FC-Hy Guide

Guidance Document for performing LCAs on Fuel Cells and H_2 Technologies

GUIDANCE DOCUMENT FOR PERFORMING LCA ON HYDROGEN PRODUCTION SYSTEMS

Deliverable D3.3 – Final guidance document

Work Package 3 – Preparation and Consultation of the Guidance Document

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Abstract: This document gives guidance for conducting a LCA study on hydrogen production. Adapted from the ILCD Handbook and the ISO 14040 series, the document gives an overview of how to carry out a LCA on hydrogen production. This is done by delivering a specific set of rules with clear specifications about the information and issues that have to be considered and reported in a LCA study on hydrogen production systems.

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Table of contents

List of figures

List of tables

List of provisions

List of abbreviations

AC	Alternating current
AoP	Areas of Protection
AP	Acidification Potential
CML	Institute of Environmental Sciences (CML)
CO_2	Carbon Dioxide
CUTE	EU project: Clean Urban Transport for Europe (No. NNE5-2000-00113)
DC	Direct current
EC	European Commission
ELCD	European Reference Life Cycle Database
EP	Eutrophication Potential
FC	Fuel Cell
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GWP	Global Warming Potential
H_2	Hydrogen
HTP	Human Toxicity Potential
ILCD	International Reference Life Cycle Data System
ISO	International Organisation for Standardisation
JRC-IES	Joint Research Centre-Institute for Environment and Sustainability
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MJ	Megajoule
NCV	Net calorific value
Nm^3	Norm cubic metre
NO_X	Nitrogen Oxide
ODP	Ozone Depletion Potential
PE	Primary Energy
PED	Primary Energy Demand
PO_4^{3-}	Phosphate
POCP	Photochemical Ozone Creation Potential
SO_2	Sulphur Dioxide
yr.	Year

List of key terms

Term	Definition
Allocation [or: Partitioning]	Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems (ISO 2006b).
Attributional modelling [or: descriptive, book-keeping]	LCI modelling frame that inventories the inputs and output flows of all processes of a system as they occur. For instance, modelling process along an existing supply chain is of this type (JRC 2010a).
Average data	Data combined from different manufacturers or production sites for the same declared unit. NOTE Average can relate to a number of issues such as technologies, products, sites, countries, and/or time.
Best case	Assuming the best possible scenario for the LCA study.
Co-product	Any of two or more products coming from the same unit process or system (ISO 2006b).
Comparative assertion	Environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function (ISO 2006b).
Comparative Life Cycle Assessment	Comparison of LCA results for different products, systems or services that usually perform the same or similar function (JRC 2010a).
Consequential modelling	LCI modelling principle that identifies and models all processes in the background system of a system in consequence of decisions made in the foreground system (JRC 2010a).
Decision context	The decision-context is a key criterion for determining the most appropriate methods for the LCI model, i.e. the LCI modelling framework (i.e. “attributional” or “consequential”) and the related LCI method approaches (i.e. “allocation” or “substitution”) to be applied (JRC 2010a).
Disclosed to the public	The audience is not specifically limited and hence includes non-technical and external audience, e.g. consumers (JRC 2010a).
End of life product	Product at the end of its useful life that will potentially undergo reuse, recycling, or recovery (JRC 2010a).
Environmental impact	Potential impact on the natural environment, human health or the depletion of natural resources, caused by the interventions between the technosphere and the ecosphere as covered by LCA (e.g. emissions, resource extraction, Land use) (JRC 2010a).
Generic data	Surrogate data used if no system specific data are available. They are developed using at least partly other information than those for the specific process, as, for example stoichiometric data or other calculation models, patents, expert judgement. Generic processes can aim at representing a specific process or system or an average situation.
Life Cycle Assessment (LCA)	Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle (ISO 2006a).
Life Cycle Impact Assessment (LCIA)	Phase of Life Cycle Assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product (ISO 2006a).
Life Cycle Inventory (LCI) data set	Data set with the inventory of a process or system. Can be both unit process and LCI results and variants of these (JRC 2010a).

Multi-functional process	Process or system that performs more than one function. Examples: Processes with more than one product as output (e.g. NaOH, Cl_2 and H_2 from chlorine-alkali electrolysis) (JRC 2010a). See also: "Allocation" and "System expansion"
Primary data	Primary data are data determined by direct measurement, estimation or calculation for the process or system under study.
Secondary data	Secondary data are data collected from literature or other published material.
Situation A	"Micro-level decision support": Decision support, typically at the level of products, but also single process steps, sites/companies and other systems, with no or exclusively small-scale consequences in the background system or on other systems. I.e. the consequences of the analysed decision alone are too small to overcome thresholds and trigger structural changes of installed capacity elsewhere via market mechanisms (JRC 2010a)
Situation B	"Meso/macro-level decision support": Decision support for strategies with large-scale consequences in the background system or other systems. The analysed decision alone is large enough to result via market mechanisms in structural changes of installed capacity in at least one process outside the foreground system of the analysed system. One example is decision support for strategies (e.g. raw materials strategies, technology scenarios, policy options, etc.) (JRC 2010a).
Situation C	"Accounting": Purely descriptive accounting / documentation of the analysed system (e.g. a product, need fulfilment, sector, country, etc.) of the past, present or forecasted future, and without implying a decision-context that would account for potential additional consequences on other systems. Two sub-cases need to be differentiated: In Situation C1 ("Accounting, with system-external interactions"), existing interactions with other systems are included in the LCI model (e.g. considering recycling benefits or avoided production for co-products). Note that these "interactions" refer to existing interactions with other systems only. This is in contrast to the additional consequences that are assumed to occur under Situation A and B, and that are assumed to be caused by the analysed decision. Situation C2 accounts for the analysed system in isolation, i.e. interactions with other systems are not accounted for, but cases of recycling and co-production are solved inside the system model (by allocation) (JRC 2010a)
Specific data	Data representing a single process (e.g. a specific technology as operated on a given site) or system. It exclusively contains data that have been collected of the actual process under consideration.
Substitution	Solving multi-functionality of processes and products by expanding the system boundary and substituting the not required function with an alternative way of providing it, i.e. the process(es) or product(s) that the not required function supersedes. Effectively the Life Cycle Inventory of the superseded process(es) or product(s) is subtracted from that of the analysed system, i.e. it is "credited". Substitution is a special (subtractive) case of applying the system expansion principle (JRC 2010a).

System	Any good, service, event, basket-of-products, average consumption of a citizen, or similar object that is analysed in the context of the LCA study. Note that ISO 14044:2006 generally refers to "product system", while broader systems than single products can be analysed in a LCA study; hence here the term "system" is used. In many but not all cases the term will hence refer to products, depending on the specific study object. Moreover, as LCI studies can be restricted to a single unit process as part of a system, in this document the study object is also identified in a general way as "process / system" (JRC 2010a).
System expansion	Adding specific processes or products and the related life cycle inventories to the analysed system. Used to make several multifunctional systems with an only partly equivalent set of functions comparable within LCA (JRC 2010a).
Unit process	Smallest element considered in the Life Cycle Inventory analysis for which input and output data are quantified. (ISO 2006a) In practice of LCA, both physically not further separable processes (such as unit operations in production plants) and also whole production sites are covered under "unit process". See also "Unit process, black box", "Unit process, single operation", and "System" (JRC 2010a).
Unit process, black box	A unit process that includes more than one single-operation unit processes (JRC 2010a).
Unit process, single operation	A unit process that cannot be further sub-divided into included processes (JRC 2010a).
Worst case	Assuming the worst possible scenario for the LCA study.

