the case of biomass, changes in corruption and perception index in 2005 and 2009 explain the different trends through those years. In the same sense, coal presents the same different trends. While in 2005 coal was imported from Australia and Canada mainly, in 2009, there was a change as to the importing country which was exclusively done by Colombia, to be finally shared in 2015 with USA and Australia.

In the same sense as environmental and economic indicators, social indicators present a dynamic behaviour which could be dramatically different when the conditions of technologies present changes through time.

These evidences are key to sustain the need to have a data depository which can be systematized, appropriate, reliable and accurate, in order to take advantage of the current process data report, to shift them to a sustainable platform with updated and continuously improved data accuracy and to assess the global performance, specifically, of the electricity sector in Chile.

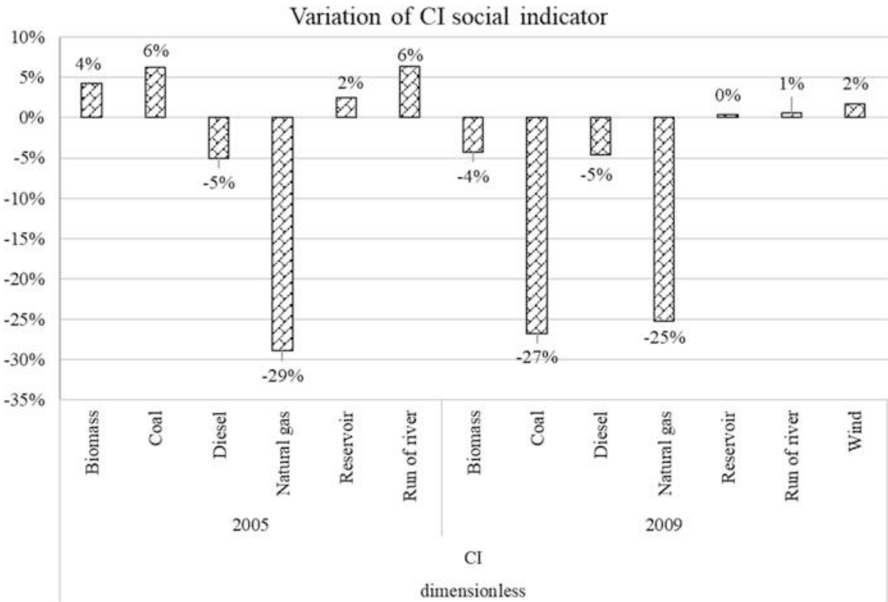

Fig. 4 Variation percentage of corruption index social indicator in 2005 and 2009 in relation to 2015

5 Conclusions

The knowledge about the local environmental reporting system could be really helpful in the case of build a database with primary data regarding the life cycle approach for processes. This system for Chile is still a matter of development, but results like these could be an important input in order to address improvements to the current system. Nevertheless, the social and economic issues are still scattered and were obtained from heterogeneous sources, which are not necessarily the best option for a detailed assessment. This is closely related with the legal need to report the operational performance instead of the global performance.

Understanding sustainability as an equilibrium between environmental, social and economic dimensions, the development of the electric sector ought to be driven to improve data quality, systematizing the reports to check and manage the global performance of the sector.

This critical analysis could be useful for decision-makers and countries in the pathway of development, which are implementing environmental open reports with perational data, specifically for the electricity generation.

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Translating LCA Evidence into Performance-Based Policy Criteria for the Photovoltaic Product Group

Nieves Espinosa, Nicholas Dodd, and Alejandro Villanueva

Abstract Life cycle assessment has the potential to generate valuable information and knowledge for policy makers, as insights can be gained by applying LCA to the development of policy criteria. This potential has been used in the development of a number of EU policy instruments aimed at photovoltaic products, i.e. Ecodesign, Energy Labelling, the EU Ecolabel and Green Public Procurement. They are the regulatory and voluntary policy instruments for sustainable production and consumption at the European Commission. Each instrument has different market objectives; e.g. Ecodesign sets mandatory minimum requirements for products entering the EU market, while the EU Ecolabel is a voluntary instrument to differentiate the most sustainable choices. An eight-step approach based on the Ecodesign methodology including a systematic LCA review has been used with a focus on the information needs of the policy instruments and an interpretation of the results per component/substance. Through the identification of hotspots at the component level and at life cycle stages, it has been possible to translate them into criteria.

1 Introduction

The EU has a number of legislative instruments which translate EU energy and climate policy goals into various strands of action. Ecodesign and Energy Labelling legislations support the Commission's overarching priority to strengthen Europe's competitiveness and boost job creation and economic growth [1, 2]. They are mandatory instruments that ensure a level playing field in the internal market, drive investment and innovation in a sustainable manner and save money for consumers while reducing CO_2 emissions. These instruments contribute to the Energy Union 2020 and 2030 energy efficiency targets, and to a deeper and fairer internal market.

Two further voluntary policy instruments contribute to fulfil the mentioned objectives: the EU Ecolabel and the Green Public Procurement. The EU Ecolabel (set up under the provisions of Regulation EC 66/2010) aims at reducing the

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negative impact of products and services on the environment, health, climate and natural resources [3]. The EU Ecolabel criteria take into account the environmental improvement potential along the life cycle of products. Green Public Procurement (GPP) is defined in COM(2008)400 as a process whereby public authorities seek to procure goods, services and works with a reduced environmental impact through their life cycle when compared to goods, services and works with the same primary function that would otherwise be procured [4]. GPP takes recently into consideration circular economy aspects in new criteria.

The Ecodesign Working plan that periodically lays out which product groups offer an energy saving potential included in its 2016–2019 edition [5] the photovoltaic group product as one that justified an analysis of the feasibility of potential implementing measures under ED and EL. In parallel, the EU Commission proposed to develop EU Ecolabel criteria for photovoltaic modules.

Given this, there was interest in examining the potential synergies between the different instruments. As a result, a preparatory study was launched by the EU Commission in November 2017 on solar modules, inverters and systems, to assess ED and/or EL requirements. Unlike the standard case, in which ED/EL products are assessed independently from Ecolabel or Green Public Procurement policies, for solar photovoltaic products, the preparatory work intended to occur at the same time for the four mentioned policies. This way, the European Commission would build the evidence base in one single research process, providing supporting information to ED/EL, GPP and EU Ecolabel decision-making processes, avoiding duplicities and overburdening. The study investigated also in great detail the potential for environmental improvement, including aspects relevant to the circular economy such as reuse, repair and recycling.

To assess the environmental impacts of electricity systems and evaluate the potential benefits brought by the switch to renewables, one obvious approach is the use of life cycle assessment (LCA) [7]. It is a useful decision-support tool to quantify the environmental impacts of a product, technology or system from a life cycle perspective, i.e. from the extraction of the raw materials through to their manufacture and use up to their end of life [8]. However, to be of relevant use, a LCA study should report the values, or give an interpretation of the results per component/substance, in order to support hotspot identification. This is specifically useful to develop requirements, e.g. for EU Ecolabel.

A systematic LCA review was conducted as part of the preparatory study with a focus on the information needs of the policy tools. The LCA review analysis has complemented the identification of hotspots at component and life cycle stages, and the determination of the type of information needed to translate hotspots into verifiable criteria on aspects of performance for which there is improvement potential. LCA evidence has therefore been translated into technical performance-based criteria for the PV product group. This has been detailed in Sect. 2. For ED, it has been preliminarily identified that for modules a minimum level of energy yield and reporting on performance degradation should be achieved under fixed climatic conditions. For inverters, a minimum efficiency shall be defined, together with repairable key components. For the EU Ecolabel, it has been found that the repairability of key components along the design lifetime, as well as energy return on investment, could be feasible. Project stage-related criteria that minimize both life cycle environmental impacts and costs, together with GWP-based impact category results – as required in some national PV capacity auctions – could be integrated into a GPP criteria set. The proposals for the four policy instruments are detailed in Sect. 3.

2 Methodology

The standard preparatory studies on Ecodesign/Energy Labelling are conducted by a specific methodology for energy-related products (MEErP) [9]. Given that a combined approach between the analysis on ED/EL, GPP and the EU Ecolabel was envisaged for this specific study, additional methodological considerations were needed to complement MEErP. Moreover, the draft Product Environmental Footprint Category Rules (PEFCR) for 'Production of photovoltaic modules used in photovoltaic power systems' have been a complementary source for the identification of environmental hotspots for photovoltaic modules [10].

For its practical operation, the current version of the MEErP makes use of the so-called *Ecoreport* tool, which is a streamlined (i.e. simplified and standardized) life cycle analysis (LCA), that leads to the identification of the environmental 'hotspots' of a product or system of products, and to a quantification of the purchase cost, and production cost over the whole life cycle of the product. Once this information is available, the second part of the process (the techno-economic-environmental assessment) takes place, which takes the form of a ranking of various design options according to their life cycle costs. The analysis of the life cycle costs leads to the identification of the design option that delivers to a consumer the least life cycle cost (LLCC). The LLCC is unique per product category and provides the optimum level from a regulatory perspective because it minimizes the total cost of ownership for the consumer, and it pushes all manufacturers, at the same time, to make the necessary improvements on their products with existing technologies to produce designs linked to the LLCC.

The EU Ecolabel criteria shall among other requirements under the regulation be based on the environmental performance of products, take into account the latest strategic objectives of the community in the field of the environment and be determined on a scientific basis considering the whole life cycle of products. Compared to ED/EL, it investigates more thoroughly chemistry and toxicity aspects and tries to define the best in class based on an overall environmental assessment.

The EU GPP criteria shall mainly take into consideration the net environmental balance between the environmental benefits and burdens, including health and safety aspects. They also shall be based on the most significant environmental impacts of the product, be expressed as far as reasonably possible via technical key environmental performance indicators of the product and be easily verifiable. They also usually include a life cycle cost perspective, to encourage consideration of the total cost of ownership and not just the lowest bid price.

Figure 1 shows the overlay of EU product policy instruments under development when looking at the relative sustainability of products they target. In particular, for example, EU Ecolabel offers a higher sustainability, and GPP support for innovation through voluntary initiatives.

As prescribed by the MEErP, base cases for modules for inverters and for systems were defined.[1] The selected base case for modules is a module consisting of multicrystalline silicon cell back surface field (BSF) design, later updated to a multicrystalline silicon cell PERC (passivated emitter rear cell) design to reflect advancements in market share. For inverters, three base cases have been selected, a 2500 W string one-phase inverter, a 20 kW string three-phase inverter and a central inverter. The selected base cases for systems are a combination of the proposed base cases for modules and inverters, deployed in three types of segments: residential, commercial and utility scale with the rated capacities of 3 kW, 24.4 kW and 1.875 MW. An environmental and economic assessment of the base cases identified along the preparatory study was undertaken following the MEErP.

Then a screening of existing LCA literature has been made to identify 'hotspots' for environmental impacts along the life cycle. These may relate to specific material flows/inputs, components or emissions related to a life cycle stage. A preliminary analysis has then been made of the potential for EU Ecolabel and/or GPP criteria to

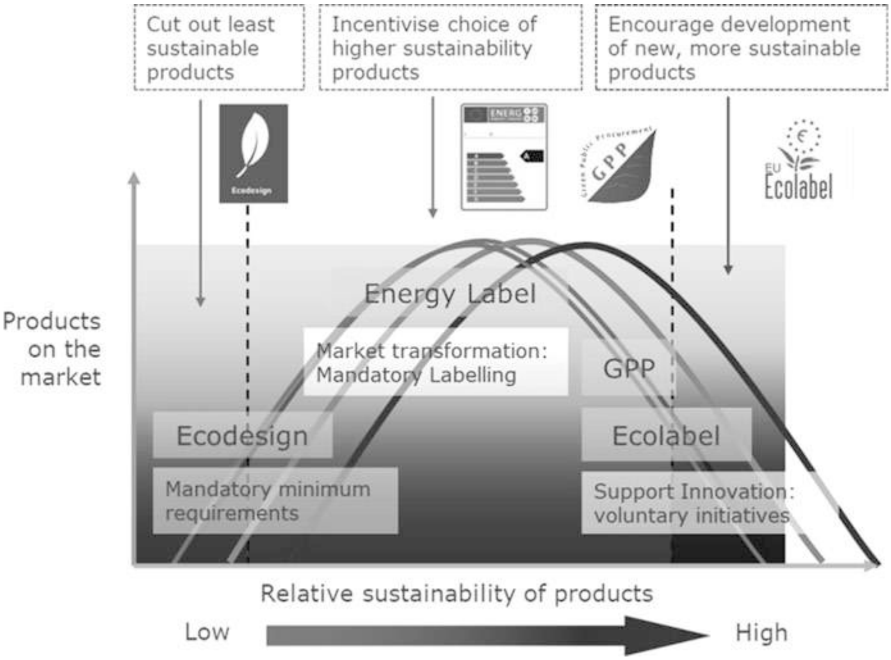

Fig. 1 Overlay of EU product policy instruments under development

[1] See Task 4 of the preparatory study for a detailed description of the base cases.

address these hotspots. Table 1 shows a summary of the analysis made to translate the findings from the LCA review for module inverters and systems into possible criteria.

