Integrated Life Cycle Sustainability Assessment: Hydrogen Production as a Showcase for an Emerging Methodology

Christina Wulf, Petra Zapp, Andrea Schreiber, and Wilhelm Kuckshinrichs

Abstract Ideally, life cycle sustainability assessment (LCSA) consists of life cycle assessment (LCA), life cycle costing (LCC) and social life cycle assessment (S-LCA) based on a joint technical model. For an integrated and consistent LCSA, however, this is not enough. Therefore, in this work, a coherent indicator selection based on the Sustainable Development Goals (SDGs) as well as an integration of the impact categories/indicators with the help of multi-criteria decision analysis is conducted. The chosen method PROMETHEE does not allow full compensation of the sustainability indicators, which reflects a possible view on sustainability. The SDG-based approach is compared with a classical approach where the weighting is based on the three sustainability dimensions. Both are tested on comparison case study of a 6 MW pressurized electrolyser located in three European countries, i.e. Spain, Germany and Austria, to illustrate the difference of industrial hydrogen production in industrialized countries with different structures of electricity markets.

1 Introduction

The Sustainable Development Goals (SDGs) published in 2015 by the UN [1] gain more and more importance. This is true not only for countries and for regions, for which they were drafted in the first place, but also for companies and academia. For life cycle sustainability assessment (LCSA), there are several approaches to link those two concepts. For example, the project "Linking the UN SDGs to life cycle impact pathway frameworks" [2] by 2.-0 LCA consultants and PRé consultants under the umbrella of the UN Life Cycle Initiative develops impact pathways for the SDGs, which are cause-effect oriented. These should, for example, serve as impact categories for the social life cycle assessment (S-LCA) [3]. Owsianiak et al. [4]

C. Wulf (✉) · P. Zapp · A. Schreiber · W. Kuckshinrichs
Forschungszentrum Jülich, Institute of Energy and Climate Research – Systems Analysis and Technology Evaluation, Jülich, Germany
e-mail: c.wulf@fz-juelich.de

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have taken the SDG indicators related to the environment and have tested if they actually help to reach environmental sustainability. For that, they did not only take principles of life cycle assessment (LCA) into account but also the planetary boundaries. A rough match between the SDGs and LCSA indicators has been done by the authors in an earlier study Wulf et al. [5]. They assigned the often used LSCA indicators to the SDGs as well as their indicators.

These approaches concentrate mainly on indicator selection and impact assessment. A further topic of LCSA is the integration of indicators with the help of multicriteria decision analysis (MCDA) [6, 7]. In this paper, it is presented how the SDGs can guide MCDA for LCSA. The implications of this approach in contrast to the understanding of sustainability based on three dimensions are discussed afterwards. The different effects are analysed on the example of comparing different locations for hydrogen production as an actual LCSA case study.

2 Methodology

In this paper, an LCSA is performed with the guidance from the SDGs (Fig. 1). They are used for the indicator selection as well as for the MCDA. The quantification of the different indicators is done with classical LCA, life cycle costing (LCC) and S-LCA, the latter performing a hot spot analysis. These SDG-guided indicator values describe the performance of the considered systems and form the input for the MCDA method PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations). In many studies, the three assessment methods are regarded as equally important because they are loosely representing the three dimensions of sustainability [6]. This premise is used to derive weighting factors for the different indicators. In this study, however, not the three dimensions of sustainability are considered as equally important, but each sustainability goal has the same importance. This leads to a different set of weighing factors than is the case with the three dimensions of sustainability. In this section, the relation between the SDGs and the LCSA indicators is explained in more detail as well as the choice of method for MCDA and how the weighting factor set is calculated.