PART I - General information

1. About this document

This document provides detailed technical guidance on how to conduct Life Cycle Assessment (LCA) (according to the ISO 14040 and 14044 standards) for fuel cells (FCs) and hydrogen production systems. It builds on the International Reference Life Cycle Data System (ILCD)[1], coordinated by the Joint Research Centre – Institute for Environment and Sustainability (JRC-IES), through the European Platform on LCA. This system promotes the availability, exchange and use of consistent and quality-assured life cycle data and methods for robust decision support in policy making and in business. The ILCD Handbook[2] is applicable to a wide range of different decision-contexts and sectors, and therefore needs to be translated to product-specific criteria, guidelines and simplified tools to foster LCA applications in the specific industry sectors. The FC-HyGuide project responds to this need by providing a guidance document on how to perform every step of a LCA for hydrogen (H_2) production systems and fuel cell technologies.

It is foreseen that this guidance document will be applied to all projects funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU) involving LCA in the field of hydrogen production systems and fuel cell technologies. By providing information on how to deal with key methodological aspects, for example definition of a functional unit, system boundary, allocation rules, relevant impact categories, etc., the guidance document will allow all hydrogen production and fuel cell technology developers to assess their own technology, and make the information available in the ILCD Data Network. The availability of data sets will therefore be increased and future LCA studies in this field supported.

The intended audience of this document is, primarily, the hydrogen productions system technology developers working on projects funded by the FCH JU. However, the document can be relevant for any LCA study of hydrogen production systems. It also provides a first example of an ILCD sectoral guidance document.

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[1] The ILCD consists primarily of the ILCD Data Network and the ILCD Handbook. The ILCD Data Network is a web-based, decentralised network of Life Cycle Inventory (LCI) data sets.

[2] The ILCD Handbook is a series of technical guidance documents in line with the ISO 14040 series. It includes explicit and goal-specific methodological recommendations, multi-language terminology, nomenclature, a detailed verification/review frame and further supporting documents and tools.

The applicability of the provisions given in the guidance document is limited to micro-level decision-context situations in the ILCD Handbook[3] (situation A) only. In general, situation A applies to decisions or studies which have only a minor relevance in the respective industry sector, so micro level decision support causes none or negligible change in the background system (further information on background and foreground systems can be found in section 6.3). This guidance document is made for the European geographical scope. A non-exhaustive list of possible application includes: evaluating a complete hydrogen production system, evaluating e.g. the reforming unit of a hydrogen production system, development of a life cycle based environmental product type I Ecolabel criteria of a hydrogen production system, identification of key environmental performance indicators of hydrogen production systems for Ecodesign/simplified LCA; significant issue analysis of a specific product, comparison of specific goods or services; benchmarking of specific products against the product group's average; development of a life cycle based Type III environmental declaration (e.g. Environmental Product Declaration) for a hydrogen production system and development of a carbon footprint.

Situation B would cover "Meso/macro-level decision support", i.e. life cycle based decision support at a strategic level (e.g. raw materials strategies, technology scenarios, policy options), which are assumed to have structural consequences outside the decision-context (they are supposed to change available production capacity). This guide does not cover this decision context because possible applications are strongly context-dependent and thus more specific rules than those defined in the ILCD Handbook cannot be given. Each application has to be evaluated on a case-by-case basis.

Currently some of the provisions reported in this guide are not detailed enough to allow unambiguously application, due to the lack of more precise information. In fact, the still limited amount of life cycle information on hydrogen production systems does not always allow extending the validity of choices, assumptions and results made to the entire product group. Thus, this guide should be conceived as a living document that will be further refined and detailed when more information from case studies will become available.

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[3] The ILCD Handbook identifies three typologies for decision contexts: situation A: micro-level (typically questions related to specific products, with no structural consequences outside the decision-context), situation B: meso/macro-level (questions at strategic level, such as raw materials strategies, technology scenarios and policy options, for example, which have structural consequences outside the decision-context) and situation C: accounting (descriptive documentation of the system under analysis).

1.1. ILCD compliance statement

The guidance document is compliant with the ILCD Handbook with reference to situation A. This means the provisions and explanations given are in line with those of the ILCD Handbook with respect to five aspects: data quality, method, nomenclature, review and documentation:

- *Data quality*

  Data quality relates to completeness, representativeness (technological, geographical and time-related), precision/uncertainty and methodological appropriateness and consistency of the data.
- *Method*

  The method relates to the appropriateness of the LCI modelling and other method provisions, and the consistency of their use.
- *Nomenclature*

  Nomenclature relates to the correctness and consistency of nomenclature which has been used (appropriate naming of flows and processes, consistent use of ILCD reference elementary flows, use of units etc.) and terminology (use of technical terms).
- *Review*

  Review relates to the appropriateness and correctness of the review type, review methods and documentation. This includes ensuring that the methods used to carry out the LCA are consistent with this guidance document, and are scientifically and technically valid. The data used must be appropriate and reasonable in relation to the goal of the study, and the interpretations reflect the limitations identified and the goal of the study. The study report is also transparent and consistent.
- *Documentation*

  Documentation relates to several topics: documentation extent (appropriate coverage of what is reported); form of documentation (selection of the applicable forms of reporting and documentation); documentation format (selection and correct use of the data set format or report template, and review documentation requirements).

If all the provisions are implemented, a LCA study conducted using this guide will be ILCD compliant.

2. How to use this document

This guidance document consists of two parts.

Part I (sections 1, 2 and 3) provides general information on the document, explaining its purpose and structure. A general description of LCA is also provided in section 3 to briefly introduce the methodology to the users.

Part II represents the core of the document. It provides detailed guidance on how to perform LCA on fuel cells and hydrogen production systems. The methodological aspects include the definition of the functional unit, the system boundary selection, allocation rules and selection of impact indicators. These are explained with reference to the technological systems under study. A specific set of rules about the information and topics that have to be considered and reported in a LCA study are described in parallel to the methodological aspects in Part II. Some of the methodological aspects and in general elements of a LCA study are mandatory, some are optional. To distinguish between these two elements, “shall” is used for all mandatory parts and “should” is used for recommended but optional elements.

The guidance document is completed with five annexes. Annex I provides LCA study reporting templates (i.e. how to report the results and conclusions of the LCA in a complete and accurate way and without bias to the audience). Annex II shows the meta documentation fields for the ILCD format to be filled out within the data sets. Annex III provides a specific data collection template. Annex IV includes a review reporting template, and Annex V gives examples from case studies on fuel cells and hydrogen production which will assist users in the application of the guidance document.

Two guidance documents have been prepared in parallel - one addresses the hydrogen production systems, and the other is related to fuel cells systems. These two guidance documents have both been prepared as part of the FC-HyGuide project.

3. Introduction to Life Cycle Assessment

Life Cycle Assessment (LCA) is an analytical tool to assist making environmentally relevant decisions concerning product systems. The scope of LCA encompasses development, production, use, disposal and recycling of products for specific applications. LCA is an established, internationally-accepted method that is defined in two ISO standards (14040 and 14044). The ISO 14040 defines LCA as follows:

“LCA is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its entire life cycle” (ISO 2006a).