3 Results

The focus of the preparatory study has been on the feasibility of employing four individual policy instruments, either individually or in combination. Each instrument has distinct characteristics and requirements that must be taken into consideration when deciding whether an intervention in the market is required. The proposals for each are each briefly summarized in Table 2 and presented in the sections below.

3.1 Policy Requirements Proposal: Mandatory Instruments

Policy recommendations based on the results of the analysis in the preparatory study and hotspots identification are presented below. In this context, the added value brought by each instrument and the potential synergies are considered as well as the relevance and feasibility of potentially having the product(s) covered by one or several schemes.

3.1.1 Recommendation 1: Ecodesign Minimum Mandatory Requirements for Modules and Inverters

(1) Requirements are proposed for modules on lifetime electricity yield, quality, durability, and circularity. On the yield, the preferred option is for an Ecodesign information requirement. The reason for selecting this option is that it is more representative of performance under real life conditions. The yield also takes into account PV module performance characteristics such as the spectral response under low light conditions. However, thresholds/information on the market spread for PV modules is currently missing.

(2) Another Ecodesign option could be to introduce a stringent set of quality and durability tests for module products. Testing is costly and timely; however, it is understood to already be considered as a market entry requirement by major manufacturers, and it may be difficult to separate the test sequences and/or to introduce recommended new aspects (such as encapsulant browning or inspections for cell cracking). Requirements for inverters on efficiency quality, durability and circularity are also important. The first option is based on the calculation the 'Euro Efficiency' of an inverter. This is an important derating factor for the performance of a solar PV system, so the removal of the worst performing, sub 94% efficient inverters, would contribute as a minimum

Table 1 Summary of hotspots to be translated into criteria for EU Ecolabel at R (residential), C (commercial) and U (Utility) segments

Product	PV tech/ system size	Hotspots LCA	Improvement measures identified (suitability)	Scoping of the improvement potential	Possible technical requirement	Verification options	Precedents
	Si tech	Ingot/wafer production	(1) Low-energy manufacturing processes (2) Si ingot slicing, e.g. change of laser cutting, lift-off, kerfless, etc.	Reduction of: (1) Primary energy consumed (2) Losses from slicing and minimizing the Si needed for the same energy output	(1) Reduction in primary energy from ingot/wafer manufacturing (2) Reduction in GWP from silicon slicing	(1 and 2) Primary energy and GHG emissions reporting standard production specific, e.g. ISO 14064, 50001 Ener. Manag. Syst.	NSF 457 (7.1.1 required criteria)
	Si tech	Grid electricity mix	Change of site to a location with a lower grid emissions factor	Reduction of GWP up to approx. 100%	Reduction in GWP from production stage electricity use	GHG emissions reporting standard production specific, e.g. 14064	French national PV auction, GHG emissions method

Modules	All techs	Silver metallization paste	(1) Use of less silver metallization paste (2) Substitute silver by copper plating	A reduction down to 50 mg per cell is expected to be possible by 2028	Report the amount of silver per m^2 or per Wp of module	No standard procedure. Could be an info requirement, similar to ROHS	–
	Thin film	Metal deposition in thin films	Use of less energy-intensive step/process	Reduction of primary energy consumed by the deposition process (reduction of, e.g. toxicity impacts)	Reduction in primary energy from metal deposition processes	Primary energy reporting according to I50001 Energy Management System. EPBT or ERoI calculation	NSF 457 (8.1 required criteria), Blue Angel proposal
		Extraction of Cd and Te	Reduce the consumption of Cd and Te	Two CIGS manufacturers – Solar Frontier and Steon – claim ‘RoHS compliant’ modules (Cd below 0.01%)	(1) Reduction of cadmium or tellurium content (2) Circular loop recovery process for semiconductor materials	(1) No standard procedure. ROHS requirement (2) Producer responsibility scheme ensuring min. recovery level, or min. recycling	NSF 457 EoL management and design for recycling and record of annual recycling and recovery rate
	Thin film	Flat glass production	Use of thinner glass, change the type, facilitate recycling or reuse	First solar series 6 has a reduced glass thickness front: 2.8 mm Back: 2.2 mm. Environmental impact of transport reduced	(1) Glass thickness for specific grade (2) Ease of separation of lamination from glass	(1) Verification of glass specification (2) Dismantling tests to show the separation	UBA WEEE criteria: on unloading storage and handling, on preferable recycling of glass
	All techs	Lifetime and degradation	Extended lifetime and lower failure rates	Reduction of degradation rate	(1) Establish a technical lifetime according to the yield (>80% at 30y) (2) Degradation target, e.g. < 0.5%/yr	(1) Declaration made based on field data or experimental laboratory test results	–

(continued)

Table 1 (continued)

Product	PV tech/ system size	Hotspots LCA	Improvement measures identified (suitability)	Scoping of the improvement potential	Possible technical requirement	Verification options	Precedents
	All techs	Energy payback time	(1) Use of less energy intensive manufacturing processes (2) Change in geographical location	(1) Rise on the energy payback time (2) Mc Si modules installed in a reference system can have 8 years or 4.31 years if they are installed in Helsinki or Sevilla, respectively	(1) To maintain an EPBT below a certain threshold for a given climate conditions (2) To include it in an energy label	No standard exists to calculate the manufacturing primary energy. Third -party verification used against EN 15804 (EPD) standard or ISO 14064 (scope 3 CO_2 emissions) for construction prod	NSF 457 (7.1.1) French national PV auction, GHG emissions calculation method
Inverters	R&C	Print board assembly	(1) Avoiding toxic elements such as Cd, Hg, Be, As, Pb and Cr (2) Pb-free soldering techniques	Hazardous substances content limitation/ improve their supply by recovery (WEEE directive)	(1) Avoiding toxic elements such as Cd, Hg, Be, As, Pb and Cr (2) Pb-free soldering techniques (3) Ease of disassembly for EoL treatments	No standards on hazardous substances in PCBs. Declaration of: (1) Substances content (targeted list (2) Lead-free content (3) Protocols for the disassembly and recycling	Ecodesign regulations for washing machines/DWs/ fridges/TVs/ servers WEEE directive – PCBs>10 cm^2

Systems	R,C,U all techs	Electricity demand in the supply chain of aluminium and copper production (construction stage)	Use of less or no framing and mounting structure, use of less cabling	Dual junction box design to reduce cabling and structure (e.g. 87% cable saving by Q cells), alternative frame materials or lighter structure or roof integrated PV	Amount of cabling from module/module connections Module's GWP to capture framing Integrated modules – how to credit the integration?	Feasibility uncertain: (1) Declaration of cabling material (2) GHG emissions reporting standard production specific, e.g. 14064	–
	U	BOS in thin-film technologies	Use of lighter structures or more sustainable materials	Share of the BOS in the total impact could be lower	Dual junction box design to reduce the amount of cabling and structure, or use of lighter structure, or roof integrated PV	Feasibility uncertain: (1) Declaration of cabling material (2) GHG emissions standard production specific, e.g. 14064	–
		Consumption of Cu from the electrical installation and Al from the mounting structure	Recycled content or recovery processes	Reduce consumption of Cu from the electrical installation and Al from the mounting structure	(1) Ease of dismantling and recovery (2) Recycled content	(1) Declaration of protocols of dismantling (2) Producer responsibility scheme ensuring min. recovery level, or min. recycling	–

Table 2 Proposal for product policy instruments, scope, life cycle stage and verification

Policy instrument	Stringency	Scope	Life cycle stage	Verification
Ecodesign	Mandatory	Products, packages of products	Requirements refer normally to measurable characteristics of the product (tested use stage product performance) Material efficiency requirements relating to other LC stages (e.g. repairability, durability) can be proposed, but need to be verified on the product itself Management system for design through manufacturing to be used for conformity assessment	Market surveillance is carried out at Member State level
Energy label	Mandatory	Products, packages of products	The chosen Energy Efficiency Index (EEI) shall address performance in the use stage. The EEI cannot be applied to other LC stages	Market surveillance is carried out at Member State level
EU Ecolabel	Voluntary	Can be products or services	Criteria can be set on any LC stage and include manufacturing sites/tested product performance	MS Competent Bodies verify compliance and award the label
Green Public Procurement (GPP)	Voluntary	Can be products or services	Criteria can be set on any LC stage and can include manufacturing sites, or tested product performance (link to the subject matter)	Through evidence from tenderers provided during the procurement

requirement. Introducing a standard for the minimum durability of inverters placed on the market, together with a focus on information about the repairability of the inverter, would be an important first step in extending the potential service life of inverters, particularly for those intended to be placed in outdoor environments – as failure rates can be high during the first ten years.

An additional overarching Ecodesign option would establish a standard for the collection, analysis and presentation of module and inverter life cycle data and Life Cycle Assessment (LCA) results in the EU. It could be initially on two impact categories – primary energy (GER) and Global Warming Potential (GWP).

3.1.2 Recommendation 2: Energy Label for Residential Systems

An Energy Label for solar PV systems is proposed to target the residential market segment in order to enable consumers to make an informed choice based on the performance of system designs offered by retailers and installers. It would need to be placed on the as-built rather than the monitored performance of a system.

3.2 Policy Requirements Proposal: Voluntary Instruments

3.2.1 Recommendation 3: EU Ecolabel for Residential Systems

It is proposed that a new EU Ecolabel product group is established targeted at residential systems of <10 kWp. The multi-criteria set is recommended to comprise two aspects: the package of modules and inverters and the design and installation service provided to the retail consumer. In the first approach, the criteria for modules and inverters could make use of input data from Policy Recommendations 1 (Ecodesign) and 2 (Energy Label) in order to set criteria that have an extended and stricter focus with pass/fail criteria on life cycle performance, hazardous substances and circular design. For the service approach, there would be criteria covering aspects of the service provided by system installers, e.g. the system design, or monitoring and maintenance.

3.2.2 Recommendation 4: EU Green Public Procurement Criteria for PV Systems

It is lastly proposed that a new GPP product group is established targeted at the procurement of well-designed, high-performance, long-term PV systems, and with a broader focus also on the public authority acting as a catalyst to increase local residential installations by aggregating household demand for systems and to create demand for green (solar) electricity via arrangements such as Power Purchase Agreements.

3.2.3 Combined Policy Option Recommendations

- Combined policy option 1: Mandatory instruments plus Green Public Procurement (GPP). Introduction of the two mandatory instruments would ensure a consistent focus in the market on long-term performance and circularity, acting at both component and system level. The introduction of the GPP criteria would then be to use public sector influence, in particular at regional and local level, to exploit a range of synergies with the mandatory instruments and provide guidance and criteria in three key areas:
  – The direct procurement of new solar PV systems, with reference to component performance and life cycle requirements proposed to be established under Ecodesign
  – The establishment of procurement frameworks for residential ‘reverse auctions’ that would facilitate an increase in residential installations, with reference to component requirements established under Ecodesign and the Energy Label

– The auction of usage rights for public assets (land and roofs) as the basis for green (solar) electricity generation, with bilateral Power Purchase Agreements as a related option

• Combined policy option 2: Voluntary instruments plus Ecodesign. While the establishment of mandatory Ecodesign requirements would establish the units of measurement and methods required for energy yield, derating factors or performance degradation, the two voluntary instruments would provide a broader means of stimulating green innovation in a coherent framework of criteria that address life cycle hotspots, focusing attention on module and inverter designs (EU Ecolabel) and on the system service 'offer' of installers (both voluntary policies).

