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D4.1 Definition of FCH-LCC guidelines

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

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EXECUTIVE SUMMARY

This document presents the Life Cycle Costing (LCC) guidelines developed within the SH2E project for fuel cells and hydrogen (FCH) systems, as a result of Task 4.2. It is based on the results and trends identified in previous tasks of the project (Tasks 2.3, and 4.1). 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 economic dimension, while their subsequent integration into sustainability assessment guidelines will be undertaken in WP5 for Life Cycle Sustainability Assessment (LCSA).

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KEY TERMS

Term	Definition
Capital Expenditure	The costs for acquiring and upgrading assets such as facilities, equipment, etc. that can be depreciated.
Chemical Engineering Plant Cost Index	A typical index for adjustment of plant construction costs between the base year used in LCC and the reference year (e.g., in the literature).
Cash flow	Is a payment especially from one central bank account to another. It is mostly used to describe payments that are expected to happen in the future.
Cradle-to-Gate	Assessment including all stages from resource extraction to the factory gate
Cradle-to-Grave	Assessment including all stages from resource extraction to the use and disposal phase
Data	"Collection of facts or organized information, usually the results of observation, experience, or experiment, or a set of premises from which conclusions may be drawn. Data may consist of numbers, words, or images" [1]
Data quality	"Characteristics of data that relate to their ability to satisfy stated requirements" [2]
Gross Domestic Product deflators	A generic index for adjustment of a price or a cost between the base year used in LCC and the reference year (e.g., in the literature).
External costs	"External costs are externalities, that are transformed into monetary values." [3]
Externalities	Externalities result from hydrogen production and use activities, when involved main actors generate negative or positive impacts by these activities on other actors and the impacts are not accounted for or compensated by the main actors.
Functional unit	Quantitative representation of the function of the system, which serves as reference for all the flows involved in the assessed system.
Inflation rate	An increase in the general price level of goods and services in an economy.
Interest rate	Is the price of money or capital expressed as a percentage.
Levelized cost of hydrogen	Discounted lifetime cost of building and operating a production asset, expressed as a cost per unit of hydrogen produced.
Learning phenomena	Reasons for decreasing cost with increasing volume of production. Different phenomena can be observed, e.g. learning-by-doing, learning-by-research.
Location factor	An index for adjusting a price or a cost between two different countries or regions. The location factor is a combination of sub-indexes related to facilities, labour, etc. An index that these sub-indexes are integrated into is often used.
Learning rate	Indicates how much production costs decrease with each doubling in the cumulative production.
Monetary valuation	"Practice of converting measures of social and biophysical impacts into monetary units" [4].

Multi-functional system	System that originates more than one functional flow.
Net present value	Value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present.
Operational Expenditure	The costs for operation such as labour, maintenance, chemicals, insurance, etc. OPEX is sometimes divided into variable OPEX that is proportional to or a function of operational parameters (e.g., production amount) and fixed OPEX that does not vary with the operation.
Plant Cost Index	A generic index for adjustment of plant construction costs between the base year and the reference year (e.g., in the literature). CEPCI is an example for a PCI.
Power-law relationship	Is a functional relationship between two quantities, where a relative change in one quantity results in a proportional relative change in the other quantity, independent of the initial size of those quantities.
Real discount rate	An interest rate adjusted to remove the effect of actual or expected inflation.
Social discount rate	Discounting future benefits and costs of public interventions
Total cost of ownership	Estimation of the expenses associated with purchasing, deploying, using and retiring a product. It is typically a consumer-oriented indicator, usually applied in the transportation sector.
Variable cost	Estimation of the expenses associated with purchasing, deploying, using and retiring a product. It is typically a consumer-oriented indicator, usually applied in the transportation sector.

ACRONYMS

CAPEX	Capital Expenditure
CEPCI	Chemical Engineering Plant Cost Index
CF	Cash Flow
EF	Environmental Footprint
EoL	End-of-Life
EPC	Engineering, Procurement, and Construction
FCEV	Fuel Cell Electric Vehicle
FCH	Fuel Cell and Hydrogen
FU	Functional Unit
GDP	Gross Domestic Product
IEA	International Energy Agency
ILCD	International Reference Life Cycle Data System
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCOH	Levelized Cost of Hydrogen
LCSA	Life Cycle Sustainability Assessment
LR	Learning Rate
MRL	Method Readiness Level
NPV	Net Present Value
NCF	Net Cash Flow
OPEX	Operational Expenditure
PCI	Plant Cost Index
R&D	Research and Development
S-LCA	Social Life Cycle Assessment
SETAC	Society of Environmental Toxicology and Chemistry
SDR	Social Discount Rate
SMR	Steam Methane Reforming
TCO	Total Cost of Ownership
TRL	Technology Readiness Level

GENERAL INFORMATION

This document provides methodological guidance on how to perform a Life Cycle Costing (LCC) of fuel cells and hydrogen (FCH) systems. It builds on previous generic LCA guidelines ISO 14040 [5] and ISO 14044 [2] the ILCD Handbook [6], as well as the FCH-specific LCA guidelines HyGuide [7, 8] and SH2E [9] as the reference methodological framework, while tailoring it with the help of LCC generic guidelines (SETAC [10], ORIENTING project [11], INTERREG project [12]) and the FCH-specific report IEA Hydrogen Task 36 [13]. This document embraces hydrogen production, hydrogen use and hydrogen production & use systems. It promotes a harmonised and consistent evaluation of the life-cycle economic impacts of FCH products through robust and well-defined tailor-made methods to effectively support case-specific accounting and decision-making processes. In this sense, the present document effectively incorporates the lessons learnt in previous work of the SH2E project, where an exhaustive review on LCC of FCH systems was carried out [14] .

The present guidelines are addressed to any LCC practitioner addressing LCC of FCH systems (hydrogen production, hydrogen use or hydrogen production & use). The practitioner is guided on how to deal with all the methodological aspects of an LCC (functional unit, system boundaries, method and discounting, etc.) and with specific topics relevant to FCH systems (e.g. cost breakdown structure or data sources). Moreover, advanced topics are also addressed, either relevant to emerging technologies with a potentially significant market share (i.e. prospectivity) or scientifically relevant in the context of LCC (e.g. verification and validation).

How to use this document

The document provides guidance on how to conduct an LCC 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.

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 LCC tools	●●●●●
4	Data available	●●●●○
3	Stable	●●●○○
2	Discussions	●●○○○
1	First ideas	●○○○○

GUIDANCE ON PERFORMING LIFE CYCLE COSTING OF FCH SYSTEMS

1. Introduction

Life cycle costing (LCC) includes all the anticipated costs associated with a product or service throughout its life. LCC is the sum of the direct, indirect, recurring, non-recurring, and other related costs occurred, or estimated to be occurred, in the design, research and development, investment, operations, maintenance, retirement, and any other support of a product over its life cycle (i.e., its anticipated useful lifespan) [15]. All relevant costs should be included regardless of funding source, business unit, management control, and so on [15].

In accordance with LCA [16], LCC is composed of four phases (1): Goal and Scope definition, (2) Life Cycle Inventory, Life Cycle Impact Assessment, and Interpretation. The phases of an LCA can be defined as follows [9, 16]

- **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, methodological choices, discount rates and so forth. It is also important to state the modelling perspective of the study, i.e. producer, user or societal actor, during this phase.
- **Life Cycle Inventory analysis**: Systematic compilation of information regarding costs along the life cycle. The level of aggregation may vary significantly over the life cycle, between different unit processes and depending on the goal of the study. A cost breakdown structure helps to cluster the collected data.
- **Life Cycle Impact Assessment**: The obtained costs are aggregated by cost categories and different cost indicators are calculated based on the modelling perspective.
- **Interpretation:** The LCC results are analysed to study contributions and potential issues (e.g., high contribution of a process whose data quality may be improved). This phase includes robustness tests, sensitivity analyses, completeness analyses, and consistency checks. Data quality and uncertainty analyses can also be performed.

LCC has been widely applied to energy systems, including FCH technologies, e.g, [17, 18]. The increasing interest in the economic implications of FCH systems has led to a rise in the number of LCC studies on hydrogen systems, as identified in the review undertaken within the SH2E project [14]. Previous projects proposed specific LCC templates for FCH technologies, e.g. for hydrogen production [19], thus providing important grounds for the development of the present SH2E guidelines. However, we would like to offer the practitioner a larger degree of freedom while addressing at the same time more FCH technology issues than other guidelines, e.g. ORIENTING [11]. Within this context, the SH2E guidelines, while being built on the existing ones, identify best practices in LCC of FCH systems and address new topics which are often pending issues not only for FCH LCC actors but also for other scientists performing LCC.

2. Goal of the Life Cycle Costing

Motivation

The goal of an LCC establishes the basis capable of correctly answering the questions posed by/to the practitioner. Hence, it strongly influences the whole setup of an LCC, comprising goal and scope, data, and quality assurance. This especially concerns the application situation since LCC is often used for decision support for investment decision. The LCC methodology is application dependent.

Description of the topic and key terms

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

Intended application(s)

The expected use of the LCC results could be more than one for a given LCC study. The applications foreseen affect not only the LCC model construction, but also the modelling perspective. In LCC three different perspectives can be distinguished (i) user, (ii) societal actor and (iii) industrial producer [10]. This further defines the modelling approach from top-down to bottom-up [15] as well as requirements for verification and data quality.