The core of the LCA methodology is thinking in product systems and accounting for several environmental goals simultaneously. This methodology helps to keep decision-makers aware of potential shift of burdens that may occur when applying particular individual solutions. The following paragraphs briefly describe the methodology, while greater detail is provided in PART II of this document.

In LCA, the entire life cycle of the product in question is described. This description includes the extraction of resources, the production of materials and intermediates from the resources, the assembly of the product from the materials, the use of the product, and the end of life (Figure 1). The compilation of all relevant processes (connected by material and energy flows) across the life cycle of the product and relevant processes from other contributing products is referred to as the product system. The purpose of building the product system is to identify the intended benefit from the product to be delivered.

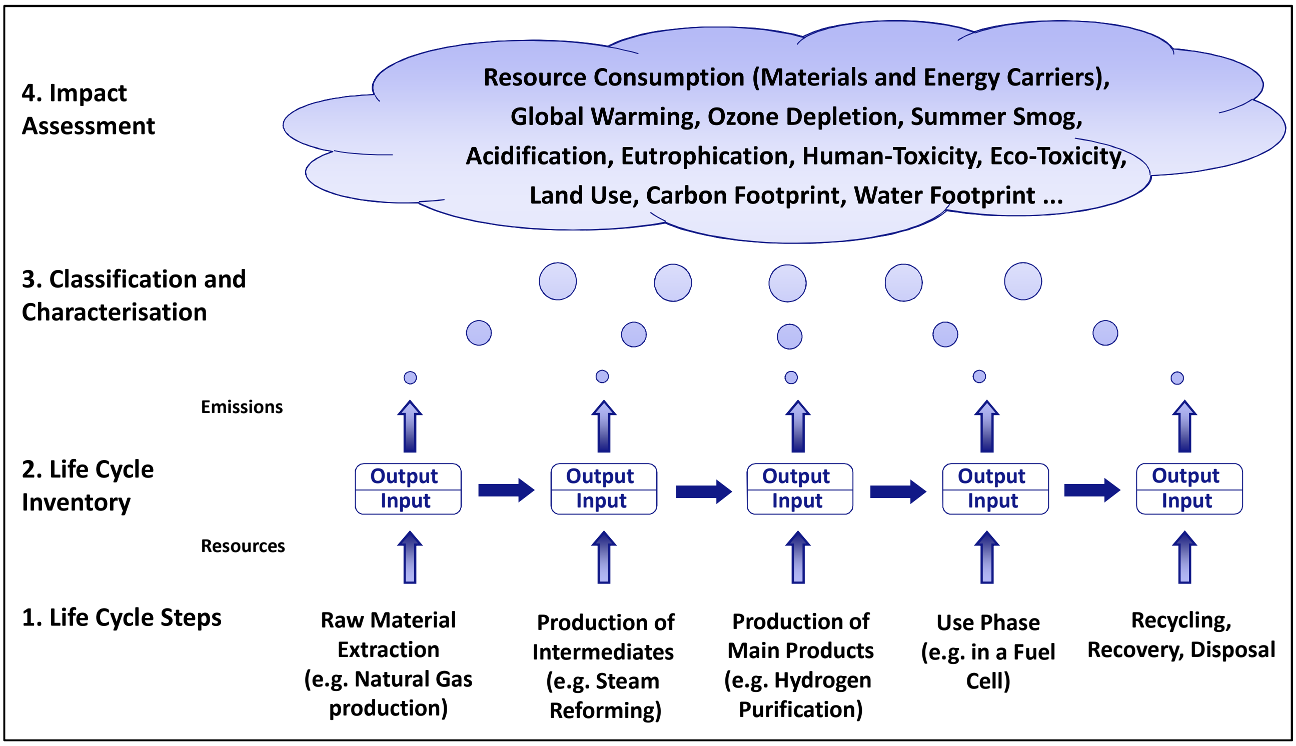

Figure 1: Overview of the LCA methodology

Performing a LCA is divided into several phases. These phases are:

- Goal definition
- Scope definition
- Inventory analysis
- Impact assessment
- Interpretation.

Most of them are done sequentially, but there are also iterative parts where the previous phases have to be reconsidered.

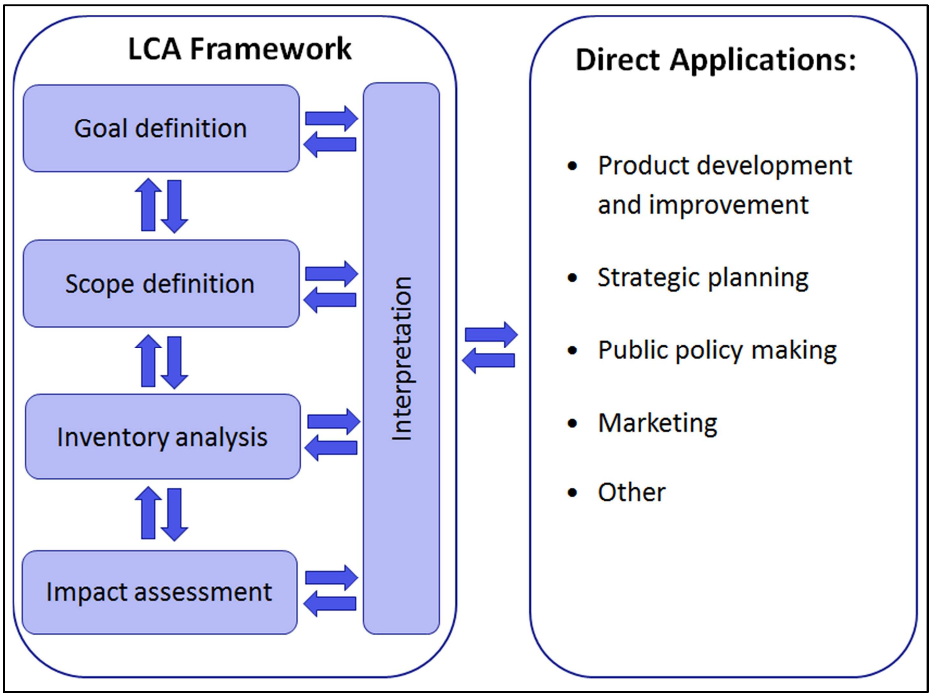

Figure 2: Methodology of LCA taken from (ISO 2006a and JRC2010a) (modified)

Figure 2 illustrates a simplified overview of LCA methodology derived from the ISO standard 14040. The main phases (goal definition, scope definition, inventory analysis, impact assessment and interpretation) are shown. The interpretation interacts with all the phases. Moreover in Figure 2 the iterative character of a LCA is shown. Once the goal of the work is defined the initial scope settings are derived, which define the requirements of the subsequent work. However, if during the Life Cycle Inventory phase of data collection and during the subsequent impact assessment and interpretation more information becomes available the initial scope settings will typically need to be refined and sometimes also revised

1) **Goal definition**

During the goal definition several aspects have to be defined:

- Intended application(s)
- Method, assumptions and impact limitations
- Reasons for carrying out the study and decision-context(s)
- Target audience(s)
- A statement whether the results are intended to be used in comparative studies which will be made public
- Commissioner(s) of the study.