4 Conclusions

Recommendations for policy criteria have been derived from the main MEErP study, LCA evidence and policy-specific methodologies, forming part of a preparatory study on the feasibility to apply Ecodesign, Energy Label, EU Ecolabel and GPP to photovoltaic products. The study has been made with stakeholder input. Several challenges relating to competing policy objectives and trade-offs have had to be solved by, for example, acting partially on life cycle stages. The different performance-based policy criteria have been carefully selected by prioritizing where to act, e.g. use of proxies to ensure no burden shifting. To further support the use of LCA in policy making for energy-generating products, solutions are needed to prioritize which impact categories to focus on and to reconcile the benefits and burdens of the electricity generated and other 'embodied' impacts. One solution could be to use weighting and normalization factors as recommended under the PEF method. However, to date, no methodology exists to consistently assess the environmental burden or benefits caused by electricity generation within the context of the entire global, regional or national footprint caused by humans. If this was to become available, this information can be expected to be provided a significant support to policy making.

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Part V
Sustainable Methodological Solutions

Enhancing Life Cycle Management Through the Symbiotic Use of Data Envelopment Analysis: Novel Advances in LCA + DEA

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Abstract The combined use of Life Cycle Assessment and Data Envelopment Analysis (LCA + DEA) arises as a growing field of research when evaluating multiple similar entities under the umbrella of eco-efficiency and sustainability. This chapter revisits a set of four recent LCA + DEA articles within the tertiary sector to explore the novel advances offered regarding the application of the well-established five-step LCA + DEA method for enhanced sustainability benchmarking. These advances – which relate to the DEA stage of the framework – include the calculation of gradual benchmarks for continuous improvement, the period-oriented benchmarking of unidivisional or multidivisional entities, and the implementation of decision-makers' preferences in the assessment. Overall, these advances further stress the suitability of using DEA to enhance the capabilities of LCA for the sustainability-oriented management of multiple similar entities.

1 Introduction

It is generally acknowledged that life cycle approaches could benefit from the combined use of other non-life cycle approaches in order to enrich decision-making processes [1]. In particular, a growing interest is found in scientific literature regarding the synergetic application of Life Cycle Assessment (LCA) and Data Envelopment Analysis (DEA) when evaluating multiple similar entities (usually

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called decision-making units, DMUs). In this regard, the symbiotic use of DEA – a linear programming methodology to calculate the relative efficiency of multiple resembling entities [2] – leads to enhance multi-criteria decision analysis by strengthening the capabilities of LCA for the eco-efficiency and sustainability management of entities.

The available reviews in the field of LCA + DEA show an increasing global interest in this area, with a growing number of case studies mainly in the primary [3] and energy [4] sectors. On the other hand, a lack of LCA + DEA studies within the tertiary sector was identified as a knowledge gap, but recently filled by a set of works addressing the sustainability-oriented management and benchmarking of retail stores as single or network (supply chain) structures [5–8]. The goal of this chapter is to explore the novel advances linked to the DEA stage of the LCA + DEA framework for enhanced sustainability benchmarking of entities by revisiting this recent set of case studies within the tertiary sector.

2 Methodology

This chapter focuses on the potentials behind the implementation – in references [5–8] – of specific DEA models that had never been used before within the well-established five-step LCA + DEA framework. As shown in Fig. 1, this LCA + DEA

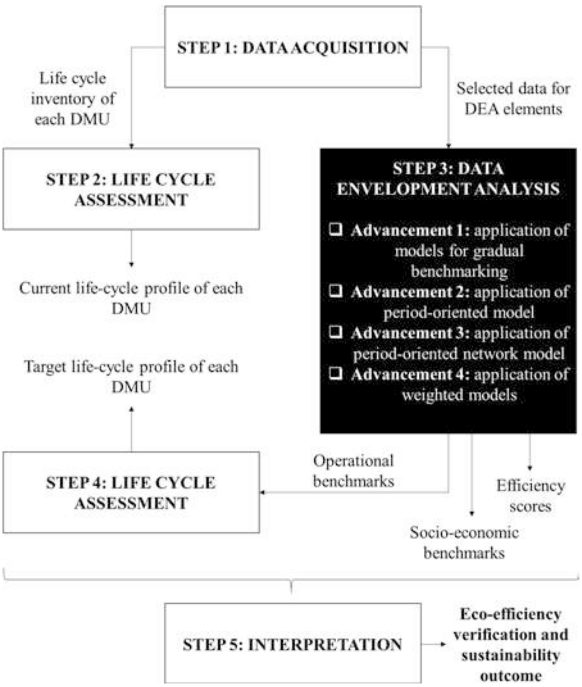

Fig. 1 Five-step LCA + DEA methodological framework and novel advancements at the DEA stage

framework involves five common stages [9]: (i) data collection for each entity under assessment (i.e., DMU) to build life cycle inventories and DEA matrices; (ii) life cycle assessment of each of the DMUs to evaluate their current life cycle profile; (iii) data envelopment analysis to compute relative efficiency scores ϕ – allowing the discrimination between efficient ($\phi = 1$) and inefficient ($\phi < 1$) DMUs – and operational and socioeconomic benchmarks (i.e., target values that would turn inefficient DMUs into efficient); (iv) life cycle assessment using life cycle inventories modified according to the operational benchmarks from the previous step, thus resulting in target life cycle profiles (or environmental benchmarks); and (v) interpretation under the umbrella of eco-efficiency and sustainability.

As mentioned above, and also highlighted in Fig. 1, the advancements reviewed in this chapter refer mainly to the DEA stage. In other words, each advancement is primarily associated with the use of specific DEA models in each original study: (i) use of DEA models for gradual benchmarking in [5], (ii) use of a period-oriented model in [6], (iii) use of a period-oriented network model in [7], and (iv) use of weighted models in [8].

Given the specific relevance of the DEA stage of the original studies, Fig. 2 shows the commonalities and singularities of these studies at this stage. Key commonalities include the inclusion of at least the store operation division for at least one annual term (year 2017) and with a common set of DEA elements. Moreover,

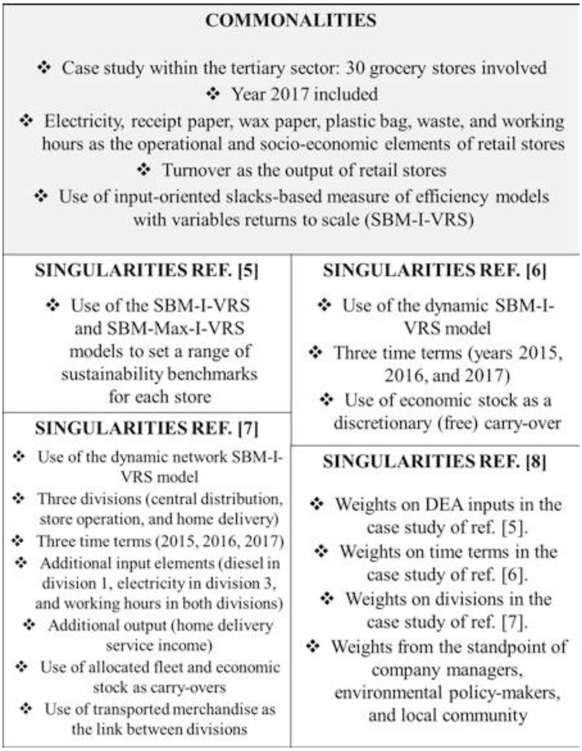

Fig. 2 Commonalities and singularities at the DEA stage of the revisited studies

all these studies use input-oriented slacks-based measure of efficiency models with variables returns to scale (SBM-I-VRS), pursuing a reduction in the DEA inputs' levels while at least maintaining the same desirable output level. However, each study uses a specific SBM-I-VRS variant [10–13], which arises as a key singularity of each study: (i) use of both the conventional static SBM-I-VRS model and the alternative static SBM-Max-I-VRS model in [5] for the computation of gradual operational and socioeconomic benchmarks of retail stores, (ii) use of the dynamic SBM-I-VRS model in [6] for period-oriented sustainability benchmarking of retail stores, (iii) use of the dynamic network SBM-I-VRS model in [7] for period-oriented sustainability benchmarking of retail supply chains, and (iv) use of weighted SBM-I-VRS models/matrices to implement weights on DEA elements, time terms, or divisions according to decision-makers' preferences from the standpoint of company managers, environmental policy-makers, or local community.

It should be noted that, even though the focus is placed on the DEA stage of the five-step LCA + DEA framework, the different operational benchmarks from the DEA step directly affect the calculation of the environmental benchmarks in the fourth step and therefore the sustainability outcome of each study. Further details on the novel potentials behind each study are provided in Sect. 3.

3 Results and Discussion

Table 1 summarizes the main potentials associated with each of the studies reviewed. As a key potential linked to the use of both the conventional SBM-I-VRS model [10] and the alternative SBM-Max-I-VRS model [11], gradual sustainability benchmarking refers to the calculation – at the DEA stage – of a range of operational and socioeconomic target values (i.e., benchmarks) for each inefficient DMU. Furthermore, these gradual operational benchmarks are subsequently translated into environmental benchmarks through LCA (fourth step of the methodological framework). The computation of gradual sustainability benchmarks avoids pursuing too ambitious target values from the beginning, rationing the pursuit of efficiency and thereby promoting continuous improvement practices.

As another key potential – in this case linked to the use of the dynamic SBM-I-VRS model [12] – period-oriented sustainability benchmarking means the

Table 1 Main potentials of the novel advancements identified in LCA + DEA

Source	Novel LCA + DEA potential
[5]	Gradual sustainability benchmarking for continuous improvement
[6]	Period-oriented sustainability benchmarking
[7]	Network sustainability benchmarking for complex structures such as supply chains
[8]	Effective implementation of decision-makers' preferences (weights)

calculation, for each inefficient DMU, of operational, socioeconomic, and environmental benchmarks not only for a time term but to a number of time terms with a continuity condition between consecutive terms [14]. This allows taking into account efficiency changes over time, adapting sustainability management accordingly. Furthermore, when the DMUs are multidivisional (e.g., retail supply chains) and therefore a (dynamic) network model is used [13], this is specifically called (period-oriented) network sustainability benchmarking, as a distinction from the (period-oriented) sustainability benchmarking of unidivisional DMUs such as retail stores. The consideration of a network structure allows analysts to address the management of potentially complex entities involving interconnected processes, herein understood as divisions.

The last potential addressed in this chapter refers to the feasibility (and advisability) of implementing decision-makers' preferences (i.e., weights) in LCA + DEA studies. In this sense, the direct involvement of decision-makers such as company managers and policy-makers in an LCA + DEA study arises as a valuable asset. In fact, when decision-makers are effectively involved in the analysis, the use of weighting approaches – in addition to the default approach of equal weights – is highly recommended [8].

Finally, Table 2 summarizes the main conclusions and/or recommendations drawn from the novel LCA + DEA studies revisited in this chapter. Overall, the state of the art in LCA + DEA offers a wide range of opportunities for the sustainability-oriented management and benchmarking of multiple similar entities, fully aligning this symbiotic methodological framework with the most relevant international initiatives such as the United Nations' Sustainable Development Goals (e.g., SDG 12 on sustainable consumption and production patterns) [15] and the European Green Deal (e.g., reducing the risk of greenwashing) [16]. Moreover, further room for new potentials is still expected, which is closely linked to the wide range of life cycle approaches and DEA models available now and in the future [1].

