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Sustainable development goals as a guideline for indicator selection in Life Cycle Sustainability Assessment

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Abstract

Life Cycle Sustainability Assessment (LCSA) emerged as a methodology allowing a detailed representation of technologies in their processes from a life cycle perspective. To conduct a profound LCSA a plausible indicator selection is needed. From a Sustainability perspective, the currently dominant political framework is the Sustainable Development Goals (SDGs) of the United Nations. In this paper, LCSA indicators are selected based on the SDGs, comparing in a first approach the implication due to the selection based on overall goals and SDG indicators level. The applicability of this selection is tested by a case study of electrolytic hydrogen production. The analysis shows meaningful differences between the goal-based and the indicator-based assessment. Only the goal-based indicator set comprises all dimensions of sustainability.

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Keywords: Indicator selection, Life Cycle Sustainability Assessment, Sustainable Development Goals, Hydrogen

1. Introduction

Life Cycle Sustainability Assessment (LCSA) emerged as a methodology allowing a detailed representation of technologies in their processes from a life cycle perspective. In addition, it enables sustainability assessments in its different perspectives (environmental, economic and social). To conduct a profound LCSA, a plausible indicator selection is needed. One possible approach to define an LCSA indicator set is to follow political decision processes. Currently, the most important political decision process on a global scale is the definition of Sustainable Development Goals (SDGs) by the UN [1], see Table 1. An indicator set chosen for technology sustainability assessment is gaining increasing relevance and reliability if related directly to SDGs.

Table 1 Sustainable development goals [1].

No.	Goal
1	End poverty in all its forms everywhere
2	End hunger, achieve food security and improved nutrition and promote sustainable agriculture
3	Ensure healthy lives and promote well-being for all at all ages
4	Ensure inclusive and equitable quality education and promote lifelong learning opportunities for all
5	Achieve gender equality and empower all women and girls
6	Ensure availability and sustainable management of water and sanitation for all
7	Ensure access to affordable, reliable, sustainable and modern energy for all
8	Promote sustained, inclusive and sustainable economic growth, full and productive employment and decent work for all
9	Build resilient infrastructure, promote inclusive and sustainable industrialization and foster innovation

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10	Reduce inequality within and among countries
11	Make cities and human settlements inclusive, safe, resilient and sustainable
12	Ensure sustainable consumption and production patterns
13	Take urgent action to combat climate change and its impacts
14	Conserve and sustainably use the oceans, seas and marine resources for sustainable development
15	Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss
16	Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels
17	Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development

The SDGs have already been recognised by the Life Cycle Assessment (LCA) community. Maier et al. [2] assign the SDGs to certain impact category groups, e.g. health or climate, and, in a second stage, assign impact categories to the category groups, e.g. respiratory diseases as part of the group health. Each impact category can be comprised of different indicators, which can be case specific or more generic LCA impact categories. The authors apply this approach to the example of the impact category group health in the context of development cooperation projects. However, no full example for an application of all impact categories is given and the direct connection between the chosen indicators and the SDGs is weakened by several steps of impact categorization. Another publication [3] assigns the SDG indicators to stakeholders based on LCA and the Product Social Metrics Handbook. This assignment, however, can only be the first step to a connection between SDGs and LCSA.

Though the SDGs are designed for countries or regions also a product based sustainability assessment method like LCSA can provide guidance. In this paper the LCSA indicators are assigned to the SDGs in a first step and their indicators published by the UN [4] in a second step for a product on the micro level. The applicability of this selection will be tested by an LCSA case study about electrolytic hydrogen production. This work is supposed to be a first approximation between LCSA and SDGs and demonstrates which problems might occur along the way.

2. Methodology

As already mentioned, the SDGs are predominantly targeted towards countries and regions. For the assessment of products they more or less do not fit. To close this gap, it is necessary to identify the motivation behind the SDGs. As the UN not only passed goals but also defined indicators and targets to lay them out further, these specifications can be used as guidelines for indicator selection in LCSA also.

The SDGs are tiered into the actual **goals**, e.g. 3 'Ensure healthy lives and promote well-being for all at all ages', see Table 1, **targets**, e.g. 3.9 'By 2030, substantially reduce the number of deaths and illnesses from hazardous chemicals and air, water and soil pollution and contamination', and SDG **indicators**, which describe how the targets can be measured, e.g. 3.9.1 'Mortality rate attributed to household and ambient air pollution' [4]. In total 169 targets and 232 SDG indicators have been developed by the UN.

