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OF HARMONISED HYDROGEN
ENERGY SYSTEMS

SH2E

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D4.2 Definition of FCH-SLCA guidelines

WP4 Harmonised extension to Life Cycle Costing and Social Life Cycle Assessment

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EXECUTIVE SUMMARY

This document presents the Social Life Cycle Assessment (SLCA) guidelines developed within the SH2E project for fuel cells and hydrogen (FCH) systems, as a result of Task 4.4. It is partly based on the results and trends identified in previous tasks of the project (Task 4.3). The implementation of the requirements and recommendations provided in the present document in a software tool is specifically addressed in Task 4.5. The present guidelines only address the social dimension, while their subsequent integration into sustainability assessment guidelines will be undertaken in WP5 for Life Cycle Sustainability Assessment (LCSA).

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ACRONYMS

EoL	End of Life
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cells and Hydrogen
GDP	Gross Domestic Product
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCSA	Life Cycle Sustainability Assessment
MCDA	Multi-Criteria Decision Analysis
MRL	Manufacturing Readiness Level
PRP	Performance Reference Point
R&D	Research and Development
SLCA	Social Life Cycle Assessment
SLCI	Social Life Cycle Inventory
SLCIA	Social Life Cycle Impact Assessment
TRL	Technology Readiness Level

GENERAL INFORMATION

This document provides methodological guidance on how to perform a Social Life Cycle Assessment (SLCA) of fuel cells and hydrogen (FCH) systems. It builds on previous deliverables of the SH2E project, generic LCA guidelines [1-3], and generic SLCA guidelines for products and organisations [4]. This document embraces hydrogen production, hydrogen use and hydrogen production & use systems. It promotes a harmonised and consistent evaluation of the life-cycle social impacts of FCH products through robust, well-defined methods to effectively support case-specific accounting and decision-making processes. In this sense, the present document takes into account the lessons learnt in previous tasks of the SH2E project, including a review on SLCA of FCH systems in Task 4.3.

The present guidelines are targeted at any SLCA practitioner conducting SLCA studies of FCH systems (hydrogen production, hydrogen use or hydrogen production & use). The practitioner is guided on how to deal with the methodological aspects of an SLCA (functional unit, system boundaries, cut-off, etc.) and specific topics relevant to FCH systems (e.g. supply chain segmentation or data sources).

How to use this document

The document provides guidance on how to conduct an SLCA of FCH systems. The provisions, recommendations and supplementary information are clearly identified in the document according to the following colour code:

In the green boxes, requirements are presented.

In the light blue boxes, recommendations are presented.

In the yellow boxes, supplementary information is reported.

Typically, concepts and options are introduced before the boxes with recommendations, requirements and additional information are provided. The different topics in the guidelines are also evaluated in terms of their “method readiness level”, i.e., a score identifying the level of development of the addressed topic under the following scheme:

Method readiness level	Meaning	Symbol
5	In SLCA tools	●●●●●
4	Data available	●●●●○
3	Stable	●●●○○
2	Discussions	●●○○○
1	First ideas	●○○○○

GUIDANCE ON PERFORMING SOCIAL LIFE CYCLE ASSESSMENT OF FCH SYSTEMS

1 Introduction and Goal & Scope

Social Life Cycle Assessment (SLCA) is a methodology to quantify the potential social impacts that a product or service entails throughout its supply chain from a life-cycle perspective [5]. The United Nations Environment Programme (UNEP) has developed generic guidelines on the matter, which were last updated in 2020 [4].

Based on conventional environmental life cycle assessment (LCA), SLCA is also composed of four phases: (1) goal and scope definition, (2) social life cycle inventory (SLCI) analysis, (3) social life cycle impact assessment (SLCIA), and (4) interpretation. Such phases can be defined as follows [1]:

- **Goal and scope definition***:* The goal defines and explains the purpose of the study, identifying the intended application(s) and the application situation or decision context. The scope describes the limits of the study in terms of the analysed system, its function and functional unit, life-cycle stages covered, assumptions, stakeholders, methodological choices, etc. It is also important to state the modelling perspective of the study during this phase.
- **SLCI analysis**: Systematic compilation of data relevant to the subsequent determination of social impacts along the product's supply chain.
- **SLCIA**: The SLCI data are evaluated to characterise the social performance of the product system according to its supply chain. The choice of the assessed social categories and indicators depends on the method selected and the modelling perspective (e.g. reference scale approach vs impact pathway approach).
- **Interpretation:** previous results are analysed to study contributions and potential areas of improvement, as well as to potentially enable technological or scenario benchmarking. This phase includes robustness tests, sensitivity analyses, completeness analyses, and consistency checks. Data quality and uncertainty analyses can also be performed.

SLCA is increasingly being applied to energy systems, as avoiding impact burden shifting across sustainability dimensions is foreseen as of critical relevance in the context of the energy transition and the decarbonisation of economies. However, literature on specific SLCA studies within the FCH sector is still scarce [6, 7] and studies are often found to be encompassed in the wider framework of Life Cycle Sustainability Assessment (LCSA) [8, 9]. Other projects (e.g. ORIENTING) proposed SLCA practical recommendations that can be interpreted in a generic way, as they do not refer specifically to a particular sector. Although such efforts provide important grounds for the development of the present SH2E SLCA guidelines, it is the aim of this work to offer the practitioner a more in-depth insight into the particularities of the FCH field. In this context, the SH2E guidelines identify and promote good practices in SLCA of FCH systems.

1.1 Goal of the Social Life Cycle Assessment

Motivation

The goal of an SLCA establishes the basis capable of correctly answering the questions posed by/to the practitioner. Hence, it strongly influences the whole setup of an SLCA. This especially concerns the application situation since SLCA is envisaged to be a tool of increasing relevance for decision making. It should be noted that concepts connected to the goal of the study – namely, modelling approach, functional unit and assessment method – are specifically addressed in Sections 1 and 3.

Description of the topic and key terms

Goal definition is the first step in an SLCA. It defines and explains the purpose of the study by answering three main questions related to: expected use of the SLCA results, application situation, and reasons for carrying out the study. These aspects are strongly linked to each other. All of them have implications in subsequent SLCA aspects (e.g. modelling approach and inventory building) and must be coherent with the practitioner's core question.

Intended application(s)

The expected use of the SLCA results could be more than one for a given SLCA study. The applications foreseen affect not only the SLCA model construction, but also the modelling perspective. For a system that is well known, it is easier to achieve higher data quality and verify the results. However, FCH systems often fall into the prospective / new technology category.

Application situation and reasons for carrying out the study

The application situation, also referred to as decision context, is intimately linked to the intended application(s) since, depending on the expected use of the SLCA results, one modelling approach may be more appropriate than another. The guidelines for FCH-specific SLCA are developed for evaluating only social aspects. If also environmental and economic aspects should be included, the practitioner should follow the LCSA guidelines (to be) developed in SH2E Task 5.4.

Requirements and recommendations

> **Box 1 Intended application of the SLCA**
>
> The intended application must be considered for SLCAs. The intended application is characterised by the intended modelling perspective and approach. The application situation must be coherent with it, by stating if the SLCA study would be used for decision support at the product level.

In terms of communication strategies, the practitioner should be as transparent as possible, with especial emphasis on the limitations of the study due to modelling choices. This prevents studies from being inappropriately used for specific interests by individuals, companies or public institutions.

> **Box 2 Limitations of the study**
>
> The SLCA practitioner has to state clearly the limitations of the study in terms of use and interpretation of the SLCA results. This is even more important when it comes to comparative SLCA studies being disclosed to the public.

Evaluation: "method readiness level"

Consideration of the application situation in SLCA ●●●●○

This section is linked to the following sections of the present guidelines:

1.2: Scope of the Social Life Cycle Assessment
2: Social Life Cycle Inventory
3: Social Life Cycle Impact Assessment

1.2 Scope of the Social Life Cycle Assessment

As for environmental LCA, and in line with ISO 14040, the following topics need to be specified for an SLCA study and model:

- Functional unit.
- System boundaries.
- Temporal and geographical scope.
- Dealing with multi-functionality.
- Intended audience.
- Data sources and data requirements.
- Modelling assumptions.
- Assumed limitations.
- Impact categories, indicators, and impact assessment method selected.

These specifications will then need to be fulfilled by the life cycle inventory and impact assessment done in the context of the specific SLCA model.

1.3 Functional Unit

Motivation

The **functional unit** of an SLCA represents the principal function of the system under study, according to the goal and scope of the SLCA [2]. It is linked to a **reference flow** to which all the inputs and outputs of the system are related [2, 11, 12]. The functional unit is, therefore, a quantitative representation of the main function of the system. In the case of systems providing more than one function (**multi-functional systems**), the practitioner must isolate/choose one of the functions since SLCA results are related to a single reference flow [11]. Besides, special attention should be paid when carrying out **comparative SLCAs** because the functional unit must represent a common function accomplished at the same level (e.g. hydrogen produced in a specific location with the same degree of purity and with the same final temperature and pressure).

This section provides guidelines for functional unit definition in SLCA of FCH systems. It considers the previous generic LCA guidelines ISO 14040 [2] and ILCD [3], previous deliverables of the SH2E project and generic SLCA guidelines for products and organisations [4].

Description of the topic

Hydrogen may be involved in a great variety of supply chains (e.g. electricity, fuels, chemicals), and might appear at different stages of the life cycle. It could be used as a fuel itself or used to fulfil another function such as energy storage and chemicals production (e.g. ammonia and methane). This versatile nature allows hydrogen to provide very different functions, which results in the need to define functional units of different sort. Therefore, it is crucial to identify the **main function of the system** and define the functional unit accordingly. In addition, many hydrogen systems are identified as multi-functional ones. For example, the chlor-alkali process could have as main function: chlorine, sodium hydroxide, or hydrogen production, which correspond to its three **functional flows**.

Because of the large heterogeneity observed regarding hydrogen-related systems, this section differentiates between **systems exclusively assessing hydrogen production, and those including its use within the system boundaries.**

The key terms around the topic of this chapter are explained below:

> **Functional unit:** Quantitative representation of the function of the system, which serves as reference for all the flows involved in the assessed system.

Functional flow: Any of the flows of a unit process that constitute its goal (or part of its goal), viz. the product outflows (including services) of a production process and the waste inflows of a waste treatment process [12].
Multi-functional system: System that originates more than one functional flow [12].

Options

Different cases are herein distinguished for functional unit definition:

Case 1: Systems exclusively assessing hydrogen production.
Case 2: Systems including hydrogen use within their system boundaries:
2a. Hydrogen for transportation.
2b. Hydrogen for fuels and chemicals production.
2c. Hydrogen for electricity and/or heat generation.

Requirements and recommendations

General requirements

The concept of functional unit was born in the framework of LCA, therefore the general recommendations proposed for functional unit definition are built on previous guidelines and international standards for LCA, while incorporating specificities typical of SLCA.

The functional unit quantitatively represents the function of the evaluated system, serving as reference for all the flows involved in the system. The **functional units of FCH systems** are commonly referred to physical or economic characteristics of hydrogen or subsequent products or services such as methane, methanol, electricity, or the travelled distance in fuel cell electric vehicles (FCEVs). Within the SLCA framework, it is common practice to refer all inputs and outputs to the final product. The following section explains the main steps in order to set the functional unit.

The first step is to identify the function of the system to be assessed. This could be straightforward in the case of systems with a single functional flow or a clear goal. For systems with various functional flows (multi-functional systems), the SLCA practitioner should identify the functional flows. Once the functional unit has been selected, the functional flow serving as reference flow of the system must be identified and quantified.

Box 3 Identification of functional unit, functional flows and reference flow

1. The function of the system to be assessed must be identified.
2. The functional flows of the system, if more than one, must be identified and reported to clearly state the methodology used for their handling later on.
3. The reference flow of the system must be indicated and quantified.

In some situations, the identification of the main function of the system may present some difficulties because of the use of hydrogen as an **energy vector**, since hydrogen can act as energy transportation or energy storage media. For example, employing renewable electricity surplus to produce hydrogen through electrolysis may have as the main goal the production of hydrogen, or just the storage of renewable electricity. The identification of the function of the system is given by a qualitative analysis by the SLCA practitioner, who needs to evaluate whether the goal of the system is to produce hydrogen or to store renewable energy. This discussion is more significant when developing comparative studies because equivalent functions are required. In the case of comparative SLCA, the functional unit must guarantee that the function of the systems is the same. Attention should also be paid to check whether all the systems achieve the minimum level of qualitative requirements set for the function [11]. These qualitative considerations are set by the SLCA practitioner depending on the goal of the system (e.g. hydrogen threshold purity for its usage in fuel cells). A clear definition of the qualitative characteristics that the product should attain is key to ensure a fair comparison between different systems. Variations on the reference flow quantity could arise if there are differences in quality or performance among the different systems assessed.

Box 4 Functional unit in comparative SLCA

1. Comparative SLCAs must ensure that the selected functional unit represents the common function of the systems and allows a fair comparison, also considering geographical location of the final output.
2. Qualitative requirements to be met by the evaluated systems, which can be made in the form of quantitative thresholds or qualitative statements, must be clearly defined (e.g. minimum hydrogen purity).

Requirements and recommendations for Case 1: Systems exclusively assessing hydrogen production

Regardless of the assessed hydrogen production pathway, a trend towards the adoption of a mass- or volume-based functional unit was identified in Task 4.1 and exposed in D4.1 of the SH2E project. Therefore, the recommendation is to state the functional unit as a description of the produced hydrogen amount [13]. Considering literature trends and regulatory frameworks, it is requested to use the **mass or volume of produced hydrogen**. For the latter, it is requested to state the volume of hydrogen at **normal or standard conditions**.

The functional unit must be accompanied in all cases with a **proper definition of the reference flow**. **Hydrogen purity, pressure and temperature** must be stated together with the quantity of produced hydrogen and the geographical location of the final output of the system. These characteristics are linked to important life-cycle stages such as purification and compression.

Box 5 Functional unit in systems assessing hydrogen production

1. The functional unit used in SLCA of hydrogen production systems must represent the quantity of produced hydrogen by means of a mass- (kg of hydrogen) or volume-based (Nm^3 or Sm^3 of hydrogen) functional unit.
2. Hydrogen purity, pressure and temperature, besides geographical location of the final output of the system, must be specified together with the functional unit.

The precise description of the reference flow was identified as one of the main gaps in LCAs of hydrogen systems (cf. D2.1 of the SH2E project) and, by analogy, suggested to be included in the chart of the systems boundaries of the SLCA study (cf. Section 1.4). This also serves to indicate the reference flow in the case of multi-functional systems.

Box 6 Reference flow in systems assessing hydrogen production

The reference flow, including the specification of hydrogen purity, pressure and temperature, should be reported in the chart of the system boundaries of the SLCA study.

Requirements for Case 2: Systems including hydrogen use within the system boundaries

The heterogeneity of hydrogen applications claims for different functional units with the aim of correctly representing the function of the system. Considering that new applications for hydrogen may appear in the short and long run, this section makes general methodological recommendations. It is useful to differentiate between the system and subsystem functions. If the FCH section is a part of a larger system (for example, power production in a transportation system), a difference should be stated between the main system and subsystem functions [14].

Case 2a. Hydrogen for transportation

When hydrogen is used as a fuel for transportation, there is a general agreement on following distance-based functional units (km, p·km, t·km) depending on the specific goal of the study. The choice of a **distance-based functional unit is therefore required** since it also allows for comparison with other powertrain technologies. The specific functional unit to be selected depends on the goal of the SLCA, but a proper definition of the reference flow must be included, reporting capacity utilisation (passengers/transported freight) and the lifetime considered for the vehicle in terms of mileage. For example, the reference flow could be stated as “to travel X km with an FCEV of medium size (Y kg) occupied by Z passengers with an expected lifetime range of W km”. The specific reference flow may include other characteristics according to the goal of the SLCA, but the relationship between distance and demand (in the form of load) must always be clear. This statement is not limited to road transport, but it also includes other modalities such as air and maritime transportation.

Box 7 Functional unit in systems assessing hydrogen use for transportation

1. The functional unit employed in SLCA of hydrogen use for transportation must represent the distance travelled for a given demand, the latter expressed as the passenger or freight load.
2. The considered demand must be specified in the reference flow, together with the lifetime range of the vehicle.

Case 2b. Hydrogen for fuels and chemicals production

Hydrogen is used in multiple processes for the synthesis of chemicals and fuels. The main applications foreseen are **methane, methanol, and ammonia production**. A functional unit that describes the produced amount must be adopted. The reference flow is to be specified stating the **purity, pressure and temperature of the produced chemical/fuel, besides geographical location of the final output of the system**. The location is important since it is one aspect of the benefit provided by the product under study. It is a different benefit if hydrogen is available in Japan or in Germany, for example.

Box 8 Functional unit in systems assessing hydrogen use for fuels and chemicals production

1. The functional unit adopted in SLCA of hydrogen use for fuels and chemicals production must represent the quantity of the produced chemical/fuel by means of a mass-based functional unit in the case of chemicals, and by either a mass- or energy-based functional unit in the case of fuels.
2. Purity, pressure and temperature of the produced chemical/fuel, besides geographical location of the final output of the system, must also be specified to guarantee a precise functional unit and fair comparisons.

Case 2c. Hydrogen for electricity and/or heat generation

Systems using hydrogen as a fuel for energy generation could be classified into electricity generation, and cogeneration. The former is conceived for the production of a single product (electricity), which is the only functional flow of the system. The function of these systems is clear and an **energy-based functional unit** is required, in accordance with common practice in LCA (D2.1 of the SH2E project) [13]. This energy-based functional unit must refer to the **output electricity**; thus, it **considers upstream efficiencies** (engine or fuel cell, rectifier for fuel cells, and generator). It is recommended to include and clearly state the upstream efficiencies.

Box 9 Functional unit in systems assessing hydrogen for electricity generation

The functional unit employed in SLCA of hydrogen use for electricity generation must represent the quantity of produced electricity in the given location. The functional unit must consider the upstream efficiencies to convert hydrogen into electricity.

For cogeneration systems, two functional flows appear: electricity and heat. The SLCA practitioner has to determine if heat is considered as a valuable product (functional flow) or, when not used, an emission to the environment. For the latter, the system would only be producing electricity and should follow the recommendations given in **Box 9**. On the contrary, when heat is a valuable product, the function of the system changes because it becomes "the production of electricity and heat" (**Box 10**).

Box 10 Functional unit in systems assessing hydrogen for electricity and heat generation

The functional unit employed in SLCA of hydrogen use for electricity and heat generation must represent the maximum energy potential that the system could transform into work (i.e. exergy-based functional unit).

This section is linked to the following sections of the present guidelines:

1.4: System Boundaries
3: Social Life Cycle Impact Assessment

1.4 System Boundaries

Motivation

The system boundaries of an SLCA specify which processes are included in the product system and therefore determine which unit processes are included in the SLCA. The system boundaries shall be consistent with the chosen goal of the SLCA [1]. The correct identification and reporting of the chosen system boundaries are crucial, especially in the case of comparative studies.