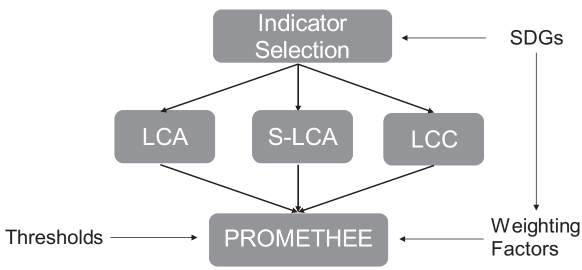

Fig. 1 Approach for integrating the SDGs into LCSA

2.1 Sustainable Development Goals and LCSA Indicators

The assignment of LCSA indicators to the SDGs is based on the previous paper [5]. The indicators are selected based on common guidelines. For the LCA, these are the recommendations from the ILCD [8] and guidance documents by theUNEP/SETAC [9]. Indicators on the midpoint level are used as implemented in the GaBi software. The S-LCA indicators are based on the respective UNEP/SETAC guidelines [10] and their interpretation in PSILCA 2 [11] for a hotspot analysis. Indicators in PSILCA 2 tackling issues that are also assessed by LCA are excluded from the selection. The LCC indicators are guided by the European Investment Bank [12]. Particular attention has been paid to avoid double or triple counting of topics. The findings of this matching can be seen in Fig. 2.

It must be mentioned that goals 2, 11 and 17 cannot be described by LCSA indicators.

2.2 Multi-criteria Decision Analysis

When performing a full LCSA, a bundle of very different indicator values with physical, monetary and other units result. In such a case, MCDA can help to structure the decision-making process. Within this MCDA guidance process, fundamental value-based choices have to be made. In particular, it has to be decided to what extent compensation between indicators is allowed. In this work, compensation is not allowed. With respect to a value-based approach, this is a very crucial assumption. However, it helps to clarify the problem. As a specific method representing this, PROMETHEE II [14] is chosen. This method is based on a pairwise comparison of the different options. The most preferable option has the highest result, which is called outranking flow Φnet. A linear preference function with indicator-specific thresholds is applied [15].

2.3 Equal Weighting of SDGs

The premise of the indicator weighting of this paper is that each SDG has the same weight. Furthermore, indicators describing one SDG have the same importance. However, this results in unequal weighting of indicators in case of different numbers of indicators per SDG. Additionally, there are some indicators describing not only one goal but two or more. For example, trade union (density as a % of paid employment total) is describing goal 8 (decent work and economic growth) as well as goal 16 (peace, justice and strong institutions) (see Fig. 1). To avoid an overestimation of such indicators, the number of indicators in one goal m is normalized with the number of assigned goals p. This is mathematically expressed in Eq. 1.

Fig. 2 SDGs and their respective LCSA indicators, icons from [13]; bold LCC indicators (four indicators), italic LCA indicators (13 indicators), normal S-LCA indicators (26)

$$w_i = \frac{1}{n \cdot m_n / p} \tag{1}$$

w_i: weighting factor of indicator i, with $\sum w_i = 1$,
n: number of goals with assigned LCSA indicators, i.e. 14
m_n: number of indicators in one goal
p: number of assigned goals

To calculate the weighting factors based on the sustainability dimensions, the number of goals with assigned LCSA indicators needs to be substituted with the number of sustainability dimensions.

3 Case Study

To test the application of the SDG-guided LCSA indicator set of already existing LCA, S-LCA and LCC are adapted in a case study. The case study comprises a comparison of three locations for hydrogen production with an advanced alkaline water electrolyser. The European countries Germany, Spain and Austria offer different opportunities for industrial hydrogen production. The LCA modelling is based on Koj et al. [16], while the LCC is taken from Kuckshinrichs et al. [17]. The S-LCA [18] is conducted using the PSILCA database [11] integrated in openLCA 1.6. The functional unit for the LCSA is 1 kg of hydrogen (30 bar) produced.

4 Discussion and Results

Here the calculated indicator weights as well as the overall result using PROMETHEE are presented and compared with indicator weights derived from the approach of equal importance of the three sustainability dimensions. The values for each LCSA indicator can be found in Annex, Table 2.

4.1 SDG-Guided Indicator Weights

The derived weighting factors for the different LCSA indicators have a wide range (Table 1). They vary between 0.006 and 0.071. The results are solely based on the numbers of indicators selected for a goal, but not on any subjective assumption on the weight of indicators. Five indicators have the highest weighting factor. These are two LCC and two LCA indicators as well as indigenous rights (human rights issues faced by indigenous people).