The LCSA indicator set comprises indicators from LCA, social LCA (s-LCA), and Life Cycle Costing (LCC). LCA is an established method to evaluate environmental impacts of technologies or products. Its methodology has been enhanced for decades. Therefore, several indicators have consensus within the community, only their methodology is continuously updated. Also for still controversial indicators, e.g. water, a consensus is sought after [5]. In contrast, social LCA (s-LCA) is a relatively new field of research with little consensus on methodology and indicators. The here applied PSILCA database is only one of several approaches, which try to operationalise social assessment. LCC is an established approach in economics [6, 7]. However, historically the approach is not linked to sustainability assessments, the chosen indicators are varying, and the methodological harmonization with LCA in the form of environmental life cycle costing is quite new [8].

In a first step of our approach the SDG goals are matched with LCSA indicators. The goals, however, are often very general. Some LCSA indicators can therefore be matched very easily, while others, which are equally important, find no connection. In a second step a look is taken at the SDG indicators, which are much more specific. As they are initially customized for regions and countries there is sometimes more argumentation needed to match them with product related LCSA indicators. Thus, a line of reasoning needs to be given for most of the indicator pairs. The target tier of the SDGs is not further discussed since it mainly pertains to the time horizon of goal fulfilment. A depiction of this approach is presented in Fig. 1.

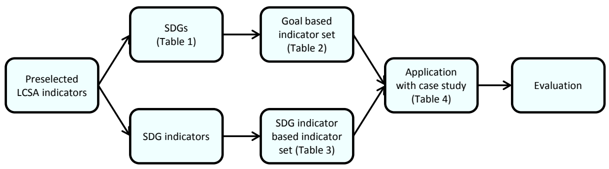

Fig. 1. Schematic diagram to link SDGs with LCSA.

The LCA indicator selection is starting from the ILCD recommendations [9] and the more recent guidance from the UNEP/SETAC [10] on a midpoint level. Only those LCA indicators implemented in the LCA software GaBi 7 are taken into consideration. The s-LCA indicators must be implemented in the PSILCA database 1.0 [11]. These indicators are based on the s-LCA guidelines [12] and the accompanying methodological sheets [13]. The PSILCA database uses the multi-regional input/output database Eora and provides data for 189 countries [11]. Consequently, the data in PSILCA is provided per sector as specified in Eora. However, social and socio-economic data is not always available per sector but rather on the country level, which is also, for example, the case for the illiteracy indicator. In such a case the developers of PSILCA used several steps to attribute data to each sector, starting by mapping the sectors to the raw data from statistical agencies as well as private and governmental databases. Afterwards data for sectors, for which raw data was not available, was extrapolated. This data was risk-assessed by PSILCA in line with international conventions and standards. For example, the risk assessment of illiteracy in the German electricity sector is stated as 'very low risk'. Given that many of the indicators used in s-LCA refer to the general societal situation in a country, exact scaling to the functional unit proves difficult.

The inventory needed as input for the PSILCA calculations are technical specification about the product system, which are translated into monetary terms using publicly available prices (e.g. Alibaba.com). PSILCA then connects these monetary amounts of each sector input with the risk-assessed social data established through the methodology described above. Advantages and disadvantages of this relatively new approach are not topic of this paper.

The LCC indicators refer to a guide prepared by the European Investment Bank [14] and literature on economic assessment of energy technologies, e.g. [15-17]. In this indicator selection double or even triple counting of indicators is prevented. Therefor only 54 indicators are looked at in PSILCA. The other PSILCA indicators are already provided for by LCA indicators.

3. Results

3.1. Indicator selection

When assigning the LCSA indicators to the SDGs on goal tier, 14 out of 17 goals can be described by LCSA indicators, see Table 2.

Table 2 LCSA indicators assigned to SDGs on goal tier (normal: LCA indicators, bold: s-LCA indicators, italic: LCC indicators).