Lack of transparency regarding the specification of system boundaries in life-cycle studies of FCH systems (cf. SH2E D2.1, for environmental LCA) was also observed, to a larger extent, in SLCA studies (SH2E Task 4.3). The definition of the system boundaries in an SLCA is herein understood as comprised of two steps:

I. Firstly, the FCH-specific life-cycle phases to be included in the assessment are to be stated. These are the foreground life-cycle phases. As shown in Figure 1, potential foreground phases include resource extraction, manufacturing, distribution, use, and end of life (EoL).

II. Then, as also shown in Figure 1, the FCH system has to be completed by including background processes linked to the above-mentioned foreground system (e.g. upstream production of the chemicals/fuels/energy and manufacture of the equipment involved in the foreground system).

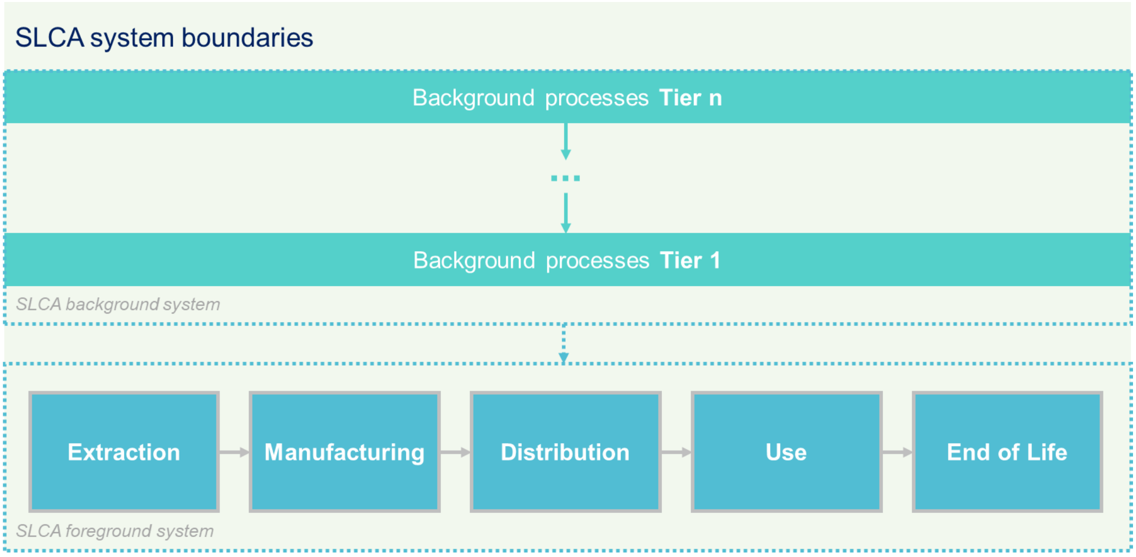


Figure 1. FCH system boundaries for SLCA

Requirements and recommendations

General requirements and recommendations

Box 11 System boundaries I

1. The system boundaries definition has to be coherent with the goal of the study.
2. The system boundaries of the analysed system must be defined and reported.

Box 12 System boundaries II

1. It is highly recommended to show the system boundaries in a chart.

Requirements and recommendations regarding FCH-specific foreground stages

FCH systems typically present a large variety of location options to place the study gate in terms of the FCH-specific foreground phase, especially in studies assessing hydrogen production. In fact, after being produced, hydrogen undergoes conditioning (purification and compression), storage, transportation, and distribution before reaching the use phase. The choice of the gate largely varies depending on the specific study (Figure 2). The setting of the foreground stages in SLCA of hydrogen systems is key to ensure that the desired reference flow is achieved and, therefore, the function of the system performed.

Different cases are herein distinguished for the definition of FCH-specific foreground stages:

Case 1: hydrogen production.
Case 2: hydrogen use.
Case 3: hydrogen production and use.

For case studies focusing on FCH technology manufacturing, the operational phase of the technology should be included. By doing so, this case study should match one of the three above-mentioned cases.

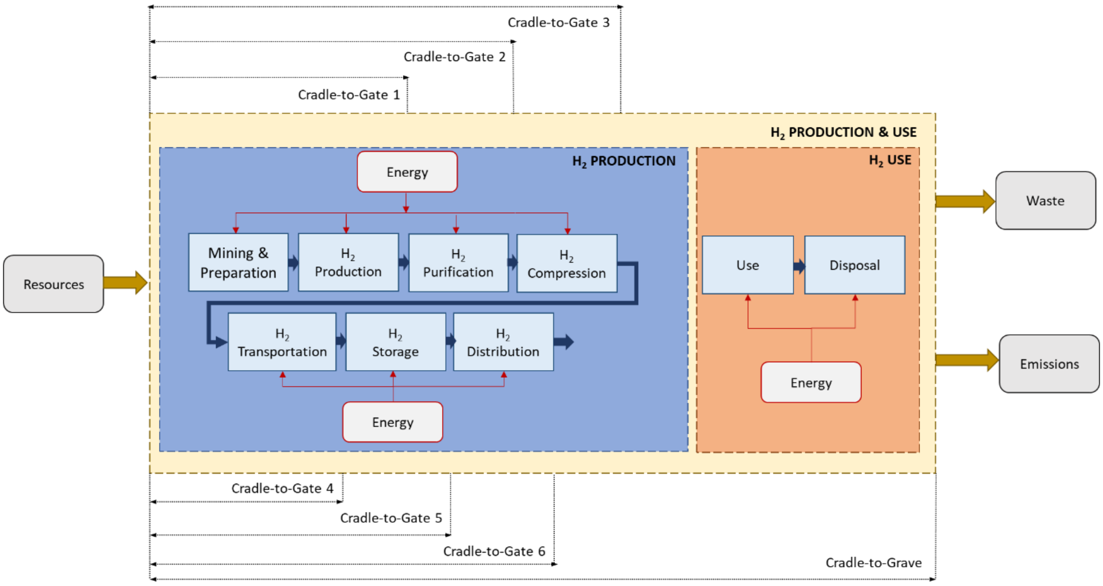


Figure 2. Foreground phases for studies assessing FCH systems

Requirements and recommendations for Case 1: hydrogen production

When conducting SLCA studies assessing only hydrogen production, it is recommended to reach hydrogen conditioning (Cradle-to-Gate 3 in Figure 2). This recommendation assures that the produced hydrogen could fulfil the function of the system (e.g. provide high-purity hydrogen for FCEVs).

Box 13 Foreground phases for systems assessing hydrogen production I

1. The foreground scope of studies on hydrogen production has to be, at least, Cradle-to-Gate 1.

Box 14 Foreground phases for systems assessing hydrogen production II

1. It is recommended to place the gate after the hydrogen conditioning section, in particular after the compression stage (Cradle-to-Gate 3).

Requirements for Case 2: hydrogen use

For studies focusing on hydrogen use, it is required to carry out the SLCA study from resource extraction to the use and disposal phase (i.e. Cradle-to-Grave). This means that hydrogen production has to be included in the analysis, checking that the considered hydrogen is suitable (purity and pressure) for the assessed application and methodologically consistent.

Box 15 Foreground phases for systems assessing hydrogen use

1. The foreground scope of studies focusing on hydrogen use has to be Cradle-to-Grave and include hydrogen production.

Requirements for Case 3: hydrogen production and use

When conducting an SLCA of systems for hydrogen production and use, cradle-to-grave studies are required.

Box 16 Foreground phases for systems assessing hydrogen production and use

1. The foreground scope of studies on hydrogen production and use have to be Cradle-to-Grave.

Requirements and recommendations to complete the FCH system

SH2E LCA and LCC (life cycle costing) guidelines indicate that all relevant unit processes and flows linked to each foreground phase should be included in the assessment; if any is to be left out, a clear justification needs to be provided. For illustrative purposes (Figure 1), each of these individual background supply chains can be understood to converge vertically into its corresponding foreground phase. This recommendation is made considering that, once the foreground system has been modelled by the practitioner, LCA and LCC databases on which the life-cycle inventory of the corresponding background processes rely usually provide information (i.e. technosphere and elementary flows entering and leaving each block) specific to those processes. However, in SLCA, the regular situation is different (Figure 3). Common SLCA databases typically provide information (i.e. technosphere and elementary flows entering and leaving each block) for sectors as a whole. This means the granularity and thus the results are less product-specific [16, 17]. Nevertheless, generic data from databases could provide hints on potential social impacts.

For the sake of practicality, the application of a cut-off criterion is expected when it comes to selecting the product-specific processes to be considered within the SLCA of FCH systems. In this regard, it is recommended that, at least, all processes with an economic contribution > 5% to the final output economic value are included following a product-specific approach. If this is not the case, the practitioner is urged to clearly state and justify the cut-off choice.

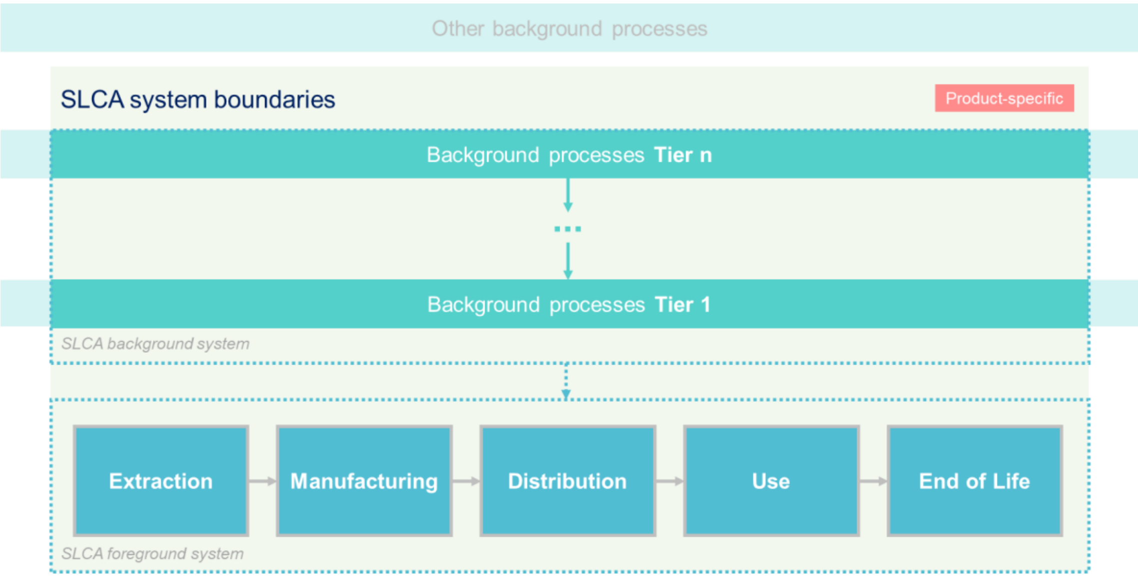


Figure 3. Product-specific approach towards the definition of FCH system boundaries for SLCA

Box 17 Product-specific system boundaries

1. The system boundaries must be representative of the FCH product, involving product-specific processes within them.

Box 18 Cut-off criteria

1. The criteria for selecting product-specific processes alongside the assessed hydrogen-related product system needs to be clearly specified.

Box 19 Cut-off criteria based on economic values

1. It is recommended to include in the SLCA system boundaries, following a product-specific approach, at least all processes with a contribution > 5% to the final output economic value.

Once the practitioner has clearly defined the SLCA product-specific system boundaries, each unit process within such system boundaries must be associated with a region. This is required because social impacts are site-dependent. For such purposes, the protocol developed by Martín-Gamboa et al. [15] could be used. The spatial granularity of the assessment must be chosen according to data availability, and in line with goal and scope.

Box 20 Spatial location of social flows

1. Each unit process within the product-specific system boundaries must be placed in a specific region. ●●●●○

Box 21 Spatial location of social flows

An example of protocol to define supply chains for SLCA studies has been developed by Martín-Gamboa et al. [15]. It helps practitioners identify unit processes within the product-specific system boundaries and their spatial location at the country level.

The final product region (cf. Section 4.3) is set as the declarant for which trade data regarding each of its linked flows are acquired. Regarding linked components, a component is found to be also manufactured in such region if its monetary export-import balance results positive. On the contrary, if the balance is negative, the main exporter is identified and the process is iterated. Ultimately, one manufacturing region is assigned to each of the final product components. A similar procedure is applied to define the origin of material flows within the system, but in this case a mix of manufacturing countries for each of the materials could be found. Finally, energy flows are assigned to the region where they are consumed.

The resultant product-specific system boundaries can be adopted as the definitive system boundaries. Alternatively, when the practitioner aims at completing the definition of the background system by considering all tiers, the use of country-level sectoral relations according to available SLCA databases is recommended.

Box 22 Completing the background system

1. The resultant product-specific system boundaries can be adopted as the definitive system boundaries.
2. When the practitioner aims at completing the definition of the background system by considering all tiers, the use of country-level sectoral relations according to available SLCA databases is recommended.

This section is linked to the following sections of the present guidelines:

1.3: Functional Unit
1.5: Spatial Scale
2.1: Data Sources and Data Collection

1.5 Spatial Scale

An SLCA requires the location of each of the unit processes within the system boundaries, as social impacts are very site-dependent (cf. Section 3). In particular, for such regionalisation, **the definition of the region (e.g. country) where the final output is produced arises as a key aspect**, as it determines the remaining locations along the corresponding supply chains (cf. Section 1.4).

Box 23 Definition of the region where the final output is produced

The SLCA practitioner has to clearly state the location (at least, country specification) of the process that produces the final output of the system (to which the functional unit is referred).

Since an SLCI may make use of economic flows, adjustments may apply due to inconsistencies between the identified countries along the assessed supply chain and those for which economic data are available (the reader is referred to Section 4.4 of SH2E D4.1 for detailed guidance on this topic).

Box 24 Economic adjustments considering geographical aspects

The SLCA practitioner may make use of LCC guidance on this matter to improve the granularity of the study.

This section is linked to the following sections of the present guidelines:

1.4: System Boundaries
3: Social Life Cycle Impact Assessment

1.6 Temporal Scale and Prospectivity

An SLCA is typically conducted in the context of **current or past** social state of affairs, as no social databases for inventories or impact assessment methods (cf. Sections 2 and 3) that address future social situations are currently available. Unlike the availability of databases for prospective environmental LCA, projection of social inventory data in currently available SLCA databases is not recommended due to concerns on suitability and uncertainty.

In this way, though conceptually feasible, **an SLCA is not to be defined prospective** according to the state of the art. Nevertheless, if the practitioner finds it accurate to model the technology at a future, more developed phase (e.g. for an emerging technology alongside prospective LCA and/or LCC), an attempt could be made to measure the social performance of the future technology according to the current/past social context, clearly acknowledging this limitation in order to avoid misinterpretation of the results.

Box 25 Limitations of SLCA for addressing emerging technologies

The SLCA practitioner has to state clearly that, if an emerging technology is being modelled according to its future expected parameters, social results still refer to a current/past social situation according to the state of the art in SLCA databases and impact assessment methods.

In that case, the following recommendations should be considered:

Box 26 Modelling of emerging technologies

1. The technical/operating parameters of the analysed product system should be set at a future time.
2. When performing a comparative SLCA study, it must be ensured that the FCH technologies under comparison are modelled at the same future time of implementation, fulfilling the same function and taking into account potential geographical implications.
3. It is recommended to model the emerging technology inventory both at the present and the future time, so that the potential social improvement under a steady social context can be addressed from a comparative perspective to understand the effect of technology development.
4. The Technology Readiness Level (TRL) and/or the Manufacturing Readiness Level (MRL) of the involved technology should be stated.

Scale effects and learning phenomena in SLCA of emerging technologies

An SLCI may make use of economic data. In this regard, the consideration of scale effects for the quantification of such flows could be relevant, especially for emerging technologies, as the representativeness of pilot-scale or early-commercialisation data is questionable. Several factors might lead to a reduction of costs in the future. These include the following learning phenomena [10]:

- Learning-by-doing/learning-by-using: Repetitive activities in manufacturing and during operation usually lead to increasing labour productivity and to incremental improvements of processes and the product itself.
- Learning-by-interacting/learning-by-searching: Targeted R&D activities improve processes and/or products. This also leads directly and indirectly to a dissemination of knowledge within networks and between research institutions, industry and consumers.
- Economies of scale: Further cost reductions are achieved through standardisation and thus the transformation of manufacturing units to mass production.
- Upscaling of the product also supports the reduction of specific costs.

Often these effects cannot be measured separately [10]. In particular, effects by learning and by economies of scale are difficult to distinguish. For specific recommendations on how to integrate scale and development effects of FCH technologies into an SLCA at a future time, the reader is referred to Section 3.1 of D4.1. Similarly, within the SLCA context, adjustments may apply in terms of (1) discount of operational economic flows due to inflation and/or escalation rates, and/or (2) the base year selected not being coherent to the monetary characterisation.

1.7 Multi-Functionality

Motivation

Multi-functionality in LCA is observed when a system delivers more than one functional flow [12, 86]. For many cases, approaches to deal with multi-functionality have been researched over the past years, and reaching a consensus in dealing with multi-functional systems is still a challenge [12]. The hierarchy defined by ISO standards and ILCD prioritises subdivision, system expansion, and, in the last case, the application of allocation [1-3].

Systems producing and/or using hydrogen often lead to different outputs, and, in many cases, these outputs are considered valuable products, resulting in multi-functional processes. These guidelines propose a comprehensive approach to deal with multi-functionality for systems producing and/or using hydrogen for energy-related applications. This builds upon the SH2E LCA guidelines (D2.2) [83] and the recommendations from the Guidelines for the Social Life Cycle Assessment of Products and Organizations 2020 [4].

Description of the topic

Hydrogen can be produced through different pathways, which means that different additional products can be obtained during its production. These products have several properties and applications, indicating the need for distinct approaches to solve the multi-functionality of the processes, aligned to the ISO 14040/14044 standards and ILCD (i.e. subdivision, system expansion, and allocation) [1-3]. Therefore, for systems producing hydrogen and other products, in which hydrogen is the quantitative reference of the modelled process in the SLCA, it is to be defined whether hydrogen is the **main product** or a secondary product (co- or by-product) of the studied process. For systems using hydrogen, the guidelines consider if the studied system is a fuel cell or another system using hydrogen for different applications.

Options

Different cases can be distinguished for multi-functionality:

- **Case 1**: Systems producing hydrogen.
- **Case 2**: Systems using hydrogen.

Requirements and recommendations

General requirements and recommendations

For processes delivering more than one function, it is necessary to identify the most suitable approach to solve the multi-functionality issue. For that reason, the first step is the identification/confirmation if the process can be really considered as a multi-functional process, through the identification of the functional and non-functional flows (Box 27) [12]. For instance, if, besides the product flow, all the output flows are elementary flows, then it is not a case of multi-functionality, as elementary flows (resources/emissions from/to nature) are not considered functional flows.