Table 1 LCSA indicators and their weights according to SDG equal weighting

Indicator	Goal	Weight	Indicator	Goal	Weight
Child labour, total	8	0.006	Youth illiteracy, total	4	0.024
Frequency of forced labour	8	0.006	Ecotoxicity, freshwater	14	0.024
Goods produced by forced labour	8	0.006	Eutrophication, freshwater	14	0.024
Trafficking in persons	8	0.006	Eutrophication, marine	14	0.024
Net present value	8	0.006	Water depletion	6	0.024
Weekly hours of work per employee	8	0.006	Association and bargaining rights	8,16	0.015
Profitability index	8	0.006	Trade unionism	16, 8	0.015
Photochemical ozone formation	3	0.007	Violations of employment laws and regulations	8, 16	0.015
Health expenditure	3	0.007	Sanitation coverage	3, 6	0.015
Non-fatal accidents	3	0.007	Gender wage gap	5	0.036
Safety measures	3	0.007	Unemployment	1	0.036
Human toxicity, cancer	3	0.007	Women in the sectoral labour force	5	0.036
Ionizing radiation	3	0.007	Acidification, terrestrial	15	0.036
Human toxicity, non-cancer	3	0.007	Eutrophication, ter.	15	0.036
Ozone depletion	3	0.007	Fair salary	1, 8	0.021
Particulate matter	3	0.007	Indigenous rights	10	0.071
Fatal accidents	3	0.007	Levelized cost	7	0.071
Social security expenditures	3, 8	0.007	Marginal cost	9	0.071
Drinking water coverage	6	0.024	Climate change	13	0.071
Education	4	0.024	Resource depletion	12	0.071
Illiteracy, total	4	0.024			

In the approach of equal sustainability dimensions, all LCC indicators have a weight of 0.083, all LCA indicators of 0.024 and all S-LCA indicators of 0.014. With the switch from dimensions to SDGs the indicator indigenous rights shows the highest increase in the weighting factor from 0.014 to 0.071. The largest decrease is recorded for the indicator net present value from 0.083 to 0.006.

4.2 PROMETHEE Results

The PROMETHEE results for the two different weighting sets are presented in Fig. 3. High results indicate the preferable outcome. In both versions, the Spanish option is identified as the least favourable one. Both weighting sets, however, lead to different results for the most preferable option. The set based on SDGs identifies Austria as the most sustainable country for hydrogen production, while an equal weighting of the sustainability dimensions leads to the conclusion that Germany is the most preferable one.

Germany shows the best results with regard to its LCC indicators (Annex, Table 2). As these indicators lose weight (in total 0.155 instead of 0.333), Germany is not considered as the most sustainable option when SDG-guided weighting is considered. The overall weight of the LCA indicators keeps relatively constant (0.352 instead of 0.333), while the social indicators gain influence (0.420 of instead 0.333).

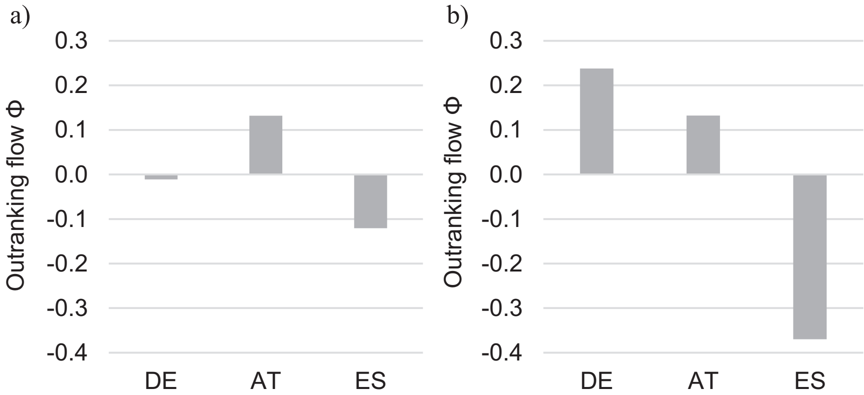

Fig. 3 PROMETHEE results of hydrogen production in three different countries: (**a**) based on SDGs, (**b**) based on sustainability dimensions (DE, Germany; AT, Austria; ES, Spain)

Table 2 LCSA indicator results, based on [5] (med. rh: medium-risk hours)