No.	LCSA Indicator
1	**Living wage, Minimum wage, Sector average wage, Unemployment rate in a country**
2	-
3	Human toxicity cancer, Human toxicity non-cancer, Ionizing radiation, ozone depletion, Particulate matter, Photochemical ozone creation**, Accident rate at workplace, Fatal accidents at workplace, Presence of sufficient safety measures, Drinking water coverage, Sanitation coverage, Health expenditure public, Health expenditure out of pocket, Health expenditure external resources, Health expenditure out of the total GDP of the country, Social security expenditure**
4	**Illiteracy rate total, Youth illiteracy rate total**
5	**Women in the labour force, Gender wage gap**
6	Resource depletion – Water, **Drinking water coverage, Sanitation coverage**
7	*Levelized cost of energy*
8	**Goods produced by forced labour, Frequency of forced labour, Tier placement referring to trafficking in persons, Children in employment total, Living wage, Minimum wage, Sector average wage, Trade union density as a % of paid employment total, Right of Association, Right of Collective Bargaining, Right to Strike, Social security expenditure, Evidence of violations of laws and employment regulations, Hours of work per employee, per day, Hours of work per employee, per week, Standard weekly hours, Standard daily hours,** *Net present value*, *Profitability index, Internal rate of return, Payback time, Dynamic payback time*
9	*Marginal cost*
10	**Human rights issues faced by indigenous people**
11	-
12	Resource depletion – Abiotic resources
13	Climate change
14	Freshwater ecotoxicity, Freshwater eutrophication, Marine eutrophication
15	Acidification, Terrestrial eutrophication
16	**Freedom of association rights, Trade union density as a % of paid employment total, Right of Association, Right of Collective Bargaining, Right to Strike, Evidence of violations of laws and employment regulations**
17	-

For the social indicators 32 out of 54 provided by PSILCA are matching to characterise the SDGs. An example for an important social issue not compatible with the SDG goal tier is corruption, which is excluded from this level of analysis. For the environmental indicators 14 out of 16 from the recommendations can be assigned to the SDGs. Only impacts regarding land use and energy demand find no place within the SDGs. The LCC indicators comprise the levelized cost of energy, the net present value of the investment, operation and deconstruction phases, the profitability index of an investment, and the marginal cost of energy supply. Generally, further economic indicators are relevant for assessing a technology such as the internal rate of return, payback time or dynamic payback time. Depending on the system boundary they are applicable only in case the use phase of the product (or the demand side paying a price for the intended product) is part of the analysis.

The assignment of LCSA indicators to the SDG indicators is listed in Table 3. Then, only twelve out of 17 goals from the SDGs can be covered on an SDG indicator tier. Apart from goal 17, which is covered neither on a goal nor on an indicator tier, the two approaches lead to different goals not being considered. For the goal tier these are goals 2 and 11. On a SDG indicator tier the goals 5, 9, 13, and 15 are not covered. Here, it is most surprising that goal 13 ('climate change') cannot be represented by the LCA impact category climate change. The SDG indicators are targeted towards climate change adaptation and not mitigation.

Table 3 LCSA indicators assigned to SDGs on indicator tier.

No.	SDG Indicator	LCSA Indicator	Reason
1.3.1	Proportion of population covered by social protection floors/systems, by sex, distinguishing children, unemployed persons, older persons, persons with disabilities, pregnant women, newborns, workinjury victims and the poor and the vulnerable	**Social security expenditure**	**Expenditure related to population can show proportion of population covered**
1.a.2	Proportion of total government spending on essential services	**Public expenditure on**	