For a system that is well known, it is easier to achieve higher data quality and to 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 LCC results, one modelling approach may be more appropriate than another. For instance, in the case of FCH products where a market is yet establishing, often commercial values for a bottom-up approach are not available and estimates using historical results from similar products or components, i.e. analogies, need to be made.

The guidelines for FCH specific LCC are developed for evaluating only economic aspects. If also environmental and social aspects should be included the practitioner should follow the LCSA guidelines to be developed in SH2E Task 5.4. However, there are reasons to combine economic with environmental aspects, e.g. impact on acidification, by monetizing them. This will be addressed in an excursus in these LCC guidelines, see Section 5.2.

Requirements and recommendations

Box 1 Intended application of the LCC

The intended application must be considered for LCCs. The intended application is characterised by the intended modelling perspective and approach. The application situation must be coherent with it, by stating if the LCC study would be employed for decision support (yes/no) and the scale of the induced changes in the considered system (micro, meso or macro).

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 employed for specific interests by individuals, companies or public institutions.

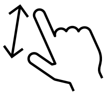
Box 2 Limitations of the study

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

Evaluation: "method readiness level"

- Consideration of the application situation in LCC ●●●●○

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



- **3: Scope of the Life Cycle Costing**
- **4: Life Cycle Inventory**
- **5: Life Cycle Impact Assessment**

3. Scope of the Life Cycle Costing

3.1 Modelling approach

3.1.1 Prospectivity

An LCC is defined prospective when **the technology studied is at an early phase of development or market deployment, but it is modelled at a future, more developed phase**. This definition has been adapted from Arvidsson et al. [20] to include most of the FCH systems.

Box 3 Prospectivity I

To be prospective within the context of these guidelines, an LCC study must meet the following requisites:

1. The system must be modelled at a future time.
2. The technical/operating parameters and capital goods of the analysed product system must be prospective.

When performing a comparative study, it must be ensured that the FCH technologies under comparison are modelled at the same future time of implementation.

Additionally, the following recommendations should be considered:

Box 4 Prospectivity II

1. The use of relevant prospective background data for processes directly linked to the foreground system (e.g., electricity production) is strongly recommended.
2. It is recommended to state the Technology Readiness Level (TRL) and/or the Manufacturing Readiness Level (MRL) of the involved technology to facilitate comparability decisions.

Scale effects and learning phenomena in prospective LCC

Prospective LCCs often require the use of pilot-scale or early commercialization data, whose direct representativeness and comparability with ex-post or retrospective LCC data is questionable. The latter refers to mature technologies for which data on large operating scales is widely available, based on years of experience (e.g., steam methane reforming (SMR)). Several factors might lead to a reduction of costs in the future. These include the following learning phenomena [21]:

- 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 standardization 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 [21]. In particular, effects by learning and by economies of scale are difficult to distinguish. Thus, here those effects are not differentiated further.

Recommendations regarding scale and development of FCH technologies in prospective LCC

The LCC practitioner should consider two types of phenomena to assess appropriately a technology in the future: (i) upscaling effects, and (ii) learning phenomena. The former aspect consists in adapting the inventory available for a small-scale system to larger operating scales. These relationships apply to the manufacturing life-cycle phase, where up- or downscaling could appear. The LCC practitioner should identify which inventory flows are independent of the operating scale. The adaptation of the inventory could be done through various methods, including the use of literature values, roadmaps and the adoption of power-law relationships based on empirical data.

Box 5 Accounting for scale effects

1. Clearly state the assumed operating scale/production capacity.
2. Adapt the investment costs to the considered scale (up/downscaling).
3. Account for learning/economies of scale phenomena.

Considering scale in prospective LCC of FCH systems

The upscaling of FCH technology in the future could be done through the use of economic scaling laws postulated for the estimation of equipment capital costs [22]. These power-law relationships allow users to account for economies or diseconomies of scale by linking different technological parameters of a system. The power-law formula relates know costs C_0 at a known capacity X_0 (initial point 0) to the wanted capital cost C_t and desired capacity X_t with a scaling factor (α), being α=1 the linear scaling particular case.

$$C_t = C_0 \left(\frac{X_t}{X_0}\right)^{\alpha}$$

As a rule of thumb, α is set to 0.6 in engineering [23]. More component specific scaling factors can be found in Peters et al. [24] and scientific papers.

Learning phenomena refer to the improvements a technology experiences over time due to the accumulated knowledge of its scientific principles and production processes, and the gradual improvement of its manufacturing process. This definition responds to both types of learning phenomena: learning-by-searching and learning-by-doing [21]. It was originally applied to estimate the cost per unit of a product, although it could be applied to study the evolution of technological parameters. The consideration of learning phenomena in prospective LCC allows practitioners to appropriately evaluate the economic performance of hydrogen systems and make fair comparisons. For instance, mature hydrogen systems have already benefited from some of these effects, optimising their conception and manufacturing. Learning phenomena could be sometimes difficult to quantify, especially for low TRL technologies, because of limited data availability regarding accumulated production. It could be expressed through different models. However, it is not simple to disaggregate learning phenomena from economies-of-scale effects. The common approach in LCC is to quantify both mechanisms together by the use of experience curves.

Considering learning phenomena and economies of scale in prospective LCC of FCH systems

Experience curves, applied to a life-cycle inventory, link the property of interest at the time assumed for the LCC model with the cumulative production at that time in the future. To do so, power-law relationships are also employed. Experience curves take into consideration both effects, economies of scale and learning phenomena. This is based on the empirically observed phenomenon that unit costs often tend to decline by a constant percentage for each doubling of cumulative production volume (e.g., cumulative installed MW of electrolyzers) [25, 26]. This is expressed by

$$C_t = C_0 \left(\frac{Q_t}{Q_0}\right)^{-b}$$

where C_0 and Q_0 are the initial capital cost and cumulative production, respectively. C_t and Q_t are the capital cost and cumulative production at time t considered in the analysis. The scaling factor b also called experience index.

This relationship can also be expressed with the learning rate (LR). It is defined as the rate at which a property, e.g. capital cost, decreases when the cumulative production is doubled [26].

$$LR = 1 - 2^{-b}$$

The second term of this last equation is called progress ration (PR):

$$PR = 2^{-b}$$

Which leads to

$$LR = 1 - PR$$

Note that experience curves may be applied independently of the scaling, since they capture two mechanisms linked with a higher production volume and experience.

For mature technologies, learning rates are based on historical data. Schoots et al. [27] documented historical data for SMR, coal gasification and electrolysis. As many FCH technologies are not mature yet, expert elicitations about the prospect of technologies might help, e.g. Schmidt et al. [28] or Holst et al. [29].

Evaluation: “method readiness level”

- Adapting the investment costs to the considered scale (up/downscaling). ●●●●○
- Accounting for learning/economies of scale phenomena. ●●●○○

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

- [2: Goal of the Life Cycle Costing]

3.1.2 Modelling perspective

One feature in cost assessment is the consideration of perspectives. Generally, three perspectives are distinguished: two more private perspectives differentiating between industrial producers and consumers as well as a more societal perspective taken by policy makers/civil society. The difference between perspectives is the focus. The focus of both private perspectives is on private efforts to invest in, run and use a technology, whereas it is on social efforts in the societal perspective [30]. Depending on the perspective the system boundaries, cost structures and assessment methodologies differ. Therefore, the stakeholder perspective needs to be defined in the Goal & Scope Definition of the LCC.

Box 6 Stakeholder perspective

The stakeholder perspective needs to be stated in the Goal & Scope Definition, differentiating between producer, consumer, and societal perspective.

The different perspectives often yield in the consideration of varying life cycle stages. The consumer perspective considers beside the acquisition cost only costs arising during the use and maintenance stage. From a producer's perspective, costs related to the production might be extended by End-of-Life costs but also R&D as well as advertising costs. The societal perspective considers the product life cycle from cradle to grave sometimes added by wider societal effects.

Typical costs considered by consumers are mainly related to ownership (total cost of ownership (TCO); see section 5.1) as described in section 5.1. From the business perspective, the net expenditure for investment is relevant. A comprehensive economic assessment also comprises further financial analysis quantifying attractiveness and supply/market flexibility. Therefore, based on Cash Flow (CF) analysis, a comprehensible set of metrics may comprise Levelized Cost of product (e.g. Levelized Cost of Hydrogen, LCOH) for cost assessment and the Net Present Value (NPV) for attractiveness analysis as defined and described in more detail in section 5.1.

For the assessment of product dependent costs there are three points which might differ from a societal or producers perspective: (1) financial and fiscal aspects, (2) environmental externalities, and (3) discounting [31].

1) Financial and fiscal aspects

Financial aspects, such as the share of private equity or debt for investment in FCH technologies, deserve closer attention from a producer's perspective the higher the share of capital expenditure to total expenditure is. On the one hand, equity and debt may require different returns, and on the other hand, only interest payments for debts are tax-deductible. Furthermore, fiscal incentives, such as investment subsidies or the crediting of tax redemptions, might be considered (e.g. [32, 33]). From a societal perspective, the perception of these aspects is not of primary interest, as all capital comes from society, which defines its own return requirements.