Box 27 Need to check for multi-functionality

It must be identified if the studied process is a case of multi-functionality or not through the identification of the functional flow(s).

In case the studied process is identified as a multi-functional process, then the ISO 14040/14044 recommendation shall be applied, according to Box 28 [1, 2]. Therefore, allocation should be avoided by applying subdivision or system expansion, if possible. In case allocation cannot be avoided, then the relationship between functional flows should be studied for the definition of the allocation factors.

Box 28 Avoiding allocation

In case of multi-functionality, allocation needs to be avoided by the application of division of unit processes into different sub-processes, according to the outputs produced.

Another alternative to avoid allocation is, when appropriate, the application of system expansion.

If allocation cannot be avoided, allocation must be applied partitioning inputs/outputs according to the physical relationships between them or other possible relationship (e.g. economic, causal or via activity variable).

Requirements and recommendations for systems producing and/or using hydrogen

Following the general recommendations, first, it must be identified if the other outputs of the process are, in fact, functional flows (Box 27). In case they can be considered emissions to nature (e.g. in many processes oxygen as an output can be regarded in this way), then elementary flows should be selected, indicating that it is not a case of multi-functionality. If the output can be considered a waste of the process, then a waste flow should be applied, and the waste treatment process should be selected.

However, if the outputs are indeed considered product flows, this indicates that one of the approaches defined by the ISO 14040/14044 hierarchy should be applied (Box 28). The particularities arising from each case (systems producing and using hydrogen) are detailed in the next paragraphs.

As outlined in the SH2E LCA guidelines (D2.2) [83], it is recommended to explore the effect of the approaches to deal with multi-functionality through sensitivity analysis (Box 29).

Box 29 Sensitivity analysis recommended

Additionally, it should be considered that:

1. Sensitivity analysis is recommended in order to compare the different approaches to deal with multi-functionality and explore the influence of subdivision (if possible), system expansion, and allocation on the results.
2. Sensitivity analysis to investigate the effects of economic values oscillation is also recommended for economic allocation.

Multi-functionality is not widely addressed in SLCA studies of systems producing and/or using hydrogen. However, when SLCA is performed as part of a broader LCSA, the decision is typically to be consistent with environmental LCA concerning how multifunctionality is handled [8, 87].

Case 1. Systems producing hydrogen

If a case of multi-functionality is identified, the functions and functional flows of the investigated systems must be defined. Following this, the user needs to consider whether the SLCA is part of an LCSA study. In this case, it is recommended to be consistent with the method chosen in the environmental LCA study to manage multifunctionality (**Box 30**). SLCA is often performed in combination with environmental LCA. It is assumed that the technical properties of the system and functional flows under study are the main drivers to orient how inputs and outputs should be split when performing both environmental LCA and SLCA.

Box 30 SLCA multi-functionality consistent with environmental LCA

If the social LCA is part of a broader LCSA study, the decision on how to manage multi-functionality must be consistent with the method chosen for the environmental LCA. Changes from the environmental LCA study must be justified.

If the SLCA study is not performed in conjunction with environmental LCA, subdivision should be preferred (Box 31). However, this is in many cases not possible, as usually the same processes deliver different products [88, 89].

The second step in the hierarchy is the application of system expansion for the other products (Box 31). To select the alternative system, allowing to account for the credits of system expansion, it must be identified if hydrogen is the main product from an industrial perspective, and if there are other possible processes producing the other outputs. System expansion is not always possible, as sometimes it is challenging to define an alternative process. System expansion is suggested for processes in which hydrogen is the main product, such as water splitting [91]. On the other hand, system expansion may not be possible for systems producing hydrogen in which hydrogen is considered the by-product of the process from an industrial perspective, e.g. steam cracking or chlor-alkali electrolysis.

Following the ISO standard hierarchy, the next possibility would be the application of allocation (Box 31). When dealing with hydrogen, it must be considered that mass allocation is not recommended [90] as this would associate a low ratio of the impacts to the hydrogen production. Hence, the first recommendation when applying allocation is the use of physical allocation using the energy content (clearly stating the energy basis; e.g., lower heating value). However, this is not possible for many secondary products [90]. If considering the energy content is not feasible, due to the characteristics of the obtained products, then physical allocation based on number of moles is suggested (provided that the calculation of the number of moles is possible). Otherwise, prioritising non-physical allocation (e.g. economic allocation) is recommended (Box 31).

Economic allocation is suggested for the cases in which the previous alternatives are not representative of the system and/or where the economic aspects of the products are relevant. The economic values selected should be from the same studied region [90]. In addition, the investigation of price oscillations over the past two years should be considered through a sensitivity analysis if relevant. Finally, if economic aspects are not relevant to distinguish the different outputs of the process, then the recommendation is the application of physical allocation based on the mass (Box 31). Further information about the choice of allocation factors for hydrogen systems are provided in the SH2E LCA guidelines (D2.2) [83].

Finally, if physical or economic allocations are not suitable for the case study, it is recommended to identify causal relationships among the functional flows or to use the activity variable (e.g. worker hours) as allocation factor (Box 31). The activity variable has a lower hierarchy in the decision guidance because it is assumed that the technical and economic characteristics of the system have a higher priority than social aspects to decide whether hydrogen production is convenient and viable. Finally, it is likely that subdivision can be applied, if the user can define allocation factors based on the activity variable, such as duration (worker hours) or added value.

In all cases, sensitivity analyses are recommended to investigate and compare the different approaches to deal with multi-functionality.

Box 31 General decision flow for multi-functionality in SLCA

1. If the SLCA study is not performed in conjunction with environmental LCA, subdivision must be preferred.
2. If subdivision cannot be applied, system expansion is the second preferable option.
3. If it is not possible to apply system expansion, physical allocation based on energy content needs to be applied when only energy(-carrier) products are involved. If not possible, physical allocation based on number of moles must be selected, otherwise economic allocation is suggested. If there is no economic relevance or the previous alternatives are not possible, mass allocation should be applied, and the limitations of this application should be stated. If the recommended allocation methods are not suitable for the investigated system, allocation factors should be defined based on causal relationships or activity variables, such as worker hours or added value.

Figure 4 provides a decision diagram to address multi-functionality for systems producing hydrogen.

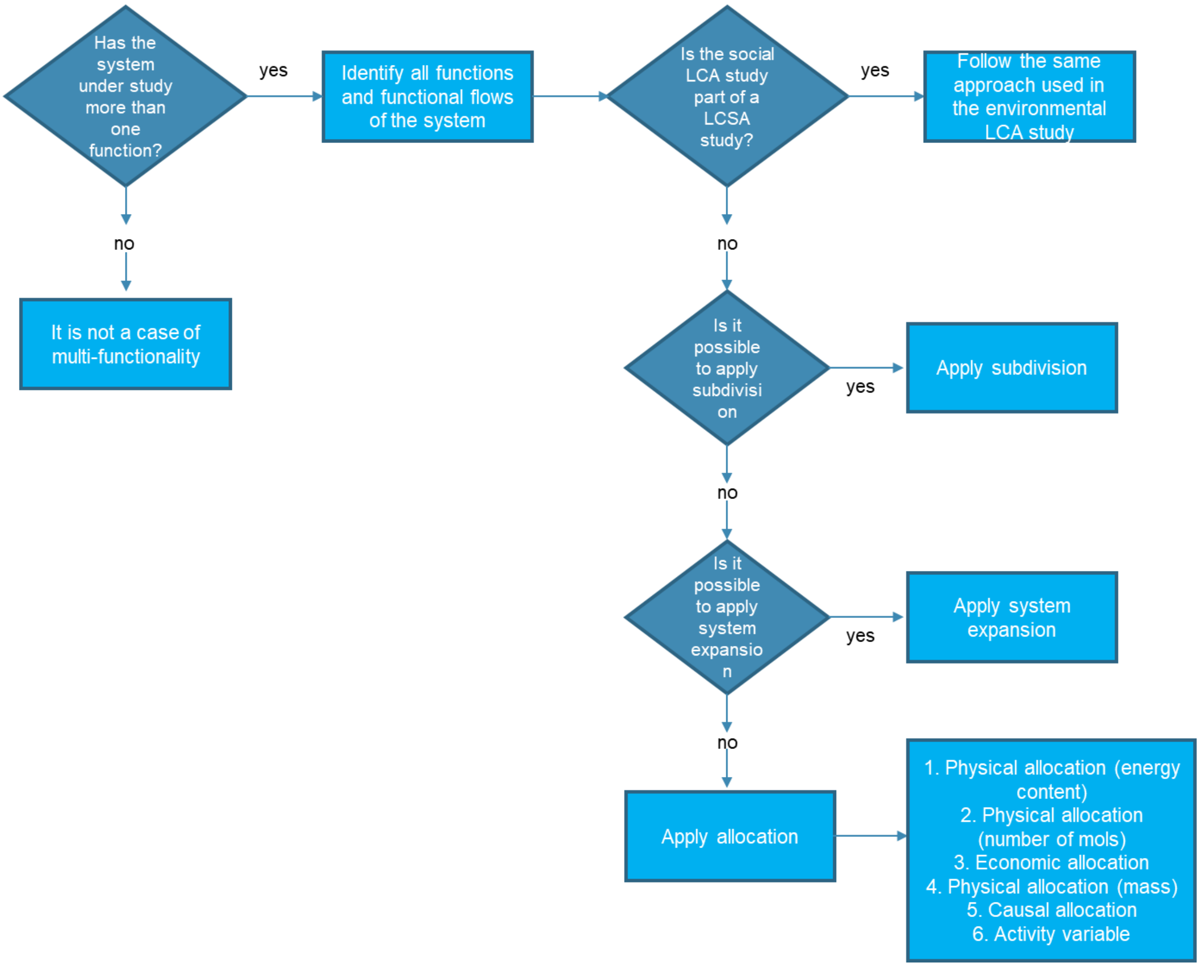


Figure 4. Decision diagram on multi-functionality in systems producing hydrogen

- **Case 2: Systems using hydrogen**

One of the most common hydrogen applications is in fuel cells. Fuel cells generate electricity and heat, which can be considered both valuable products in many cases. Therefore, this would represent a case of multi-functionality. The produced water is usually not a functional flow, as it can be modelled as a waste. For fuel cells, it might be not possible to apply subdivision, as the same system is generating both electricity and heat. On the other hand, sometimes system expansion can also constitute an issue in case it is needed to identify a representative alternative for heat production. Regarding the application of allocation, exergy should be defined as the functional unit and the reference for allocation (Box 32) [88]. If it is not possible to apply physical allocation based on exergy, then economic allocation should be applied (Box 32).

The different approaches to deal with multi-functionality should be investigated through sensitivity analysis. Sensitivity analysis to investigate the effects of economic values oscillation is also recommended for economic allocation.

If heat is not a valuable product, it should be modelled as an emission to the environment (therefore an elementary flow, and not a case of multi-functionality); the water produced in fuel cells can also be modelled as an elementary flow [12, 88].

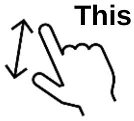
Box 32 Fuel cells and multi-functionality

For fuel cells constituting a case of multi-functionality, in case physical allocation is applied, exergy must be applied for the calculation of the partitioning factors between electricity and heat. If it is not possible to apply physical allocation, economic allocation is the second alternative for the definition of the allocation factors.

For all the other cases with systems that apply hydrogen for the most distinct functions, the general recommendations for multi-functionality should be respected, and sensitivity analysis to investigate the different approaches and compare their effect on the results is recommended (Boxes 27- 29).

Evaluation: "method readiness level"

- Identification of multi-functionality ●●●●●
- Dealing with multi-functionality in systems producing hydrogen ●●●●○
- Dealing with multi-functionality in systems using hydrogen ●●●○○



This section is linked to the following section of the present guidelines:
1.3: Functional Unit
1.4: System Boundaries

2 SOCIAL LIFE CYCLE INVENTORY

2.1 Data sources and data collection

Motivation

Just as any other life-cycle approach, SLCA needs data. Since these data are somewhat different from data used in other life-cycle approaches, it makes sense to think about rules and guidance for collecting data for SLCA, and to provide and evaluate data sources as well.

Description of the topic and key terms

SLCA data needs can be summarised as follows. SLCA needs:

(1) Inventory data and life-cycle data.
(2) Indicator values.
(3) Supporting information.
(4) Further information related to impact and context.

Inventory data and life-cycle data are similar to data used in other life-cycle approaches. These are data about processes along the life cycle; these processes are connected, and thus form a life cycle, by exchanging products or services.

Indicator values are specific to SLCA and can represent many different aspects, depending on the social issue they are to express. They can be qualitative, ordinal, or quantitative, and can come from many different sources as well. Quite often, also, the indicators represent information that is not specific to a process in a life cycle, but rather specific to a sector or country. Examples are unemployment rates or living wages, or access to resources.

Supporting information refers to any information needed for SLCA calculation for a technical reason, not related to impacts or life-cycle modelling. Examples are the activity variable (e.g. worker hours), which in turn needs information about personal costs per time and the costs of the product produced, and the performance reference values used in the risk assessment.

Then, further information can be used in SLCA, especially concerning context and social acceptance, and also related to impact pathways, for assessing the impacts of social interventions.

It is a question where to get all this information from, how to collect the information if the source is identified, and –in case there are several sources– which sources to use. These questions are discussed in this section. The 2020 version of the UNEP guidelines for Social Life Cycle Assessment of Products and Organizations contains a dedicated chapter about data sources for SLCA [4]. Regarding collection of indicator-specific information, those guidelines provide a figure that shows the broad "portfolio" of indicator data sources, especially for the foreground system (Figure 5).

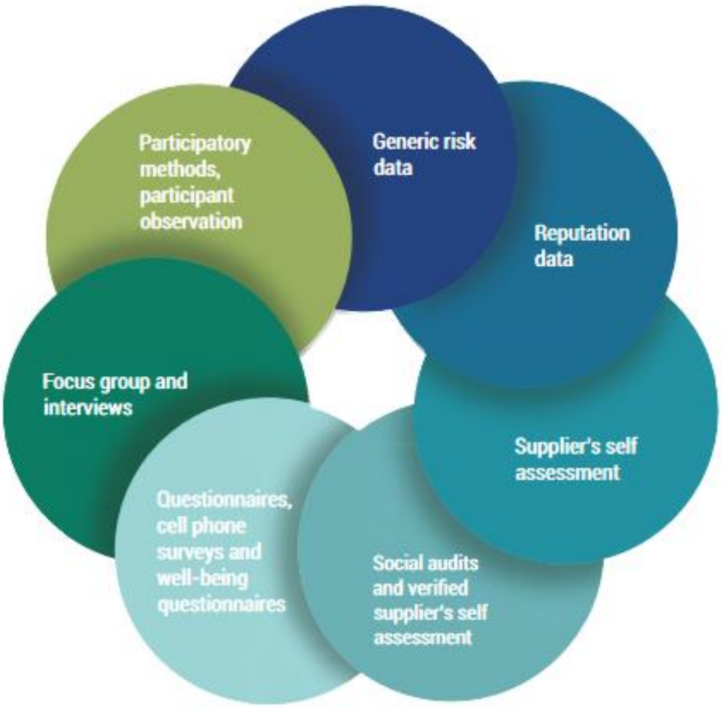


Figure 5. Data sources for SLCA indicator information, with a focus on the foreground system [4, p. 68]

In addition to foreground data, the use of generic or secondary data is common in SLCA. This refers to information about indicators in the life cycle as well as information about "less specific" indicators even for the foreground system. These "less specific" indicators are indicators that refer to broader contexts, e.g., illiteracy rates or contribution of the sector to economic development. For these, even for the foreground system, data need to be collected from sources such as ILOSTAT [18], WHO [19] and others, evidently depending on the selected indicators. Also, the supporting information, especially details about the activity variable, can often be taken from generic data sources. For example, the Eora database, which is the life-cycle "backbone" for the SLCA database PSILCA, contains information about wages per industrial sector, worldwide [20], in so-called satellite tables. While collecting indicators and other information from these generic sources is rather straightforward, an interesting question is how to combine information from different sources in one SLCA model and study, and, in addition, whether information provided by a given source is actually correct, valid, and fit for the purpose at hand.

As "social data" are more volatile than inventory data in LCA, by their nature somewhat subjective, and also more sensitive than typical LCA data, it is good to scrutinise SLCA data. It is important to be transparent about the sources, and ideally use different sources for important aspects, applying a triangulation. This was already discussed in the first edition of the social LCA guidelines, and is still mentioned in the current, 2020 edition [4, p. 78].

Requirements and recommendations

Data sources need to fit to the indicators and goal and scope settings of the SLCA study and model. While non-fitting inventory data will be “caught” via the data quality assessment, non-fitting or inconsistent indicators are less easy to identify and handle.

The collected information needs to be consistent across the entire life-cycle models. For a model with foreground and background system, indicators need to be consistent between the background and the foreground system. If a generic data source, such as a generic database, is used for obtaining information in the background system, the indicators from the database need to be provided for the foreground model as well. Otherwise, the entire model and calculation is not a life-cycle model.

> **Box 33 SLCIA indicators in foreground and background**
>
> Indicators provided for the background system must also be provided for the foreground system. Likewise, indicators provided for the foreground system must be provided for the background system as well.

> **Box 34 SLCIA indicators and inventory data**
>
> The data source used must fit to the data needed for the study and model. Especially, the scope of the social indicator must fit to the source used. Indicators with a country- or sector-wide scope need to be obtained from sources that provide country- or sector-wide indicator values.

To reflect the subjective nature of social information, important information should be obtained from different sources, applying a triangulation. Important in this sense is information that has a severe contribution to the result, or that is difficult to obtain from one source alone.

> **Box 35 Triangulation**
>
> For important information, different sources should be consulted, and the value used in the SLCA model and study should then be obtained as a combination from these data sources, in order to obtain a more stable information basis.

Evaluation: “method readiness level”

The options and recommendations are already used in practice: ●●●●●

This section is linked to the following sections of the present guidelines:

As data are prevalent in any aspect of the modelling, data sources and thus this section are linked to all inventory (Section 2) and impact assessment (Section 3) chapters, as well as to the goal and scope chapters (Section 1) since the requirements for data are set there.

2.2 Data Quality

Motivation

Just like for environmental LCA and LCC, it is also interesting in SLCA to understand how far the considered information fits to the decision at stake. Hence, data quality addresses how well information fits to stated requirements, and thus, for example, to a decision.

Description of the topic and key terms

As for LCA, data quality for social data and for SLCA is defined as fitness for purpose, following ISO 14040/14044 [1, 2]: "Data quality: characteristics of data that relate to their ability to satisfy stated requirements". This means that data quality is not a final, given attribute of stored data, but it rather results from a comparison of given data attributes to requirements. These requirements may be implicitly or explicitly stated (e.g. in goal and scope of an SLCA model) or may come out of a decision situation. If the requirement is to obtain a dataset from 2020, a dataset from 2022 is good but not perfect; if the goal is to obtain a dataset from 2022, a dataset from 2022 fits perfectly.