	(education, health and social protection)	**education**	
2.5.2	Proportion of local breeds classified as being at risk, not-at-risk or at unknown level of risk of extinction	Ecosystem toxicity, Climate change, Acidification, Eutrophication (marine, freshwater, terrestrial)	Climate change will effect biodiversity [18], Acidification reduces biodiversity [19], Eutrophication leads to a loss in biodiversity [20]
3.3.2-3.3.5	Tuberculosis incidence per 100,000 population Malaria incidence per 1,000 population Hepatitis B incidence per 100,000 population Number of people requiring interventions against neglected tropical diseases	Climate change	Climate change can lead to more infection diseases [18]
3.4.1	Mortality rate attributed to cardiovascular disease, cancer, diabetes or chronic respiratory disease	Particulate matter, Photochemical ozone creation, Human toxicity cancer and non-cancer, Ozone depletion, Ionizing radiation	Particulate matter and photochemical ozone can lead to chronic respiratory diseases [21, 22], more UV-B radiation leads to cancer [23] as well as exposure to ionizing radiation [24]
3.8.2	Proportion of population with large household expenditures on health as a share of total household expenditure or income	**Health expenditure, out of pocket**	
3.9.1	Mortality rate attributed to household and ambient air pollution	Particulate matter, Human toxicity cancer and non-cancer	Particulate matter can lead to an early death as well as cancer [25]
4.6.1	Proportion of population in a given age group achieving at least a fixed level of proficiency in functional (a) literacy and (b) numeracy skills, by sex	**Illiteracy rate total, Youth illiteracy rate total**	
6.1.1	Proportion of population using safely managed drinking water services	**Drinking water coverage**	
6.2.1	Proportion of population using safely managed sanitation services, including a hand-washing facility with soap and water	**Sanitation coverage**	
6.4.2	Level of water stress: freshwater withdrawal as a proportion of available freshwater resources	Resource depletion – Water	
6.5.1	Degree of integrated water resources management implementation (1-100)	**Presence of certified environmental management systems**	**Integrated water resource management is one of the relevant environmental management systems**
7.3.1	Energy intensity measured in terms of primary energy and GDP	Cumulative energy demand	Measures energy intensity for a product
8.4.1, 8.4.2/ 12.2.1, 12.2.2	Material footprint, material footprint per capita, and material footprint per GDP Domestic material consumption, domestic material consumption per capita, and domestic material consumption per GDP	Resource depletion – Abiotic resources	
8.5.1	Average hourly earnings of female and male employees, by occupation, age and persons with disabilities	**Minimum wage per month, Sector average wage per month**	
8.5.2	Unemployment rate , by sex, age and persons with disabilities	**Unemployment rate in a country**	
8.7.1	Proportion and number of children aged 5-17 years engaged in child labour, by sex and age	**Children in employment total**	
8.8.1	Frequency rates of fatal and non-fatal occupational injuries, by sex and migrant status	**Accident rate at workplace, Fatal accidents rate at workplace**	
8.8.2	Level of national compliance of labour rights (freedom of association and collective bargaining) based on International Labour Organization (ILO) textual sources and national legislation, by sex and migrant status	**Right of Association, Right of collective bargaining, Right to Strike**	
10.2.1	Proportion of people living below 50 percent of median income, by sex, age and persons with disabilities	**Living wage per month, Minimum wage per month**	
10.3.1/ 16.b.1	Proportion of population reporting having personally felt discriminated against or harassed in the previous 12 months on the basis of a ground of discrimination prohibited under international human rights law	**Human rights issues faced by indigenous people**	**Indigenous people are one of the groups at risk for discrimination**
11.3.1	Ratio of land consumption rate to population growth rate	Land use	Land use for a product instead of land use for a country
11.6.2	Annual mean levels of fine particulate matter (e.g. PM2.5 and PM10) in cities (population weighted)	Particulate matter	
14.1.1	Index of coastal eutrophication and floating plastic debris density	Marine eutrophication	

14.3.1	Average marine acidity (pH) measured at agreed suite of representative sampling stations	Acidification	Aquatic ecosystems are part of general acidification [9]
16.2.2	Number of victims of human trafficking per 100,000 population, by sex age and from of exploitation	**Tier placement referring to trafficking in persons**	
16.5.1	Proportion of persons who hat at least one contact with public official and who paid a bribe to a public official, or were asked for a bribe by those public officials, during the previous 12 months	**Corruption Index or country**	
16.5.2	Proportion of businesses that had at least one contact with a public official and that paid a bribe to a public official, or were asked for a bribe by those public officials during the previous 12 months	**Active involvement of enterprises in corruption and bribery**	

For the LCA indicators all 16 are assigned to the SDG indicators. For the social assessment, in contrast, only 22 out of 54 PSILCA indicators can be matched. For example, the connection between the PSILCA indicator illiteracy and the SDGs is established by SDG indicator 4.6.1. This indicator corresponds to the statistics provided by UNESCO, which also serves as the basis for the PSILCA calculations of illiteracy. Without having full knowledge of the methods used in developing the PSILCA database we assume that the positive UNESCO literacy statistics were simply reversed to provide data for illiteracy. The decrease in indicators employed compared to the goal tier can be explained by the increased level of detail of the SDG indicator tier. For example, important social issues liked forced labour are not included on this level.