2) Environmental externalities

Externality assessments translate impacts on the environment or the society into costs. Therefore, it can be part of the wider societal perspective. From a producer's perspective internalized or soon to be internalized cost components might be of higher interest. However, for the integration of externalities see also section 5.2.

3) Discounting

Discounting procedures result in different discount rates, keeping in mind different risk perceptions and the expected return on private equity from the investor's view [17]. Social discount rates (SDR) tend to be lower than discount rates from consumers, which tend to be lower than discount rates from industry. Generally, this is because individuals tend to be concerned with their own welfare in the near future and to be risk-averse, discounting the future heavily. In contrast, society tends to have a longer-term perspective, entailing lower discount rates [34, 35] (see also section 3.1.3).

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

- **2: Goal of the Life Cycle Costing**
- **3.1.3: Scope of the Life Cycle Costing – Discounting**
- **5.2: Life Cycle Impact Assessment – Excursus: Consideration of externalities**

3.1.3 Discounting

Motivation

Costs change over time, due to inflation and also market changes and other factors; money that is earned in future cannot be used in present time for investing or consumption, and thus cannot generate more money (in a successful investment) or, in case consumption is needed and no other money source available, money needs to be borrowed, at a cost.

Both aspects together motivate a change of the value of costs and income occurring in future; this is what discounting is about.

Description of the topic and key terms

In simple terms, discounting can be described as follows:

"Discounting renders benefits and costs that occur in different time periods comparable by expressing their values in present terms" [36].

This rendering is typically performed via an exponential formula, where the net present value of costs and income over time, with a given discount rate, is calculated as follows [37]:

$$F = P(1+r)^n$$

Equation 1

$$P = F\left[\frac{1}{(1+r)^n}\right]$$

Equation 2

With

P: present-day cost or value,

F: cost or value at a future date, n periods from the present; the sum is equivalent to P with compound interest at r (discount rate) over n periods,

r: value representing a specific change over time periods; discount rate per period of time, n: number of discount periods, mostly expressed in years,

the real discount rate can be estimated considering the inflation and nominal interest rate [37].

$$r^* = \frac{i - f}{1 + f}$$

Equation 3

With

f: inflation rate

i: nominal interest rate

r*: real discount rate, an interest rate adjusted to remove the effect of actual or expected inflation

Combining two different aspects in the discount rate is very common; other than nominal interest rates and inflation, authors propose a social and an economic interest rate [38], for example. Also non-constant discount rates are discussed [39], but much less commonly used; the technical application is a bit more complicated, but most importantly, the motivation and communication of changing discount rates is more difficult. In view of intergenerational equity, lower discount rates in future can make sense, though, as they less “count down” future impacts [40]. Applying discount rates is very common in LCC studies outside of the sustainability context [3].

Options

First, it has to be decided **whether to apply discounting** for LCC data or not. This has strong implications in the result of the LCC analysis, especially for long living goods, and on the life cycle model and its calculation. Applying a discount rate requires an inventory that is calculated over time, i.e. the time of each elementary flow is available.

Then, the question is about the discount rates, the selected inflation rate and the selected nominal interest rate.

Recommendations

For LCC in FCH systems, discounting is important, since FCH systems for producing or using hydrogen often are infrastructure and have a longer life time. It is important to reflect future uncertainty in data; ignoring it provides a picture that is quite different from reality.

Whether to apply a discounting for LCC or not:

For LCCs about longer living goods, applying discounting has a strong effect on the results, with a realistic discounting rate. FCH systems often deal with longer living goods, be it for producing or for using hydrogen. Discounting also reflects industry practise outside of the sustainability domain, for LCC. It is therefore recommended to apply discounting for LCC, for FCH systems.

Box 7 Discounting I

For FCH systems, discounting is to be applied.

The question about the **calculation of the discount rate**: The discount rate has to be calculated so that both the inflation rate and the interest rate are considered. The formulas are given in equations 1, 2 and 3.

Box 8 Discounting II

The discount rate is calculated as follows:

$$F = P(1 + r)^n$$

$$P = F\left[\frac{1}{(1 + r)^n}\right]$$

With

P: present-day cost or value;

F: cost or value at a future date, n periods from the present; the sum is equivalent to P with compound interest at r (discount rate) over n periods

r: value representing a specific change over time periods; discount rate per period of time

n: number of discount periods, mostly expressed in years

The real discount rate can be estimated considering the inflation and nominal interest rate [2].

$$r^* = \frac{i - f}{1 + f}$$

With

f: inflation rate

i: nominal interest rate

r*: real discount rate, an interest rate adjusted to remove the effect of actual or expected inflation

The question of default values for the nominal interest rate, the inflation rate and the resulting real discount rate:

The discount rates are to be entered by the user. Typical values are 5% for the real discount rate, albeit with recent inflation of about 10%, rates might be set higher. The applied rate must be documented with the result, see Section 3.1.3.

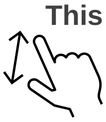
Box 9 Real discount rate

The applied real discount rate must be documented and clearly communicated with the result.

Evaluation: "method readiness level"

- LCC discounting, for use only LCC, in FCH systems ●●●●●
- LCC discounting, for use with LCA, in FCH systems ●●○○○

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



- 5.1: Life Cycle Impact Assessment – Calculation method

3.2 Functional Unit

Motivation

The **functional unit** of a Life Cycle Costing (LCC) represents the principal function of the system under study, according to the goal and scope of the LCC [2, 41]. The functional unit is, therefore, a quantified performance of a product system for use as a reference unit. On the other hand, the reference flow is a measure of the process flows in a given product system required to fulfil the function expressed by the functional unit. In the case of systems providing more than one function (**multi-functional systems**), the practitioner must isolate/choose one of the functions since LCC results are related to a single reference flow [41]. Besides, special attention should be paid when carrying out **comparative LCCs** because the functional unit must represent a common function accomplished at the same level (e.g., hydrogen produced with the same degree of purity and with the same final temperature and pressure).

The concept of functional unit is typically related to Life Cycle Assessment (LCA) studies. In general, the same functional unit must be applied to LCA (if available) and LCC to ensure full consistency, especially when framed in the context of Life Cycle Sustainability Assessment (LCSA) studies.

This section seeks to propose general recommendations for functional unit definition in LCC of FCH systems. It considers the previous generic LCA guidelines ISO 14040 [2] and ILCD [6], and the FCH-specific LCA guidelines HyGuide [7, 8] and SH2E [9] as the reference methodological framework, while tailoring it with the help of LCC generic guidelines (SETAC [10], ORIENTING project [11], INTERREG project [12]) and the FCH-specific report IEA Hydrogen Task 36 [13].

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 employed 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 [42]. 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 would have three options for the main function: chlorine, sodium hydroxide, or hydrogen production, which are corresponding to its three **functional flows.**

Because of the great heterogeneity observed regarding hydrogen-related systems, this section differentiates between **systems exclusively assessing hydrogen production, and those including its use within the system boundaries.** This disaggregation leads to more concrete recommendations, and it is in line with the system boundaries observed for LCC of FCH systems (**Section 3.3**).

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 [43].
- **Multi-functional system:** System that originates more than one functional flow [43].

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 LCC.

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). Disregarding the chosen functional unit, within the LCC framework, it is a common practice to refer all inputs and outputs to the final product. The following section establishes main steps that are to be made in order to state the functional unit.

The first step is to identify the function of the system that wants to be assessed (Box 10). 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 LCC practitioner should identify the functional flows as recommended in the **Supplementary Box "Multi-functionality in LCC"**. Once the functional unit has been selected, the functional flow serving as reference flow of the system must be identified and quantified.

It is worth noting that a potential functional unit for LCC is the system profitability itself, which could be applied to any system with an economic nature (including FCH ones). However, it is not supported by the present guidelines with the aim of increasing the level of specificity in terms of system function.

Box 10 Identification of function, 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 employed for their handling later on (Supplementary Box "Multi-functionality in LCC").
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 an energy transportation or energy storage media. For example, employing renewable electricity surplus to produce hydrogen through electrolysis may have as 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 LCC 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 LCC, 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 (Box 11) [41]. These qualitative considerations are set by the LCC 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 11 Functional unit in comparative LCCs

1. Comparative LCCs must ensure that the selected functional unit represents the common function of the systems and allows a fair comparison.
2. Qualitative considerations to be achieved by the evaluated systems, which can be made in the form of quantitative thresholds or qualitative statements, must be clearly defined.

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

Regardless of the assessed hydrogen production pathway, a convergence in literature can be observed on the adoption of a mass- or volume-based functional unit [14]. Therefore, the recommendation is to state the functional unit as a description of the produced hydrogen amount [44]. Considering literature trends and regulatory frameworks, it is requested to use the **mass or volume of produced hydrogen** (Box 12). For the latter, it is requested to state the volume of hydrogen at **normal or standard conditions**.

Hydrogen purity, pressure and temperature must be stated together with the quantity of produced hydrogen (Box 12). These characteristics are linked to important life cycle stages such as compression and purification and affect hydrogen cost, being especially crucial in comparative LCC.

Box 12 Functional unit in systems assessing hydrogen production

1. The functional unit employed in LCC 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 must be specified.

The precise description of the reference flow was identified as one of the main gaps in LCAs of hydrogen systems [42] and, by analogy, suggested to be included in the initial flow diagram of the LCC (see Section 3.3).