While data quality is a big topic for LCA, with literally hundreds of recent articles, there seems less discussion about data quality in SLCA. The Guidelines for Social Life Cycle Assessment of Products and Organizations state that "For the time being, there is still no comprehensive guidance document addressing general data quality requirements and management for social and socio-economic data in SLCA", while "It is important to address the data quality and integrity, as this is fundamental to ensure the reliability and validity of the findings, to reach useful conclusions" [4, p 75]. Those guidelines mention the data quality assessment done in the PSILCA database as a practical example [4, p 77]. This assessment uses the pedigree matrix concept, which is also used for LCC and environmental LCA. Also here, the matrix (Figure 6) is square, and is using the same five indicators: reliability of the source, completeness conformance, temporal conformance, geographical conformance, and further technical conformance. The indicators are assessed in five scores. The data quality assessment was developed some years ago [21, 23] and is now fully implemented in an SLCA database [22].

Score / Indicator	1	2	3	4	5
Reliability of the source(s)	Statistical study, or verified data from primary data collection from several sources	Verified data from primary data collection from one single source or non-verified data from primary sources, or data from recognized secondary sources	Non-verified data partly based on assumptions or data from non-recognized sources	Qualified estimate (e.g. by expert)	Non-qualified estimate or unknown origin
Completeness conformance	Complete data for country-specific sector/ country	Representative selection of country-specific sector / country	Non-representative selection, low bias	Non-representative selection, unknown bias	Single data point / completeness unknown
Temporal conformance	Less than 1 year of difference to the time period of the dataset	Less than 2 years of difference to the time period of the dataset	Less than 3 years of difference to the time period of the dataset	Less than 5 years of difference to the time period of the dataset	Age of data unknown or data with more than 5 years of difference to the time period of the dataset
Geographical conformance	Data from same geography (country)	Country with similar conditions or average of countries with slightly different conditions	Average of countries with different conditions, geography under study included, with large share, or country with slightly different conditions	Average of countries with different conditions, geography under study included, with small share, or not included	Data from unknown or distinctly different regions
Further technical conformance	Data from same technology (sector)	Data from similar sector, e.g. within the same sector hierarchy, or average of sectors with similar technology	Data from slightly different sector, or average of different sectors, sector under study included, with large share	Average of different sectors, sector under study included, with small share, or not included	Data with unknown technology / sector or from distinctly different sector

Figure 6. Pedigree table for data quality assessment for SLCA data adapted from [21]

Similar as for LCA and LCC, it makes sense to provide data quality in SLCA for the following "scopes":

for unit process datasets (1a),
for process datasets exchanges (i.e. input/output flows, 1b),
for aggregated datasets sometimes (2),
and for study calculation results (3).

For aggregated datasets and for calculation results, this requires a decision about how to aggregate data quality scores. In LCA studies, users can set the requirements for the LCA, in goal and scope. In SLCA studies, this makes sense as well, thinking of the identical definition of data quality. A logical consequence is, again, that users can also specify how data quality and data quality assessment is understood, following these requirements, for the given study.

Options

The first option is **whether to apply a data quality assessment** for SLCA data or not. Then, the question is about which **scope of data quality** to apply:

- only for scope 1a, unit processes
- scope 1a+1b, unit processes and elementary flows
- scope 1a+1b+2, unit processes and elementary flows and aggregated datasets
- scope 1a+1b+2+3, unit processes and elementary flows and aggregated datasets and study results

A further question is whether **uncertainty** should be reported in addition to data quality indicator results. As the link to uncertainty is not too strong, it is for now recommended to not consider the link to uncertainty for data quality.

Finally, about the aggregation of data quality scores, this is relevant

- for the **aggregation over the life cycle**. Here, there are several options possible; for one, it is to be decided whether the contribution of a process to a life cycle needs to be considered or not, by only counting extremes; then, if contribution of processes is to be considered, how the aggregation is to be performed.
- for the **aggregation of various data quality indicator results**. An aggregation eases the handling of data quality results but loses detail. Possibly, only some aspects can be aggregated, while others remain separate.

Requirements and recommendations

Whether to apply a data quality assessment for SLCA data or not: Since SLCA studies are typically about decision support, and information about the reliability of data considered is important in decisions, data quality seems essential.

> **Box 36 Assessing data quality in SLCA**
>
> Data quality has to be documented and a data quality system with different data quality indicators has to be applied for SLCA studies in general and about hydrogen systems specifically.

The question about which **scope of data quality** to apply: Since aggregated processes are in the end calculation results, it does not make sense to either only look at data quality for study results or only look at data quality for aggregated datasets. Then, as a decision in the end is about the calculation result, it makes sense to look at the data quality in the calculation result. Data quality for a dataset can address information about meta data for the process, which seems important, as data quality for individual inputs and outputs. Overall, therefore, it is recommended to consider data quality at scopes 1a, 1b, 2 and 3 together, as was also recommended for LCC data (SH2E D4.1).

> **Box 37 Scope of data quality assessment**
>
> Data quality has to be considered for unit process data sets, for exchanges, for aggregated data sets, and for calculation results and studies.

Which **kind of data quality indicators** are to be considered: Since in the end all aspects are ideally reflected in the data quality, and since this is also feasible, it makes sense to perform the data quality assessment for scopes 1a+1b+2+3, i.e. for flows, unit processes, aggregated datasets and study results. It is proposed to use the pedigree matrix for eco-efficiency considerations [21] as a starting point, and potentially revise it in line with the further methodological development in SH2E.

> **Box 38 Pedigree schema for data quality**
>
> For time being, the SH2E data quality indicator system should be built on the pedigree table [21], considering measurement, support, and modelling related indicators. This means that the system follows a pedigree table approach, with integer scores for indicator states.

The **degree of user interaction:** A data quality assessment needs to reflect user input, considering the “ability to satisfy stated requirement” definition, and thus needs to calculate data quality on the fly where it progresses through the SLCA model.

> **Box 39 Data quality to reflect user input**
>
> Data quality calculation needs to reflect user input and be calculated on the fly as it propagates through the SLCA model.

About the **aggregation of data quality scores, per indicator over the life cycle**: A mere counting of extremes seems to omit too much information and is therefore not considered as a way forward; for the “processes-contribution” approach, data quality can be considered as quantitative amount or as squared quantitative amount (in line with error propagation, emphasising larger scores). Both seem to have merits.

> **Box 40 Aggregation of data quality**
>
> An aggregation of data quality scores, per indicator over the life cycle, needs to consider the contribution of each process to the calculation result; a mere counting of extremes does not seem promising as it loses too much information.

Evaluation: “method readiness level”

Data quality assessment, pedigree, with user input, contribution calculation: ●●●○○

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
3: Social Life Cycle Impact Assessment

2.3 Activity Variable

Motivation

It is often mentioned that data about social impacts, and social indicators themselves, are not always quantitative values, but instead they can also be ordinal or even qualitative values, as already stated in the first version of the UNEP guidelines for a social LCA of products: “Generally, practitioners of SLCA will need to incorporate a large share of qualitative data, since numeric information will be less capable of addressing the issues at hand” [24, p. 9].

This is a difference from environmental LCA, where impact category results are always numeric values: kg CO_2-eq for example, or also weighted single score results. To allow a calculation of SLCA models with the same algorithms and software tools used for environmental LCA, Greg Norris proposed already in the early days of SLCA an “activity variable”, to, basically, turn qualitative SLCA data into quantitative elementary flows that are understood in LCA models [25].

Description of the topic and key terms

Given that social life-cycle models need to deal with qualitative and ordinal data frequently, calculating life-cycle models for SLCA requires some thoughts, as it is not straightforward to aggregate or otherwise calculate with non-numeric data, especially if the usual software tools and data structures that are common for environmental LCA are used. Even though quite some social indicator values are numeric, they are often “intensive”, i.e., they do not scale with the system size, but are instead relative amounts, as for example the unemployment rate. A so-called “activity variable” was proposed by Greg Norris in 2006 to turn qualitative social data into quantitative data that fits to the environmental LCA data structures and also tools. The first version of the UNEP guidelines defined the activity variable as follows: “An activity variable is a measure of process activity or scale which can be related to process output. Activity variables, scaled by the output of each relevant process, are used to reflect the share of a given activity associated with each unit process. Thus, for attributes concerning labor conditions, a relevant activity variable is worker-hours. Process-specific coefficients of worker-hours per unit of process output are used to estimate the share of total life-cycle worker-hours associated with each unit process” [24, p. 98]. Basically, this means that the higher the worker hours, the higher the share of a process in a life cycle, and the higher its contribution to an impact indicator result of the overall system. This concept is broadly applied in SLCA today. Both the Social Hotspots Database (SHDB) and the PSILCA database are using it, and it seems also widely used in case studies. The entire procedure for bringing social data into the LCA structure is as follows:

- Social indicator impact results per life-cycle process are classified into risk scales.
- For the process, an amount for the activity variable is specified.
- An elementary flow is added to the process, for the respective indicator, the unit of this flow is the unit of the activity variable, the amount is the amount of the activity variable, and the name is a combination of the indicator and the risk class.

Two concrete processes, one from the SHDB and one from the PSILCA database, may serve as examples.

SHDB: The process ‘metals nec’ in Greece produces goods for 1 USD, one addressed indicator is maternal leave, pay and duration. The assessment of this indicator for this process is medium risk (“MR”). Results for other social indicators are truncated here.

Outputs

Flow	Category	Amount	Unit
Maternal Leave (Pay, Duration):MR	social-issue/unspecified	3.57797E-5	work hours
metals nec (nfm) - GRC		**1.00000**	**USD 2011**

PSILCA: the process ‘manufacture of fabricated metal products, except machinery and equipment’ in Greece produces goods for 1 USD; several social indicators, all risk-assessed, with the same amount of worker hours, are seen as elementary output flows (e.g. female in employment, low risk). Also here, only some few social indicators are shown.

Outputs

Flow	Category	Amount	Unit
Manufacture of fabricated metal products, except machinery and equipment - GR	**Greece/Industries**	**1.00000**	**USD**
Active involvement of enterprises in corruption and bribery; medium risk	Value Chain Actors/Corruption	0.01613	h
Certified environmental management systems; medium risk	Local Community/Access to material resources	0.01613	h
Children in employment, female; low risk	Workers/Child labour	0.01613	h
Children in employment, male; medium risk	Workers/Child labour	0.01613	h
Children in employment, total; medium risk	Workers/Child labour	0.01613	h
Contribution of the sector to economic development; low opportunity	Society/Contribution to economic development	0.01613	h
DALYs due to indoor and outdoor air and water pollution; very low risk	Workers/Health and Safety	0.01613	h
Domestic and external health expenditure (% of current health expenditure); low risk	Society/Health and Safety	0.01613	h

The 2020 version of the UNEP guidelines for SLCA [4, p. 75] provides a figure to illustrate the use of the activity variable in a life cycle (Figure 7):

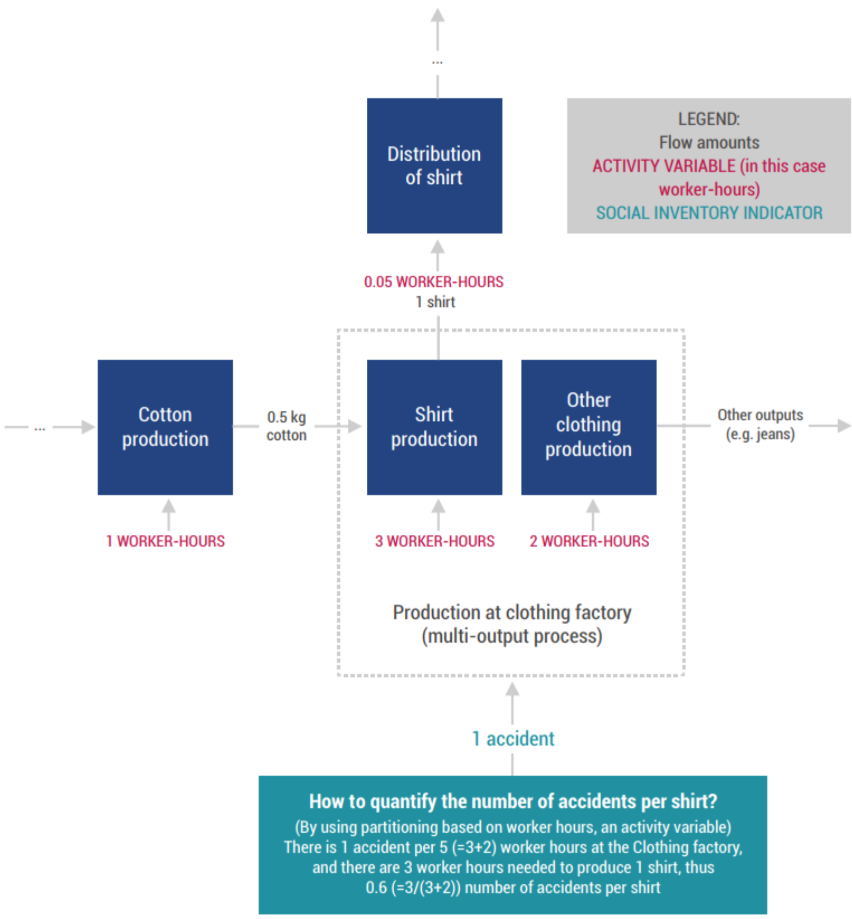


Figure 7. Explanation of the use of the activity variable “worker hours” for a simple life-cycle example [4]

While the activity variable turns indeed any social data into a numeric amount that can be calculated in a normal life-cycle assessment, it has some drawbacks:

1. It is uncommon in environmental LCA process datasets to have the same amount for all elementary flows; this is confusing to users, and it is also inefficient since this is redundant information.

2. The "real value" of the social impact is hidden behind the risk assessment of the social issue; it is not necessarily accessible and visible.
3. The risk assessment is an evaluation process that can be non-transparent; there are no commonly accepted rules that determine when a given real value of a social indicator is medium risk, low risk, or high risk. This depends also on the region, and possibly also on the specific case.
4. Worker hours relate to worker-related impacts but are not really linked to community or society-based indicators.
5. Worker hours are sometimes not available or difficult to collect, and they always bring in additional uncertainty to the indicator calculation result.

There are a couple of proposals to refine and extend or even overcome the activity variable concept for SLCA. Zimdars et al. [26] proposed to add biophysical pressure and value added as two additional activity variables, to be used in parallel to worker hours. This helps to mitigate the above-mentioned limitation #4, but still community-related indicators are not well covered and the other limitations remain.

Similarly, version 5 of the SHDB seems to use two different activity variables, depending on the indicator. Specifically, USD are used for indicators that directly express monetary terms. Looking again at the process dataset 'metal nec' in Greece, this is as follows:

Outputs

Flow	Category	Amount	Unit	C
Cardiovascular diseases, Estimated Age SDR (per ...	social-issue/unspecified	3.57797E-5	work hours	
Cases of HIV (per 1000 adults 15-49 years):ND	social-issue/unspecified	3.57797E-5	work hours	
Cases of Tuberculosis (per 100,000 population):LR	social-issue/unspecified	3.57797E-5	work hours	
Center for Systemic Peace - State Fragility Index:...	social-issue/unspecified	3.57797E-5	work hours	
Collective bargaining coverage:HR	social-issue/unspecified	3.57797E-5	work hours	
Corruption Perception Index, 3 year trend, Trans...	social-issue/unspecified	3.57797E-5	work hours	
Corruption Perception Index, Transparency Inter...	social-issue/unspecified	3.57797E-5	work hours	
Corruption, Competitiveness Report WEF:MR	social-issue/unspecified	3.57797E-5	work hours	
Democracy Index, EIU:MR	social-issue/unspecified	3.57797E-5	work hours	
Dengue Fever, Incidence rate (per 100,000 popul...	social-issue/unspecified	3.57797E-5	work hours	
Discrimination in the Workplace (Qualitative):MR	social-issue/unspecified	3.57797E-5	work hours	
Environmental Performance Index (Yale):LR	social-issue/unspecified	3.57797E-5	work hours	
Evidence-Based Risk to Migrant Workers - Qualit...	social-issue/unspecified	3.57797E-5	work hours	
Export tax payments	social-issue/unspecified	0.02572	USD 2011	
Factor tax payments	social-issue/unspecified	0.00388	USD 2011	
Forced Labor Risk:HR	social-issue/unspecified	3.57797E-5	work hours	
Freedome of Speech, Freedom House:LR	social-issue/unspecified	3.57797E-5	work hours	
Gender Inequality Index (GII), UNDP Human Dev...	social-issue/unspecified	3.57797E-5	work hours	
Gini Coefficient:MR	social-issue/unspecified	3.57797E-5	work hours	
Global Peace Index:LR	social-issue/unspecified	3.57797E-5	work hours	
Global State of Democracy Indices, IDEA:MR	social-issue/unspecified	3.57797E-5	work hours	
High Conflict Heidelberg Institute:MR	social-issue/unspecified	3.57797E-5	work hours	
Hours of Paid Employment	social-issue/unspecified	0.00598	work hours	
Human Development Index:MR	social-issue/unspecified	3.57797E-5	work hours	

By closer inspection, however, the USD-unit indicators are not risk-assessed, which means that the USD is not an activity variable, but the social indicator value is here used as a normal, quantitative indicator result that can be calculated similar to kg CO_2 emissions in environmental LCA.

Ciroth et al. [27] proposed a way to overcome the need for an activity variable entirely. Looking at currently used social indicators for the PSILCA database, they demonstrated that all indicators can be quantified, via a coding of each indicator. The calculation is different from a normal LCA calculation (see, e.g., [28, 29]). Boolean values need to be coded into 0 and 1, ordinal values into class numbers, relative amounts such as the unemployment rate can remain as they are. Then, the numeric amount of each social indicator in each process is divided by the contribution of this process to the life-cycle inventory result, so by its scaling amounts. Technically, each process indicator result is divided by the scaled diagonal of the technology matrix A, to obtain a "normalised" result for each indicator.

$$r_k = \frac{g_k}{\sum_{i=1}^{n} a_{ii} s_i}$$

With r_k: normalised result for indicator k

g_k: life-cycle calculation result for indicator k

a_{ii}: product amounts in the diagonal of the technology matrix A, for process i

s_i: scaling factor for process i

The benefit is that the result is easier to understand and reflects the indicator value directly, without a risk assessment step. A drawback is that no local, process-specific assessment is performed, but instead the assessment is done for the entire life cycle. This, however, is so far also the case for the risk assessed and activity-variable-transformed social indicator values, and thus not a strong disadvantage.