2) **Scope definition**

During the scope phase the following aspects are defined:

- The function, functional unit and the reference flow

- Life Cycle Inventory modelling (multi-functionality)
- System boundary and cut-off criteria
- Life Cycle Impact Assessment methods and categories
- Type, quality and sources of required data and information
- Data quality requirements
- Comparisons between systems
- Critical review needs
- The intended reporting.

3) Life Cycle Inventory

A model of the product system is conceived to represent the interaction of the product system with the environment. The model is commonly programmed in a dedicated LCA software tool and covers each step of the life cycle from the raw material extraction through to the product's end of life in a series of interconnected steps called processes. Interaction with the environment is represented as elementary flows crossing the system boundary, e.g. resources taken from nature and introduced into the product system or emissions arising from combustion, physical, thermal or chemical conversion processes which are vented into the environment. The elementary flows which make up the interaction of a product system with the environment are compiled. This compilation is referred to as the Life Cycle Inventory (LCI). Up to this point, the focus has been on the product system. In the next step it shifts towards the environment.

4) Impact Assessment

The large number of resources and emissions that make up the LCI are translated into a handful of environmental impact categories in the Life Cycle Impact Assessment (LCIA) phase. Each flow from the LCI is grouped into one or more categories. Within each category, the flows are aggregated using equivalence factors called characterisation factors. These factors are based on the physical and chemical properties of the impact-causing substances, as well as on the fate of the flows once they leave the product system towards the environment. The aggregated value is called a "potential impact" and is most commonly given in kg equivalent of a certain reference substance for the respective category. For example, the unit of the impact "Global Warming Potential" (GWP) is kg carbon dioxide equivalent (kg CO_2-eq.). Methane (CH_4) has a 25 (IPCC 2007) times greater impact on global warming than carbon dioxide (CO_2) over a 100 years span in relation to greenhouse gas impacts. So it is characterised with a factor of 25 when aggregating GWP.

5) Interpretation

Robust conclusions and recommendations relating to the goal and scope of the study are developed in the last phase. The results of the other phases are considered collectively and analysed in terms of the accuracy achieved and the completeness and precision of the data and the assumptions that were used.

Grouping and weighting, i.e. aggregation of all the environmental impacts into one single environmental value so as to tell which option is "best" when comparing product systems, is often requested. However, it is important to note that the aggregation of independent impact categories requires normative decisions. ISO 14044 specifies in section 4.1 that "It should be recognized that there is no scientific basis for reducing LCA results to a single overall score or number" (ISO 2006b). Grouping and weighting is based on subjective assessments rather than scientific findings and is therefore generally not recommended and not allowed for comparisons of different products, services or processes. For comparisons, always a complete set of indicators has to be used, e.g. it is not permitted to use Carbon Footprint alone for comparative studies. Most reports cover multiple impact categories, which allow trade-offs between different environmental impacts to be recognised and considered.

Decision-makers can use LCA to gain a sound information basis as a foundation for decisions. The strength of the methodology lies in the two core aspects mentioned at the beginning of this text: thinking in product systems and accounting for all relevant impact categories. This ensures that shifts of environmental burdens between life cycle stages (or between impact categories) are recorded and decision makers can modify their processes to optimise the holistic environmental benefits. The ability for multi-dimensional evaluation of system solutions is especially crucial when particular technology efficiencies have been maximised and substantial improvements can only be achieved through such system solutions.

Provisions 1: The iterative nature of L CA

Shall: Take an iterative approach to LCA, expecting two to four iterations during the process of completing the study:

- Define the goal at the beginning of the study
- Derive the scope definition accordingly
- Compile easily available LCI data for the foreground and background system
- Calculate the LCIA results
- Identify significant issues and perform initial completeness, sensitivity and consistency checks on this first model.
- Based on this proceed to the next iteration: Start with fine-tuning or revising the scope (in some cases even the goal), improve the life cycle model accordingly, etc.
- Starting from the beginning of the study, document the details of the initial goal and scope definition, key LCI and LCIA items, and the key initial results of the sensitivity, consistency and completeness checks. During subsequent iterations, use this preliminary core report as work in progress and constantly revise, fine-tune and complete it during production of the final report.

Shall: If a review is performed, identify and involve critical reviewer(s) and - if required or desired - interested parties, from the beginning of the study

PART II - Guidance on performing a Life Cycle Assessment study on hydrogen production

This section provides comprehensive information for experts such as technical engineers, decision-makers in industry and government policy on how to perform a LCA of hydrogen (H_2) production. Therefore, the methodological background is explained in detail, and each important phase of a LCA – mandatory or optional – is described here. The information on the methodological background is adapted according to ISO 14040, 14044 and the ILCD Handbook (ISO 2006a), (ISO 2006b), (JRC 2010a). The specific rules (including technical description and the information which has to be reported) are provided alongside the methodological information.

4. Introduction to hydrogen production systems

There are different ways to produce hydrogen. Suresh *et al* (2010) gives an estimate of the amount of hydrogen produced globally from different sources and through different methods. In 2008 almost the complete hydrogen production was based on fossil fuels. The breakdown of the total production is as follows: 49 % natural gas, 29 % liquid hydrocarbons, 18 % coal and 4 % electrolysis and others. The main production technologies within hydrogen production systems are:

- Steam reforming
- Catalytic reforming (refinery)
- Gasification
- Partial oxidation
- Electrolysis.

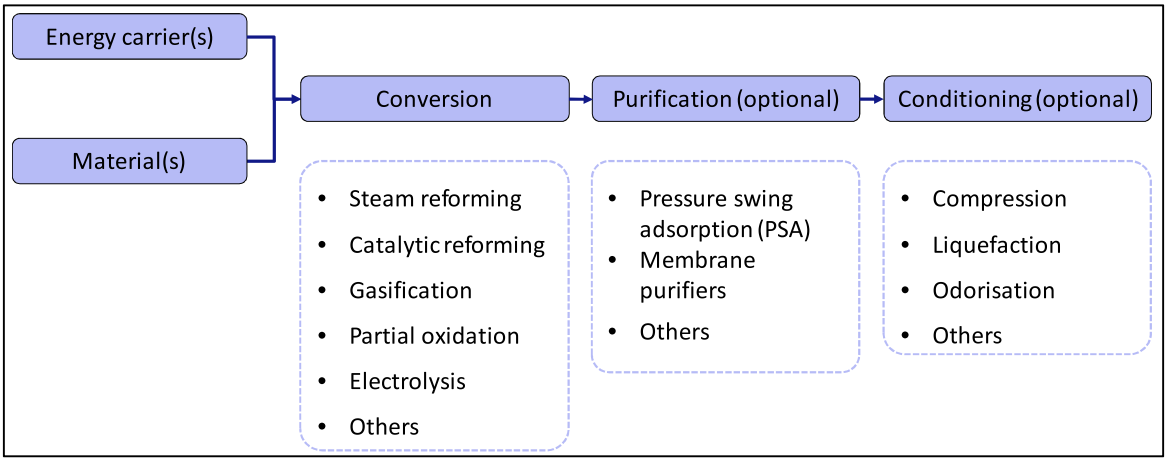

Figure 3: Different pathways of hydrogen production

Some of the production technologies are linked to a certain fuel. Natural gas, for example, is mainly used for steam reforming. Steam reforming is the production of hydrogen using water and natural gas under the influence of high temperatures, slightly increased pressure and a catalyst.