Box 13 Reference flow in systems assessing hydrogen production

The reference flow, completely defined through the specification of hydrogen purity, pressure and temperature, should be indicated in the initial flow diagram of the LCC.

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 [45].

Case 2a. Hydrogen for transportation

The most assessed application of hydrogen is hydrogen use as a fuel for transportation [42]. 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** (**Box 14**) since it also allows for comparison with other powertrain technologies. The specific functional unit to be selected depends on the goal of the LCC, and a proper definition of the reference flow must be included, reporting capacity utilization (passengers/transported freight) and the lifetime considered for the vehicle in terms of mileage. For example, “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 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 14 Functional unit in systems assessing hydrogen use for transportation

1. The functional unit employed in LCCs of hydrogen use for transportation must represent the distance travelled for a given demand, expressed as the passenger or freight load.
2. The considered demand must be specified together with the lifetime measured in terms of mileage.

Case 2b. Hydrogen for fuels and chemicals production

Hydrogen is employed 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 employed (Box 15). **Purity, pressure and temperature of the produced chemical/fuel** must be stated.

Box 15 Functional unit in systems assessing hydrogen use for fuels and chemicals production

1. The functional unit employed in LCCs 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 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 commonly employed [42], a trend previously identified in literature [44]. This energy-based functional unit must refer to the **output electricity (Box 16)**; 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 16 Functional unit in systems assessing hydrogen for electricity generation

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

For cogeneration systems, two functional flows appear: electricity and heat. The LCC 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 16**. On the contrary, when heat is a valuable product, the function of the system changes because it becomes “the production of electricity and heat”. In this case, in contrast to the SH2E LCA guidelines [9], the LCC practitioner must undo this inherent multi-functionality (see Supplementary Box “Multi-functionality in LCC”), identifying the main product and defining an energy-based functional unit (**Box 17**). When undoing the multi-functionality inherent in this type of system, special attention is needed to account appropriately for the context-specificity of the additional product (e.g., in terms of heat/electricity price).

Box 17 Functional unit in systems assessing hydrogen for electricity and/or heat generation

The functional unit employed in LCC of hydrogen use for electricity and heat generation must represent the quantity of the main energy product identified by the practitioner (energy-based functional unit). The context-specificity of the other energy product must be taken into account when undoing the multi-functionality inherent in the system.

Multi-functionality in LCC

Multi-functionality is a typical topic in LCA [9]. However, since the presence of more functional flows can be a specificity of FCH technologies, it is important to deal with multi-functionality also in the framework of LCC.

Box 18 Check for multi-functionality

It must be identified if the investigated process is a case of multi-functionality through the identification of the functional flows.

If the system under study is multi-functional, the identification of all the functional flows is crucial to identify all the economic flows. Any multi-functionality shall be solved by applying subdivision or system expansion. For instance, in the case of a process producing a co-product (e.g., oxygen) besides the main product (e.g., hydrogen), revenues must be attributed to the co-product when calculating the LCOH (see Section 5.1).

Box 19 Handling multi-functionality

1. 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.
2. Another alternative to avoid allocation is the application of system expansion.

Once all the functional flows are identified and quantified, the LCC evaluation of the FCH system can be carried out following the recommendations in Section 5.1.

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

3.1: Scope of the Life Cycle Costing – Modelling approach
3.3: Scope of the Life Cycle Costing – System boundaries
5.1: Life Cycle Impact Assessment – Calculation method

3.3 System Boundaries

Motivation

The system boundaries of an LCC specify which processes are included in the product system and therefore determine which unit processes shall be included in the LCC. The system boundaries shall be consistent with the chosen goal of the LCC [2]. The correct identification and reporting of the chosen system boundaries are crucial, especially in the case of comparative studies.

The usual **lack of transparency regarding the flows included in the system boundaries** as identified for LCA studies of FCH systems in [42] can be extended to LCC studies, which often causes problems during comparison and benchmarking. For instance, very few studies include the EoL of capital goods and, if so, few details are reported without a clear identification of the EoL scenarios. Another specificity of FCH systems is the **large variety of locations to place the study gate**, 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 (see Figure 1). The setting of the system boundaries in LCC of hydrogen systems is key to ensure that the function of the system performed.

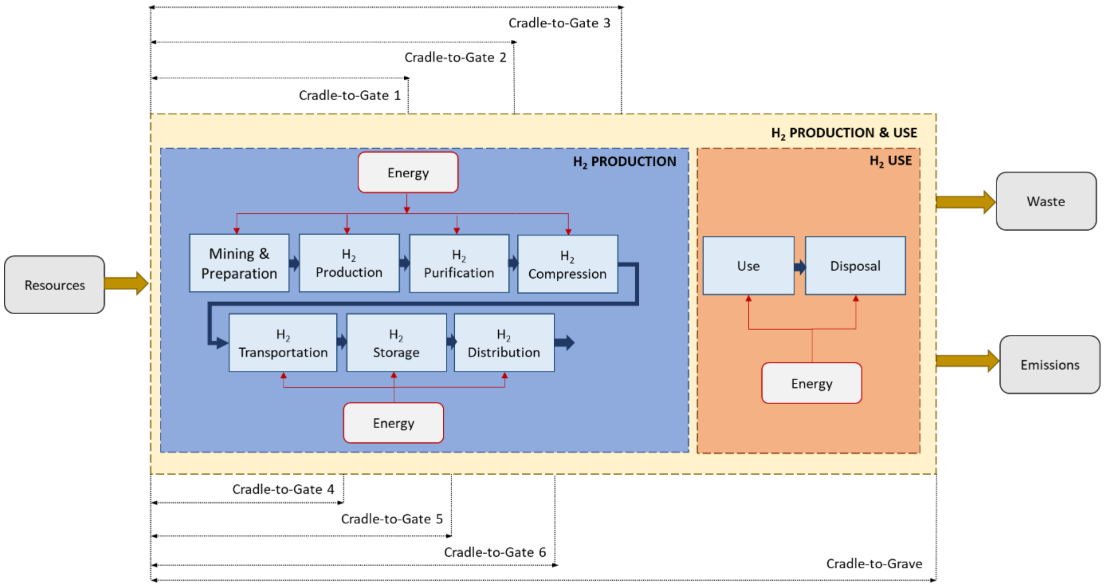


Figure 1. System boundaries for studies assessing FCH systems

Description of the topic and key terms

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

- **Cradle-to-Grave:** LCC including all stages from resource extraction to the use and disposal phase.
- **Cradle-to-Gate:** LCC including all stages from resource extraction to the gate.

Options

Different cases are herein distinguished for the system boundaries definition:

- **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 cases before.

Requirements and recommendations

General requirements and recommendations

Box 20 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.
3. The system boundaries have to include the capital goods life cycle, including their EoL, with an appropriate reporting of the latter (see Section 5.1).
4. The geographic provenance of all the economic flows must be clearly stated and defined.

This latter recommendation facilitates a correct quantification and traceability of the flows included in the Life Cycle Inventory, as described later in Section 4.

Box 21 System boundaries II

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

Disregarding the chosen system boundaries, the cost of all life cycle stages should be included for each stage of the process (i.e., knowledge development, primary production, components production, manufacturing, use, and end of life) as specified in the cost breakdown structure (Section 4.1).

Requirements and recommendations for Case 1: hydrogen production

When conducting LCC studies assessing only hydrogen production, the recommended system boundaries are cradle-to-gate, including hydrogen conditioning (Cradle-to-Gate 3 in Figure 1). This recommendation assures that the produced hydrogen could fulfil the function of the system (e.g., provide high-purity hydrogen for FCEVs). The reference flow definition, which involves hydrogen specifications and thermodynamic conditions (e.g., pressure, temperature, purity), might vary depending on the goal of the study and the intended application. Regardless of the final gate chosen for the assessment, these aspects need to be clearly specified and reported, see Section 3.2.

Box 22 System boundaries for systems assessing hydrogen production I

1. The system boundaries of studies on hydrogen production have to be, at least, Cradle-to-Gate 1.
2. All the relevant economic flows have to be included in the assessment. If any is disregarded, it must be reported and justified.

Box 23 System boundaries 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 LCC 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. In case of direct implementation of life-cycle costs of the produced hydrogen, additional aspects should be considered concerning the LCC scope of the system (see Section 3.1) to avoid the implementation of costs that do not necessarily fit the time of modelling and/or scale of the assessed hydrogen use. It should be noted that the case where hydrogen production is modelled by the user falls into Case 3 (hydrogen production and use).

Box 24 System boundaries for systems assessing hydrogen use

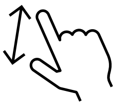
1. The system boundaries of studies focusing on hydrogen use have to be Cradle-to-Grave and include hydrogen production.
2. All the relevant economic flows have to be included in the assessment. If any is disregarded, it must be reported and justified.

Requirements for Case 3: hydrogen production and use

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

> **Box 25 System boundaries for systems assessing hydrogen production and use**
>
> 1. The system boundaries of studies on hydrogen production and use have to be Cradle-to-Grave.
> 2. All the relevant economic flows have to be included in the assessment. If any is disregarded, it must be reported and justified.