Table 2 Main conclusions and recommendations from novel LCA + DEA studies

Source	Main conclusions/recommendations
[5]	High applicability of the LCA + DEA methodology to the service sector Feasibility of using the SBM-Max model within the LCA + DEA framework as a useful tool for gradual multidimensional benchmarking of resembling entities for continuous improvement
[6]	Suitability of the LCA + DEA methodology for period-oriented sustainability management and benchmarking of similar entities
[7]	General recommendation of enriching LCA + DEA studies by moving from unidivisional DMUs to multidivisional ones
[8]	General recommendation of enriching conventional LCA + DEA studies (which use equal weights by default) by implementing preferences from the decision-makers involved in the analysis

4 Conclusions

The novel advances explored in this chapter contribute to further strengthening the symbiosis between LCA and DEA, providing valuable general recommendations in this growing field of research. Hence, these advances are expected to boost the applicability of LCA + DEA for enhanced life cycle management, e.g., at the company level. Finally, although these advances lead to increase the interest in LCA + DEA, a high number of potentials – at the level of both methodological choices and case studies addressing new DMU categories – still remain to be unveiled.

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Carbon Footprint as a First Step Towards LCA Usage

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Abstract In order to reduce the current intensive and inefficient use of resources and especially the negative impacts on the environment, some initiatives have emerged in different areas. Life Cycle Assessment (LCA) has been one of the most accepted and used methodology. Despite this fact, there are countries where LCA is not yet fully implemented. On the other hand, there is another approach, the carbon footprint (CF), that can follow the same life cycle approach patterns considering the phases and steps of a LCA. In this sense, this study proposes CF use as an introductory methodology of the life cycle thinking in companies at countries where LCA is still not effectively in use. The proposal is conducted through a bibliographic study and a field research. The findings point to acceptance of the proposal, considering that with the use of CF, the companies will come to know and use the principles of life cycle thinking, thus facilitating the understanding and the implementation of LCA.

1 Introduction

The continued use of natural resources at rates above the planet's regenerative capacity, mainly due to production and consumption, has brought our ecosystem to a reality of unprecedented fragility. In this sense, human activities have caused negative impacts on the environment at all scales.

Among the various evidences, those related to the various parameters of the Earth system where changes are leading the Earth system away from the relative equilibrium it had known since the beginning of the Holocene can be highlighted, and there is now discussion about the use of the term Anthropocene to specify the changes in the Earth system caused by the human species in a planetary scale, taking into account the impact of the accelerated accumulation of greenhouse gases on climate and biodiversity and also the irreversible damage caused by the overconsumption of natural resources, among others [1].

A fact that reinforces this concern is the understanding that there are nine environmental boundaries, which, once overcome, can generate severe and nonlinear

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changes on the continental and planetary scale. Some of these boundaries have already been extrapolated, such as climate change, loss of biosphere integrity, changes in the terrestrial system and changes in the biogeochemical cycles of phosphorus and nitrogen [2, 3].

Another alarming data was released recently by the Intergovernmental Panel on Climate Change (IPCC), where contrary to what was expected in the face of the Paris agreement, which promised a radical transformation in technologies, investments and consumption modes, new and severely worrying data from this latest study published in 2018 (Global Warming of 1.5) exposes that the huge effort to stop global warming must be carried out immediately, precisely from 2020, or the consequences will be catastrophic [4].

Faced with the challenges posed by the ecological urgency presented, some movements emerged, such as the Paris Agreement and the Sustainable Development Goals (SDG), agreements that will require innovative approaches and contributions from all, in this sense, specifically as organizations; they started to use environmental management practices, being one of the most usual ways to initiate these practices through certifications, among which is ISO 14000.

ISO 14000 deals with the need to adapt to any change in environmental conditions, and it embodies a life-cycle approach to address these environmental aspects; among the norms of this set of norms are those referring to the carbon footprint and the life cycle assessment. Among these two proposals, life cycle assessment (LCA) is considered a valuable tool in environmental sustainability for the industry, when reviewing the complex interaction between environmental aspects and the product life cycle, being today recognized as one of the main and most comprehensive environmental tools/methodologies.

However, the dissemination of the use of this methodology is not uniform in the world, and many countries still do not use it fully; on the other hand, there is the other methodology, the carbon footprint (CF), which presents characteristics similar to LCA and brings less complexity in its implementation and may be a way to start implementing life cycle thinking in organizations.

To summarize, this chapter points out the following: (i) carbon footprint and LCA assess environmental impacts during the life cycle of products/services. The first is based on a mono-category assessment (only those related to climate change) and the second with a broader approach (multi-category based), both pointing impacts not only during the production process but also during extraction of inputs, use and end of use of products. (ii) Carbon footprint can be a first step on implementing LCA in companies. The findings point to a possibility of considering the use of the carbon footprint as a first stage in the implementation of the LCA, considering that with the use of CF, the companies will come to know and use the principles of life cycle thinking, thus facilitating the understanding and the implementation of LCA.

2 Mono- and Multi-category Assessment

In the recent past, proposals related to the reduction of environmental impacts were focused on the internal perimeter of companies, but according to current initiatives, based on the life cycle, this focus started to be supported in all phases, from the extraction of raw materials to transport, production and consumption, including final disposal and reuse. This seeks to reduce and even eliminate environmental impacts throughout the life cycle.

The life cycle assessment methodology seeks to improve the performance and environmental sustainability of production systems by providing detailed information with a view based on life cycle thinking. LCA has become a key element of environmental policies or voluntary actions in countries of the European Union, the United States, Japan, Korea, Canada, Australia and among emerging countries, such as India and, recently, China [5]. But this reality is not replicated in other countries, leaving aside, mainly developing countries.

For the United Nations Environment Program (UNEP) [6], the concept of life cycle thinking considers obtaining reliable information on environmental, social and economic impacts and makes this information available to decision-makers. It thus offers a way to incorporate sustainability into decision-making processes. It can be considered that among the various barriers related to LCA studies, the complexity of its preparation, thus consuming a lot of resources and time, is one of its main obstacles.

LCA is a multi-category methodology, as it is based on different categories of environmental impact to carry out its assessment and thus verify the necessary trade-offs, according to the options made. But in addition to this more robust and complex methodology, there are others that can be called mono-categories. This is the case for the carbon footprint that is based on only one impact category, that of greenhouse gas (GHG) emissions, related to global warming. This methodology provides reliable information on this impact, as in the case of LCA, on the life cycle.

The carbon footprint is a relatively new field of study. Its predecessor was the ecological footprint that is a measure of resource use and determines how much land area is needed to maintain a given population indefinitely [7]. The carbon footprint, however, appeared in the literature later, as described by [8], when it became more widely accepted that greenhouse gas emissions need to be reduced to avoid overheating the planet. Carbon footprint (CF) has quickly become a widely accepted term to further stimulate consumers' growing concern about issues related to climate change, being the instrument used to describe GHG emissions [9].

2.1 Standards Related to LCA and CF

Among the standards, ISO 14000 standard was initially developed with proposals for standards that organizations would follow to minimize the harmful effects on the environment generated by their activities [10]. Like ISO 9000, ISO 14000 also provides practical implementation of criteria, which includes plans aimed at making decisions that favour the prevention or mitigation of environmental impacts. The standard of management of the system in families of norms establishes requirements to direct the organization of processes that influence quality (ISO 9000) or processes that influence the impact of the organization's activities on the environment (ISO 14000).

ISO 14000 represents a voluntary international environmental standard that focuses on the structure, implementation and maintenance of an environmental management system in order to motivate organizations to systematically address the environmental impacts of their activities and establish a common approach to the challenges imposed by the ecological urgency experienced [10].

ISO 14001 standard establishes the organization's environmental management system and thus [10]:

- Promotes the assessment of the environmental consequences of the organization's activities
- Seeks to meet society's demand
- Determines policies and objectives based on the environmental indicators defined by the organization (they can portray needs from the reduction of pollutant emissions to the rational use of natural resources)
- Results in cost reduction, service provision and prevention
- Is applied to activities that may affect or affect the environment
- Is applicable to the organization as a whole

The ISO 14040 series of standards describes the principles and structure of a life cycle assessment [11]; in this sense, ISO 14044 specifies requirements and provides guidelines for LCA. As pointed out by [12], these standards include the definition of the purpose and scope of the LCA, the life cycle inventory analysis (LCI) phase, the life cycle impact assessment phase, the life cycle interpretation phase, communication and critical review of the LCA, the limitations of the LCA, the relationship between the phases of the LCA and considerations for using value choices and optional elements.

In reference to the carbon footprint, the first standard that defined it was the Green House Gas Protocol (GHG Protocol) [13], an initiative that originated in 1998, which brings together members of academia, governments and NGOs, under the coordination of the World Business Council for Sustainable Development (WBCSD) and the World Resources Institute (WRI).

The GHG Protocol formed the basis for most other carbon footprint standards. There are currently three highlighted standards for calculating the carbon footprint: ISO 14067:2018; GHG Protocol Product Life Cycle Accounting and Reporting

Standard (World Resources Institute and the World Business Council for Sustainable Development); and PAS 2050:2011 specification for the assessment of the life cycle greenhouse gas emissions of goods and services, developed by the British Standards Institution (BSI).

As for the carbon footprint normalized by ISO, in addition to ISO 14067, there are two other standards that were initially presented in 2006, namely, ISO 14064 and ISO 14065. ISO 14064, management of GHG emissions and removals, establishes standards for the quantification, monitoring and verification/validation of GHG emissions, while ISO 14065 addresses the requirements for GHG project validation and verification organizations [14]. ISO 14067: 2018 was based on the current ISO standards related to life cycle assessments (ISO 14040, ISO 14041, ISO 14042, ISO 14043 and ISO 14044) for the details for quantification, on standards related to environmental labels and statements (ISO 14020, ISO 14024 and ISO 14025) for the formatting for communication, specifies principles, and on requirements and guidelines for the quantification and communication of a product's carbon footprint [18]. This being the closest standard to ISO standards related to LCA.

For a world that continues to face this ecological urgency, organizations must continue/start to recognize the need to manage their environmental challenges and contribute to finding solutions to this common problem. Thus, the use of organizations of methodologies such as CF and LCA is very important in the face of this enormous challenge.

3 Methods and Data

This theoretical chapter aims at investigating the relationship between LCA and CF. Based on input from the literature on LCA and CF, the available evidence for this relationship was analyzed in the context of using CF as a predecessor to LCA implementation as a first step towards effective application introducing life cycle thinking. To structure the debate, a conceptual approach was carried out, and a field research on international researchers' and practitioners' perceptions on the potentially of the proposal to have CF as a first step to LCA usage will be presented.

3.1 Illustrative Case: Testimony of Experts

To add to the debate on the potentially positive use of the CF as a predecessor of the LCA, an illustrative case on international researchers' and practitioners' perceptions on this proposal will be presented.

3.1.1 Data Collection and Sample

Data collection is aimed at identifying the following aspects (among others): the state of the art of the LCA and the relationship between CF and LCA. For this purpose, a survey was designed which was disclosed and submitted through the LC Net, November–December 2015 edition, the newsletter of the Life Cycle Initiative. SurveyMonkey was used – an online survey development cloud-based software, which provides customizable surveys – for the data collection via web. The survey consisted of 15 questions organized in 9 categories according to the aspects being investigated. For the purposes of this chapter, though, it will discuss only the data related to the relationship between CF and LCA, one of the categories presented at this survey.

The questions covering this topic were structured as open questions and are composed of two questions that sought to understand at what stage is the use of the carbon footprint and validate the proposal that this can be a tool to promote the use and dissemination of LCA.

The Life Cycle Initiative was chosen to be the channel to access international researchers and practitioners with experience on LCA as it is regarded as a worldwide influential organization on the issues concerning LCA practices and its dissemination. At the time of data collection, November–December 2015, 106 Life Cycle Initiative members participated on the survey. The number of international respondents and the scope of their place of work/origin in 31 countries expressed a higher frequency of European countries with 67.0%, followed by North America with 16.0%. Regarding the time of experience, the verified distribution demonstrated a maturity of the researchers/professionals who participated, since 66.0% of the respondents had more than 6 years of experience with LCA.

3.2 Survey Responses

There were two questions on the questionnaire considering this topic. The first asked about the use and the way of using the carbon footprint in countries, seeking to understand if the methodology was already effectively used and if it would be a feasible option and already used as a first stage before the LCA. 99 responses were received: 65 (65.7%) were positive regarding the widely use of the carbon footprint, 4 (4.0%) did not know how to position themselves and 30 (30.3%) were negative concerning its use (e.g. Fig. 1). Of the 31 countries whose specialists participated in the survey, only 2 did not use the carbon footprint effectively.