Catalytic reforming is only carried out in oil refineries where hydrocarbon molecules are rearranged to produce specialised high-octane fuel. Hydrogen is produced in large quantities as a “co-product”.

Partial oxidation can be done with almost all kinds of hydrocarbons (natural gas, fuel oil, bitumen etc.). Partial oxidation is, as the name implies, a chemical reaction where only part of the fuel is oxidised due to the fact that the fuel-air mixture is sub-stoichiometric[4]. As a result, a hydrogen rich syngas is produced, which can be used to generate pure hydrogen.

Electrolysis means the decomposition of water by an electric current that is applied by cathodes and anodes. The water is split into hydrogen and oxygen.

After the hydrogen is produced in the conversion step, often it undergoes a purification step. The use of conversion and purification is determined mainly by the intended end use of the hydrogen. For example, a fuel cell may require hydrogen of certain purity. The type of distribution also influences the conditioning. For instance, hydrogen is often odorised for pipeline transportation.

Product group: Hydrogen production system

To compare different hydrogen production routes the whole production system has to be evaluated. However if the study focus is on only one segment of the whole production system, it is also possible to evaluate a specific segment and carry out comparisons of different processes for that one segment.

Therefore studies evaluating the entire hydrogen production system must be distinguished from the studies evaluating only a part of the supply chain. For example, if only the reforming vessel within the steam reforming production system is evaluated, the rest of the H_2 production system has to be included using secondary data (the use of secondary data is explained in section 7.3). However the report must make clear which part of the data is secondary and which is not. The source of the secondary data must also be included in the report.

4.1. Product information requested and standards to use

In general, the guidance document is to be applied for the production of high purity hydrogen (>95 %) and not for assessing syngas or low purity hydrogen (<95 %), i.e. for hydrogen production where hydrogen is not produced in a negligible amount (as co-product) or in low quality.

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[4] This means that the amount of fuel supplied only allows for less than an equal chemical reaction of the components.

The properties of the hydrogen produced will be described briefly. Information about the major properties need to be given by stating the hydrogen quality standard which has been met, such as the ISO TS 14687 (ISO 2007) dealing with hydrogen quality, or the SAE J2719 (hydrogen quality guideline for fuel cell vehicles) (SAE 2005). As hydrogen quality standards evolve and new standards might be developed, these newer standards are recommended.

Further properties and general information can be addressed as well.

Provisions 2: How to state the hydrogen properties

Shall: State the following hydrogen properties:

- Purity (e.g. 99.995 %)
- Aggregate state (e.g. liquid)
- Pressure (e.g. 200 bar)
- Temperature (e.g. ambient temperature).

Should: State the following hydrogen properties:

- Impurities (e.g. X % Nitrogen)
- Quantity produced by volume and/or mass (e.g. YY Nm^3 / h).

4.2. Producer's information requested

Information about the hydrogen producing company has to be given and reported. For further information on mandatory information regarding the hydrogen producer refer to Provision 3.

The technology used for the hydrogen production must be described including the main components of the system and the material used as feedstock. In the case of steam reforming, for instance, system components are feed pre-treatment, reformer vessel, shift reactor, water pre-treatment, H_2 purification unit, compressor and hydrogen storage unit. Feedstock can be fossil fuels such as natural gas or liquefied petroleum gas (LPG) for instance. A process flow diagram has to be included to show the system evaluated.

If the study evaluates only components or a part of the production system, only these components' parts must be described. However the product system which they are part of has to be named. If co-products are produced, the type and amount (e.g. mass, calorific value etc.) has to be stated as well. This identification of the co-products is important for addressing the multi-functionality issue in the context of product related LCA studies (for more details see section 6.2.1).

Provisions 3: Description of the hydrogen producer and the product system

Shall: State the following information regarding the hydrogen producer:

- Overall H_2 production capacity
- Number of sites
- Technologies used in the H_2 production systems
- Geographical coverage by region, where does the hydrogen producer have production sites (Europe, North America …).

Shall: State the following information regarding the hydrogen production system:

- Production technology used
- Year of construction
- Production capacity (per day or year)
- Actual production (per day or year)
- Any on-site electricity or heat production (if existing)
- Flow diagram including main components
- Total market share of this production site.

Should: State the following information regarding the hydrogen production system:

- Location of the production site under evaluation
- Technical service life
- Type of production site (laboratory, pre-commercial, commercial scale)
- Type of storage (including e.g. liquefaction facility or other capability).

5. Goal of the Life Cycle Assessment study on hydrogen production

The goal definition is always the first phase when performing a LCA. According to ISO 14040, defining the goal of a LCA study includes (ISO 2006a), (JRC 2010a):

- Intended application(s)
- Method, assumptions and impact limitations

- Reasons for carrying out the study and the decision-context(s)[5]
- Target audience(s)
- A statement whether the results are intended to be used in comparative studies which will be made public
- Commissioner(s) of the study.

Provisions 4: Goal of the LCA study

Shall: Unambiguously define the goal of the study according to the goal definition in the ISO 14044 standard.

5.1. Intended application(s)

The intended application(s) of the study has (have) to be stated in the report. Note that there can be more than one intended application within a LCA study. Examples for intended applications are shown below.

Provisions 5: How to define the intended application(s)

Shall: Unambiguously state the intended application (in the case of more than one application, state all), indicating if it is for internal (to the organization commissioning the study) use or for external use (results of the LCA to be disclosed to the public). Specific purpose could be (non-exhaustive list):

Internal use:

- Identification of Key Environmental Performance Indicators (KEPI) for Ecodesign
- Significant issue analysis of a specific hydrogen production system
- Significant issue analysis of parts of a hydrogen production system (e.g. electrodes or purification technology).

External use:

- Development of life-cycle based Type I Ecolabel criteria
- Development of a life-cycle based Type III environmental declaration (e.g. Environmental Product Declaration - EPD)
- Calculation of a carbon footprint of a hydrogen production system
- Calculation of a carbon footprint of part of a hydrogen production system (e.g. reforming section of CO_2 shift of a steam reformer).

[5] Further specifications on decision contexts can be found in footnote 3

Internal/external use:

- Comparison of environmental aspects of specific modules of the hydrogen production system
- Benchmarking of a specific hydrogen production system against the product group's average
- Evaluation of the primary energy demand of a hydrogen production system.
- Environmental aspect comparisons of part(s) of a hydrogen production system (e.g. performance of a purification unit).

5.2. Method, assumptions and impact limitations

The methods, assumptions and impact limitations (see section 6.4 on impact categories) chosen have to be stated prominently in the report, as they might influence the overall results of the study. For example a common intended application for LCA is assessing the carbon footprint. When evaluating the carbon footprint, the impact categories under investigation are limited to the global warming potential. This limitation influences the data collection for example, as only data and emissions impacting the global warming potential have to be gathered.

Within this guidance documents no limitations are made. The document is tailor-made for performing a (complete) Life Cycle Analysis on hydrogen production. Hydrogen production includes many possible applications in the field of environmental evaluation. When using this guidance document for applications such as the carbon footprint, the practitioner has to keep in mind that some of the rules and specifications in the document might not apply to that particular study.