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



- 3.1: Scope of the Life Cycle Costing – Modelling approach
- 3.2: Scope of the Life Cycle Costing – Functional Unit
- 4.1: Life Cycle Inventory – Cost Breakdown Structure
- 4.4: Life Cycle Inventory – Currency, base year definition, adjustments, geographical aspects
- 5.2: Life Cycle Impact Assessment – Excursus

4. Life Cycle Inventory

4.1 Cost Breakdown Structure

Motivation

In general, there are many types of cost items, depending on the entity that bears the costs and the life cycle stages [46]. The cost items to be considered in the costing should be determined based on the goal and scope of the LCC, see Sections 0 and 3. Examples for cost items are given in Table 1.

Requirements and recommendations

The procedure of cost items to be considered is as follows:

- Determine the entities that bear the costs (e.g., companies, consumers, or society) according to the modelling perspective of the study (see Section 3.1.2).
- Select the life cycle stages to be considered based on the system boundaries considered in Section 3.3.
- List the cost items included in the selected life cycle stages.
- Select the cost items to be accounted for from the list.

> **Box 26 Consideration of life cycle stages**
>
> The life cycle stages to be considered in an LCC are knowledge development (including R&D), primary production (materials, energy, etc.), components production, manufacturing, use and end of life. Reasons for non-consideration need to be verified.

The life cycle cost of hydrogen consists of various cost elements in the facilities and equipment in the value chain and its lifecycle stage. See [46] for which cost items should be considered depending on the entity bearing the costs. In the case of business entities carrying out hydrogen business, the cost can be divided into capital (CAPEX) and operating expenditures (OPEX). CAPEX that attributes to the acquisition and construction of equipment and facilities typically include Investment and End of life (EoL) costs. In many cases, most of the investment cost is Engineering, Procurement, and Construction (EPC) costs. Various literature, e.g. [47], gives detailed estimation methods of EPC cost. EoL costs consist of decommissioning at the end of the operation period and/or the revenue (negative costs) from the disposal of equipment and facilities. If the objective is to assess the detailed difference between lifecycle costs of similar hydrogen production technologies, the aggregated costs such as the EPC cost can be broken down into more detailed cost items through their lifecycle stages such as knowledge development (including R&D), primary production (materials, energy, etc.), components production.

OPEX attribute to the operation of facilities and equipment. These costs typically include labour, maintenance, feedstock, consumables, utilities such as electricity and gas, insurance, and administrative costs. Maintenance costs include the cost of additional personnel needed on-site during maintenance periods and replacement parts. Consumables consist of chemicals and other costs that are consumed on a constant basis. Costs for permits and licenses are required depending on the technologies utilized in the project. Examples of cost items in a typical hydrogen supply chain are shown in Table 1. OPEX are sometimes divided into fixed and variable costs. Fixed OPEX are usually calculated as an annual percentage of the CAPEX [24].

Examples of the cost items for hydrogen production, transport and storage, and utilization, mainly borne by the entities carrying out hydrogen business

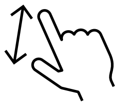
The hydrogen supply chain consists of production, transport and storage, and utilization of hydrogen. The costs consist of CAPEX and OPEX both of which are also divided into sublevels.

Table 1: Exemplary cost breakdown structure

	Cost items	Production	Transport and storage	Utilization
CAPEX	Investment	EPC cost, land, interests, subsidy, R&D, engineering, design, and planning	EPC cost, land, interests, subsidy procurement cost of tankers, R&D, engineering, design, and planning	EPC cost, land, interests, subsidy procurement cost of equipment, R&D, engineering, design, and planning
	End of life	Decommissioning and salvage value	Recycle cost, resale value	Decommissioning and salvage value
OPEX	Labour	Operational labour	Wages for drivers	
	Maintenance	Maintenance labour and parts	Maintenance parts and service cost	Maintenance labour and parts
	Feedstock	Natural gas, biomass, electricity	N/A	N/A
	Utilities	Fuel, electricity, cooling water, steam etc.	–	–
	Consumables	Chemicals, lubricant	–	–
	Insurance and taxes	–	–	–
	Administration	Costs for management and headquarters, etc.	–	–

The cost items are not necessarily exhaustive.

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



- 3.1: Scope of the Life Cycle Costing – Modelling approach
- 3.3: Scope of the Life Cycle Costing – System Boundaries

4.2 Data sources and availability

Motivation

As for LCA, LCC relies on data for the life cycle models, and results depend on data used in these models. LCC models' data requirements differ to some extent from data needed for LCA, although of course there exist also similarities, as LCA and LCC are life cycle approaches. For this reason, it is necessary to look into data sources and possible data processing for LCC specifically.

Description of the topic and key terms

LCC models contain data about processes that are connected via product and waste flows and are thus very similar to LCA.

An LCC model, however, can contain life cycle stages such as product design not commonly used in LCA. Costs, especially, are of a very different nature than physical inputs and outputs of processes, for a variety of reasons.

- Costs are assessment results, and not a physical reality. A common German definition for costs state that these are "bewerteter Güterverzehr" (i.e., assessed consumption of goods) [48]. The assessment result depends on the assessment method, simply speaking, and can thus change over time and from one person to another, in principle.
- Somewhat in contrast, costs are often easier to observe, as market prices or company prices, and / or are used in company accounting systems
- For a given "thing", e.g. a specific order of a given product (1 Nm^3 of hydrogen), costs depend on several aspects, such as:
  - Is this a one-time offer or recurring offer?
  - What is the order quantity?
  - Brand name of the provider, and also reputation of the buyer
  - Location of the offer
- Further, prices will change due to market fluctuations, e.g. shortage of natural gas, or currency changes
- Some cost data are public; direct purchase costs are identical to the purchase price, and for the purchase price, Alibaba or amazon are two examples of websites with literally millions of different products with prices.
- Some cost data are created and used only internally, in companies for example, to have cost figures for things that actually do not directly cost anything, such as rent for a building the company owns.
- For internal cost systems, but also, to a lesser degree, for externally shared cost information, applied cost structures and allocation have a large influence on the cost figures.

Sources for cost data

In addition to generic websites, there are dedicated tools and cost databases, such as makersite [49] or mintel [50].

Further, there are of course stock markets, for a variety of goods, e.g. the London metal exchange for metals [51].

For fuels, BP stats [52] is often used, as they provide a convenient overview over time.

For mineral prices, the US Geological Survey provides detailed overviews with price information [53].

There are also numerous guides on cost estimation, e.g.,[54], which shows that cost estimates can be a source of cost data as well.

Options

Options for cost data are which source for cost data is to be used, and for a source, which data fits best. Due to currency changes, a higher volatility of prices and costs, economies of scale, and a more flexible cost and modelling for cost than for emission data for example used in LCA, cost data is "richer" and more difficult to handle in a consistent way. On the other side, purchase cost data are often quite easily available from public sources, which is an advantage compared to data for LCA. Further, purchase data can "summarise" as an estimate an entire supply chain cost, which again makes the handling of cost data easier, compared to LCA data.

Requirements and recommendations

For a given product, cost information varies with a set of attributes that need to be known to understand the provided cost. These attributes include:

- Time validity.
- Region.
- Currency.
- Way of measurement or way to obtain the cost information.

Specifically for cost data obtained from a purchase or from market prices, the following attributes are interesting, in addition:

- Amount of purchase.
- Repeated or single purchase.
- Public market price or price of a specific transaction, offered only to specific clients.

For estimated cost data, or for cost data obtained from sources internal to an organisation, the following attributes are interesting in addition:

- Cost model.
- Cost breakdown structure considered.
- Assumed reliability of provided cost data.

Frequently, cost data is more detailed than LCA data, especially if cost data is drawn from public marketplace data sources such as alibaba.com. In order to link cost data to LCA data, it is then recommended to build averages across fitting detailed "real world" data from the data source, in order to obtain a more generic result.

Cost data sources can be used in combination, using data from a better fitting, more specific data sources as first priority and completing information with more generic information from other sources.

For important cost data in an LCC model, it can be useful to consider data from several sources, allowing for triangulation.

> **Box 27 Data sources general attributes**
>
> Cost data from a data source must be completed with these general attributes:
>
> - Time validity (time data was obtained or is referring to).
> - Region data relates to.
> - Currency.
> - Way of measurement or way the cost information was obtained.

> **Box 28 Data sources additional attributes**
>
> For cost data from a purchase or from market prices, the following attributes must be provided, in addition to the general attributes:
>
> - Amount of purchase.
> - Type of purchase (repeated purchase or single purchase).
> - Whether the price is a public market price or price of a specific transaction, offered only to specific clients.

> **Box 29 Attributes of estimated and internal data sources**
>
> For estimated cost data and for cost data obtained from sources internal to an organisation, the following attributes are to be provided, in addition to the general attributes:
>
> - Cost model.
> - Cost breakdown structure considered.
> - Assumed reliability of provided cost data.

> **Box 30 Multiple sources for one data point**
>
> If cost data is available from several sources, for one cost data point, the information with the best data quality is to be taken, in principle. However, the overall number of data sources used in a model should also influence the decision, and it is preferable to have fewer cost data sources in a model. It can be useful to keep information from other cost sources as well, to allow for triangulation, in a cost sensitivity analysis.

Evaluation: "method readiness level"

While data sources for LCC are in itself of course not a method, the proposal to include additional attributes to the sheer cost amount made here may be new.