The second research question was related to the proposal to use the carbon footprint as a facilitator and first step towards the dissemination of LCA practice. 97 responses were received: 71 (73.2%) were positive; 15 (15.5%) had restrictions on the LCA being more complete and requiring more details in its execution, in addition to presenting restrictions on the use of the carbon footprint as a decision tool; 2

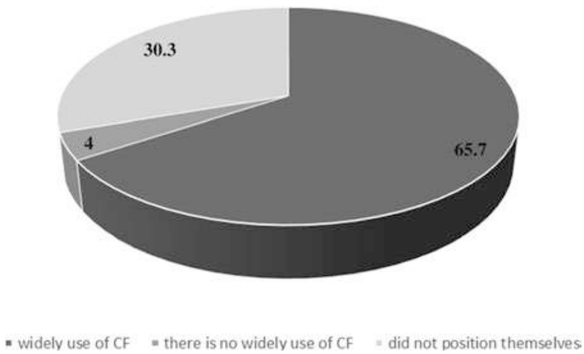

Fig. 1 Usage of carbon footprint in countries

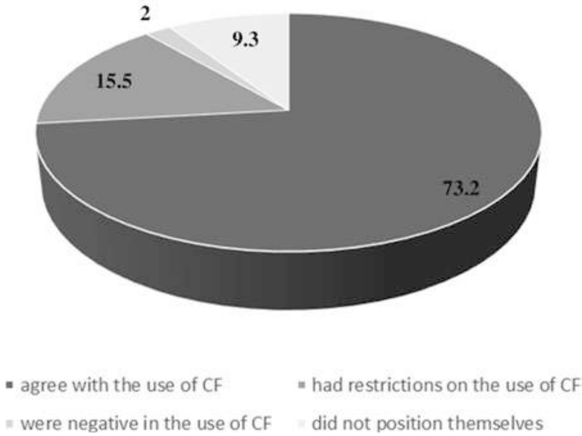

Fig. 2 Use of the carbon footprint as a first step towards the dissemination of LCA practice

(2.0%) were negative regarding its use as a first step in implementing an LCA; and 9 (9.3%) were unable to position themselves (e.g. Fig. 2).

The comments received on this proposal to use the carbon footprint as a first step towards the effective implementation of LCA were divided into three groups. One group presented positive comments on the proposals, consisting of 15 placements; another group with 9 placements presented what could be improved after the execution of the carbon footprint. The third and last group, with 14 comments, criticized the use of the carbon footprint as a precursor to LCA.

A compilation of the positive comments regarding the use of CF as a precursor to the LCA is that when conducting a carbon footprint assessment, companies come to better understand direct and indirect emissions; they come to better understand what is the approach of the life cycle and the fundamental stages of an LCA study and recognize the needs of people and resources, in addition to becoming aware of the interpretation of the results when making decisions. In this way, carbon footprint requires the execution of the most difficult parts of an LCA study, and to complement this initial study, it would be necessary to basically only collect additional data (the multi-criteria aspect) on the processes already verified in the calculation of the carbon footprint. This evolution towards an LCA study would be relatively simple.

In relation to the comments that indicated an acceptance but with a clear understanding of the differences and the needs of future actions, we have as a compilation that for companies, it is easier to start with the carbon footprint to understand the concept of LCA. The company may be frightened when faced with many categories of impact that at first may not be relevant to its products. The use of a single criterion can help for simplicity, but it involves a lot of uncertainty and choices based on a single factor. The interpretation of an LCA study is more technical due to the different impact categories addressed and is also more complex than that of the data generated by a CF.

As for the negative comments, the compilation of these positions points to a concern that a complete LCA study is more complex than just an accounting of GHG gases, made by a CF. The use of the carbon footprint may limit the understanding and scope of environmental issues in companies, making matters that are extremely complex really simplistic. Companies that perform a CF may not fully understand the concept of the life cycle and may be satisfied with just this study without understanding that they can do more through an LCA study. In the survey, 81.82% of respondents reported that the tool is used in their countries of residence/professional practice, a scope that covers 28 of the 30 countries involved in the research. The proposal to use the carbon footprint as a precursor to the LCA was accepted by the community of researchers/international experts with an approval of 73.20% of the respondents and a perceived concern on the part of 15.46% of the respondents regarding a possible loss of perception of the advantages of using the LCA methodology.

4 Discussion

In the survey, 81.82% of respondents reported that the tool is used in their countries of residence/professional practice, a scope that covers 28 of the 30 countries involved in the research. The proposal to use the carbon footprint as a precursor to the LCA was accepted by the community of researchers/international experts with an approval of 73.20% of the respondents, with a perceived concern on the part of 15.46% of the respondents regarding a possible loss of perception of the advantages of using the LCA methodology.

This concern is due to the fact that because the carbon footprint is mono-category, it verifies the impacts related only to its category (GHG emissions/global warming) and provides unilateral decision-making aimed at reducing the environmental impacts related to this category and that may eventually promote other impacts not perceived by the tool (since they are not evaluated by the tool). This fact does not occur with the LCA methodology, since it measures the impacts related to a considerable group of different categories and is able to provide information on the trade-offs that will occur due to the decisions taken with reference to these evaluated categories.

As a result of these respondents' cautious positions and positive opinions regarding the proposal, 38 comments were analysed, and from these it can be concluded that according to what was reported in the survey, the carbon footprint, although simpler than the LCA, brings the life cycle approach, its methodology and its steps into companies and can collaborate as their first contact with this approach model; the carbon footprint provides insight into the impacts generated and their dimensions for companies; the use of the carbon footprint becomes a facilitator as the life cycle study is carried out for only one impact category.

As negative aspects pointed out, several of them are relevant and are presented here: there is a need for other knowledge besides those related to the impacts responsible for global warming to be acquired and present when carrying out the LCA study; the possible difficulty in conducting the interpretation of the LCA study when carried out by the company that initially only conducted carbon footprint studies, due to the trade-offs visualized and glimpsed in as a result of the LCA studies; the fear that the methodology used to execute the carbon footprint is based on the GHG protocol or PAS 2050, which could distance the company from understanding the life cycle approach and the use of the LCA methodology; concern was shown for small businesses that would not be able to afford the costs of an LCA study; limitations regarding the need to use software for LCA studies when, for carbon footprint studies, they are not necessary; and concerns about the possibility that after the use of the carbon footprint the use of the LCA may be disowned.

The carbon footprint, being considered an integral part of an LCA study, follows the same pattern (when based on ISO 14067) of the life cycle approach as the phases and steps to be followed in its application, thus bringing the practice of the life cycle approach to the companies that execute it. Another issue regarding the use of the carbon footprint as a first step in the implementation of the LCA is that this methodology, mainly due to the results and commitments assumed by the countries participating in COP 21, tends to have greater use and eventual collection, even legal, in these countries.

5 Conclusion

The carbon footprint, being considered an integral part of an LCA study, follows the same pattern (when based on ISO 14067) of the life cycle approach as the phases and steps to be followed in its application, thus bringing the practice of the life cycle approach to the companies that execute it. Another issue regarding the use of the carbon footprint as a first step in the implementation of the LCA is that the CF methodology, mainly due to the commitments assumed by the countries participating in the COP 21, Paris Agreement, tends to have greater interest and use in the countries signatories to the agreement.

The use of the carbon footprint also directly corroborates other objectives to be achieved by nations, referring here to the Sustainable Development Goals (SDGs). Among the 17 objectives assumed, the carbon footprint has a direct relationship, especially with the thirteenth objective – "Take urgent measures to combat climate change and its impacts", in addition to having other interfaces with others of the 17 objectives.

The concern reported in the survey by a portion of the respondents, regarding a possible replacement of the LCA by the carbon footprint, should be considered, but the purpose of this study is not to propose CF use as the main methodology, but to enable companies to have contact and experience with the life cycle approach, and from this first experience, they can evolve to the admittedly more complete methodology which is the LCA.

Thus, the present study suggests that the carbon footprint should be considered as a methodology to be used as a precursor to LCA studies in companies, a factor that tends to facilitate a comprehensive implementation of LCA in countries where this practice is not yet a reality. It is hoped that this study can motivate more in-depth research and practical applications that can reinforce the pointed interrelation and proposal.

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Society's Perception-Based Characterization Factors for Mismanaged Polymers at End of Life

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Abstract Society's perception of an environmental impact often turns it into the drive to measure, remediate and ultimately solve the perceived problem. In some cases, this situation is noticeable even before scientists can properly establish the cause-effect pathway, for example, plastic debris effect on the oceans. This work strives to understand how public opinion deals with this transitory gap of knowledge and how to measure society's viewpoint through marine litter. A Life Cycle Assessment was addressed comparing reusable and single-use drinking straws, from which a "society's perception based" characterization factor for mismanaged polymers at end of life was proposed. Results showed that the factor may reach up to 1 order of magnitude higher than the characterization factors of producing the polymer and may indicate that decisions with no data to support can lead to rebound effects.

1 Introduction

Marine litter consists of items that have been deliberately discarded, unintentionally lost or transported by winds and rivers, into the sea and on beaches [1]. Based on this concept, it is not difficult to understand why plastic products conform most of the waste found in oceans [2]. Plastic products are often incorrectly disposed [3, 4] at end of life (EoL), worsened by the lack of economic value as waste [5, 6]. In addition to collection and sorting difficulties, this economic condition discourages plastic waste flows to circulate in the current recycling schemes. Plastic are easily transported into nature due to general product characteristic, e.g. lightweight,

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small-sized and the float potential. Consequently, plastic waste may reach oceans via inland waterways, wastewater outflows and transport by wind or tides [7].

Statistical researchers endorse this scenario. In the European Union, 80–85% of marine litter, measured as beach litter counts, is plastic, with single-use plastic items representing 50% and fishing-related items representing 27% of the total [8]. Estimates based on 192 coastal countries pinpoint that from 31.9 million MT of mismanaged plastic in 2010, 4.8 to 12.7 million MT entered the ocean [7]. However, despite the significant values raised by these references, which indicates a constant accumulation over the decades, the issue gained prominence only in the last years, when global society started to worry about the effects of marine litter, mainly due to its impacts over marine biodiversity.

The disposable plastic drinking straw may be indicated as the most representative flagship of this current society's concern. It has been a hot topic since 2015, after a video showing a drinking straw stuck in a sea turtle's nose [9]. Since then, this product turned into the image of marine litter problem and boosted by society's opinion about the situation, propelled a large movement to eliminate plastic straws from our daily lives [10–15].

There are two aspects of this situation that became clear since 2015: (a) the overall movement had positive influence on marine litter waste problem recognition and (at some extension) on directing efforts to solve it, and (b) with laws, policies and prohibitions, alternative solutions as reusable straws or specially designed cup lids that perform the same function, gained prominence. However, despite the common intention to deal with plastic waste on the oceans, alternative scenarios may suffer with trade-off conditions as pointed by [6, 16, 17], whereas the simple prohibition without the proper scientific validation may cause rebound effects in medium to long terms (e.g. increase climate change).

Life Cycle Assessment (LCA) is able to identify this trade-off conditions between different scenarios [18–21] being recognized as a trustworthy, scientific and understandable approach that uses several mathematical models to address sustainability aspects of human activities [22–24]. However, it currently lacks a marine impact focus and robust models to account for the environmental effects of leakage into the natural environment [5, 25] especially related to the Life Cycle Impact Assessment (LCIA) framework [25–27]. On top of that, current EoL scenarios dealing with plastic waste on LCA, as sanitary landfilling, are not well addressed by impact category mechanisms due to specific product characteristics (low degradability; impacts are predominantly physical but may be also biological/chemical thorough the years) and the difficulties reproducing such complex cause-effect chains in a mathematic model. As an effect in these cases, LCA can produce some asymmetry that can lead into a misleading decision-making with not carefully considered premises and critical analysis over modelling.

Consequently, there is a major gap between scientific research and the environmental technical analysis related to "what is happening" in marine ecosystems. While this bridge is not built, this gap is being fulfilled by society judgement over the theme.