Provisions 6: Method, assumption and impact limitation

Shall: Assure sufficient consistency of methods, assumptions and data throughout the LCI/LCA study. Document any inconsistencies and consequences of these inconsistencies regarding the conclusion of the study.

5.3. Reasons for carrying out the study, and decision-context

The reasons for carrying out the study have to be unambiguously stated within the goal definition.

The drivers and the motivation have to be documented. In the case of H_2 production, the reasons might be to include environmental information in the product development to guide a decision for the next steps, or to increase market share through environmental claims, or giving decision support for legislation on funding of H_2 as an energy carrier.

The decision-context must be defined as it can influence how the study is conducted. As stated in section 1 of this document, and as defined in the ILCD Handbook this guidance document on hydrogen production is based on situation A[6].

Provisions 7: Reasons for carrying out the study

Shall: Unambiguously state the reasons for carrying out the study.

5.4. Target audiences

Another part of the goal definition is the identification of the target audience. The target audience determines how the report is constructed, i.e. the report has to be written in such a manner that it is easily understandable for the target audience. For example, the audience may be "technical" or "non-technical". For technical experts or researchers in the field of H_2 production, the technical detail level of the report is high. For politicians and decision-makers the report is supposed not to focus on the technical details but more on explaining the results in a non-technical manner not withstanding its technical base. Beside of the general distinction in technical/non-technical there might be various other possibilities how the target audience can orientate the format of a report. Some might want an EPD for example; this makes the whole study follow the corresponding product category rule (PCR). It may be internal audience then the format might be an executive summary plus a presentation. Defining the target audience and hence the report format allows to better determine the resources needed for the study.

Provisions 8: Target audience

Shall: Unambiguously state the target audience of the study.

Should: Consider the audience when deciding how the report is written:

- Technical audience: experts or researchers in the field of hydrogen production - the focus should be on the technical details.
- Non-technical audience: politicians and decision makers - less technical detail.

Should: Consider specific formats, that might be demanded e.g. when writing an environmental product declaration.

[6] In general, situation A applies to decisions or studies which have only a minor relevance in the respective industry sector so micro level decision support causes none or negligible change in the background system.

5.5. Comparisons intended to be disclosed to the public

If the intention of the LCA study is a comparison of production technologies, it is important to include the statement that the study is comparative. In this case, for instance, the system boundary have to be defined consistently and the functional unit (e.g. amount of H_2 produced) of both systems has to be the same.

If the study is to be disclosed to the public, this also has to be stated. This intention will then lead to the requirement for the critical review. More details on the critical review procedure for comparative assertions is given in section 6.8 “Identification of critical review needs”, and section 11 “Critical review of the study on hydrogen production”.

Provisions 9: Statement if the study is comparative

Shall: Include the statement if the study is comparative.

Shall: Include the statement if the study is to be disclosed to the public.

5.6. Commissioner of the study

The commissioner and the (co)financier of the study have to be stated in the report as well as other actors involved in the study such as other persons, groups, companies, organisations. This might be important, when e.g. the producer of a hydrogen production system finances a study that compares his own system with the system of a competitor. In such a case, the LCA credibility might suffer if the financer is not disclosed beforehand.

Provisions 10: Commissioner of the study

Shall: Unambiguously identify the commissioner of the study and name all organisations that are involved (directly/indirectly) in the study.

Should: State the practitioner conducting the study.

6. Scope of the Life Cycle Assessment study on hydrogen production

During the scope phase the object of the LCA study is defined, such as the exact product or system under investigation (JRC 2010a). For studies relevant to this specific guidance document, the object is a LCA of hydrogen production. The LCA could cover either single processes or components such as the catalysts used, or entire product systems. Given that whole supply chains are important, the object could be, for instance, the supply chain for producing hydrogen via steam reforming with all its single process steps.

This phase, together with the Interpretation, is the most important one of the LCA methodology since it requires several resources for unambiguously defining what the LCA study is about and for whom. In fact, the depth and the breadth of LCA can differ considerably depending on the Goal and Scope of a particular LCA and errors made in this phase have strong consequences on the results (adapted from (Fullana et al. 2011)).

6.1. Function, functional unit and reference flow

For hydrogen production, the function of the system is the “production of hydrogen”. The functional unit is defined as a “quantified performance of a product system for use as a reference unit” (ISO 2006a). In general a functional unit has to be precise and quantifiable.

For H_2 production systems, the functional unit must be “production of a certain amount of hydrogen”. If time aspects, i.e. the duration to produce a certain amount of hydrogen, are of relevance, the time to produce the amount of hydrogen is to be included also.

If no co-products apart from hydrogen are produced, the functional unit can be defined unambiguously and easily. When the system under analysis has more than one function i.e. it has different products as outputs, an integrated functional unit must be defined carefully. Within chlorine-alkali electrolysis, for instance, the functions are the production of chlorine, sodium hydroxide and hydrogen, and the functional unit has to be referred to as hydrogen. Hence the functional unit is the production of a certain amount of hydrogen. This allows the comparison of multi-function systems with single function systems.

A reference flow is linked to the functional unit. They are sometimes but not necessarily, the same. The reference flow is a “measure of the outputs from processes in a given product system required to fulfil the function expressed by the functional unit” (ISO 2006a). For H_2 production the reference flow could be different from the functional unit. For example the functional unit “production of a certain amount of H_2” would not be precise as it does not specify the properties of H_2 such as purity, pressure and temperature. These properties can influence the overall results. It has an impact on the energy demand if there is e.g. a high pressure compressor included in the system. For the precise definition of the reference flow for H_2 production, the exact state of the H_2 has to be defined.

The values of purity, pressure and temperature can vary according to the product system evaluated and they have to be stated. So the final reference flow would therefore be e.g. “1 MJ of hydrogen (NCV) with 99.98 % purity and 200 bar @15 °C”.

Provisions 11: Functional unit

Shall: Use the following functional unit:

1 MJ of hydrogen (net calorific value (NCV)).

Provisions 12: Reference flow

Shall: Use the following reference flow:

1 MJ of hydrogen (net calorific value (NCV)) with XX % purity and YY bar @ ZZ °C.

6.2. Life Cycle Inventory modelling

As defined in section 1, this guidance document refers to situation A according to the ILCD Handbook (JRC 2010a). Situation A relates to basic principles of LCI modelling. The model represents a supply chain of the system under investigation populated with the necessary LCI data. The detailed modelling principles are explained in the following sections.

Provisions 13: Life Cycle Inventory modelling

Shall: Use the International System of Units (SI) in the Life Cycle Inventory modelling.

Shall: Use an attributional modelling approach in LCA studies of hydrogen production systems, in line with the requirements of the ILCD Handbook for the decision context (Situation A).

Note: The requirements of attributional modelling are described in the following sections.

6.2.1. Multi-functionality

Multi-functionality refers to a product system having more than one function. Therefore a multi-functional process is defined as a "process or system that performs more than one function" (JRC 2010a). One well known example relevant to hydrogen production is the chlorine-alkali electrolysis process that produces chlorine, sodium hydroxide and hydrogen.