- Data sources, with additional attributes

  ●●●○○

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

- 2: Goal of the Life Cycle Costing
- 4.3: Life Cycle Inventory – Data quality

4.3 Data quality

Motivation

For LCC data it is interesting to understand how far the considered information fits to the decision at stake, and as for LCA, data quality addresses how well information fits to stated requirements, and thus, for example, to a decision.

The concept of data quality in LCC is thus similar to data quality in LCA, and as consequence, the discussion in this section has strong similarities to the discussion of data quality for LCA [9]. It is not identical though, as cost data has some properties that deserve specific consideration.

Description of the topic and key terms

As for LCA, data quality for cost data and for LCC is defined as fitness for purpose, following ISO 14040/14044 [2, 5]:

“Data quality: characteristics of data that relate to their ability to satisfy stated requirements”

Again, 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 a Life Cycle Costing 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 LCC, or “Environmental LCC”, specifically, i.e. LCC that is conducted with the idea to have it consistent with LCA. Statements about LCC data in the context of LCA and sustainability assessments appear often somewhat naïve or plain: “In order for the project to be effective, it is important to ensure the quality of the data collected.” [55]. “Another relevant aspect is data availability and quality […]. Data regarding costs are not always available. Literature suggests that also databases and published prices may be used for background processes. Also cost data and functions may be used but it must be paid particular attention as this may lead to inaccuracies.” [56].

Very similar to LCA, also for LCC, data quality has several aspects or “dimensions”: time, location / geography, reliability of the source, currency. Some are identical, but some are also different to the ones used in LCA.

A publication from 2008 discusses data quality for eco-efficiency approaches. It specifically proposes a data quality concept that is meant to be used in parallel to an LCA data quality assessment [57]. The proposal follows the pedigree approach that is used in the FCH-LCA guidelines, and thus seems a convenient way to address data quality for cost data of FCH systems.

The proposed pedigree data quality matrix is shown in Table 2. Key differences to the LCA pedigree matrix are highlighted.

Table 2: Pedigree table for data quality assessment for LCC data [57]

Indicator score	1	2	3	4	5
Reliability of source	Verified data based on measurements	Verified data partly based on assumptions or non-verified data based on measurements	Non-verified data partly based on assumptions.	Qualified estimate (e.g. by industrial expert)	Non-qualified estimate or unknown origin
Completeness	Representative data from a sufficient sample of sites over an adequate period to even out normal fluctuations	Representative data from a smaller number of sites but for adequate periods	Representative data from an adequate number of sites but from shorter periods	Representative data but from a smaller number of sites and shorter periods or incomplete data from an adequate number of sites and periods	Representativeness unknown or incomplete data from a smaller number of sites and/or from shorter periods
Temporal differences	Less than 0.5 years of difference to year of study	Less than 2 years difference	Less than 4 years difference	Less than 8 years difference	Age of data unknown or more than 8 years of difference
Geographical differences	Data from area under study, same currency	Average data from larger area in which the area under study is included, same currency	Data from area with slightly similar cost conditions, same currency, or with similar cost conditions, and similar currency	Data from area with slightly similar cost conditions, different currency	Data from unknown area or area with very different cost conditions
Further technological differences	Data from enterprises, processes, and materials under study	Data from processes and materials under study from different enterprises, similar accounting systems	Data from processes and materials under study but from different technology, and/or different accounting systems	Data on related processes or materials but same technology	Data on related processes or materials but different technology

Similar as for LCA, it makes sense to provide data quality in LCC for the following “scopes”:

- for unit process LCA datasets (1a),
- for process LCA datasets exchanges (i.e. input/output flows, 1b),
- for aggregated datasets sometimes (2),
- and for LCA 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 the goal and scope definition. In LCC 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 LCC data or not.

Then, the question is about which **scope of data quality** to apply (unit process dataset, elementary flows, etc., see above):

- 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

a) 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.
b) 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

For a data quality assessment in LCC of FCH systems, there does not seem a principal difference between hydrogen-based systems and LCCs for other products; therefore, the sections are combined.

Whether to apply a data quality assessment for LCC data or not:

Since LCCs are typically about decision support, and in decisions, information about the reliability of data considered is important, data quality seems essential.

> **Box 31 Data quality I**
>
> Data quality has to be documented and a data quality system with different data quality indicators has to be applied for LCCs 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 for 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 metadata 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.

> **Box 32 Data quality II**
>
> 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 select the “all of the above” option. It is proposed to use the pedigree matrix for eco-efficiency considerations [57] as a starting point, and potentially revise it in line with the further methodological development in SH2E.

Box 33 Data quality indicator system

The SH2E data quality indicator system should be built on the eco-efficiency pedigree table [43], considering measurement, support, and modelling related indicators. It will possibly be revised with the further method development in SH2E. 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 radiates through the LCC model.

Box 34 Data quality III

Data quality calculation has to reflect user input and be calculated on the fly as it radiates through the LCC 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, emphasizing larger scores). Both seem to have merits.

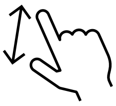
Box 35 Data quality IV

An aggregation of data quality scores, per indicator over the life cycle, has 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:



- 2: Goal of the Life Cycle Costing
- 3.1.1: Scope of the Life Cycle Costing – Discounting

4.4 Currency, base year definition, adjustments, geographical aspects

Motivation

This subsection specifies currency, base year definition, adjustments, and geographical aspects to adjust the assumptions used for this costing activity and to compare fairly the results to be obtained with other data from your previous analyses, literature, and so on.

Base year definition

The base year is used in order to take account of the effects of differences in prices and exchange rates. The temporal scope of the study is already selected in the goal and scope definition, see Sections 0 and 3. The base year is also used when comparing the results obtained with other costing results from the literature because prices differ from year to year in general. It is advisable to select the most recent year for which the statistical data necessary for costing is available or the base year used in other results to be compared.

Box 36 Base year

The base year of the LCC calculations must be defined and documented.

Currency

The currency of the country or region where the plant will be built is often chosen. In the case that hydrogen is produced or utilized in Europe, the currency used would be Euro. For academic papers, reports, and global analyses, the U.S. dollar is often used for simplicity. If different data sources with different currency units are used for input data, the applied exchange rate should be documented due to reasons of transparency.

Box 37 Currencies

In the case of considering multiple originally different currencies, the corresponding conversion rates must be documented. An appropriate currency to compare the obtained results with those from other analyses and competing technologies needs to be selected.

Adjustments

Since prices change over time, the construction cost of the same plant in the same location even changes from year to year of construction. The change can be adjusted using an index that is the ratio of the cost in the considering base year to the one in the reference year. The Chemical Engineering Plant Cost Index (CEPCI) is typically used for adjustment of chemical plant construction. The ratio of the GDP deflators in considering and reference years can be used for adjustment for generic cost items in the case that index which is specific to the item is not available. Note that the GDP deflator includes the influence of other domestic economic activities, which are not used in the analysis.

Box 38 Price changes

The influence of price changes over time must be reflected and documented by appropriate recalculations adjusted to the base year.

Adjustment of the price change between in the different years

As an example, the adjustment of the construction cost of a hydrogen production plant are considered here. If the base year for the analysis is 2020 and the reference year for construction costs obtained in the literature is 2018, the following equation gives the adjusted construction costs for 2020:

$$C_{2020} = C_{2018}\left(\frac{PCI_{2020}}{PCI_{2018}}\right)$$

with

C_{2020}: cost in 2020,

C_{2018}: cost in 2018,

PCI_{2020}: plant cost index in 2020,

PCI_{2018}: plant cost index in 2018, and

PCI_{year} is the indicator that describes the ratio of the cost in the base year to the one in the reference year.

Geographical aspects

Since prices (labour and material costs), climate, and other factors that affect construction costs differ from country to country, construction costs change even when similar facilities are to be constructed. In order to adjust these effects, a country-specific location factor needs to be used.

Box 39 Geographic location

Differences in construction costs resulting from geographic location must be documented and – if available – location factors for adjustments should be used.

Adjustment of location using the location factor

The adjustment of the construction cost of a hydrogen production plant can be considered as following. If the reference plant in the literature is located in the Gulf coast and the construction site for costing is located in the Netherlands, the adjusted construction cost can be calculated by the following equation:

$$C_{Netherlands} = C_{Gulf\ coast}\left(\frac{LF_{Netherlands}}{LF_{Gulf\ coast}}\right)$$

with

$C_{Netherlands}$: adjusted cost in The Netherlands,

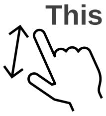
$C_{Gulf\ coast}$: reference costs in Gulf coast,

$LF_{Netherlands}$: location factor of The Netherlands, and

$LF_{Gulf\ coast}$: location factor of Gulf coast.