Indicator	Unit	Germany	Austria	Spain
Child labour, total	Med. rh	0.98	1.08	0.60
Frequency of forced labour	Med. rh	0.46	0.57	0.16
Goods produced by forced labour	Med. rh	0.30	0.29	0.22
Trafficking in persons	Med. rh	2.30	2.81	1.34
Weekly hours of work per employee	Med. rh	0.26	0.48	0.45
Net present value	m€$_{2015}$/kg H_2	−50.1	−58.1	−59.4
Profitability index	Med. rh	−6.38	−7.45	−7.74
Fatal accidents	Med. rh	0.40	0.55	0.26
Health expenditure	Med. rh	6.07	6.24	3.59
Non-fatal accidents	Med. rh	4.03	13.82	27.12
Safety measures	Med. rh	4.89	5.71	5.15
Human toxicity, non-cancer	nCTUh	37.5	14.8	27.1
Human toxicity, cancer	100 nCTUh	9.77	5.07	4.34
Ionizing radiation	100 Bq U235 eq	27.6	0.33	32
Ozone depletion	ng CFC-11 eq	6.32	4.38	5.03
Particulate matter	100 mg $PM_{2.5}$ eq	20	8.7	24.6
Photochemical ozone formation	g NMVOC	30	16.4	33

(continue)

Table 2 (continue)

Indicator	Unit	Germany	Austria	Spain
Social security expenditures	Med. rh	5.79	5.72	2.62
Drinking water coverage	Med. rh	2.60	2.90	1.65
Education	Med. rh	3.01	2.32	4.56
Illiteracy, total	Med. rh	4.45	4.43	2.21
Youth illiteracy, total	Med. rh	0.75	0.81	0.45
Ecotoxicity, freshwater	CTUe	5.59	3.31	3.71
Eutrophication, freshwater	10 mg P eq	12.8	13.3	9.32
Eutrophication, marine	m g N-eq	11.2	7.31	11.6
Water depletion	m^3 world eq.	22	22.3	43.1
Assoc. + barg. Rights	Med. rh	6.54	16.48	1.81
Trade unionism	Med. rh	25.75	18.46	43.89
Violations of employment laws and regulations	Med. rh	1.93	3.22	3.04
Sanitation coverage	Med. rh	13.89	14.17	8.15
Gender wage gap	Med. rh	5.47	31.94	7.96
Unemployment	Med. rh	0.81	0.77	37.43
Women in the sectoral labour force	Med. rh	1.85	1.93	3.93
Acidification	mMole H^+ eq.	44.5	21.6	50.3
Eutrophication, terrestrial	10 mMole N eq.	11.6	6.5	12.1
Fair salary	Med. rh	5.46	7.73	2.30
Indigenous rights	Med. rh	1.44	1.79	0.78
Levelized cost of hydrogen	$€_{2015}$/kg H_2	3.64	4.22	4.31
Marginal cost	$€_{2015}$/kg H_2	3.72	4.52	4.73
Climate change	kg CO_2 eq	29.8	29.8	29.8
Resource depletion	10 mg Sb eq	12.9	3.88	9.38

5 Conclusions

In this work, two different approaches how to cluster sustainability indicators are presented. The results show that the method considered can have a significant influence on the overall preference of options. In the case of hydrogen production in Europe, the classification based on the SDGs prefers a location in Austria, while the other classification based on the dimensions of sustainability results in a preference for a German location.

Using the same indicator set, other classifications are possible. In this paper, the dimensions of sustainability are separated by different methods. The indicators, however, can also be classified by other ways of argumentation. This could mean that human health indicators are assigned to the social dimension [e.g. 19]. In many cases, the three dimensions of sustainability are used [6]. There are other approaches available like the proposed SDGs that have different implications. For example, the SDGs do not cover indicators assessing corruption, and the stakeholder group consumers are not represented. In addition, the focus of the SDGs is less on the economic indicators and more on the social ones. In contrast, regarding the three dimensions of sustainability, some indicators might be assigned to different dimensions, e.g. resource depletion.

Another way to establish weighting factors for MCDA is not to derive them from concepts, but to ask stakeholders, e.g. residents and users or LCSA practitioners, about their preferences. It is to be expected that such an approach would probably lead to a different weighting set than the one presented. Here, the social indicator with the highest weighting factor is indigenous rights. Even though this is a very important topic, in the context of hydrogen production in three different European locations, it is probably not the most pressing social issue. Consequently, several questions arise that need to be answered in the future. An important one will be how sustainability is understood in LCSA and which principles should be at the basis?

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