The need to calculate potentially non-numeric indicator values is of course valid for any SLCA model, independent from whether the model is about hydrogen or any other product. Especially for hydrogen systems, with their novel, innovative products, and correspondingly novel production, use, and also EoL life-cycle phases, information about social impacts linked to social indicator values is even more uncertain, which comes with a lack of established conventions for assessing the risk of indicator values.

Options

The first option is **whether to accept social indicators** for SLCA that are not entirely quantitative, i.e. numerical.

Second, the question is about **whether a risk assessment of the indicators should be done**. If yes, a follow-up question is how it is to be done, i.e., how the risk classes are to be obtained, for indicator values.

Next question is whether an activity variable is to be used, or not. And if yes, the **activity variable used for turning the risk-assessed indicator values needs to be specified**: what is a suitable activity variable, for various stakeholders, type of impacts, and indicator units; a side question is whether the activity variable and risk assessment should be bypassed, by calculating the direct values of the indicators.

Requirements and recommendations

For calculating SLCA models for FCH systems, it seems inevitable to accept social indicators that are not only numerical. Many of the social indicators used in recent studies and social LCA databases are qualitative or intensive.

Box 41 Quantitative and qualitative indicators

SLCA models in FCH systems will need to deal with social indicators that are quantitative and also other indicators that are qualitative; the calculation of social indicators in SLCA thus needs to be able to deal with qualitative and quantitative indicators and data.

To allow calculating qualitative indicator values, both the direct calculation and the risk assessment and activity variable “pathway” seem equally suited.

Box 42 Direct calculation or risk assessment with activity variable

For dealing with non-numerical social indicator values, the direct calculation [27] or a risk assessment and quantification via an activity variable are to be used, as two options.

Box 43 Direct calculation

In Option 1 (direct calculation [27]), each indicator has to be coded into a number format:

- Boolean values as 0 and 1.
- Ordinal classes as numbers (e.g. 1, 2, 3, etc.).
- Relative values and ratios can remain unchanged.

The calculation can then be performed as a normal LCA calculation, in LCA software, but afterwards, results need to be normalised, using the following equation:

$$r_k = \frac{g_k}{\sum_{i=1}^{n} a_{ii} s_i}$$

With r_k: normalised result for indicator k

g_k: life-cycle calculation result for indicator k

a_{ii}: product amounts in the diagonal of the technology matrix A, for process i

s_i: scaling factor for process i

Box 44 Risk assessment with activity variable

In Option 2 (risk assessment and activity variable), for each indicator, a risk assessment has to be performed, to classify indicator results into risk classes. For all indicators in a study, the same classes are to be used, but the indicator values threshold for each class need to be decided per indicator. This risk assessment has to be clearly documented and motivated. The original indicator values must be documented. Result is one elementary flow for each risk-assessed class for each indicator.

Next, one or several activity variables need to be developed, and quantified per process dataset. It is common to use worker hours for all indicators, but other activity variables can be used as well. It is also possible to have different activity variables for different social indicators in the same process dataset. Also, the choice of the activity variable has to be motivated, and the calculation of the activity variable has to be documented.

Finally, the elementary flows representing the risk-class for each indicator need to be added to the process dataset. The LCA calculation can then be performed as usual.

Evaluation: “method readiness level”

Both options are already used in practice: ●●●●●

This section is linked to the following section of the present guidelines:

3: Social Life Cycle Impact Assessment

3 Social Life Cycle Impact Assessment

3.1 Impact Assessment

Motivation

Based on the inventory gathered in an earlier phase, the (potential) social impacts are calculated in the SLCIA stage. Whether impact are potential or actual impacts depends on the data used in the inventory (cf. Section 2). If actual impacts are to be calculated, site-specific data must be used, otherwise potential social impacts are generated. Two main impact assessment types exist, the Reference Scale Approach (Type 1) and the Impact Pathway Approach (Type 2) [4], where each holds a diversity of methodological variations [30, 31]. According to [4], the Reference Scale Approach is used “If the aim is to describe a product system with a focus on its social performance or social risk”, and the impact pathways “If the aim is to predict the consequences of the product system, with an emphasis on characterizing potential social impacts”. Within the goal & scope definition, the practitioner must decide which approach to use [4].

Description

<u>Reference Scale Approach</u>

The social performance of an activity is assessed with the Reference Scale Approach. After reference scales are established, the collected data (inventory) are assessed with their help. The definition of reference scales is rendered for every indicator individually. Once the reference scales are defined, numerical values can be assigned, to be able to aggregate the results. They can be linear or non-linear, i.e., one point for each level or individually adjusted to the study. Examples for scale levels including non-linear numerical values are 100 for a very high risk, 10 for a high risk, 1 for a medium risk, etc. (Boxes 46 and 47). The assignment of numerical terms is not mandatory, also non-numerical terms can be used, e.g., using a colour code, even though this is less common [4].

In most cases, data are allocated into an ordinal scale of, e.g., one to five levels, where each relates to a performance reference point (PRP). According to [4], PRPs are “thresholds, targets, or objectives that set different levels of social performance or social risk, which allow to estimate the magnitude and significance of the potential social impacts…”. The PRPs are derived from, e.g., legislation, best practice examples from industry or international standards and can be qualitative or quantitative. The purpose of this procedure is to evaluate the extent of the positive and/or negative impact of data [4]. An example for PRPs for the indicator “Public expenditure on education” is also presented in Box 46.

Additional information on aggregation and weighting can be found in Box 45:

Box 45 Aggregation and weighting

During the impact assessment of the Reference Scale Approach, aggregation and weighting might take place in various forms. According to [4], “It can be applied to aggregate indicators into social subcategories but also to produce a set of stakeholders’ level performances, aggregate subcategory results into impact categories or to a single overall score.” Using the same units is a precondition. Positive and negative impacts cannot be offset against each other. Under all circumstances, the aggregation steps must be reported transparently to avoid misinterpretation. Applying weights prior to aggregation is necessitated. Either equal weights for equal relevance or weighting approaches of various kinds can be applied, e.g., prioritisation either according to the most robust indicators or the worst performance as well as according to expert or stakeholder values [4].

If the Reference Scale Approach is chosen, the use of a database with an included impact assessment method is possible, e.g., PSILCA (Box 46) [22] or SHDB [32] (Box 47). In these cases, the impact assessment method including reference scales, performance reference points, etc. are predefined for all impact categories and indicators, but can be changed individually. In addition to the advantage of saving time, the calculation procedure is provided and includes, depending on own choices of the scope of the study, the supply chains of the product system. On the other hand, the use of a predefined assessment might be unsuitable for the own study, less specific and thus bear the risk of data distortion or biases.

Nevertheless, as described above, the impact assessment for an SLCA can also be conducted without using a predefined impact assessment model provided by a database, but instead gather own data and establish reference scales, PRPs, etc.

Within the Reference Scale Approach, activity variables can be used (cf. Section 2.3). This is a further choice to be made by selecting an appropriate assessment type; it has a major influence on the conduction of the impact assessment.

If the Reference Scale Approach is used, the variants can be categorised into four types: using an activity variable and a database (e.g. [34-36]), using an activity variable but no database (e.g. [37]), not using an activity variable but a database (e.g. [27, 38]), or neither using an activity variable nor a database (e.g. [39]). Further variants within the use of the database include either using predefined measures as reference scales and PRP´s or entering own data (Figure 8).

Box 46 PSILCA

The embedded impact assessment method within the PSILCA database is a Reference Scale Approach. It includes a risk and opportunity assessment as presented in Table S1. For each of the levels as well as if there are no data available, a numerical characterisation factor is defined, which adds weights to all possible options. With the help of worker hours used as an activity variable, aggregation throughout the product system can be done [22].

Table S1: Reference scale and risk levels [22]

Reference scale	
Risk level	**Characterisation factor**
Very low risk	0.01
Low risk	0.1
Medium risk	1
High risk	10
Very high risk	100
No risk / opportunity	0
Low opportunity	0.1
Medium opportunity	1
High opportunity	10
No data	0.1

The reference scale is individual to every indicator. For example, the PRPs for the indicator “Public expenditure on education” are presented in Table S2. For instance, If the indicator raw value is 3%, the associated risk level of the reference scale is “high risk”.

Table S2: Performance reference points within risk assessment [22]

Indicator value y, %	*Risk level*
$0 \leqslant y < 2.5$	*very high risk*
$2.5 \leqslant y < 5$	*high risk*
$5 \leqslant y < 7.5$	*medium risk*
$7.5 \leqslant y < 10$	*low risk*
$10 \leqslant y$	*very low risk*

Box 47 SHDB

The SHDB relies on the Reference Scale Approach. Data are divided into four risk levels according to the characterisation model – low, medium, high, and very high risk. Each risk level corresponds to a numerical value ranging from zero to three, respectively. The weighting is conducted in a separate step, where the indices are multiplied by 1.5, if they are regarded as especially important [32]. Worker hours are used as an activity variable to reveal the labour intensity [33].

Reference scale	
Risk level	Index
Low risk	0
Medium risk	1
High risk	2
Very high risk	3

Impact Pathway Approach

The Impact Pathway Approach is the second impact assessment type. Within this type, cause-effect chains are built which reflect social mechanisms/stressors and their respective consequences. Within a qualitative or quantitative cause-effect chain, so-called inventory indicators, e.g., remuneration, are translated with a characterisation model into midpoint indicators, e.g., fair wage, which show impacts in the centre of the chain, whereas endpoint indicators, e.g., social equity, show impacts at the end, which is regarded as the social consequence. Beyond every social consequence, an area of protection, e.g., social well-being, bundles the final damage. The impacts can be positive or negative, but there is a lack of positive ones at the time being [4].

To define an impact pathway, social mechanisms must be identified in order to determine one or more social consequences [40]. As within the Reference Scale Approach, the inventory is classified into impact categories. One difference is the characterisation procedure, by which the inventory is converted into midpoint and endpoint indicators [4]. Different approaches for characterisation have been developed in the past, e.g., in references [41] and [42]. Once established, the impact pathways are applicable to different studies.

A differentiation is made between qualitative and quantitative assessments. A qualitative cause-effect chain creates a big picture of a situation, as it demonstrates the interrelations of social conditions towards an area of protection. Interdisciplinary perceptions (e.g. social science, natural science, economics, psychology, etc.) are used to build these diverse relations between social activities (e.g. by a company) and social topics, and may also include societal challenges. An example refers to indicator frameworks, where qualitative, quantitative, or semi-quantitative midpoint and/or endpoint indicators are defined. First, a specific social topic is chosen and classified as midpoint or endpoint. With the help of interdisciplinary knowledge, cause-effect chains are built, and a respective inventory gathered. These steps are iterative and might be redefined during the assessment. The characterisation follows in the form of existing models, novel models (own establishments) or case-specific (e.g., distance to target). Within the last step, the calculation takes place [4].

Cause-effect chains can also be quantitative, using numeric values. The goal is to explain one situation (not the big picture as within the qualitative cause-effect chains). This can be done with a mechanic modelling approach (in the style of LCA) or with a regression-based modelling approach. There are several approaches for the former. One targets on human health (e.g. with the disability-adjusted life years –DALY– approach) and includes inventory, characterisation, and calculation. Another uses activity variables and disaggregates social aspects into a single midpoint indicator, and a third one summarises social impacts into a single score. Within the regression-based modelling approach, correlations are built. They are based on economic regression models and target at identifying the influence of a product or product system to a social topic [4] (Figure 8).

When it comes to FCH systems, most existing SLCA studies rely on the Reference Scale Approach [44]. This is not surprising, as also in other industries and sectors, the Impact Pathway Approach is currently underrepresented [45, 46]. One reason is the absence of an accepted characterisation model [47]. Overall, the maturity of the impact pathway assessment type is not sufficient yet and not all impact categories are addressed, even though developments are going on [48, 49]. Up to now, no cause-effect chain especially for FCH systems exists. Impact pathways are independent of a specific sector and are only available for a few social impacts, mainly income and health [49]. This hampers a comprehensive assessment of all relevant stakeholders and impact categories. Most of the reviewed SLCA studies about FCH systems used the PSILCA database, outlined in Box 46 [6, 30, 34, 36, 51-56].

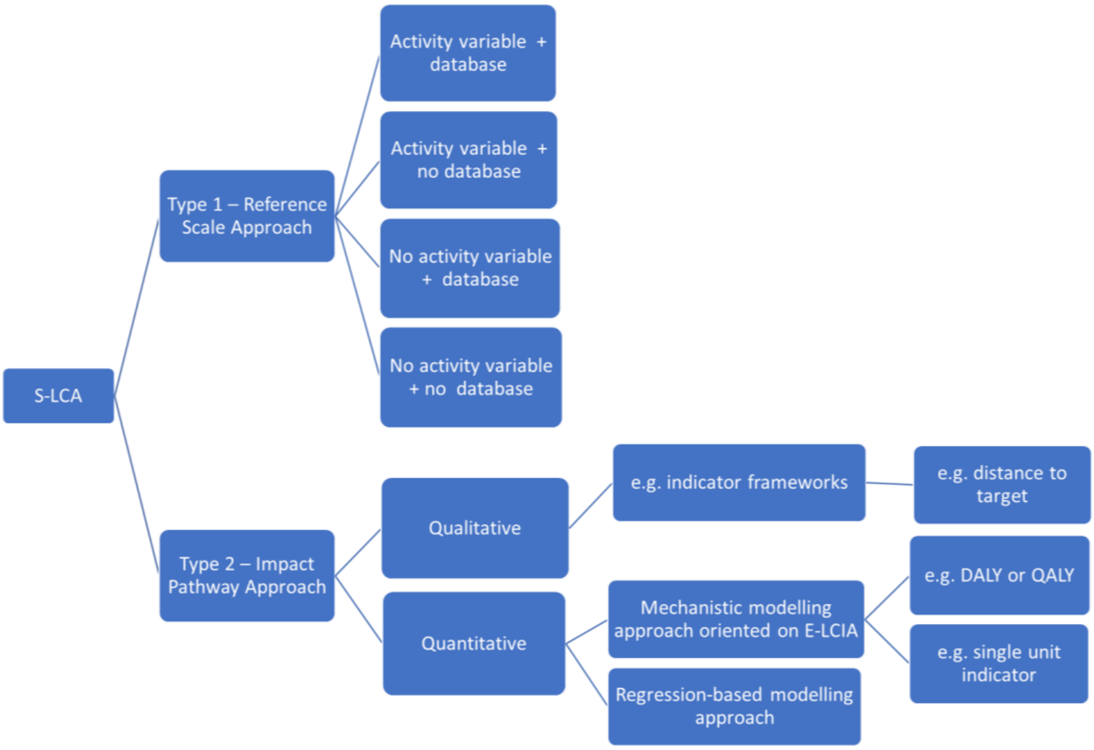


Figure 8. SLCA approaches (own figure based on [4] and [43])

Requirements and recommendations

The choice of either the Reference Scale or the Impact Pathway Approach is dependent on the goal of the study. When it comes to practical implementation, the Reference Scale Approach is more mature and thus applicable to a broader range of product systems, stakeholders and impact categories. This makes the approach more practical for FCH systems and thus a requirement to use the Reference Scale Approach.

Box 48 Reference scale approach

It is required to use the Reference Scale Approach (Type 1) for the assessment of FCH systems.

A generalised recommendation for the assessment of FCH systems regarding the use of a database cannot be made. This also applies to the definition of reference scales and PRPs, etc. Also here, the choice of the variation is strongly dependent on the goal and scope of the study and on data availability. Prior to the application of a database with an included impact assessment method (e.g. PSILCA or SHDB), a critical disputation of the underlying assumptions should be made to check the applicability of them for the own study. Where appropriate, amendments and alignments should be made to align with the goal of the FCH system under study.

Evaluation: "method readiness level"

Readiness level for reference scale approach: ●●●●○

Readiness level for impact pathway approach: ●●○○○

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
2: Social Life Cycle Inventory
3.2: Impact Categories
3.3: Indicators

3.2 Impact Categories

Motivation

Impacts occurring on people along the life cycle of a product or service can be manifold and of various kinds. In addition, they can be positive or negative. Thus, these impacts can be bundled into groups. According to [4], they are called impact categories, examples are human rights, governance or working conditions. Impact categories are in turn divided into several subcategories that "comprise socially significant themes or attributes". With the help of one or more impact indicators, the respective subcategories can be assessed (cf. Section 3.3). Each impact category is linked to one stakeholder group (cf. Section 5.1), e.g., worker, the local community, society, value chain actors, consumers, and children [4]. Other classifications exist and are described in the next passage.

Description

There is no uniform linguistic delimitation of the terms for impact categories and, in addition, the grouping of social topics can differ. An example is shown in Table 1, the impact category "working conditions" belongs to the stakeholder group "workers" and comprises the subcategories "fair salary" and "working hours" [4]. The indicators used to assess fair salary are, among others, "Lowest paid worker, compared to the minimum wage and/or living wage" and "Number of employees earning wages below poverty line" [4, 57]. In another example, the terms for the social topic "working conditions" differ: in PSILCA two subcategories are used, i.e., "Fair salary" and "Working time". For the former, the impact category is named "Fair salary" and measured with the indicators "Minimum wage", "Living wage" and "Sector average wage". For the latter, the subcategory is "Working time", and the impact category and the indicator are called "Weekly hours of work per employee" [22]. A non-exhaustive overview of stakeholder groups and subcategories from [4] can be found in Box 49.

Table 1. Terminology of impact categories, subcategories and indicators for the examples salary and working time

	Stakeholder	Impact Category	Subcategory	Indicator(s)
[4, 57]	Worker	Working conditions	Fair salary	Lowest paid worker, compared to the minimum wage and/or living wage
				Number of employees earning wages below poverty line
				…
	Worker		Working hours	Number of hours effectively worked by employees (at each level of employment)
				…
[22]	Worker	Fair salary	Fair salary	Minimum wage, per month
				Sector average wage, per month
				Living wage lower bound
				Living wage upper bound
				Living wage, per month
	Worker	Weekly hours of work per employee	Working time	Weekly hours of work per employee

Box 49 Stakeholder groups and subcategories [4]

Worker	Local community	Value chain actors	Consumers	Society	Children
Freedom of association and collective bargaining Child labour Fair salary Working hours Forced labour Equal opportunities/ discrimination Health and safety Social benefits/ social security Employment relationship Sexual harassment Smallholders including farmers	Access to material resources Access to immaterial resources Delocalisation and migration Cultural heritage Safe and healthy living conditions Respect of indigenous rights Community engagement Local employment Secure living conditions	Fair competition Promoting social responsibility Supplier relationships Respect of intellectual property rights Wealth distribution	Health and safety Feedback mechanism Consumer privacy Transparency End-of-life responsibility	Public commitments to sustainability issues Contribution to economic development Prevention and mitigation of armed conflicts Technology development Corruption Ethical treatment of animals Poverty alleviation	Education provided in the local community Health issues for children as consumers Children concerns regarding marketing practices

If constraints on time and monetary effort exist, possibly not all impact categories can be assessed, even though this is highly recommended. Depending on the goal & scope, the context, the range of supply chains, etc., the choice of impact categories might vary [4]. A precise prioritisation of the impact categories to be assessed is fundamental to conducting the SLCA but, as with the prioritisation of stakeholders, there is no consensus yet about how to select the most important impact categories and subcategories [45, 58].