Table 3: Example of location factors [47]

Country	Region	Location factor
United States	Gulf Coast	1.00
	East Coast	1.04
	West Coast	1.07
	Midwest	1.02
Canada	Ontario	1.00
	Fort McMurray	1.60
Mexico		1.03
Brazil		1.14
China	imported	1.12
	indigenous	0.61
Japan		1.26
SE Asia		1.12
Australia		1.21
India		1.02
Middle East		1.07
France		1.13
Germany		1.11
Italy		1.14
The Netherlands		1.19
Russia		1.53
United Kingdom		1.02



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

- 3.3: Scope of the Life Cycle Costing – System Boundaries

5. Life Cycle Impact Assessment

5.1 Calculation Method

Motivation

Besides constituting one of the three LCSA pillars, LCC alone is often the main source of criteria to decide whether to invest in a product or not. Despite that, there is not a uniform LCC methodology, apart from spare sector-specific guidelines (e.g., LCC of electricity [58]) and some more comprehensive codes of practices or projects aiming at multiple sectors [10-12]. One first attempt of harmonizing the LCC methodology for FCH systems was made in the IEA Hydrogen Task 36 [13], where the use of LCOH was proposed for technologies addressing hydrogen production.

As in the case of environmental LCA [9], the specificities of FCH systems (e.g., presence of multiple functional flows) need to be taken into account when performing an LCC, while it is often simpler to distinguish the economic flows in terms of revenues or costs. On the other hand, the modelling perspective (producer, consumer or investor-oriented) influences the choice of the calculation method to be applied, as described in Section 3.1.2.

In the following section, the calculation methods to be applied to evaluate the costs of FCH products in their life cycle are described.

Description of the topic and key terms

An LCC calculation that is resolved over time, i.e. where inputs and outputs are distinguished over time, requires a modified inventory calculation and additional inventory information. The LCC calculation as such follows the principle of LCA calculation (see [59]), but considers benefits, i.e. revenues, as negative costs [60].

For a time-resolved inventory, for each process, a start time and a duration, or a start time and end time is needed, and from goal and scope, the required timely resolution is needed in addition. The required timely resolution can be for example one year.

The system can then be calculated for each time step separately, considering the currently active processes. In time step two, a handover of still running processes from step 1 is needed.

In case the time resolution of processes in the life cycle is higher than the required system resolution, an aggregation within one system resolution time step can make sense.

For example, if a floor needs to be cleaned every day, and the system needs to be calculated for every year, it can be good to aggregate the cleaning processes in the year and calculate the system then for, e.g., 365 cleaning processes at once [61].

This only works for predictably life cycles, without random events. Random events can be introduced in the algorithm and system description as well, they could trigger starting and ending of processes. For example, a reactive maintenance for a hydrogen engine can be needed.

Options

Different options are contemplated and spread in literature to compute the life-cycle economic performance of FCH systems. Besides, the calculation method depends on the modelling perspective and goal/scope of the study, as specified in Sections 0 and 3.

The levelized cost of hydrogen (LCOH) is defined as the discounted lifetime cost of building and operating a production asset, expressed as a cost per unit of hydrogen produced [62], as expressed in Eq. 4 [63]. It includes all the relevant costs faced by the **producer**, including capital, operating, fuel and financing costs.

$$LCOH = \frac{\sum_n \frac{I_n + M_n + O_n - R_n}{(1+r)^n}}{\sum_i \frac{E_n}{(1+r)^n}} = \frac{I + M + O - R}{E}$$

Equation 4

with

I_i = investment in year i (currency units),

M_i = maintenance and service cost in year i (currency units),

O_i = operational cost in year i (currency units),

E_i = hydrogen output in year i (mass units),

R_i = revenue income (from additional products) in year i (currency units), and

r = cost of capital (rate).

Similarly, the Total Cost of Ownership (TCO) involves an estimation of the expenses associated with purchasing, deploying, using and retiring a product. This is typically a **consumer-oriented** indicator, usually applied in the transportation sector [64, 65].

$$TCO = A + O + M - Salv.$$

Equation 5

with

A = acquisition cost,

O = operational cost,

M = maintenance cost, and

Salv. = salvage or remaining value.

Different cases are herein distinguished according to the system boundaries definition:

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

For case studies focusing on FCH technology manufacturing, the operation of the technology should be included. By doing so, this case study will match one of the three cases before.

Recommendations and requirements

General recommendations and requirements

Box 40 Basics calculation method

1. The calculation method used for the Life Cycle Costing of FCH products must be clearly stated and defined.

Recommendations and requirements for Case 1: hydrogen production (producer perspective)

Box 41 Indicator I

In case of hydrogen production, the LCOH indicator must be used (expressed in economic units per functional unit, e.g. €/kg H_2):

$$LCOH = \frac{\sum_n \frac{I_n + M_n + O_n - R_n}{(1+r)^n}}{\sum_n \frac{E_n}{(1+r)^n}}$$

with

I_i = investment in year i (currency units),

M_i = maintenance and service cost in year i (currency units),

O_i = operational cost in year i (currency units),

E_i = hydrogen output in year i (mass units),

R_i = revenue income (from additional products) in year i (currency units), and

r = cost of capital (rate).

Recommendations and requirements for Case 2: hydrogen use

The applications of hydrogen use can be subdivided into mobility applications and use of hydrogen as feedstock for the synthesis of chemicals or electricity generation. In the first case, the function of the system is the transport of passengers/goods (consumer perspective), while in the second case the function corresponds to the production of chemicals/electricity (producer perspective).

Box 42 Indicator II

1. In case of hydrogen use in mobility applications, the TCO indicator must be used, expressed in economic units per functional unit (€/p·km if the main function is the transport of passengers or €/t·km if the main function is the transport of goods).

$$TCO = A + O + M - Salv.$$

with

A = acquisition cost,

O = operational cost,

M = maintenance cost, and

Salv. = salvage or remaining value.

2. In case of hydrogen use for the synthesis of chemicals/fuels, the Levelized Cost of the produced chemical/fuel must be used.
3. In case of hydrogen use for electricity generation, the Levelized Cost of Electricity must be used.

Recommendations and requirements for Case 3: hydrogen production and use

While in the case of hydrogen use the hydrogen cost is usually taken as the delivered hydrogen price, in this case the hydrogen production cost is internally calculated. In any case, the function of the overall system falls in case 2 (mobility, synthesis of chemicals/fuels, electricity generation), for which the recommendations given in Box 3 apply.

Other metrics: Net Present Value

Another option is to calculate the net present value (NPV), defined as the value of all future cash flows (positive and negative) over the entire life of an investment discounted to the present, as expressed in Eq. 3. NPV is a financial indicator that aims to capture the value of an investment opportunity, therefore it is an investor-oriented indicator.

$$NPV = \sum_i \frac{NCF_i}{(1+r)^i} = \sum_i \frac{R_i - I_i - M_i - O_i}{(1+r)^i}$$

where NCF_i is the net cash flow for year i and r is the discount rate.

The LCOH can also be expressed as:

$$LCOH = \frac{NPV of Total\ Costs\ Over\ Lifetime}{NPV of Hydrogen\ Production\ Over\ Lifetime}$$

The LCOH is the average price at which hydrogen should be sold to have a null NPV, assuming a constant hydrogen price for the whole lifetime. Hence, the use of a levelized cost indicator avoids assuming prices often subject to high uncertainty (e.g. hydrogen price).

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

- 3.1: Scope of the Life Cycle Costing – Modelling approach
- 3.2: Scope of the Life Cycle Costing – Functional Unit
- 3.3: Scope of the Life Cycle Costing – Discounting
- 4: Life Cycle Inventory

5.2 Excursus: consideration of externalities

At first, it should be clarified that the following excursus on externalities describes an optional aspect of this guideline's LCC methodology. Reasons for the optionality of considering externalities and dealing with it are included in this excursus as well.

Any activity during the life cycle of FCH technologies can cause impacts, which affect "outside" parties. If these effects are not taken into account, compensated or accounted for, the term "externalities" can be used. Externalities are non-market goods and products [4]. Definitions of the term are various in diction but similar in their general structure (e.g., [4, 66-69]). Regarding FCH technologies production and use, externalities can be defined exemplarily as follows:

> *Externalities result from hydrogen production and use activities, when involved main actors generate negative or positive impacts by these activities on other actors and the impacts are not accounted for or compensated by the main actors.*

Since many definitions use the terms costs and benefits, a direct link to the topic of economics is given. With reference to this, it is important to separate clearly the terms "externalities" and "external costs". Summarized, this can be expressed by Morel et al. (2018): "External costs are externalities, that are transformed into monetary values." [3]

Bachmann and Pizzol et al. [4, 70] define externalities as "market failures". As a basis for this, Pigou's description of the divergence between private and social costs, which was already formulated in the 1920s, can be applied [71]. Corrections of such failures can be realized by turning externalities into internalities by a monetary valuation of the externalities [4, 72, 73]. From the perspective of LCC, externalities result in indirect or external cost, which are borne by government and society (taxes, medical expenses, insurance payments, natural capital loss, life quality loss) [74]. As part of the total cost calculation (also named social, true or full cost) of products and services, external costs should be considered in the same currency and with reference to the same base year as the other cost items (e.g., CAPEX and OPEX) [75]. Reasons for considering external costs by monetary valuation or rather internalization have been formulated by Pigou [71] and were subsequently supported by arguments. Without consideration over-production of negative externalities and under-production of positive externalities take place [76, 77]. Positive externalities, which can be described as "unpaid benefits" (e.g., subordinate job creation for third parties by company settlement) [78, 79], offer environmental, social or economic advantages, which can result in trade-off between positive and negative externalities [80]. The following Figure 2 shows exemplarily the relation of indirect external costs to the direct and total cost.