Although the chosen LCC indicators match the general focus of goals 7, 8, and 9, they do not really fit to the respective SDG indicators. The main reason is that SDG indicators do not focus on process-relevant assessments of the investment, operation, and demolition phases of plants, installation sites, respectively on economic efficiency and the rationales for investment in and operation of plants. They rather focus on assessing other scales of economic systems such as sectoral, macro-economic, development economics, institutional and socio-economic ones.

3.2. Case study

To test the application of the new found LCSA indicator sets in a case study already existing LCA and LCC are adapted. It comprises a comparison of three locations for hydrogen production with an advanced alkaline water electrolyzer. The countries Germany, Spain and Austria offer different opportunities for industrial hydrogen production. The LCA modelling is based on [26], while the LCC is taken from [17]. The s-LCA is conducted with the PSILCA database [11] integrated in openLCA 1.6. The functional unit for the LCSA is 1 kg of hydrogen produced.

The two indicator sets identified above are applied for this case study. For the LCSA goal-based indicator set 50 indicators are calculated while for the LCSA SDG indicator-based indicator set only 38 indicators are calculated. The results are listed in Table 4.

Beginning with the SDG indicator tier, for the social analysis the hydrogen production is measured against 22 social indicators. The PSILCA database combines indicators into impact categories and uses medium risk hours as unit of measurement. When calculating risk points, PSILCA produces a default output of 35 impact categories, which represent either single indicators or combined indicator sets in impact categories. The SDG indicator-based assessment provides risk levels for 17 impact categories.

The indicator-based analysis shows that out of the three locations under investigation hydrogen production in Austria (14.2 med risk hours) exhibits the highest level of social risks, followed by Spain (13.4 med risk hours) and Germany (10.1 med risk hours). Overall, the risks associated with each process stem mainly from the water (ø 60 %) and electricity (ø 40 %) sector and their upstream chains; other sectors only exert marginal impact. The overall highest level of social risks is found for ‘Fair salary’ (Germany: 1.4 med risk hours, Austria: 1.9 med risk hours) and ‘Unemployment’ (Spain: 2.0 med risk hours).

The goal-based assessment provides risk levels for 21 impact categories based on 32 social indicators. The analysis shows no difference in the ranking of locations in terms of social risk; however, the differences between the overall risk levels per location become slightly more pronounced (Austria: 15.5 med risk hours, Spain: 14.1 med risk hours, Germany: 10.1 med risk hours). In the goal-based assessment four of the impact categories considered in the indicator-based assessment are no longer included, instead, seven different impact categories are added. For example, the goal-based assessment includes the impact categories ‘Frequency of forced labour’ and ‘Goods produced by forced labour’. While forced labour is of high importance in relation to Sustainable Development, the s-LCA indicators associated with these impact categories cannot be matched with SDG indicators.

For the LCA applying the goal-based indicator set comprises the 14 identified indicators. It can be clearly stated that Austria shows the best results as it is the best country in ten out of 14 indicators. When comparing the other two countries (Spain and Germany) ranking is harder to tell as Spain shows worst results for seven and best for three indicators while Germany shows worst results for five and best for one indicator.

When applying the SDG indicator-based indicator set 16 indicators should be calculated. ‘Land use’, however, is implemented in GaBi but not with the characterisation model the UNEP/SETAC recommends [10]. Due to the ongoing scientific discussion in the LCA community this indicator is excluded from the indicator set leaving 15 indicators to be calculated. The one additional indicator does not change the overall picture already painted by the slightly smaller goal-based indicator set. Still Austria is by far the best option (best in twelve out of 15 indicators) and Spain as well as Germany still close together (seven worst indicator results each). The following statements are valid for both indicator sets:

The decisive factor is the electricity supply in all three countries. Its share amounts to 80 % in case of Austria and even 90 % in case of Spain and Germany for most indicators. Against this background it is not surprising that Austria has the lowest environmental impacts due to their high share of hydro power (58 % [27]) on the total electricity mix.