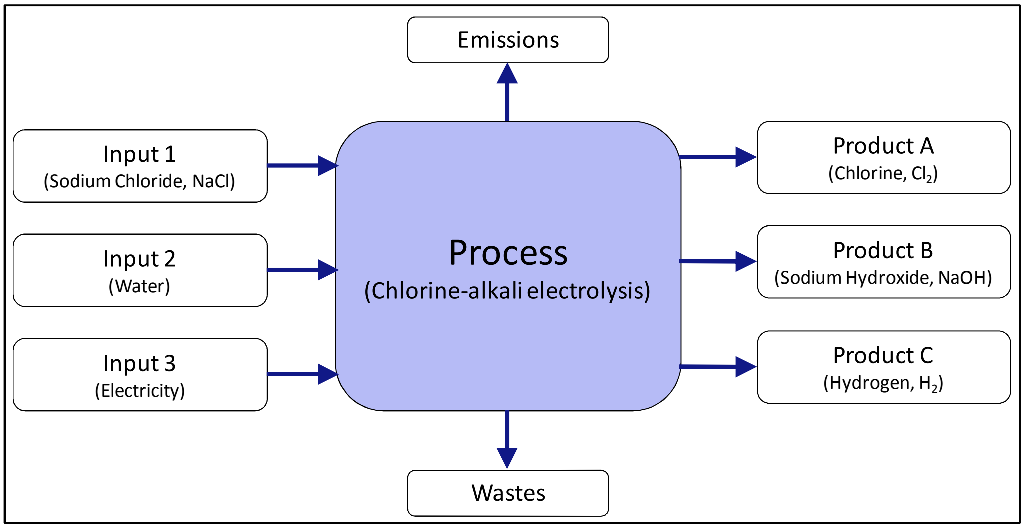

Figure 4: Scheme of multi-functional processes (JRC 2010a) (modified)

The main flows of the chlorine-alkali electrolysis are displayed in Figure 4. Inputs are sodium chloride, water and electricity. Products are chlorine, sodium hydroxide and hydrogen. A staged approach is needed in order to address the environmental impacts for each product in an appropriate manner.

The ISO 14044 and the ILCD Handbook show a hierarchy of possible solutions for solving multi functionality (ISO 2006b), (JRC 2010a):

1. Subdivision
2. System expansion
3. Allocation.

The first approach is subdivision, which means subdividing the processes into several small processes. A production site of a company can be multi-functional, as it often produces several goods (hydrogen and other goods for example). If the H_2 production is a separate process the production site can be subdivided into several processes and enable evaluation of the H_2 production alone. In the case of chlorine-alkali electrolysis however, the process cannot be subdivided further, as it is a single process delivering several products.

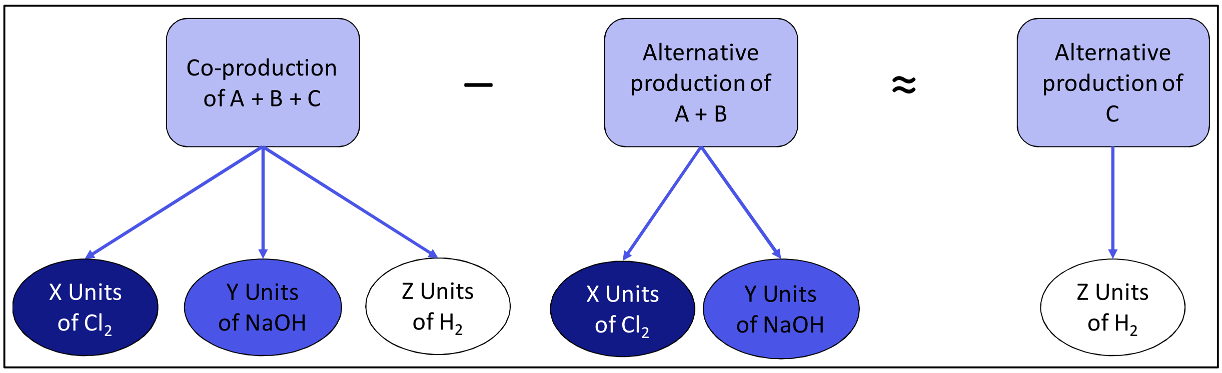

Figure 5: System expansion for solving multi-functionality (JRC 2010a) (modified)

The second approach is system expansion. System expansion means to add or subtract a process with another function to make the original process comparable to other systems (Figure 5). In the case of the chlorine-alkali electrolysis this method will not work as there is no other technically comparable method for large scale production of chlorine.

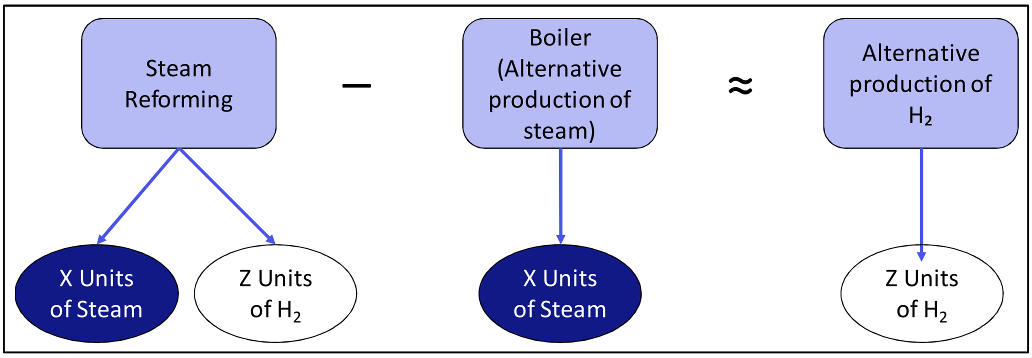

Figure 6: System expansion using the example of a steam reformer

For steam reforming (or more generally a system with heat or steam as a co-product) the system expansion methodology is applicable (Figure 6). This is because the steam generated by the steam reforming process could otherwise be produced in an external boiler. Hence, the environmental profile of the external boiler, using the same fuel (natural gas), could be subtracted from the steam reforming environmental profile. The same method can be applied for the heat produced in the partial oxidation. But generally this method has to be applied only if the heat or steam is actually used.

If system expansion is used the process or environmental profile being substituted has to be suitable. If e.g. electricity is subtracted, it can make a great difference from an environmental point of view if a country specific electricity grid mix or a renewable electricity data set is subtracted. The data sets subtracted have to be mentioned in the report unambiguously.

Allocation is the third means of solving multi-functionality. ISO 14044 (ISO 2006a) defines allocation as “partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems". This definition means that the impacts are attributed to the different products using an allocation factor.

When using the allocation method, the important step is to determine the allocation factor. The ISO 14044 recommends the following hierarchy of allocation:

1. Physical relationships between the products,
2. Other relationships between the products.

Physical properties as allocation factors representing the physical relationship between the different products, such as mass or calorific value, are to be used. For instance, a refinery produces hydrogen as well as other energy carriers, so the allocation factor would be the energy content. However for the chlorine-alkali electrolysis this would not be appropriate as the energy content of the chlorine is not important for its use.

Another possibility would be to choose the market value. In this case it must be guaranteed that the values are generated under the same circumstances. To do this, comparable circumstances in relation to the market value have to be chosen. It can make a great difference if a product is purchased from a chemical store in small amounts or from a wholesale supplier in large amounts. Regardless of which allocation factor is chosen, it must always be cross checked with other allocation factors by performing a sensitivity analysis. The allocation factor chosen must be stated explicitly and quantitatively in the report.