Society has built an opinion about this theme based on important evidences, although empirical and anecdotal, in most cases, on the impacts plastic can cause in marine environment. However, there is still lack of scientific development to assure the real magnitude of the damage or to trace the cause-effect pathway. Nevertheless, public policies established worldwide based only in this perception may not comprise the whole picture and may be potentially subject to failure, for example, promoting environmental trade-offs between life cycle stages or different product alternatives. Thus, the aim of this paper is to provide insights to this discussion by calculating the impact factor that is addressed to the LCA score by a new impact category based on society's perception on marine litter.

2 Material and Methods

A comparative LCA ISO compliant (i.e. LCA conducted by a LCA consulting company and reviewed by an independent third-part reviewer institution) [19, 28] was performed to assess five different drinking straws, representatives of the main commercial one-way and reusable alternatives available in the Brazilian market in 2018. However, for the sake of brevity, only plastic (marine litter case related) and stainless steel (best LCA score within reusable alternatives) options are presented since they are also the base case study of this paper. Boundaries were stablished from cradle to grave for the functional unit (FU) of "to drink 300 ml of a generic liquid from a regular glass". Their main characteristics and simplified scenario scoping are presented in Table 1.

Table 1 Main characteristics of product systems under analysis

Characteristics	Plastic drinking straw	Stainless steel drinking straw
Illustrative image		
Length/diameter (cm)	21.00/0.50	20.00/0.61
Predominant material	Polypropylene (PP)	Stainless steel/304
Main material weight (g)	0.33	11.03
Packaging	Low-density polyethylene	N.A.
Packaging weight (g)	0.09	N.A.
Additional elements	N.A.	Wire-nylon brush, cotton bag
Kit weight (g)	0.42	26.87
Washing	No	Yes
Lifetime (reuses)	One way	500 uses
End of life	Sanitary landfill	Sanitary landfill

Information from [6, 29–31] and product acquisition

The foreground data regarding raw materials weight is from primary sources, measured through a gravimetric procedure by precision scale on real (acquired) products, including primary packaging and additional elements. For raw material acquisition and material transformation, data were gathered exclusively from secondary sources such as the ecoinvent® database version 3. The washing step of stainless steel straw represents a manual and domestic process, representing an average of ten processes measured in loco for water and washing agent consumptions and effluent generation. EoL flows (including straws, packaging and complimentary elements) represent raw materials consumption based on mass balances, whereas landfilling was based on secondary data from literature and ecoinvent® database version 3.

A hybrid LCIA method based on IPCC [32], CML-IA [33] and ReCiPe 2008 at the midpoint level [34] was adopted with addition to an LCI-based impact category related to land use. Normalization was based on CML-IA divided by world population for ozone depletion, photochemical oxidation and eutrophication; CML non-baseline divided by world population for acidification; CML 2 divided by world population for resource consumption; ReCiPe divided by world population for climate change; and ILCD for respiratory inorganics and an estimated factor for land use. Weighting factors were defined based on major Braskem stakeholder's opinion, including company representatives, society and external specialists. The impact categories, characterization methods and normalization (N. factors) and weighting factors (W. factors) are listed in Table 2.

From the single score (SS) LCA results, we proposed a new impact category, namely, marine litter. This category aims to represent the society perception regarding the presence of plastic debris on the oceans, and, therefore, does not represent the traditional bottom-up approach that defines, scientifically, the cause-effect pathway (LCA characterization models). The rationale in this paper's proposal considers that characterization factor could be derived from top-down strategy (Fig. 1), based on the premise that society perception on this matter is correct.

From this perception, overall LCA SS of plastic systems should be, at least, equally environmentally harmful than other alternatives. When this condition is not

Table 2 LCIA single score method (characterization, normalization and weighting)

Impact categories (category indicator)	Source method	N. factors	W. factors
Climate change (kg CO_2 eq.)	IPCC (2013) 100a	1.45E-04	170.73
Ozone depletion (kg CFC-11 eq.)	[35]	4.41E-09	101.63
Respiratory inorganics (kg PM2.5 eq.)	[36]	0.263	109.76
Photochemical oxidation (kg C_2H_4 eq.)	CML-IA	2.72E-11	109.76
Acidification (kg SO_2 eq.)	CML-IA (non-baseline)	2.99E-12	101.63
Resource depletion, water (m^3)	ReCiPe	1.73E-03	101.63
Land use (m^2.a)	ReCiPe	8.91E05	101.63
Resource consumption (kg Sb eq.)	CML-IA	6.39E-12	101.63
Eutrophication (kg PO_4 eq.)	CML-IA	6.32E-12	101.63

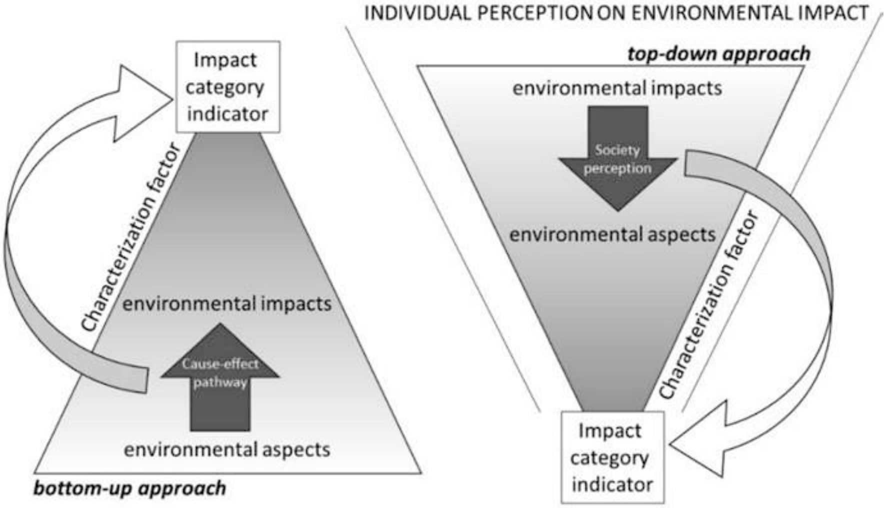

Fig. 1 Different approaches for characterization factor definition

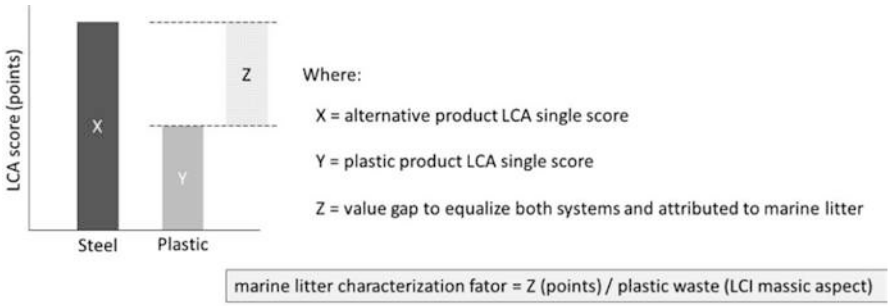

Fig. 2 Marine litter characterization factor mathematical concept (in compliance with the amount of plastic waste generated and their risk of becoming litter)

respected, the final LCA value gap is, therefore, attributed to the marine litter impact category representing society perception, as illustrated in Fig. 2.

3 Results and Discussions

3.1 Life Cycle Assessment of Drinking Straws

Each product system has a specific behaviour in terms of LCI as shown in Table 3. Plastic drinking straws (one-way product) have simple packaging, consisting of LDPE films (0.09 g) that are discarded directly during the use phase. Stainless steel

Table 3 Drinking straws Life Cycle Inventory (LCI)

	Flows[a]	Unit	Plastic drinking straw	Stainless steel drinking straw
Inputs	Polypropylene	g	0.33	–
	Stainless steel	g	–	0.022[b]
	Tin wire	g	–	9.7E-03[b]
	Nylon	g	–	5.1E-04[b]
	Cotton	g	–	0.021[b]
	LDPE	g	0.09	–
	Tap water	L	–	0.60
	Detergent	g	–	1.00
Outputs	**Drinking straw (FU)**	**p**	**1.00**	**1.00**
	Effluent (water/detergent)	L	–	0.61
	Plastic residues for treatment (sanitary landfill)	g	0.42	5.1E-04[b]
	Metal residues for treatment (sanitary landfill)	g	–	2.3E-02[b]
	Textile residues for treatment (sanitary landfill)	g	–	2.1E-02[b]

[a]Material/resource flows considering the amount of inputs/outputs to perform the FU
[b]LCI flows influenced by reuse rates 1/500 rate)

drinking straw (reusable product) has a carrying bag (made of woven cotton) to accommodate both the straw and the cleaning brush. Similarly to the reusable straw, these elements are influenced by reuse rate, having their inputs diluted to fill the FU. In the use phase, stainless steel straw presuppose a washing phase, where water (with 600 ml of tap water) and a washing agent (1 g of linear alkyl sulfonate, LAS detergent) are consumed. At last, EoL stage is represented by output flows in accordance with mass balance over the previous life cycle steps. Therefore, reusable straws have lower solid wastes than one-way straws, but on the other hand, they have a significant liquid effluent generated during the washing process (use phase).

Within the LCA scoping of this paper, single score results show a better environmental performance for plastic drinking straw with lower impacts (31.3μPt) if compared to stainless steel drinking straw (393.2μPt), as depicted by Fig. 3. Climate change, respiratory inorganics and resource depletion (water) are the main contributors to the final single score of both drinking straws with the major difference in terms of values related to the water consumption, followed by impacts due to respiratory effects.

Raw material acquisition (i.e. PP production/pellet), commonly a hotspot for one-way plastic LCA [37, 38], is the main driver for all impact categories in the case of the plastic drinking straw. Stainless steel straw has hotspots positioned mainly in additional element production (woven cotton and wired tin), detergent production and tap water consumption (during washing process). Those conditions turn the stainless steel straw into a worst environmental choice than plastic drinking straw,

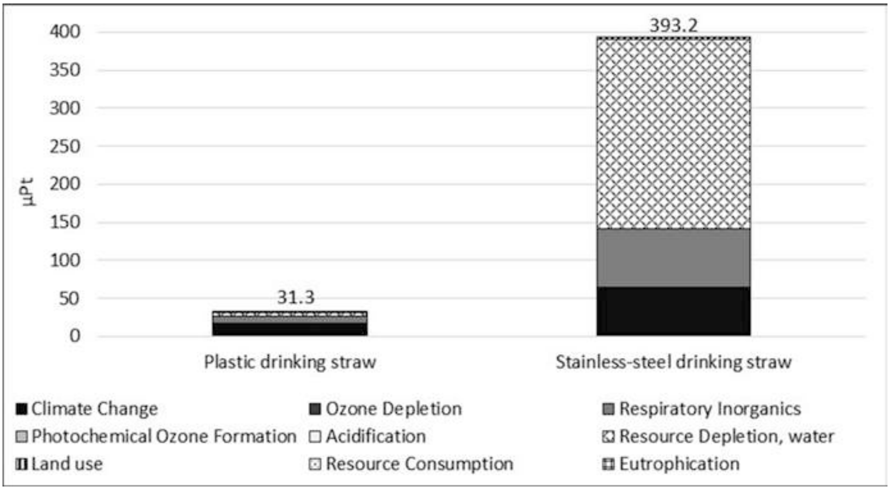

Fig. 3 Single score LCA results

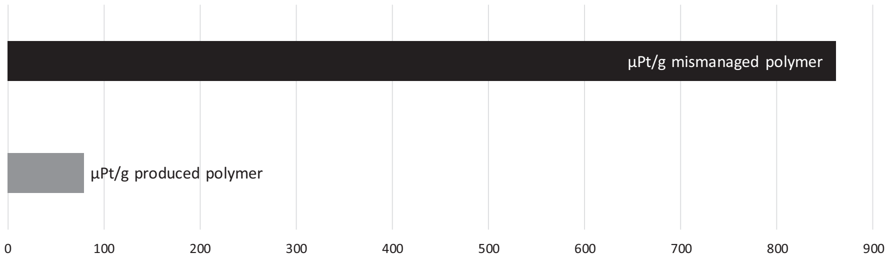

Fig. 4 Perspective of the magnitude of the new impact characterization factor considering 100% of plastic as marine litter

with its production (including mining and steel processing) and EoL being significantly diluted by reuse rate. Similar results are shown by [37, 39, 40].