Dreyer et al. [60] proposed a methodology for an impact assessment which includes the selection of impact categories. They divide them into impact categories with an obligatory or an optional character, having said that this has not prevailed during the last years. The study suggests a two-fold approach, combining a bottom-up and a top-down view for impact category selection. The former starts with the angle from the producing business including themes that can be influenced by the company and the relevance for them. Within the top-down part, the importance from the viewpoint of the society is taken into account.

Participatory approaches, the involvement of actors prior to the study, e.g., focus groups, can support decisions made on impact category selection. In addition, materiality assessments are a promising way to facilitate the prioritisation [4, 46, 61]. Unfortunately, the same issue with the selection of stakeholders occurs for the materiality assessment. A relevant framework could provide guidance, e.g., the different sector standards from the Global Reporting Initiative (GRI), but up to now there is no sector standard for hydrogen or hydrogen systems from GRI [62]. Nevertheless, a materiality assessment with the help of, e.g., expert judgement can pose another option [63]. Literature reviews and interviews also pose ways to identify the most relevant impact categories [64]. Siebert et al. [65] developed an approach for indicator selection within four stages. The first is a revision of global and national sustainability standards, the second a respective screening of SLCA case studies. In a third step, a stakeholder interview is conducted. In the last step, the viability of indicators is tested. It was initially developed for the wood sector but can be transferred to other sectors. By choosing appropriate indicators, also the corresponding impact categories become apparent. In either case, a transparent description of arguments for the prioritisation has to be included into the documentation [4].

Within SLCA there are impact categories that are more established than others. This is partly dependent on the stakeholder group. Children as stakeholders have not yet been assessed, why also the impact categories provided did not come into place. For impact categories for consumers, it is similar, as this stakeholder group has been rarely studied yet under a life-cycle perspective [45, 46].

Material topics for assessing FCH systems within an SLCA can vary. Most standalone SLCAs or studies conducted within an LCSA assess impact categories concerning workers and the society as stakeholders. Only one includes also the local community and consumers [39]. The work by Campos-Carriedo et al. [44] includes an overview of examples of assessed impact categories.

Once relevant topics are identified, they can be translated into impact categories and subcategories. It is important to keep in mind that the selection of impact categories and subcategories as well as the constitution of their classification is dependent on the goal and scope of the study.

Requirements and recommendations

Depending on the goal of the study, the impact categories to be assessed vary. The prioritisation of impact categories must therefore be in line with the goal. A transparent description of the justification must be included.

Box 50 Impact categories

Impact categories to be assessed have to be in line with the goal of the study.

Box 51 Justification of impact categories

A transparent description of the justification of impact category prioritisation must be included.

As the terminology of impact categories and subcategories differs across different guidelines, standards and databases, it is recommended to follow the classification in [4]; on the one hand, to increase comparability between studies and, on the other, due to its status of a guiding document in the SLCA field.

Box 52 UNEP guidelines [4] as basis

It is recommended to follow the UNEP guidelines [4] when it comes to the terminology and classification of impact categories and subcategories.

Evaluation: “method readiness level”

Readiness level for impact category availability: ●●●●●

Readiness level for impact category selection: ●●○○○

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
3.3: Indicators
5.1: Stakeholders

3.3 Indicators

Motivation

Within an SLCA, the social topics can be classified into different impact categories and subcategories and address a specific group of stakeholders (cf. Sections 3.2 and 5.1). Within every impact category, one or more indicators are used to represent the social topic. They have the purpose of including the collected data in the calculation within the impact assessment and thus must be in line with the chosen approach. Indicators can be quantitative, semi-quantitative and qualitative and are defined during the goal and scope phase of the study. Indicators can address different specification levels, e.g., they can be generic, company or site-specific, etc. The data collection for all indicators takes place in the inventory phase [4].

Description

As with the topic of impact categories and subcategories, the terminology of indicators might vary between different frameworks, standards, or databases. In addition, which indicators serve as a measure for an impact category is not unified [4, 22, 32, 63]. Own defined indicators as well as predefined indicators provided by, e.g., the methodological sheets of the UNEP guidelines can be used [57]. In either case, it is of high importance that the following criteria are met: (1) reliability, (2) validity, and (3) objectivity. More information on this procedure can be found in [4].

There is no standardised procedure yet to prioritise impact categories and indicators [58, 66]. Different ways for indicator selection have been proposed. For example, a four stage sequence for indicator selection in the wood industry was developed by Siebert et al. [65]. First, global, and national sustainability standards as well as SLCA case studies are revised. This is followed by the conduction of stakeholder interviews. The findings are tested according to their viability in the last step. This can also be applied to other sectors.

A study from Rahman [67] for the selection of indicators for energy systems addressed a literature review of 30 European SLCA and LCSA studies. The indicators assessed within the studies were checked according to their relevance, i.e., if they are mentioned by the UNEP guidelines or the United Nations Sustainable Development Goals (SDGs). In addition, the relevance was dependent on the frequency of their use within the reviewed literature. In a second step, the identified indicators were checked according to their data availability [67].

In addition to the missing standardisation of indicator selection, there is a lack of indicators to reflect positive outcomes (cf. Section 5.2). Furthermore, some aspects, e.g., land use conflicts or competitions as well as demographic aspects, cannot be quantified yet [68]. This shows the need to define own indicators if the predefined ones do not serve the goal of the study. The practitioners must set them up according to the selected impact categories. In either case, the selection must be transparently documented and comprehensible.

Within SLCAs of FCH systems, the list of assessed indicators is long. For example, the study in [44] can be checked. By screening them, it is important to keep in mind that the there is a dependence of the indicators on the selected impact categories and subcategories. In addition, indicators are highly dependent on the goal and scope definition of the study. If the SLCA study is conducted within an LCSA, one should be aware of possible overlaps between LCA and SLCA indicators – especially if databases are used. Overlaps might address topics such as climate change, which can be part of an LCA as well as of an SLCA, e.g., the indicator “Infrared radiative forcing” within LCA [2] and the indicator “Embodied CO_2-equivalent footprint” within the PSILCA database [22]. There are situations, however, where the same effect can be used both in environmental LCA and SLCA in a meaningful way, without double-counting concerns. For example, resource depletion can be an issue in environmental LCA, but also in SLCA when it comes to the access of local communities to resources.

No general recommendation can be made regarding the sufficiency or completeness of indicator sets. It is highly dependent on the goal of the study as well as on the availability and quality of data (cf. Section 2.2). Thus, some indicators might be regarded as inadequate for one study, but essential for another.

Requirements and recommendations

For the specific case of FCH systems, no recommendations can be made regarding indicators, as the final technologies are manifold and can have different supply chains with a high variety of sectors and products included. The indicators to be studied are influenced by the selection of stakeholders, impact categories and subcategories and highly dependent on the goal of the study and thus must suit it. In addition, it has to be checked individually if an indicator can measure an FCH system specific social topic.

> **Box 53 Indicator assessment**
>
> Indicators to be assessed have to be in line with the goal of the study.

> **Box 54 Suitability of indicators**
>
> The suitability of an indicator to measure the social topic to be assessed must be checked.

Nevertheless, the indicators proposed in [57] are widely accepted and include many different topics. In addition, they provide guidance on the overall assessment of a social topic. It is therefore recommended to use them in addition to own defined indicators.

> **Box 55 Recommended indicators**
>
> It is recommended to use the indicators provided in [57] as well as own defined indicators.

Evaluation “method readiness level”

Readiness level for indicators availability: ●●●●●

Readiness level for indicators selection: ●●○○○

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
2: Social Life Cycle Inventory
3.2: Impact Categories
5.1: Stakeholders

4 Interpretation

Motivation

All results from the study need to be “checked and discussed in depth”, which “forms a basis for conclusions, recommendations, and decision-making in accordance with the Goal and Scope definition” [4]. In the UNEP guidelines [4], the conduction of the interpretation follows ISO 14044 [2]. The analysis of results includes several steps to check the completeness, consistency, sensitivity, data quality and materiality, and entails also the conclusion, limitations and recommendations of the study [4].

Description

All parts of the interpretation phase and its embedment into the SLCA methodology are shown in Figure 9. It has an iterative nature.

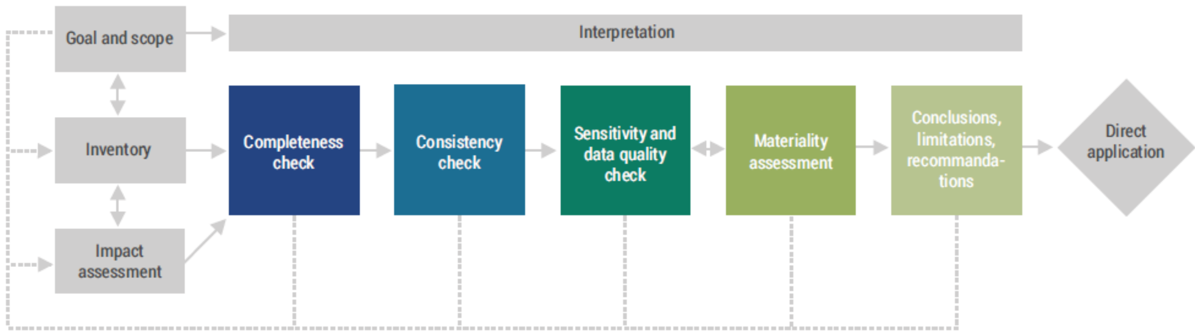


Figure 9: Elements of interpretation and its embedment into the overall SLCA methodology [4]

Within the **completeness check**, the requirements from the goal and scope phase are checked against their implementation in the inventory and the impact assessment. All objectives that could not be achieved, as well as the respective reasons for it, are identified and can be complemented through the iterative nature of the SLCA methodology. If it cannot be complemented, the goal and scope should be updated [4].

The **consistency check** has its focus on data from the inventory and the impact assessment and answers the question whether they are unambiguous and in line with the goal and scope [4] .

An uncertainty analysis is included in the **sensitivity and data quality check** and comes into place if two products or services are compared. It is of qualitative or quantitative nature. With the latter, the uncertainty stemming from, e.g., the aggregation of indicators or the application of scoring factors can be assessed. Qualitative evaluations focus on the product system model and its data and their effect on the results. The sensitivity check determines the influence of assumptions on the study. They can concern cut-off criteria, data in general or the calculation procedure. Another method to check the influence of assumptions is a scenario analysis [4].

The materiality assessment comes into place in several stages of the life cycle (cf. Sections 3.2, 3.3 and 5.1). In the interpretation stage, the aim is to determine “significant social performances or impacts, risks, stakeholders’ categories, life cycle phases of processes, in accordance with the Goal and Scope of the study.” The terminology “materiality” used within SLCA indicates the significance, this means if something is “of such relevance and importance that it could substantially influence the conclusions of the study, and the decisions and actions based on those conclusions. Materiality is thus independent from the level of influence that an organization plays on the different phases of the product system under study” [4]. It can be carried out standalone or with a contribution analysis. The contribution analysis shows the percentage or a qualitative ranking of the share of a specific social impact of a process, stakeholder or the life-cycle phases. If the assessment is based on trade information, i.e., input-output based SLCAs, hotspot assessments can be made by identifying the major contributors to the results. The degree of influence from the company on a social topic can be examined with the help of an influence analysis which complements the materiality assessment [4].

Results can be aggregated if this facilitates understanding. In this case, the results should also be provided in their initial presence for transparency reasons and they should be in line with the goal and scope of the study [4] .

A critical review progress is also part of the interpretation phase, as it increases the credibility and quality of the study. It can either be carried out by an expert, internal or external to the organisation, or by other interested parties or a review panel. In addition, it can be conducted in line with ISO 14044 [2].

The last of the iterative interpretation phases is the **conclusion** part, that answers the aims and questions defined during the goal and scope phase. Limitations must be stated, and recommendations be drawn for future work. Stakeholders can be involved. A combination with other methodologies could be helpful, e.g., multi-criteria decision analysis (MCDA) methods [4]. In general, there is a difference in interpretation if a standalone SLCA is conducted or if the SLCA is part of an LCSA [4]. When it comes to LCSA of FCH systems, social performance indices are often used in addition to overall sustainability indices. For LCSA studies of FCH systems, the results of the three assessment types, LCA, LCC and SLCA (single scores), are typically combined with the help of MCDA. Standalone SLCAs are mostly interpreted by hotspot assessment, either on country or product level [44].

Requirements and recommendations

When it comes to the interpretation of SLCAs of FCH systems, it is highly recommended to go through all process steps of an interpretation suggested in [4], including completeness check, consistency check, sensitivity and data quality check, materiality assessment, and conclusion with limitations and recommendations.

> **Box 56 Steps in the interpretation**
>
> The interpretation should include the following steps: completeness check, consistency check, sensitivity and data quality check, materiality assessment, and conclusion with limitations and recommendations.

Within the SH2E guidelines, it is required that the reference scale approach for impact assessment is applied (cf. Section 3.1). One prominent and widely recognised approach is the use of input-output models. Thus, within the interpretation of studies of FCH systems, it is recommended to do a hotspot assessment, where processes, components, and countries with a high degree of responsibility for a social impact are identified. By doing so, critical aspects in the life cycle of FCH systems can be identified.

> **Box 57 Input-output models in SLCA and interpretation**
>
> If an SLCA based on input-output models is conducted, it is recommended to carry out a hotspot assessment.

Very often, the databases PSILCA or SHDB are used when an SLCA based on input-output models is conducted. If this is the case, it is of paramount importance to interpret the results in the right way (Box 58).

Box 58 Interpretation of database results

Even though in the databases PSILCA and SHDB all units of the results have the supplement “medium risk hours” (e.g. “Fair Salary medium risk hours”), every impact category has its own unit. In PSILCA, for example, the unit for the impact category “Fair salary” is “FS medium risk hours”. This cannot be directly compared or aggregated with, e.g., “CL medium risk hours” from the impact category “Child Labour”.

It is tempting to compare the results one by one, as the units sound similar, but this is not correct (in the same way as it is not correct to compare kg SO_2-eq to kg CO_2-eq in environmental LCA). This error is often found in SLCA studies.

Evaluation “method readiness level”

Readiness level for interpretation: ●●●●●

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
2: Social Life Cycle Inventory
3.1: Impact Assessment
5.1: Stakeholders

5 Special and Cross-Cutting Topics

5.1 Stakeholders

Motivation

Every action pursued by an organisation can affect people in various kinds, either directly or indirectly, and it is of paramount importance to manage these social impacts. In a so-called stakeholder approach, social impacts can be categorised into different stakeholder groups. Within the UNEP guidelines [4], these are workers, local community, society, value chain actors, consumers, and children. Each stakeholder group can bundle a set of social topics. Sticking to the terminology of the UNEP guidelines [4], these are called impact categories, and reflect either positive or negative effects on the respective people. These impact categories in turn are divided into subcategories, of which each holds a group of indicators for measurement (cf. Sections 3.2 and 3.3). Thus, the stakeholder classification poses the basis of an SLCA, as it defines the social topics to be addressed [4].

Description

Depending on the goal and the specific situation, different stakeholder classifications can be used, e.g., own ones, even though this is not recommended because of the vanishing comparability with other studies. Other classifications exist, e.g., the Social Value Initiative divides people into four groups, which are workers, local community, society, and smallholders [63]. PSILCA divides stakeholders into four groups: workers, local community, value chain actors, and society. Their goal is to also include consumers [22].

None of the stakeholder groups can be regarded as more or less important, why it is recommended to include all relevant stakeholder groups in the assessment. This is often not practical, due to complexity reasons and constraints on ,e.g., time, effort, or data availability. Depending on the supply-chain specifications, e.g., the location, complexity, or cultural and political situations as well as the overall goal, the choice of stakeholders to be assessed might vary. The level of maturity of impact categories and indicators might also have an influence on the prioritisation of stakeholders. There is no consensus about stakeholder selection yet [58]. All stakeholders affected within the system boundaries should be included if data and respective impact categories as well as indicators for the assessment are present [4].

One option to select stakeholder groups is by conducting a hotspot assessment, e.g., with SHDB or PSILCA [69]. The guidelines in [4] suggest three criteria for stakeholder selection: impact (who is affected), legitimacy (who represents a group), and completeness (inclusion of different representations and attributes). With the help of a materiality assessment, stakeholders can be prioritised, by either selecting groups who have a high probability to be influenced to a large extent or if the target audience wants to have this information. In either case, an expert judgement is necessary to support the selection [63]. Next to materiality assessments, participatory approaches (focus groups) can help to select stakeholders [4]. The prioritisation of stakeholders can be justified with the help of experts, stakeholder integration, existing literature and data availability [46].

Workers are the most established stakeholder group within SLCAs in many sectors, followed by the local community and the society. Value chain actors and consumers are underrepresented up to now [43, 45, 46]. Children as stakeholders are a relatively new group, introduced in the update of the UNEP guidelines [4]. Thus, an assessment of children as an own stakeholder group is not present yet.

Within the assessment of FCH systems, the selection of stakeholders also becomes apparent, if not all of them can be assessed. According to a literature review, the most assessed stakeholders are workers followed by the society [6, 30, 39, 50, 51, 54-56]. There is a lack of inclusion of the local community as well as indigenous groups, leading to a research need to assess them [59]. To conduct a materiality assessment, a relevant framework to provide guidance can help, e.g., the different sector standards from GRI, but up to now there is no sector standard for hydrogen or hydrogen systems [62].

Due to the complex and globally distributed supply chains, workers are affected in various forms and at many stages of the life cycle. Also, users of FCH systems, called consumers in the SLCA context, can have an interest in an assessment of this technology, as doubts and fear may be present among them, mostly regarding health & safety issues. In addition, their acceptance can be increased if communication is transparent and honest [70]. The potential of job creation through FCH systems affects the stakeholder group local community [35]. A possible positive outcome of the establishment of FCH systems is the contribution to the economic development and affects the stakeholder group society.

Requirements and recommendations

To preserve a good overview of the manifold social topics, a classification into stakeholder groups is required.

Box 59 Stakeholder classification

For the assessment of complex social impacts, a classification into stakeholder groups is essential.

The prioritisation of stakeholders to be assessed is conditioned by the goal of the study. For instance, depending on the system boundaries, the selection of stakeholders might be different; e.g., if the use phase is not included, there is no need to include consumers and children[1] within the use phase, as they lie outside the scope of the assessment. Thus, the prioritisation of stakeholders must be in line with the goal. It is of great importance to be transparent and to provide information and arguments on the selection process.

[1] Children: child labour can still be present, but it is included in a subcategory within the stakeholder group of workers according to [4].