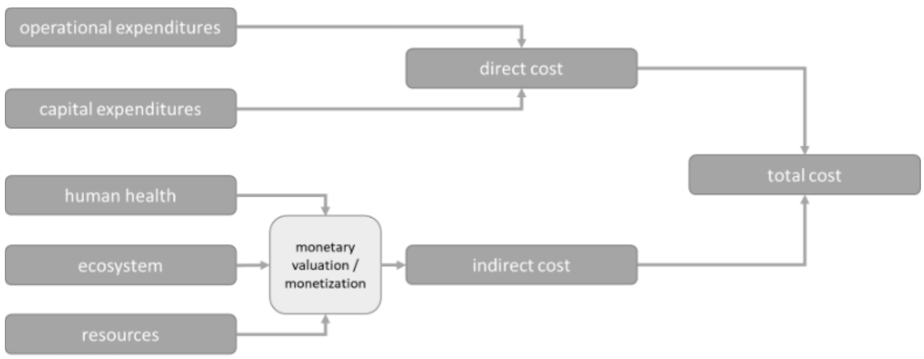


Figure 2. Exemplary monetary valuation structure for total cost calculation with distinction by direct and indirect cost (modified from [81])

Types of externalities

Conceptual distinctions of externalities in literature range from the mentioned simple distinction of positive and negative externalities [4, 82], to the distinction between origins along utilization chain (production and consumption externalities; [83, 84]) or the concerned reference areas (human health, ecosystem, resources; [81]), to detailed breakdowns regarding different issues (environmental, economic and social issues; [75]). The variety of these distinctions reflects different understandings depending on viewpoints and the diversity of methods for quantifying externalities (see methods section in this Excursus). This fact already indicates that a clear methodological specification regarding FCH application is not impossible.

Externalities and their monetization are well established in cost benefit analysis, but in a significantly smaller scope in the context of LCAs [4, 85]. Regarding the consideration of externalities in LCA contexts, Pizzol et al. describe the use of monetary valuation in the weighting phase of LCA [4]. If considered, externalities, relevant for the further monetary valuation, must be identified and validated, whereby a standard procedure for non-market goods and products identification is not given. It has to be noted that "significant risks of double-counting" arise by combined assessments of LCA or S-LCA with LCC [86, 87]. Thus, the consideration of externalities is rather recommendable when performing LCC exclusively.

Guidelines and externalities

The consideration of the topic "externalities" was neglected in the most life-cycle-related guidelines and reference works (e.g., [2, 5, 6]) but in some cases externalities are mentioned or considered (e.g., [10, 16, 88, 89]). With regard to the European EF 3.0 method [88] for LCA, externalities are considered as "weighting" topic, while the SETAC code of practice for LCC [10] names externalities as "ignored costs" and raises the question of double-counting.

More specific information on the consideration of externalities can be found in the published output of the projects NEEDS, which deals with the costs and benefits of energy policies and of future energy systems, and ExternE, which developed a methodology to calculate environmental external costs [90, 91]. With a focus on the transport sector, the European Commission has published a "Handbook on the external costs of transport" [92]. A generally applicable guideline for the identification of externalities and the monetary valuation of externalities does not exist. In fact, these topics are discussed and presented in the relevant contexts in each case. This becomes very clear when looking at the methods for monetization presented and explained in different publications [4, 93]. As an attempt to minimize the problem of this multiplicity, the two norms ISO 14007 ("gives guidelines for organizations on determining the environmental costs and benefits associated with their environmental aspects") and ISO 14008 ("specifies a methodological framework for the monetary valuation of environmental impacts and related environmental aspects") can be mentioned [94, 95].

Externalities methodology – monetary valuation

Based on the study's aim and the type of externalities, applied methods of monetization differ by considered safeguard subjects (e.g., human health, resource depletion, ecosystems) or indicators (e.g., global warming, ecotoxicity) [4, 73, 96]. In many cases the methods directly refer to endpoint or midpoint impact categories from LCA (e.g., STEPWISE2006 [97], ECOVALUE08 [98]), so the focus is on environmental-related externalities.

A comprehensive review of selected existing monetary valuation approaches (class of methods) and methods (different versions of same approach) was performed by Pizzol et al. [4]. The focus of this work was the assessment of usability by criteria such as scientific foundation, documentation, completeness, uncertainty, complexity and LCA relevance and compatibility. Based on this work Amadei et al. [73] have shown an extended and updated spectrum of methods. Furthermore, monetary valuation coefficients for the impact categories of EF 3.0 [99] were collected and applied to a case study in this publication. Further overlooking descriptions on monetary valuation methods and data can be found in Arendt et al. [93], Bieleki et al. [100], and Sovacool et al. [101], for example. An overview of selected methods and related literature is given in Table 4 of the supplementary information below.

Different studies have shown that the application of different monetary valuation methods led to strongly varying results [73, 102]. This can be traced back to different reasons. One exemplary is the quantitative variety of monetary valuation coefficients. Simplified, a frequently encountered calculation principle is the monetary valuation by multiplication of environmental impacts (e.g., global warming in kg CO_2 eq./FU) with defined factors (e.g., monetary valuation coefficients in €/kg CO_2 eq.) [73]. Furthermore, the valuation can be limited to selected external cost (e.g., [103]), whereby depending on the method used, this should be avoided and otherwise be justified. Summed up the applied monetary valuation method depends on study specific decisions. So, todays' large variety of understandings and methodological approaches for externalities and their monetary valuation as well as resulting strongly varying findings argue against regular use of this approach.

Box 43 Externalities

1. Considering externalities and their monetary valuation should not be applied combined with other assessments than LCC, i.e. LCA or S-LCA, to avoid double counting.
2. The consideration of externalities and their monetary valuation within a standalone LCC is not recommended due to heterogeneous methods and approaches.

Externalities modelling methods

The following table provides an overview of different approaches and methods for monetary valuation of externalities, exemplary defined methods and relevant publications (data from [4, 73, 93]). In addition to more obvious environmental-related externalities such as energy (e.g., [74, 103, 104]), fuel and transport (e.g., [105-107]) or waste management (e.g., [108-110]), some of the shown methods also take into account externalities from other perspectives (e.g., social topics).

Table 4: Exemplary methods of monetary valuation by approach (data from [4, 73, 93])

Approach	Method	Exemplary method of implementation	Related literature
Observed preferences	Market price	ReCiPe	A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level [111]
Revealed preferences	Averting behaviour	ECOTAX2002	Weighting in LCA Based on Ecotaxes - Development of a Mid-point Method and Experiences from Case Studies [112]
	Travel cost	Travel cost	Cost-benefit analysis: concepts and practice [85]
	Hedonic pricing	Hedonic Pricing	Monetary Valuation with Impact Pathway Analysis: Benefits of Reducing Nitrate Leaching in European Catchments [113] Fixed-effects Hedonic Price Model for Statistical Value of Live Estimations [114] Estimating the economic value of cultural ecosystem services in an urbanizing area using hedonic pricing [115]

Stated preferences	Contingent valuation	Contingent valuation of life expectancy loss	Economic valuation of air pollution mortality: A 9-country contingent valuation survey of value of a life year (VOLY) [116] ExternE: externalities of energy: methodology 2005 update [117]
		Contingent valuation of biodiversity loss	Economic valuation of biodiversity: sense or nonsense? [118] Scope insensitivity in contingent valuation of complex environmental amenities [119]
	Conjoint analysis: Choice experiment	LIME 1/LIME 2/LIME 3	Statistical analysis for the development of national average weighting factors - visualization of the variability between each individual's environmental thoughts [120] Weighting across safeguard subjects for LCIA through the application of conjoint analysis [121]
Budget constraint	Budget constraint	STEPWISE2006	Using the budget constraint to monetarise impact assessment results [97] Preparing characterisation methods for endpoint impact assessment [122]
Abatement cost	Abatement cost	MAC/RCA	Monetary Valuation of Emissions in Implementing Environmental Policy [123] The Maximum Abatement Cost Method for Assessing Environmental Cost-Effectiveness [124] Calculating Cost-effectiveness for Activities with Multiple Environmental Effects Using the Maximum Abatement Cost Method [125]
Mixed approach	Mix - contingent valuation & market prices	ECOVALUE08	Ecovalue08 - A new valuation set for environmental systems analysis tools [98]
	Mix - contingent valuation, market prices and abatement cost	EPS2000	EPS weighting factors-version 2020d [126] A systematic approach to environmental priority strategies in product development (EPS). Version 2000 - General system characteristics [127]

Mixed approach	Mix - contingent valuation & market prices	META-Analysis	The value of the world's ecosystem services and natural capital [128] Global estimates of the value of ecosystems and their services in monetary units [129] Economic valuation of biodiversity: A comparative study [130]
	Mix - contingent valuation, market prices and abatement cost	MMG Method	Annex: Monetisation of the MMG Method (Update 2017) [131]
	Mix - market price and damage cost	ECOFYS	Subsidies and costs of EU energy [132]
	Mix - contingent valuation, market prices and abatement cost	ExternE / NEEDS	Towards life cycle sustainability assessment: drawing on the NEEDS project's total cost and multi-criteria decision analysis ranking methods [75] ExternE: Externalities of energy - Vol. 1 – Summary [133]

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