For the chosen case the economic indicators are restricted. As the use phase of the product and respective returns from market activities are excluded, the internal rate of return and payback times cannot be calculated. For all four remaining economic indicators the German site performs best. From a cost perspective, the price of electricity for the hydrogen technology has a decisive impact. Therefore, it should be kept in mind that the projection of electricity prices is subject to a range of assumptions, including the political influence on cost components such as grid transport, taxes, and contributions to finance renewable energy sources. If, contrary to the assumption here, electricity prices are going to adjust over time, and if the energy-intensive industries will lose its beneficial regulatory status with respect to the German Renewable Energy Act (EEG), the relative advantage of the German site may disappear. At the moment Germany has the lowest prices for electricity due to the regulatory status of energy-intensive industries within the financial support of renewable energy sources.

Table 4 LCSA indicator results (bold: SDG goal and indicator tier; italic: only goal tier; normal: only SDG indicator tier).

	DE	AT	ES
Environmental indicators			
Acidification, Mole of H+ eq	0.0445	0.0216	0.0503
Climate change, kg CO_2-eq	29.8	10.2	16.2
Ecotoxicity freshwater, CTUe	5.59	3.31	3.71
Eutrophication freshwater, kg P eq	1.28E-4	1.33E-4	9.32E-5
Eutrophication marine, kg N eq	1.12E-2	7.31E-3	1.16E-2
Eutrophication terrestrial, Mole of N eq	0.116	0.065	0.121
Human toxicity, cancer effects, CTUh	3.75E-8	1.48E-8	2.71E-8
Human toxicity, non-cancer effects, CTUh	9.77E-7	5.07E-7	4.34E-7
Ionizing radiation, human health, kBq U235 eq	2.76	0.03	3.20
Ozone depletion, kg CFC-11 eq	6.32E-8	4.38E-8	5.03E-8
Particulate matter/Respiratory inorganics, kg $PM_{2.5}$ eq	2.00E-3	0.87E-3	2.46E-3
Photochemical ozone formation, kg NMVOC eq	0.0300	0.0164	0.0330
Resource depletion, mineral, fossils and renewables, kg Sb eq	1.29E-4	0.39E-4	0.94E-4
Primary energy demand[a], MJ	534	341	513
AWARE[b], m^3 world eq	21.9	22.3	43.1
Social indicators in medium risk hours			
Association and bargaining rights	0.5	1.0	0.3
Certified environmental management systems	0.8	1.4	0.7
Child Labour	0.4	0.4	0.3
Corruption	1.2	1.7	1.3
Drinking water coverage	0.2	0.3	0.2
Education	0.5	0.7	0.9
Fair Salary	1.4	1.9	1.5
Fatal accidents	0.2	0.4	0.2
Frequency of forced labour	0.3	0.4	0.2
Gender wage gap	0.5	1.9	0.9
Goods produced by forced labour	0.0	0.0	0.0
Health expenditure	1.2	1.7	1.6
Illiteracy	1.1	1.3	1.1
Indigenous rights	0.3	0.4	0.7
Non-fatal accidents	0.5	1.1	1.5
Safety measures	0.2	0.3	0.2
Sanitation coverage	0.6	0.7	0.5
Social security expenditures	0.5	0.6	0.4
Trade unionism	0.8	1.3	1.0
Trafficking in persons	0.3	0.4	0.3
Unemployment	0.2	0.3	2.0
Violations of employment laws and regulations	0.5	0.8	0.7
Weekly hours of work per employee	0.3	0.5	0.4
Youth illiteracy	0.8	0.9	0.6
Economic indicators			
Levelized cost of hydrogen[c], €$_{2015}$/kg H_2	3.64	4.22	4.31
Net present value, m€$_{2015}$/kg H_2	-50.1	-58.1	-59.4
Profitability index	-6.38	-7.45	-7.74
Marginal cost[d], €$_{2015}$/kg H_2	3.72	4.52	4.73

[a] from ren. and non ren. resources (net cal. value); [b] OECD+BRIC average for unspecified water; [c]taking into account tax deductible expenditures; [d]levelized marginal cost in case of increasing variable operation and maintenance cost in real terms

4. Conclusions

While the SDGs focus on changing conditions on a country-level, LCSA analysis is geared towards a particular process or technology mostly on micro level. This uneven focus can lead to imprecise predictions of whether or not a particular process can contribute to reach the SDGs.