Box 60 Impact categories in line with goal and scope

Impact categories to be assessed have to be in line with the goal of the study.

Box 61 Stakeholder prioritisation

A transparent description of the justification of stakeholder prioritisation must be included.

Especially, workers are very likely to be affected to a high extent. Therefore, they should be included in the assessment, except they are not part of the product system. In some cases, the local community can be a key stakeholder in terms of job creation. If this is the case, they are to be included in the assessment. Even though the group of consumers are underrepresented yet, they might play an important role within the assessment of FCH systems, especially regarding health & safety issues. Consumers have a high interest in having information about this topic, as it has an influence on the acceptance of FCH systems. It is recommended to assess this stakeholder group. At present, children are not expected to play a major role in the assessment of FCH systems and, in addition, there is no established way yet to measure impacts on them. Even though this does not mean they are not important, they can be handled with less prioritisation for the time being. In order to include the contribution to economic development, the society as a stakeholder group should be included.

Over time, the state of research as well as political or socio-cultural situations might change. This highlights the need to identify current developments prior to the assessment; on the one hand, to be able to keep up with possible ways to include the different stakeholder groups in an SLCA and, on the other, to satisfy recent changes.

Evaluation

Readiness level for stakeholders selection: ●●●○○

Readiness level for workers: ●●●●●

Readiness level for local community: ●●●●○

Readiness level for society: ●●●●○

Readiness level for value chain actors: ●●●●○

Readiness level for consumers: ●●○○○

Readiness level for children: ●○○○○

This section is linked to the following sections of the present guidelines:

1.1: Goal of the Social Life Cycle Assessment
3.2: Impact Categories
3.3: Indicators

5.2 Positive Impacts

Motivation

Both negative and positive pressures on stakeholders are in the scope of SLCA. Positive social impacts are defined as "benefits accruing through the product life cycle that make a positive contribution to the improvement of human well-being" [4]. It is important to account for positive impacts in SLCA (i) to capture value created for different stakeholders in life cycles, (ii) to provide a comprehensive assessment of advantages and disadvantages of production and consumption pathways, and (iii) as a motivation for companies to go beyond business as usual [4].

Description of the topic

For the time being, there is no straightforward definition of what should be considered as a positive social impact. However, a positive impact is not just the absence of a negative impact; it rather refers to value generated by the life cycle under study for different stakeholders. As pointed out in the UNEP guidelines [4], positive impacts depend on the context, can be direct or indirect, and cannot compensate for negative impacts. Furthermore, the UNEP guidelines identify three possible types of positive social impacts [4]:

- Type A – Positive social performance going beyond business as usual, through best practices beyond what is required by national law or what other companies in the sector do.
- Type B – Positive social impact through presence (product or company existence), such as the creation of infrastructure and jobs in an area that would not have those opportunities if the companies were not there.
- Type C – Positive social impact through product utility, linked to the fulfilment of the function of certain products, such as vaccines and water treatment plants. This is the most debated type of positive impact, as it can be argued that product utility is usually already captured by the functional unit and all products are designed to serve a given purpose.

Positive indicators are not widely addressed in existing SLCA databases or studies; the only positive indicator is currently available in the PSILCA database and is named “Contribution to economic development”. This is assessed in PSILCA through different “opportunity” levels, depending on the share of the analysed sector in the national Gross Domestic Product (GDP) [22].

Requirements and recommendations

General requirements and recommendations

Although the importance of measuring and communicating positive social impacts is acknowledged, this topic is not yet fully established in SLCA. The main challenges refer to (i) identification of positive impacts, (ii) assessment of positive aspects through quantifiable indicators and scales, and (iii) aggregation and communication of positive impacts together with negative ones.

Despite these challenges, it is recommended to address benefits (i.e. positive impacts) of the system under study in SLCA. When benefits are identified, the user needs to define indicators to assess them in a quantitative, semi-quantitative or qualitative way (cf. Section 3.3). For Type I assessment, a performance reference scale needs to be defined to reflect positive aspects. Type II assessment has not yet identified a specific method to account for positive impacts. Therefore, Type I is recommended, as it is a more established approach (Box 62). After those data have been collected for the defined positive indicators, positive impacts should be assessed. In the assessment step, it is recommended not to aggregate or weigh positive and negative impacts, as they should not compensate each other [4] (Box 62). In the event of aggregation and weighting, it is highly recommended to also report the positive and negative impacts separately.

Box 62 Positive impacts for different stakeholders

When performing SLCA, it is recommended to address positive impacts on different stakeholders. The following steps are recommended:

1. Identify benefits and positive consequences of the system under study.
2. Define positive social indicators to describe the identified aspects. Indicators can be quantitative, semi-quantitative or qualitative.
3. Apply Type I assessment by defining performance reference scales for the positive social indicators.
4. Communicate positive social impacts in a clear and transparent way, avoiding aggregating and weighting them with negative social impacts.

Box 63 Social handprinting

Social handprinting is an approach to consider positive impacts in life cycles by investigating the change introduced to improve social impacts in comparison to business as usual [4, 71]. To perform social handprinting, the following steps are proposed [4]:

- Conduct materiality assessment to identify social hotspots in the investigated life cycle.
- Categorise the social hotspots in impact categories.
- Define the baseline of the assessment, i.e., the business-as-usual situation.
- Identify root causes for the hotspots within the different impact categories.
- Define the change needed to improve hotspots beyond business as usual and the related expected outcome.
- Measure the impact generated by implementing the change, which results in the social handprint.

Requirements and recommendations for systems producing and/or using hydrogen

Positive social impacts of life cycles producing and/or using hydrogen have been often discussed in literature [72, 73]. However, given that assessment of positive impacts is not yet fully established and that SLCA databases focus on negative impacts, few studies have managed so far to quantify these benefits. Indeed, "contribution to economic development" is the only positive indicator that is usually assessed in studies that use the PSILCA database [30, 74]. As for hydrogen systems, the same general recommendations from Box 62 apply for the assessment of positive social impacts. No specific guidance can be given for the selection of positive indicators for hydrogen systems, as this depends on the goal and scope of the study and the characteristics of the life cycle. However, it is possible to list a number of positive social indicators and topics mentioned in literature related to hydrogen production:

- Contribution to economic development [30, 75, 76].
- Local job creation [30, 73].
- Conservation of fossil fuels [30, 75].
- Community infrastructure [76].
- Health benefits of economic development [30].
- Career development [30].
- Social satisfaction [30].
- Technology development [77,4, 75].
- Community engagement [77].
- Skills development [75, 76].
- Women's empowerment [75].
- Energy security [77].

- Knowledge creation and dissemination [77].
- Capacity building [73].
- Research and development [77].

Evaluation: "method readiness level"

Identification of positive impacts ●●●○○
Availability of social indicators in social LCA databases ●○○○○
Availability of reference scales for positive social impacts ●○○○○
Assessment of positive impacts in social LCA: quantification and communication ●●○○○
Social handprinting: ●○○○○

This section is linked to the following section of the present guidelines:

5: Social Life cycle Impact Assessment
7.1: Stakeholders

5.3 Verification and Validation

Motivation

Already the FCH-LCA guidelines (SH2E D2.2) contain a section about verification and validation, where the key terms are defined as follows: “Verification is known in modelling theory as checking whether a model is technically done correctly. […] Model validation deals with building the right model” [78]. For SLCA, the same points apply: what is needed to make an SLCA model technically correct, and how can this be checked and ensured (verification)? And how can it be checked and ensured that the right SLCA is built (validation)?

Description of the topic and key terms

For the description of verification and validation for life-cycle approaches in general, readers are referred to the (environmental) FCH-LCA guidelines (SH2E D2.2), while this section discusses differences and special aspects of SLCA models. For SLCA, impacts cannot be really objectively measured. This makes a verification of models depending on specified calculation and modelling rules more complicated than for environmental LCA models. In environmental LCA, “normal” natural science laws apply for many aspects in the model, be it calculation of emissions, or assessment of impacts. In SLCA, human perception and subjective feeling is much more important, which is not the same from one person to another, and thus cannot measured in an entirely objective manner.

Social sciences have developed a broad portfolio of tools and approaches for observing and evaluating social impacts [79, 80], with early works already from the 1930’s [81]. However, it seems fair to state that verification and validation is challenging and often debated in the social sciences [82]. One can imagine, however, a hierarchy of data sources and of modelling rules for SLCA, where some lead to technically more correct and better models. The UNEP SLCA guidelines [4] provide a figure which contains such a hierarchy for data collection methods in SLCA (Figure 10), plotting various methods over effort and reliability of statements.

These data collection methods provide data for SLCA models, which in turn leads to more or less “good” models, meaning models that are modelled more correctly and model what they are supposed to model, i.e., which have a higher degree of verification and of validation. This fits to the pathway from data to approved data in the hybrid verification and validation model for LCA developed in SH2E D2.2 (Figure 11).

However, regarding the hierarchy suggested by the SLCA guidelines in [4], it can be argued whether, for example, structured interviews with domain experts are always more credible than video documentation. While the question of source reliability is already not easy for environmental LCA, it is even more complicated for SLCA, due to the subjective, and in the end often not directly measurable, nature of social effects and impacts. And consequently, verification and validation of models is more complicated for SLCA than for other sustainability dimensions. As a conclusion, it is for SLCA even more necessary than for other sustainability dimensions to state the model and concept used for assessing social impacts along the life cycle, to be transparent about modelling decisions, and to use several sources for data that contributes to important parts of an SLCA model, using triangulation, and considering a potential bias in different sources. A recent example for the consideration of source bias and triangulation in news media is, e.g., ground news [84, 85].

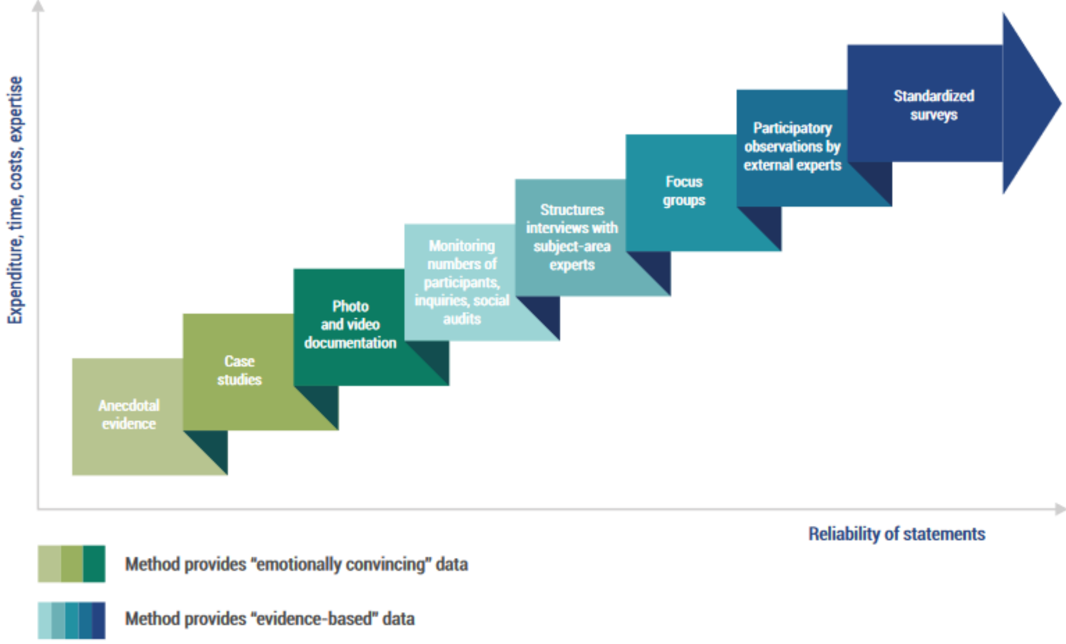


Figure 10. Various data collection methods in SLCA plotted over assumed reliability and effort [4]

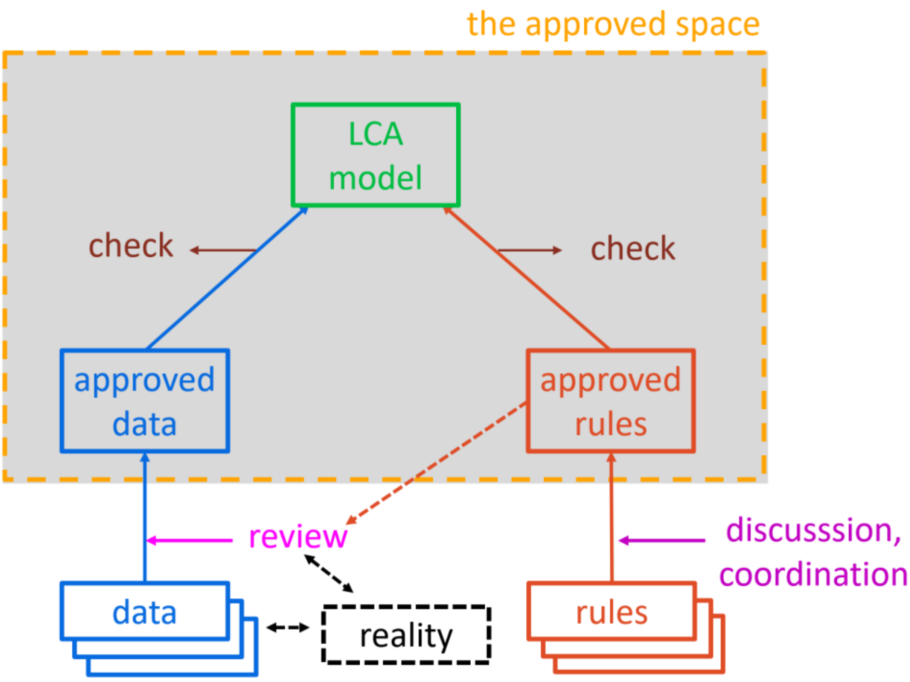


Figure 11. Hybrid approach for verification and validation of LCA models, with approved data and approved rules to "mimic" empirical validation of data and rules for LCA models [83]

For FCH systems, these general statements hold as well. In addition, FCH systems are often less mature and in early TRL stages, which makes an assessment of social aspects even more challenging, and more so the verification and validation of FCH-SLCA models.

Requirements and recommendations

There are three main requirements and recommendations related to verification and validation in SLCA. These are, to some extent, also mentioned in other sections of this text, but here the recommendations come from the two fundamental questions for SLCA models: is the model technically correct? and is it the right model?

Box 64 Transparent documentation of impact assessment

The model and concept used for assessing social impacts along the life cycle must be transparently described for SLCA models and studies.

Model and concept, in this sense, can be a risk assessment of social indicators, with transparent documentation of the performance reference points, or the direct calculation. Also, the impact assessment performed must be documented and transparently described. Details are provided in the activity variable and in the impact assessment sections of this text.

Box 65 Clear description and motivation of modelling decisions

Modelling decisions must be clearly described and motivated for SLCA models. Results from SLCA models can only be seen in the context of the modelling decisions, which must be communicated together with the results.

While this very broad requirement could be considered self-evident, the specific issues for SLCA applied to FCH systems seem to deserve this special emphasis on documentation.

Box 66 Use of multiple sources, source bias and triangulation

For data that contribute to important parts of an SLCA model, or that are considered important for other reasons, it is recommended, as stated also in the data sources section, to use several sources, applying triangulation. Furthermore, it is recommended to consider and address a potential bias in different sources, especially in the interpretation.

Evaluation: "method readiness level"

The options and recommendations are already used in practice: ●●●●●

6 References

[1] *ISO 14040: Environmental management — Life cycle assessment — Principles and framework*. International Organization for Standardization, 2006.

[2] *ISO 14044: Environmental management — Life cycle assessment — Requirements and guidelines*. International Organization for Standardization, 2006.

[3] European Commission-Joint Research Center, “ILCD Handbook on LCA: General guide for Life Cycle Assessment,” 2010. doi: 10.2788/38479.

[4] “Guidelines for Social Life Cycle Assessment of products and organizations,” 2020. Available: https://www.lifecycleinitiative.org/wp-content/uploads/2021/01/Guidelines-for-Social-Life-Cycle-Assessment-of-Products-and-Organizations-2020-22.1.21sml.pdf

[5] L. Pollok, S. Spierling, H. J. Endres, and U. Grote, “Social life cycle assessments: A review on past development, advances and methodological challenges,” *Sustainability (Switzerland)*, vol. 13, no. 18, p. 10286, Sep. 2021, doi: 10.3390/SU131810286/S1.

[6] E. Bargiacchi, F. Campos-Carriedo, D. Iribarren, and J. Dufour, “Social Life Cycle Assessment of a Proton Exchange Membrane Fuel Cell stack,” *E3S Web of Conferences*, vol. 334, p. 09001, 2022, doi: 10.1051/E3SCONF/202233409001.

[7] S. K. Springer, C. Wulf, and P. Zapp, “Social life cycle assessment of fuel cell electric vehicles,” in *Life Cycle Innovation Conference 2022*, Jan. 2022, vol. 278.

[8] A. Valente, D. Iribarren, and J. Dufour, “Comparative life cycle sustainability assessment of renewable and conventional hydrogen,” *Science of the Total Environment*, vol. 756, Feb. 2021, doi: 10.1016/j.scitotenv.2020.144132.

[9] J. F. Hake *et al.*, “Towards a Life Cycle Sustainability Assessment of Alkaline Water Electrolysis,” *Energy Procedia*, vol. 105, pp. 3403–3410, 2017, doi: 10.1016/j.egypro.2017.03.779.

[10] B. Reimers and M. Kaltschmitt, “Kostenentwicklung der Offshore-Windstromerzeugung – Analyse mithilfe der Erfahrungskurventheorie,” *Zeitschrift für Energiewirtschaft*, Nov. 2014, doi: 10.1007/S12398-014-0142-Z.

[11] H. Baumann and A. Tillman, “The hitch hiker’s guide to LCA: an orientation in life cycle assessment methodology and application,” 2004.

[12] Ciroth A, Arvidsson R. Life Cycle Inventory Analysis - Methods and Data [Internet]. Ciroth A, Arvidsson R, editors. Life Cycle Inventory Analysis - Methods and Data. Cham: Springer; 2021. Available from: https://link.springer.com/book/10.1007/978-3-030-62270-1#about

[13] A. Valente, D. Iribarren, and J. Dufour, “Life cycle assessment of hydrogen energy systems: a review of methodological choices,” *Int J Life Cycle Assess*, vol. 22, no. 3, pp. 346–363, Mar. 2017, doi: 10.1007/S11367-016-1156-Z.

[14] J. S. Cooper, “Specifying Functional Units and Reference Flows for Comparable Alternatives,” *Int J Life Cycle Assess*, vol. 8, no. 6, pp. 337–349, 2003, doi: 10.1007/BF02978507/METRICS.