3.2 Society's Perception-Based Characterization Factor

Assuming that the difference of 362 μPt between the SS results from Fig. 3 should be attributed to the plastic drinking straw final disposal flow, according to the equation in Fig. 2, we can estimate the marine litter characterization factor as 860 μPt per gram of mismanaged polymer (assuming that 100% of polymer consumption in the plastic drinking straw life cycle becomes marine litter). Comparing the impact estimated for the final disposal flow with the PP production demonstrates that this factor represents an increase of 1048% (Fig. 4). This means that the mismanaged flow represents an impact 10.5 times higher compared to the polypropylene upstream chain (i.e. equivalent to 1 order of magnitude). If we assume that 3% of the world's plastic production ends up in the oceans [7], the characterization factor would increase up to 28722 μPt per g of mismanaged plastic. In this case, the environmental impact assigned to marine litter would represent 363 times more than its own production (a difference of 2.6 orders of magnitude).

Analysing the results with a different perspective based on the normalization and weighting factors of the Braskem's LCIA method for the climate change category, the impact of plastics in the ocean would be equal to 2.2E-2 kg of CO_2 eq. This result represents an impact 20 times higher than the total plastic drinking straw life cycle emissions (1.04E-3 kg CO_2 eq. or 18 μPt) to perform the FU when correctly disposed in a landfill.

4 Conclusions

According to LCA results, polymer-based solutions tend to have better environmental performance when compared to the stainless steel reusable alternative, if correctly disposed. While reusable options heavily depend on consumers' behaviour at use phase, polymer single-use option is dependent of consumers' behaviour at end-of-life step.

The lack of characterization factors to account for the potential impacts exerted by plastics in the natural environment, mainly those in the ocean, indirectly turns the society's perception of the problem, the qualitative measure of the "characterization factor" for the marine litter impact category, without a sound scientific basis.

When attributing this perception on the results of a comparative LCA of drinking straws, following the rationale of society's perspective for marine litter, the impact of mismanaged plastics can potentially represent 10.5 and 363 times greater than its own production impacts if 100% and 3% of the plastic are considered marine litter, respectively. In both situations, the value seems to be overrated.

Other perspective, based on the climate change at midpoint LCIA level, indicates that it would be necessary 20 times more CO_2 equivalent emissions only to equalize the single score results of 0.42 g of mismanaged plastic. In both cases, LCA results due to characterization factor based on public opinion seem to be significantly higher and unbalanced with the other life cycle stages of the plastic drinking straw. Thus, society does not perceive the impacts of the polymer straw application as LCA results may indicate, mainly in order of magnitude.

Even though this work's aim is to present a case as an exercise and not to properly calculate a reproducible characterization factor, it gives insight about the current LCA gap of knowledge and how far an LCA result may be from public opinion. Doubtlessly science should not be nudged by any perception, and real characterizations factors are still to be calculated. The lack of data, high complexity of the subject, and the difficulty of proper communication between scientific community and social influencers tend to lead people to the precautionary side and to make decisions with no data to support. In this case, society becomes very prone to suffer from rebound effects.

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Research Activities on LCA and LCM in Poland

Zenon Foltynowicz and Zbigniew Stanisław Kłos

Abstract The main goal of this paper is to present the history and actual situation in research on LCA and LCM in Poland. This task will be performed by reviewing the different activities and their results in this field, from the very beginning. The paper includes the review of the activities of LCA/LCM main research centres in Poznań (Poznań University of Technology (PUT), Poznań University of Economics and Business (PUEB)), Cracow (Polish Academy of Sciences, AGH University of Science and Technology, Cracow University of Economics), Zielona Góra (University of Zielona Góra), Bydgoszcz (UTP University of Science and Technology), Katowice-Gliwice (Silesian University of Technology), Częstochowa (Częstochowa University of Technology) and Szczecin (ZUT Western Pomeranian University of Technology). LCA/LCM researches are also performed in several smaller research groups in R&D centres. In the end of the paper, some conclusions referring to the actual situation of research on LCA/LCM, dealing with critical evaluation of the LCA/LCM centres in Poland location, issues and problems addressed, areas of the projects covered and the desired activities in the future, are presented.

1 Introduction

Environmental life cycle assessment has developed fast over the last three decades. A comprehensive review of the historical development of LCA has recently been presented by Guinée [22]. So far, a description and summary of the state of research on LCA in Poland has been made several times, for the first time in 1990 [24]. The first studies worldwide, which are currently considered as LCA, were carried out in the late 1960s and early 1970s. In the years 1970–1990, the LCA concept was

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developed with widely divergent approaches and terminologies. The 1990s brought about a remarkable increase in research activities around the world, reflecting, inter alia, the number of published LCA guides and textbooks. In 1990–2000, harmonization of methods took place, thanks to SETAC coordination and ISO standardization activities, providing a standardized framework and terminology as well as platforms for debate and harmonization of LCA methods. In addition, the first scientific journals appeared with LCA as their main subject.

2 Early Works in Poland

As a starting point, the first attempts of introduction of LCA/LCM aspects into research practice in Poland are presented. These "pre-historical" activities were connected with the implementation of life cycle frames into analysis of environmental impacts of technical objects, as it was presented in a paper focused on consideration on the usefulness of determination of environmental impacts of the machine and device existence in the life cycle [23], published in Scientific Works of PUT, series: Machines and Vehicles, in 1986 (author: Zbigniew Kłos). Among other activities, the first book on LCA-related issues by Zbigniew Kłos entitled "Environment Protection Oriented Property of Technical Objects. A Study of Valuation of Machines and Devices Influence on Environment", published by Editions of PUT in 1990 [3], and the first PhD thesis "Ecobalancing of Machines and Devices with the Example of Air Compressors", defended by Grzegorz Laskowski at Faculty of Machines and Vehicles, PUT, in 1999 (supervisor: Zbigniew Kłos), should be pointed out. Then there were in the 1990s other activities accomplished, like engagement in work activities of European LCA research groups: SETAC-Europe Workgroup on LCA and Conceptually Related Programs and SETAC-Europe Workgroup on LCA Case Studies and participation in the European Union Research Programme LCANET as well as in thhe European Union Concerted Action CHAINET (Zbigniew Kłos). More about these works were presented in publication of Kłos [25] and Adamczyk [1] working at the University of Economics in Cracow. Since then, there have been more and more publications on the subject. In addition to these two centres, which initiated the LCA research in Poland, this topic began to develop in the following scientific centres: PUEB, University of Zielona Góra, Gdynia Maritime Academy, Mineral and Energy Economy Research Institute of Polish Academy of Sciences, Central Mining Institute and Wood Technology Institute. The innovative scope of LCA research in these centres has been discussed in a number of scientific reports, among others in the review papers of Kłos [16, 25, 26, 65], Lewandowska [15, 16, 32, 39, 65] and Kulczycka [32].

This review paper characterizes individual centres, scientists working in them and the main research topics. Our goal is not to re-describe them; however short characteristics will be presented in the research part when discussing the results of the bibliometric ranking. The growing number of publications in both national and significant international journals was also pointed out in these studies. The list of publications of Polish researchers in the journals possessing impact factor already includes several dozen items. The first publication in a leading journal, IJLCA, with Kłos co-authorship appeared in 2000 [57] and subsequent completely by national authors in 2004 [40, 43]. The following years brought further publications together with the growing number of centres starting research in the field of LCA/LCM. These publications meet a growing interest as evidenced by their increasing number of citations. However, no comparative analysis of these publications has yet been carried out. The aim of this work is therefore not only the presentation of scientists from a given Polish LCA centres but also an attempt of the bibliometric analysis of Polish LCA's scientist performance. The question arises: what kind of indicators would be really useful for such analysis? Under evaluation of a paper, the three main factors, impact factor of a journal, number of citations and year of publication, seem to determine the importance of a given publication.

3 Proposed Bibliometric Method of Polish LCA's Scientist Achievement Evaluation

3.1 Methodology

The number of scientific publications and the number of journals have increased considerably in the last few years. How to find out in this thicket which are valuable and which are not worth? Some probably remember that there is Eugene Garfield who began a new era in the processes of evaluation and measurement of scientific publications with his radical invention, the Science Citation Index (SCI), which enabled the statistical analysis of large-scale scientific literature [19]. Then, several methodologies for evaluating scientific papers were proposed [54]. Early work in this field, consisting in determining the quality of the best works, as mentioned in [54], approached the qualitative dimension of the work represented by the journal's impact factor and the number of citations of the analysed works.

The quality of work should be assessed through its impact on the scientific community. With this in mind, we used the Methodi Ordinatio [54], a method in order to rank publications of Polish LCA researchers.

3.2 Methodi Ordinatio Description

Methodi Ordinatio is a multi-criteria assessment model (InOrdinatio) used to rank publications according to a set of criteria such as journal impact factor in which the paper was published, year of publication and number of citations [54]. The equation InOrdinatio (1) is applied to identify the scientific works' ranking:

$$\text{InOrdinatio} = (\text{IF}/1000) + \text{alfa} * [10 - (\text{ResearchYear} - \text{PublishYear})] + \text{Ci} \quad (1)$$

Where:

- IF is the journal impact factor in which the paper was published.
- alfa is the weighting factor ranging from 1 to 10, to be attributed by the researcher.
- ResearchYear is the year in which the research was developed.
- PublishYear is the year in which the paper was published.
- Ci is the number of times the paper has been cited in the literature.

The authors of the method [54] adopted the following assumptions for the equation InOrdinatio:

(a) Originally, the impact factor IF is divided by 1000 (thousand), striving to normalize its value in relation to the other criteria. We do not agree with this assumption because it depreciates this important indicator. That is why in our calculations it was assumed that we will multiply IF by 10 to give it the right rank. It is not easy to publish an article in a journal characterized by a relatively large IF. The use of the journal impact factor in academic review, promotion and tenure evaluations has been very recently discussed by McKiernan et al. [50].
(b) The equation contains a weighting factor "alfa", the value of which the researcher assigns. It can be from 1 to 10. If its value is close to 1, it means that the researcher assigns less importance to the year of publication as a criterion, and the closer to 10, when he assigns the greater importance of this criterion.

3.3 Methodi Ordinatio Application for Analysis of Polish Authors LCA's Publications

3.3.1 Adopted Research Assumptions

The scope of the research included publications in the field of LCA by Polish specialists. Their list was established on the basis of research in the scientific community. To calculate the InOrdinatio indicator, it was decided to use publications from the period 1995–2019. In the study, year 2010 was adopted as the current turning point. For years below 2010, the value of "alpha" as 5 was arbitrarily assumed. For the present decade, the value of "alpha" was assumed to be 10, because a shorter time elapsed since the publication and this means less time to quote by the scientific community.

3.3.2 Source of Data

There are several databases from which bibliometric data can be obtained, such as WoS or Scopus. However, in this work, it was decided to use the Google Scholar database, because it indexes not only IF journals but also other scientific publications, including books that do not have IF. Thus, data on the number of citations of publication data were obtained from Google Scholar citation. Included were publications that had LCA and/or LCM in the title or keywords as well as full headings Life Cycle Analysis/Assessment as well as Life Cycle Management.

In several cases, a problem was found due to the lack of a given author's profile on the Google Scholar platform. At that case, other available sources were used.

There are several ways to determine the citation index, including SCI, JCR and SJR. The study decided to use only JCR citation indicators that were obtained from the webpages of the magazine. Annual indicators were used, although the use of so-called 5-year indicators was also taken into account; however, they are not favourable for recent publications.

3.3.3 Calculation of InOrdinatio

The modified equation InOrdinatio (2) was applied for calculation:

$$\mathrm{InOrdinatio} = 10 * \mathrm{IF} + \mathrm{alfa} * \left[10 - \left(\mathrm{ResearchYear} - \mathrm{PublishYear}\right)\right] + \mathrm{Ci} \tag{2}$$

As previously justified, IF was multiplied by 10 to reflect the importance of this indicator.