The difference in issues included in the goal- and indicator-based assessment leads to slightly different definitions of Sustainable Development. This impressively portrays the importance of a diligent indicator selection.

For the LCA the two identified indicator sets show only slight differences (one indicator) while for the s-LCA significant differences are observed. For the LCC even no indicator set on SDG indicator tier can be compiled. This emphasises the difference between the sustainability assessment on a country or region level and on a process chain level.

In consequence, to assign the LCSA indicators to the SDGs requires a longer line of argumentation based on the fact that the SDGs are conceptualized for country or regional level while LCSA aims at products at micro level. Only for few indicators, e.g. unemployment, nearly perfect congruence is provided. In contrast, the LCA indicator particulate matter is assigned to the goal 3 and the SDG indicators 3.4.1 and 3.9.1 because of the effects of particulate matter to human health on the endpoint level (mixing endpoint and midpoint level is another limitation of this approach). In addition this impact category is also assigned to the SDG indicator 11.6.2. This SDG indicator has clear connections to the LCA impact category particulate matter but is less comprehensive. Sometimes the idea behind the SDGs and SDG indicators is plainly translated into LCSA indicators because a translation with perfect overlap is not possible.

The LCSA case study on different hydrogen production sites shows that only the goal based indicator set can be applied for a full sustainability assessment comprising all dimensions of sustainability. For this case study no qualitative differences in the results of the LCA and s-LCA of the indicator sets can be found. Further case studies have to proof if this is a universally valid statement.

In sum, the SDG goal-based indicator set proves appropriate to be applied in an LCSA study. The SDG indicator-based indicator set reveals more matching problems between SDGs and LCSA. In particular the economic assessment related to the SDGs is difficult because of the discrepancies between the macro-economic intentions of the SDGs and the microeconomic nature of LCC. Nevertheless, taking a look at the SDG indicators for a particular case provides an enhanced understanding of the SDGs and guide indicator selection.

References

[1] UN General Assembly. Resolution adopted by the General Assembly on 25 September 2015: Transforming our world: the 2030 Agenda for Sustainable Development. New York: United Nations, 2015.

[2] Maier S, Beck T, Francisco Vallejo J, Horn R, Söhlemann J-H, Nguyen T. Methodological Approach for the Sustainability Assessment of Development Cooperation Projects for Built Innovations Based on the SDGs and Life Cycle Thinking. Sustainability 2016;8:1-26.

[3] Goedkoop M, Martinez EV, de Beer I. LCA as the tool to measure progress towards the Sustainable Development Goals. 8th Life Cycle Management Conference, Luxembourg: LIST, 2017.

[4] UN. Revised list of global Sustainable Development Goal indicators. Report of the Inter-Agency and Expert Group on Sustainable Development Goal Indicators (E/CN.3/2017/2), Annex III, New York: United Nations, 2017.

[5] Boulay A-M, Bare J, Benini L, Berger M, Lathuillière MJ, Manzardo A, Margni M, Motoshita M, Núñez M, Pastor AV, Ridoutt B, Oki T, Worbe S, Pfister S. The WULCA consensus characterization model for water scarcity footprints: assessing impacts of water consumption based on available water remaining (AWARE). The International Journal of Life Cycle Assessment 2017.

[6] Korpi E, Ala-Risku T. Life cycle costing: a rview of published case studies. Managerial Auditing Journal 2008;23:240-261.

[7] Okano K. Life cycle costing - an approach to life cycle cost management: A consideration from historical development. Asia Pacific Management Review 2001;6:317-341.

[8] Swarr TE, Hunkeler D, Klöpffer W, Pesonen H-L, Ciroth A, Brent AC, Pagan R. Environmental life cycle costing: A code of practice. Pensacola, Brussels: SETAC; 2011.

[9] EU-JRC. Recommendations for Life Cycle Impact Assessment in the European context - based on existing environmental impact assessment models and factors. International Reference Life Cycle Data System (ILCD) handbook, Luxembourg: European Commission-Joint Research Centre - Institute for Environment and Sustainability, 2011.