[15] M. Martín-Gamboa, A. C. Dias, L. Arroja, and D. Iribarren, “A protocol for the definition of supply chains in product social life cycle assessment: application to bioelectricity,” *Sustain Energy Fuels*, vol. 4, no. 11, pp. 5533–5542, 2020, doi: 10.1039/d0se00919a.

[16] Koese, M., Blanco, C. F., Vert, V. B. & Vijver, M. G. (2023) A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage. *J Ind Ecol*, 27, 223-237. https://doi.org/10.1111/jiec.13347.

[17] Moltesen, A., Bonou, A., Wangel, A. & Bozhilova-Kisheva, K. P. (2018) Social Life Cycle Assessment: An Introduction. In: Hauschild, M. Z., Rosenbaum, R. K. & Olsen, S. I. (eds.) *Life Cycle Assessment: Theory and Practice.* Springer International Publishing.

[18] ILOSTAT [Online]. Accessed: May 23rd, 2023. https://ilostat.ilo.org/

[19] WHO UNICEF global data on Water Supply, Sanitation and Hygiene [Online]. Accessed: May 2[3rd], 2023. https://washdata.org/

[20] The Eora Global Supply Chain Database [Online]. Accessed: May 23[rd], 2023. https://worldmrio.com/

[21] A. Ciroth, F. Eisfeldt, M. Srocka: Data quality in Social LCA studies, SETAC Nantes 2016 platform presentation, online https://www.greendelta.com/wp-content/uploads/2017/03/SOCIALLCA_DQ_SETACNANTES2016.pdf. Accessed: May 23[rd], 2023.

[22] K. Maister, C. Di Noi, A. Ciroth, M. Srocka, PSILCA V3 database documentation, GreenDelta, 2020.

[23] Data quality in openLCA [Online]. Accessed: May 23[rd], 2023. https://www.openlca.org/project/data-quality/

[24] Andrews, E. S., Barthel, L.-P., Beck, T., Benoit, C., Ciroth, A., Cucuzella, C., Gensch, C.-O., Hérbert, J., Lesage, P., Manhart, A., Mazeau, P., Mazijn, B., Methot, A.-L., Moberg, A., Norris, G., Parent, J., Prakash, S., Reveret, J.-P., Spillemaeckers, S., Ugaya, C. M. L., Valdivia, S., Weidema, B. (2009): UNEP/SETAC Life Cycle Initiative: Guidelines for social life cycle assessment of products, 2009.

[25] Norris GA (2006) Social impacts in product life cycles - towards life cycle attribute assessment. *Int J Life Cycle Assess* 11(1):97–104. https://doi.org/10.1065/lca2006.04.017

[26] Zimdars, C., Haas, A., Pfister, S. (2018). Enhancing comprehensive measurement of social impacts in SLCA by including environmental and economic aspects. Int J Life Cycle Assess 23, 133–146, 10.1007/s11367-017-1305-z.

[27] Ciroth A, Di Noi C, Srocka M (2019) Revisiting the activity variable in social LCA, beyond worker hours. Presentation LCA XIX, Tucson. https://www.greendelta.com/wp-content/uploads/2019/11/2019_LCA_XIX_Revisiting-the-activity-variable-in-SLCA.pdf

[28] Heijungs, R., Suh, S. (2002). The Computational Structure of Life Cycle Assessment. Kluwer, 10.1007/978-94-015-9900-9.

[29] Srocka, M., Montiel, F. (2021). Algorithms of Life Cycle Inventory Analysis. In: Ciroth, A., Arvidsson, R. (eds) Life Cycle Inventory Analysis. LCA Compendium – The Complete World of Life Cycle Assessment. Springer. https://doi.org/10.1007/978-3-030-62270-1_7

[30] Iribarren, D., Calvo-Serrano, R., Martín-Gamboa, M., Galán-Martin, Á. & Guillén-Gosálbez, G. (2022) Social life cycle assessment of green methanol and benchmarking against conventional fossil methanol. *Science of the Total Environment,* 824, 153840. http://dx.doi.org/10.1016/j.scitotenv.2022.153840.

[31] Sureau, S., Neugebauer, S. & Achten, W. M. J. (2020) Different paths in social life cycle impact assessment (S-LCIA)—a classification of type II impact pathway approaches. *Int J Life Cycle Assess,* 25(2)**,** 382-393. 10.1007/s11367-019-01693-9.

[32] Benoît Norris, C., Norris, G. A. & Aulisio-Cavan, D. (2013) Social Hotspot Database Supporting Documentation. New Earth.

[33] Benoît-Norris, C., Cavan, D. A. & Norris, G. (2012) Identifying Social Impacts in Product Supply Chains: Overview and Application of the Social Hotspot Database. *Sustainability,* 4(9)**,** 1946-1965.

[34] Akhtar, M. S., Khan, H., Liu, J. J. & Na, J. (2023) Green hydrogen and sustainable development – A social LCA perspective highlighting social hotspots and geopolitical

implications of the future hydrogen economy. *J Clean Prod*, 136438. https://doi.org/10.1016/j.jclepro.2023.136438.

[35] Delpierre, M., Quist, J., Mertens, J., Prieur-Vernat, A. & Cucurachi, S. (2021) Assessing the environmental impacts of wind-based hydrogen production in the Netherlands using ex-ante LCA and scenarios analysis. *J Clean Prod,* 299, 126866. https://doi.org/10.1016/j.jclepro.2021.126866.

[36] Werker, J., Wulf, C. & Zapp, P. (2019) Working conditions in hydrogen production. *J Ind Ecol,* 23, 1052-1061. https://doi.org/10.1111/jiec.12840.

[37] Hoque, N., Biswas, W., Mazhar, I. & Howard, I. (2020) Life Cycle Sustainability Assessment of Alternative Energy Sources for the Western Australian Transport Sector. *Sustainability,* 12(14), 5565. https://doi.org/10.3390/su12145565.

[38] Springer, S. K., Wulf, C. & Zapp, P. Opportunities and challenges of using direct quantification of indicators in PSILCA – An example of Social Life Cycle Assessment of fuel cell electric vehicle production. *International Conference of Social Life Cycle Assessment (SLCA 2022)*. Aachen, Germany, 05-08.09.2022.

[39] Masilela, P. & Pradhan, A. (2021) A life cycle sustainability assessment of biomethane versus biohydrogen – For application in electricity or vehicle fuel? Case studies for African context. *J Clean Prod,* 328, 129567. https://doi.org/10.1016/j.jclepro.2021.129567.

[40] Vanclay, F. (2002) Conceptualising social impacts. *Environmental Impact Assessment Review,* 22(3), 183-211. https://doi.org/10.1016/S0195-9255(01)00105-6.

[41] Neugebauer, S., Traverso, M., Scheumann, R., Chang, Y.-J., Wolf, K. & Finkbeiner, M. (2014) Impact Pathways to Address Social Well-Being and Social Justice in SLCA—Fair Wage and Level of Education. *Sustainability,* 6(8). 10.3390/su6084839.

[42] Weidema, B. P. (2006) The Integration of Economic and Social Aspects in Life Cycle Impact Assessment. *Int J Life Cycle Assess,* 11(1), 89-96. https://doi.org/10.1065/lca2006.04.016.

[43] Wu, R., Yang, D., Chen, J. 2014. "Social Life Cycle Assessment Revisited". *Sustainability* 6, no. 7: 4200-4226. https://doi.org/10.3390/su6074200.

[44] Campos-Carriedo, F., Dufour, J. & Iribarren, D. (2023). *Trends and gaps in social life cycle assessment of hydrogen-related systems*. 11th Life Cycle Management Conference, Lille (France), 6-8 September 2023.

[45] Rebolledo-Leiva, R., Moreira, M. T. & González-García, S. (2023) Progress of social assessment in the framework of bioeconomy under a life cycle perspective. *Renew Sustain Energy Rev,* 175, 113162. https://doi.org/10.1016/j.rser.2023.113162.

[46] Tragnone, B. M., D'Eusanio, M. & Petti, L. (2022) The count of what counts in the agri-food Social Life Cycle Assessment. *J Clean Prod,* 354, 131624. https://doi.org/10.1016/j.jclepro.2022.131624.

[47] Chhipi-Shrestha, G. K., Hewage, K. & Sadiq, R. (2015) 'Socializing' sustainability: a critical review on current development status of social life cycle impact assessment method. *Clean Technol Environ Policy,* 17(3), 579-596. 10.1007/s10098-014-0841-5.

[48] Harmens, R., Goedkoop, M., Alvarenga, R. A. F., Boone, L., Martinez, E. C., Zanchi, L., Zamagni, A., Sonderegger, T., Ruiz, E. M., Saling, P. & Cordella, M. (2021) Critical evaluation of social approaches. ORIENTING project.

[49] Sureau, S., Neugebauer, S. & Achten, W. M. J. (2020) Different paths in social life cycle impact assessment (S-LCIA)—a classification of type II impact pathway approaches. *Int J Life Cycle Assess,* 25(2), 382-393. 10.1007/s11367-019-01693-9.

[50] Mattioda, R. A., Fernandes, P. T., Casela, J. L. & Canciglieri, O., Jr. (2017) Social Life Cycle Assessment of Hydrogen Energy Technologies. In: Scipioni, A., Manzardo, A. & Ren, J. (eds.) Hydrogen Economy - Supply Chain, Life Cycle Analysis and Energy Transition for Sustainability. London, UK; San Diego, CA, US; Cambridge, MA, US; Oxford, UK; Elsevier Ltd.

[51] Campos-Carriedo, F., Puig-Samper, G., Bargiacchi, E., Iribarren, D. & Dufour, J. (2022). *Social life cycle assessment of a solid oxide electrolysis cell stack.* 23rd World Hydrogen Energy Conference. Istanbul, Turkey 26-30.06.2022.

[52] Eynard, U., Martín-Gamboa, M., Valente, A., Mancini, L., Arrigoni-Marocco, A., Weidner, E. & Mathieux, F. SLCA applied to hydrogen technologies in Europe: challenges for critical raw materials' responsible sourcing. *Social Life Cycle Assessment Conference (SLCA 2022)*. Aachen, Germany.

[53] Springer, S. K., Wulf, C. & Zapp, P. Social life cycle assessment of fuel cell electric vehicles. *3rd Life Cycle Innovation Conference 2022* Berlin, Germany, 30.02.2022.

[54] Valente, A., Iribarren, D. & Dufour, J. (2021) Comparative life cycle sustainability assessment of renewable and conventional hydrogen. *Sci Total Environ,* 756, 144132. https://doi.org/10.1016/j.scitotenv.2020.144132.

[55] Valente, A., Iribarren, D. & Dufour, J. (2019) Life cycle sustainability assessment of hydrogen from biomass gasification: A comparison with conventional hydrogen. *Int J Hydrogen Energy,* 44(38), 21193-21203. https://doi.org/10.1016/j.ijhydene.2019.01.105.

[56] Wulf, C., Zapp, P., Schreiber, A. & Kuckshinrichs, W. (2021) Setting Thresholds to Define Indifferences and Preferences in PROMETHEE for Life Cycle Sustainability Assessment of European Hydrogen Production. *Sustainability,* 13, 7009. https://doi.org/10.3390/su13137009.

[57] UNEP (2021) Methodological Sheets for Subcategories in Social Life Cycle Assessment (SLCA). In: Traverso, M., Valdivia, S., Luthin, A., Roche, L., Arcese, G., Neugebauer, S., Petti, L., D'Eusanio, M., Tragnone, B. M., Mankaa, R., Hanafi, J., Benoit Norris, C. & Zamagni, A. (eds.). United Nations Environment Programme (UNEP).

[58] Huertas-Valdivia, I., Ferrari, A. M., Settembre-Blundo, D. & García-Muiña, F. E. (2020) Social Life-Cycle Assessment: A Review by Bibliometric Analysis. *Sustainability*, 12(15), 6211.

[59] Emodi, N. V., Lovell, H., Levitt, C. & Franklin, E. (2021) A systematic literature review of societal acceptance and stakeholders' perception of hydrogen technologies. *Int J Hydrogen Energy*, 46(60), 30669-30697. https://doi.org/10.1016/j.ijhydene.2021.06.212.

[60] Dreyer, L., Hauschild, M. & Schierbeck, J. A Framework for Social Life Cycle Impact Assessment. *Int J Life Cycle Assess* 11, 88–97 (2006). https://doi.org/10.1065/lca2005.08.223

[61] Bouillass, G., Blanc, I. & Pérez-López, P. (2021). Step-by-step social life cycle assessment framework: a participatory approach for the identification and prioritization of impact subcategories applied to mobility scenarios. *Int J Life Cycle Assess* 26. 10.1007/s11367-021-01988-w.

[62] GRI, Global Reporting Initiative, [Online]. Accessed: May 23rd, 2023, https://www.globalreporting.org/standards/download-the-standards/

[63] Goedkoop, M. J., de Beer, I. M., Harmens, R., Saling, P., Morris, D., Florea, A., Hettinger, A. L., Indrane, D., Visser, D., Morao, A., Musoke-Flores, E., Alvarado, C., Rawat, I., Schenker, U. W., Head, M., Collatta, M., Andro, T., Viot, J.-F. & Whatelet, A. (2020) Handbook for Product Social Impact Assessment. Amersfoort, Netherlands.

[64] P. M. Falcone & E. Imbert, 2018. "Social Life Cycle Approach as a Tool for Promoting the Market Uptake of Bio-Based Products from a Consumer Perspective," *Sustainability*, 10(4), 1031.

[65] Siebert, A., Bezama, A., O'Keeffe, S. & Thrän, D. (2018) Social life cycle assessment indices and indicators to monitor the social implications of wood-based products. *J Clean Prod*, 172, 4074–4084. 10.1016/j.jclepro.2017.02.146.

[66] Kühnen, M. & Hahn, R. (2017) Indicators in Social Life Cycle Assessment: A Review of Frameworks, Theories, and Empirical Experience. *J Ind Ecol*, 21(6), 1547-1565. https://doi.org/10.1111/jiec.12663.

[67] Rahman, T. (2020) sLCA-Indikatoren für Energiesysteme auf verschiedenen regionalen Ebenen. Graduate Engineer Masterthesis Fachhochschule Burgenland GmbH.

[68] Mancini, L. & Sala, S. (2018) Social impact assessment in the mining sector: Review and comparison of indicators frameworks. *Resour Policy*, 57, 98–111. 10.1016/j.resourpol.2018.02.002.

[69] Traverso, M., Mankaa, M. N., Valdivia, S., Roche, L., Luthin, A., Garido, S. R., Neugebauer, S. & (eds) (2022) Pilot projects on Guidelines for Social Life Cycle Assessment of products and organizations 2022. Paris, France: Life Cycle Initiative.

[70] Vallejos-Romero, A., Cordoves-Sánchez, M., Cisternas, C., Sáez-Ardura, F., Rodríguez, I., Aledo, A., Boso, Á., Prades, J. & Álvarez, B. (2023) Green Hydrogen and Social Sciences: Issues, Problems, and Future Challenges. Sustainability, 15(1), 303.

[71] Benoît Norris, C., Norris, G.A., Azuero, L., Pflueger, J., 2019. Creating Social Handprints: Method and Case Study in the Electronic Computer Manufacturing Industry. Resources 8, 176. https://doi.org/10.3390/resources8040176

[72] F. Mneimneh, H. Ghazzawi, M. Abu Hejjeh, M. Manganelli, and S. Ramakrishna, "Roadmap to Achieving Sustainable Development via Green Hydrogen," *Energies*, 16(3), 1368, 2023.

[73] D. Villagrasa, "Green hydrogen: Key success criteria for sustainable trade & production. A synthesis based on consultations," 2022.

[74] Mancini L., Eynard U., Eisfeldt F., Ciroth A., Blengini G., Pennington D., Social assessment of raw materials supply chains. A life-cycle-based analysis, EUR 29632 EN, Publications Office of the European Union, Luxembourg. 2018 ISBN 978-92-79-99074-8, doi:10.2760/470881, JRC112626.

[75] G. Zhao and E. Ravn Nielsen, "Social Impact Assessment of BIG HIT. A report into the societal impact of the project," Technical University of Denmark, 2018.

[76] F. Mneimneh, H. Ghazzawi, M. Abu Hejjeh, M. Manganelli, and S. Ramakrishna, "Roadmap to Achieving Sustainable Development via Green Hydrogen," *Energies*, 16(3), 1368, 2023.

[77] N. Hoque, W. Biswas, I. Mazhar, and I. Howard, "Life cycle sustainability assessment of alternative energy sources for the Western Australian transport sector," *Sustainability*, 12(14), 5565, 2020.

[78] Balci, O. (1998). Verification, Validation, and Testing. In Handbook of Simulation, J. Banks (Ed.). https://doi.org/10.1002/9780470172445.ch10.

[79] Lois, Daniel, Kopp, Johannes, Hartmann, Florian G. Social Science Data Analysis: An Introduction. Deutschland: Springer Fachmedien Wiesbaden, 2023.

[80] Häder, Michael. Empirical Social Research: An Introduction. Deutschland: Springer Fachmedien Wiesbaden, 2022.

[81] Marie Jahoda, Paul Felix Lazarsfeld, Hans Zeisel: Die Arbeitslosen von Marienthal. Ein soziographischer Versuch über die Wirkungen langandauernder Arbeitslosigkeit. Hirzel, Leipzig 1933.

[82] McKie, Linda & Ryan, Louise. (2016). An End to the Crisis of Empirical Sociology? Trends and Challenges in Social Research. 10.4324/9781315738192.

[83] SH2E EU JU project: D2.2 Definition of FCH-LCA guidelines, 2022.

[84] We all live in a media bubble. This app wants to burst it, ground news [Online]. Accessed: May 23rd, 2023. https://www.digitaltrends.com/news/ground-news-app-media-bias/

[85] Ground news start page, [Online]. Accessed: May 23rd, 2023. https://ground.news/

[86] Guinée JB, Heijungs R, Huppes G. Economic Allocation: Examples and Derived Decision Tree. *Int J Life Cycle Assess* 2004;9(1):23–33.

[87] Valente A, Iribarren D, Dufour, J. Life cycle sustainability assessment of hydrogen from biomass gasification: A comparison with conventional hydrogen. *Int J Hydrogen Energy* 2019, 44, 21193–21203, doi:10.1016/j.ijhydene.2019.01.105.

[88] Masoni P, Zamagni A. FC-HyGuide. Guidance Document for performing LCAs on Fuel Cells. Brussels, Belgium; 2011.

[89] Lozanovski A, Schuller O, Faltenbacher M. Guidance Document for Performing LCA on Hydrogen Production Systems. Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies. 2011.

[90] IPHE Hydrogen Production Analysis Task Force. Methodology for Determining the Greenhouse Gas Emissions Associated with the Production of Hydrogen. 2021.

[91] Shiva Kumar S, Himabindu V. Hydrogen production by PEM water electrolysis – A review. *Mater Sci Energy Technol* 2019;2(3):442–54.