4 Results and Discussion

Research is done on the base of analysis of research activities on LCA and LCM presented in details in "Bibliometric analysis of Polish LCA's scientist performance" [14]. For each leading author from a given centre, the most-read publications with at least ten citations were usually selected. In the tables presented in report [14], they were listed according to the decreasing number of citations, from the highest first. After the InO calculations, the five best publications for the centre were selected.

The results started to be presented in alphabetical order according to the name of the leading author in the given centre, with Janusz Adamczyk, as the first author considered.

In Table 1 [14] the results of InOrdinatio for authors from the University of Zielona Góra are presented. The authors began publishing in 2014, but their best publications were published in high IF journals and reach InOrdinatio above 100 with the best InOrdinatio of 147.5. The main areas of their interest are ecological

Table 1 The results of InOrdinatio for authors from the University of Zielona Góra

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[58]	8.050	37	2016	**147.5**	1
2	[12]	3.324	28	2015	101.24	5
3	[2]	5.901	26	2014	134.01	2
4	[9]	3.844	19	2014	107.44	3
5	[10]	5.715	15	2016	102.15	4
6	[11]	5.715	14	2016	101.15	6

Table 2 The results of InOrdinatio for authors from the Central Mining Institute

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[4]	3.590	119	2013	**214.9**	1
2	[5]	4.900	32	2016	111.0	2
3	[18]	5.651	27	2017	103.51	4
4	[27]	5.715	23	2016	110.15	3
5	[7]	4.601	18	2016	94.01	5
6	[60]	4.610	15	2017	81.10	
7	[6]	3.173	15	2016	56.73	

and economic aspects of reducing low emissions using the LCA technique and LCA application in the construction industry.

Wacław Adamczyk from Cracow University of Economics should be second. His publication achievements can be found in the literature list [3]; however, the lack of his Google Scholar profile makes impossible the analysis of Methodi Ordinatio. However, it should be mentioned that Adamczyk and his team is one of the precursors in promoting life cycle thinking in relation to products. Noteworthy is also the organization of several editions of the Ecology of Products conferences, which resulted in important monographs [3]. The use of the LCA method in the decision-making processes of production companies and in their product policy is currently the main scope of activity of this research group.

In Table 2 [14] the best publications of the group whose leader is Burchard-Korol are presented. The group leader while working at the Central Mining Institute has carried out extensive work on the application of life cycle assessment and eco-efficiency in mining and quarrying sectors. From 2018 (at the Silesian University of Technology, Faculty of Transport), she has been examining the importance of assessing the environmental life cycle of transport. Noteworthy is the publication [4], which already has 119 citations, which gives rather high InOrdinatio equal 214,9.

Similar research issues were carried out by Czaplicka-Kolarz (currently she works at the Silesian University of Technology, Faculty of Organization and Development). Her papers were summarized in Table 3 [14] with the best InOrdinatio equal 111.0.

Table 3 The results of InOrdinatio for Czaplicka-Kolarz from the Central Mining Institute

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[5]	4.900	32	2016	**111.0**	1
2	[18]	5.651	27	2017	103.51	2
3	[7]	4.601	18	2016	94.01	3
4	[6]	3.173	15	2016	56.73	4

Table 4 The results of InOrdinatio for Foltynowicz group (from Poznan University of Economics and Business)

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[43]	1.6	39	2004	**130.0**	1
2	[44]	1.8	19	2008	92.0	4
3	[40]	0.366	14	2004	92.66	3
4	[39]	1.6	10	2004	101.0	2

Table 5 The results of InOrdinatio for research group from Poznan University of Technology

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[57]	1.039	62	2000	157.39	3
2	[41]	3.148	50	2010	**171.48**	1
3	[35]	3.148	32	2010	163.24	2
4	[65]	3.988	29	2014	118.88	4
5	[45]	3.089	26	2013	116.89	5*
6	[17]	3.173	19	2016	80.73	
7	[32]	2.362	13	2011	116.82	5*
8	[59]	3.988	12	2014	101.88	
9	[34]	3.988	8	2014	97.88	

*Same rank because of very small difference

Table 4 [14] presents the achievements of Foltynowicz group from Poznan University of Economics and Business, which was the third one who started LCA in Poland. The initial research was devoted to comparative LCA analysis of industrial objects followed by the expansive works of Lewandowska. The highest rate of InOrdinatio (130.0) is attributed to exhibit paper published in 2004 [43]. Currently, the group publishes works in the field of renewable energy (see [51, 52]).

Table 5 [14] presents the achievements of the research group from PUT Poznań (Kłos, Kasprzak, Kurczewski, et al.). The authors began publishing before year 2000 [23–25]. Their best publications reach InOrdinatio above 100 with the best of 171.48. The main areas of their interest are very broad, among other life cycle thinking in small and medium enterprises and an environmental life cycle assessment of machines and devices.

Table 6 The results of InOrdinatio for Korol

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[27]	5.715	23	2016	**110.15**	1
2	[6]	3.173	15	2016	56.73	2

Table 7 The results of InOrdinatio for research group from Mineral and Energy Economy Research Institute of the Polish Academy of Sciences in Cracow

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[33]	0.79	30	2015	77.9	
2	[45]	3.089	26	2013	**116.89**	1
3	[21]	4.732	24	2017	91.32	
4	[37]	3.173	24	2016	85.73	
5	[31]	3.331	23	2016	86.31	
6	[28]	0.25	23	2004	100.5	3
7	[20]	0.153	21	2005	92.5	5
8	[30]	2.6	20	2009	96.0	4
9	[29]	1.0	19	2007	89.0	
10	[32]	2362	13	2011	116.62	2

The achievements of Korol from the Central Mining Institute who is dealing with the evaluation of environmental footprints of biopolymers are shown in Table 6 [14].

Next, the achievements of two groups, whose leaders are strong women in LCA's science, will be presented. Table 7 [14] presents the achievements of the group whose leader is Kulczycka (Mineral and Energy Economy Research Institute of the Polish Academy of Sciences in Cracow). The issues of many works are very broad, but as befits the institute in which they work, it mainly concerns LCA issues in the field of the mineral and energy industry. The tabular summary (Table 7 [14]) shows how IF affects the InOrdinatio index. Although the largest is equal to 116.89, most publications have high citation.

Table 8 [14], which presents the achievements of the group led by Lewandowska from Poznan University of Economics and Business, contains more articles than in other cases. The reason is not only the number of publications but also the fact that they are the result of extensive cooperation with other research groups. Twelve of these works have InOrdinatio above 100. The largest InOrdinatio reach values in the range 150–170. The issues of these works include both practical and methodological aspects in the field of LCA.

The next two cases present the results of groups that publish a lot, but either in Polish language or in magazines with small IF, which affects not very high InOrdinatio. Table 9 [14] presents the achievements of the Nitkiewicz team. Nitkiewicz comes from the Kraków group of Adamczyk and currently forms a group in Częstochowa (Center of Life Cycle Modeling). Research work of this group is directly related to LCA and its applicability. Group members have

Table 8 The results of InOrdinatio for research group from Poznan University of Economics and Business

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[55]	2.296	60	2014	132.96	4
2	[38]	2.362	53	2011	156.62	*3*
3	[41]	3.148	50	2010	**171.48**	**1**
4	[56]	3.341	40	2014	123.41	
5	[43]	1.6	39	2004	130.0	
6	[42]	2.296	35	2014	106.96	
7	[46]	2.465	35	2013	119.65	5
8	[35]	3.148	32	2010	163.24	*2*
9	[47]	3.324	31	2015	104.24	
10	[65]	2.296	29	2014	101.96	
11	[45]	3.089	26	2013	116.89	
12	[37]	3.173	24	2016	85.73	
13	[17]	3.173	19	2016	80.73	
14	[44]	1.8	19	2008	92.0	
15	[40]	0.366	14	2004	92.66	
16	[32]	2.362	13	2011	116.62	

Table 9 The results of InOrdinatio for research group from the Faculty of Management at Częstochowa University of Technology

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[61]	1.08	10	2015	**60.8**	1
2	[62]	0	7	2014	57	2
3	[53]	1.334	1	2017	43.34	3

Table 10 The results of InOrdinatio for research group from UTP University of Science and Technology in Bydgoszcz

Order number	Publication number according to the list	IF	Number of citation	Year of publication	InOrdinatio	Ranking
1	[63]	0.763	11	2017	**38.63**	1
2	[13]	1.21	9	2018	31.1	2
3	[64]	1.214	4	2018	26.14	3

published about 30 scientific works, however, mainly in Polish publishing houses, which results that only three of them have citations. This is reflected in the low InOrdinatio values.

The situation is similar in the case of Tomporowski research group from UTP Bydgoszcz. Table 10 [14] presents selected achievements of this research group, which are cited publications from indexed periodicals. Although these publications have been published in recent years, they already have citations. Other numerous publications in non-indexed periodicals affect InOrdinatio. The subject of this research is very current and focuses on various aspects of the LCA of an offshore wind farm.

In addition to the above research groups, LCA/LCM analyses are carried out in several other centres, as evidenced by the number of licenses purchased for SimaPro or GaBi computing programs, like at ZUT (West Pomeranian University of Technology, Szczecin [8]), Łódź University [48, 49] and COBRO Institute [36, 66, 67].

5 Reassuming and Conclusions

The bibliometric analysis of Polish LCA's scientists' performance has been performed. Based on the review of discipline-related journals and the information collected, InOrdinatio was determined using the Methodi Ordinatio. The year of publication and the number of citations of the publication were taken into account, as well as the IF of the magazine in which the article was published. On this basis, InOrdinatio was determined, and the best five publications from a given centre were

Table 11 Ranking of the best papers from Polish LCA research groups

Ranking number	Publication number[a]	IF	Number of citation	Year of publication	InOrdinatio	InOrdinatio 5s	Group
1	[4]	3.590	119	2013	214.90	523.42	Burchard-Korol group
2a	[41]	3.148	50	2010	171.48	743.95	Lewandowska PUEB group
2b	[41]	3.148	50	2010	171.48	727.88	PUT Poznań group Kłos
3	[58]	8.050	37	2016	147.50	592.34	Univ. of Z. Góra group
4	[43]	1.6	39	2004	130.00	415.66	Foltynowicz PUEB group
5	[45]	3.089	26	2013	116.89	522.51	Kulczycka group
6	[5]	4.900	32	2016	111.00	478.73	Czaplicka-Kolarz et al.
7	[27]	5.715	23	2016	110.15	166.88	Korol et al.
8	[61]	1.08	10	2015	60.80	161.14	Częstochowa LCM Center
9	[63]	0.763	11	2017	38.63	95.87	UTP Bydgoszcz group

Source: own research

[a]Publication number according to the References section

selected. This allowed the ranking of the best publications of Polish authors to be made. Table 11 presents a summary of the best works from individual research groups.

The largest InOrdinatio characterized a work by Burchard-Korol et al. [4], which has been cited 119 times. Second place comes joint publication of authors from PUEB and PUT. The third place is for the group from the University of Zielona Góra. The largest InOrdinatio does not always seem to reflect the actual position of a given group, especially when other publications have smaller InOrdinatio. That is why InOrdinatio was summarized for the five best publications from a given group, resulting in InOrdinatio 5s. It turned out that the leader is Lewandowska group, which accumulated almost 744 InOrdinatio 5s points. The second place with the result of 728 points of InOrdinatio 5s was taken by the team led by Kłos. The third position is occupied by the group from the University of Zielona Góra with 592 InOrdinatio 5s and next (523 InOrdinatio 5s) places are for the Burchard group and Kulczycka group. InOrdinatio was determined using JRC indexes. Perhaps the use of other parametric indexes would affect the ranking results, which will be checked in the future.

It is worth noting that the cooperation of the PUT, PUEB and Polish Academy of Sciences in Cracow groups brings very good scientific and bibliometric results. It is also worth mentioning that Polish scientists are establishing international cooperation, which also brings effects in the form of indexed publications.

One should also mention the numerous monographs on the subject of LCA/LCM by Polish authors, which, however, appeared in Polish. Polish scientists are also co-authors of numerous chapters in monographs. Over 20 doctorates in this field were already defended, and several researchers also obtained postdoctoral degrees. This aspect, however, goes beyond the accepted scope of this study.

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