[10] UNEP SETAC. Global Guidance for Life Cycle Impact Assessment Indicators: Volume 1. Paris: United Nations Environment Programme, Sustainable Lifestyles, Cities and Industry Branch, 2017.

[11] Ciroth A, Eisfeldt F. PSILCA – A Product Social Impact Life Cycle Assessment database: Database version 1.0 - Documentation. Berlin: Greendelta, 2016.

[12] Andrews ES, Barthel L-P, Beck T, Benoît Norris C, Ciroth A, Cucuzzella C, Gensch C-O, Hébert J, Lesage P, Manhart A, Mazeau P, Mazijn B, Methot A-L, Moberg Å, Norris G, Parent J, Prakash S, Reveret J-P, Spillemaeckers S, Ugaya CML, Valdivia S, Weidemann B. Guidelines for Social Life Cycle Assessment of Products: Social and socio-economic LCA guidelines complementing environmental LCA and Life Cycle Costing, contributing to the full assessment of goods and services within the context of sustainable development. C. Benoît Norris, B. Mazijn (Eds.), Paris: United Nations Environment Programme, 2009.

[13] Benoît Norris C, Traverso M, Valdivia S, Vickery-Niedermann G, Franze J, Azuero L, Ciroth A, Mazijn B, Aulisio D. The Methodological Sheets for Subcategories in Social Life Cycle Assessment (S-LCA). UNEP/SETAC, 2013.

[14] European Investment Bank. The economic appraisal of investment projects at the EIB. Luxembourg, 2013.

[15] Branker K, Pathak MJM, Pearce JM. A review of solar photovoltaic levelized cost of electricity. Renewable and Sustainable Energy Reviews 2011;15:4470-4482.

[16] Stephan A, Battke B, Beuse MD, Clausdeinken JH, Schmidt TS. Limiting the public cost of stationary battery deployment by combining applications. Nature Energy 2016;1:Art. No 16079.

[17] Kuckshinrichs W, Ketelaer T, Koj JC. Economic Analysis of Improved Alkaline Water Electrolysis. Frontiers in Energy Research 2017;5.

[18] Stocker TF, Qin D, Plattner G-K, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM. Climate Change 2013: The Physical Science Basis. - Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge: Intergovernmental Panel on Climate Change, 2013.

[19] Wenzel H, Hauschild M. Environmental assessment of products: Volume 2. London: Chapman & Hall; 1998.

[20] Horrigan L, Lawrence RS, Walker P. How sustainable agriculture can address the environmental and human health harms of industrial agriculture. Environmental Health Perspectives 2002;110:445-456.

[21] Humbert S. Geographically Differentiated Life-cycle Impact Assessment of Human Health. University of California, 2009.

[22] Stroh K. Bodennahes Ozon: UmweltWissen – Schadstoffe. Augsburg: Bayerisches Landesamt für Umwelt, 2013.

[23] Abarca JF, Casiccia CC. Skin cancer and ultraviolet-B radiation under the Antarctic ozone hole: southern Chile, 1987–2000. Photodermatology, Photoimmunology & Photomedicine 2002;18:294-302.

[24] Frischknecht R, Braunschweig A, Hofstetter P, Suter P. Human health damages due to ionising radiation in life cycle impact assessment. Environmental Impact Assessment Review 2000;20:159-189.

[25] WHO. Burden of disease from Ambient Air Pollution for 2012: Description of method. Geneva: World Health Organization, 2014.

[26] Koj JC, Wulf C, Schreiber A, Zapp P. Site-Dependent Environmental Impacts of Industrial Hydrogen Production by Alkaline Water Electrolysis. Energies 2017;10:860.

[27] Capros P, De Vita A, Tasios N, Papadopoulos D, Siskos P, Apostolaki E, Zampara M, Paroussos L, Fragiadakis K, Kouvaritakis N, Hoglund-Isaksson L, Winiwarter W, Purohit P, Bottcher H, Frank S, Havlik P, Gusti M, Witzke HP. EU Energy, Transport and GHG Emissions: Trends to 2050, Reference Scenario 2013. Luxembourg: Publications Office of the European Union; 2013.