Figure 7 shows an example with the main products of the chlorine-alkali electrolysis. These products are used for the allocation example In Table 1.

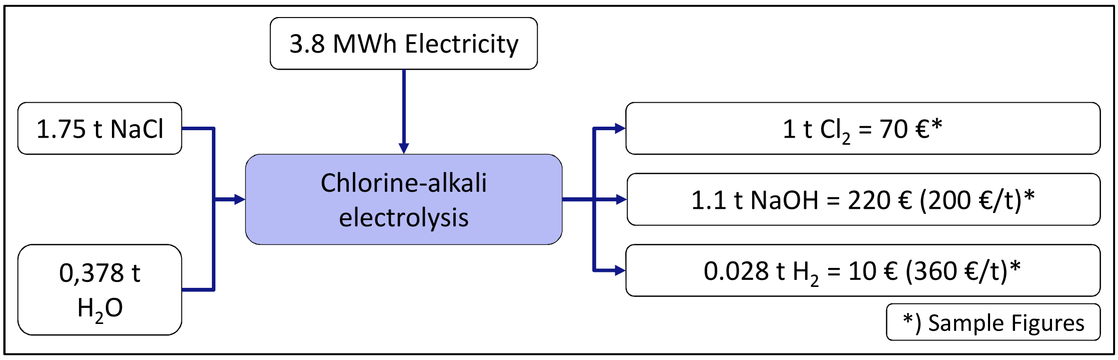

Figure 7: Sample products of chlorine-alkali electrolysis with sample prices

Table 1: Allocation example chlorine-alkali electrolysis[7] (results rounded)

Process input	Total process	Allocation by	1 t Cl_2	1.1 t NaOH	0.028 t H_2
Electricity	3.8 MWh	Mass	1.79	1.96	0.05
		Market Value	0.89	2.79	0.13
Sodium chloride (NaCl)	1.75 t	Mass	0.82	0.90	0.02
		Market Value	0.41	1.28	0.06

Table 1 shows different possible allocation factors. The allocation is calculated by mass and by market value. The distribution of the inputs to the products varies with the different allocation factors. If allocation is applied in the study, several scenarios with different distribution keys have to be documented, as shown in Table 1.

The effect of the allocation or of the other possibilities for solving multi-functionality, on the reliability of the final results and conclusions has to be determined by a sensitivity analysis (section 9.2.2). Such an analysis discloses whether an approach chosen leads to significantly different results or not. This analysis will highlight any faults or misinterpretations. The method chosen for solving multi-functionality, as well as the sensitivity analysis, have to be explicitly stated in the report. How to solve the multi-functionality issue for hydrogen production systems is described in section 7.4.

[7] The impacts of the water supply have to be allocated following the same principles.

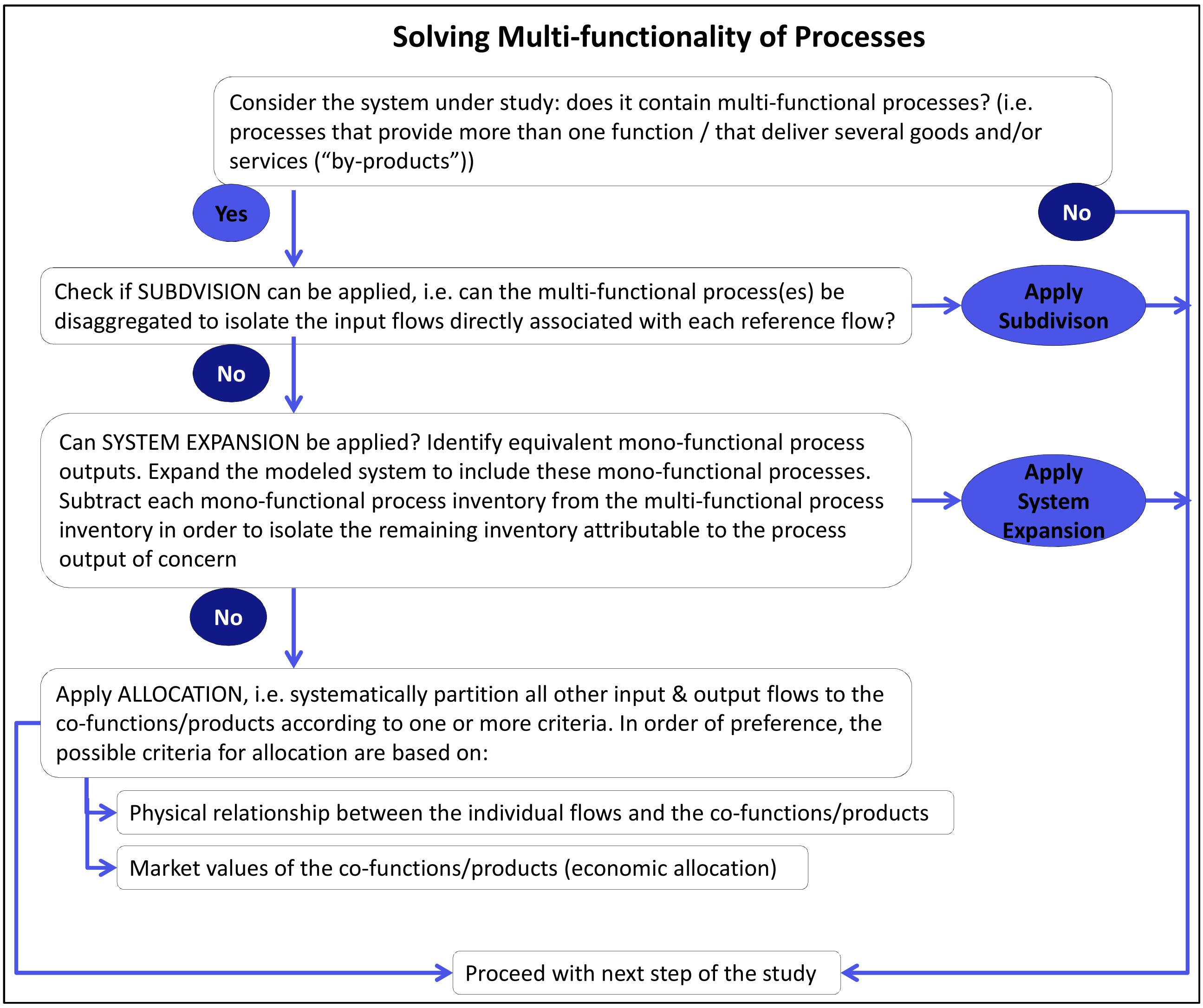

Figure 8: Decision tree for solving multi-functionality provided by JRC-IES (modified)

Provisions 14: Multi-functionality

Shall: Analyse if there are any co-products created and/or heat generated that is used by another process in order to identify if multi-functionality exists.

Shall: If there is multi-functionality, use the decision tree to resolve the issue.

6.3. System boundary and cut-off criteria (completeness)

6.3.1. System boundary

The ISO 14040 defines the system boundary as a "set of criteria specifying which unit processes are part of a product system" (ISO 2006a). For H_2 production it means that both the process steps which are included in the LCA study and those which are excluded have to be defined.

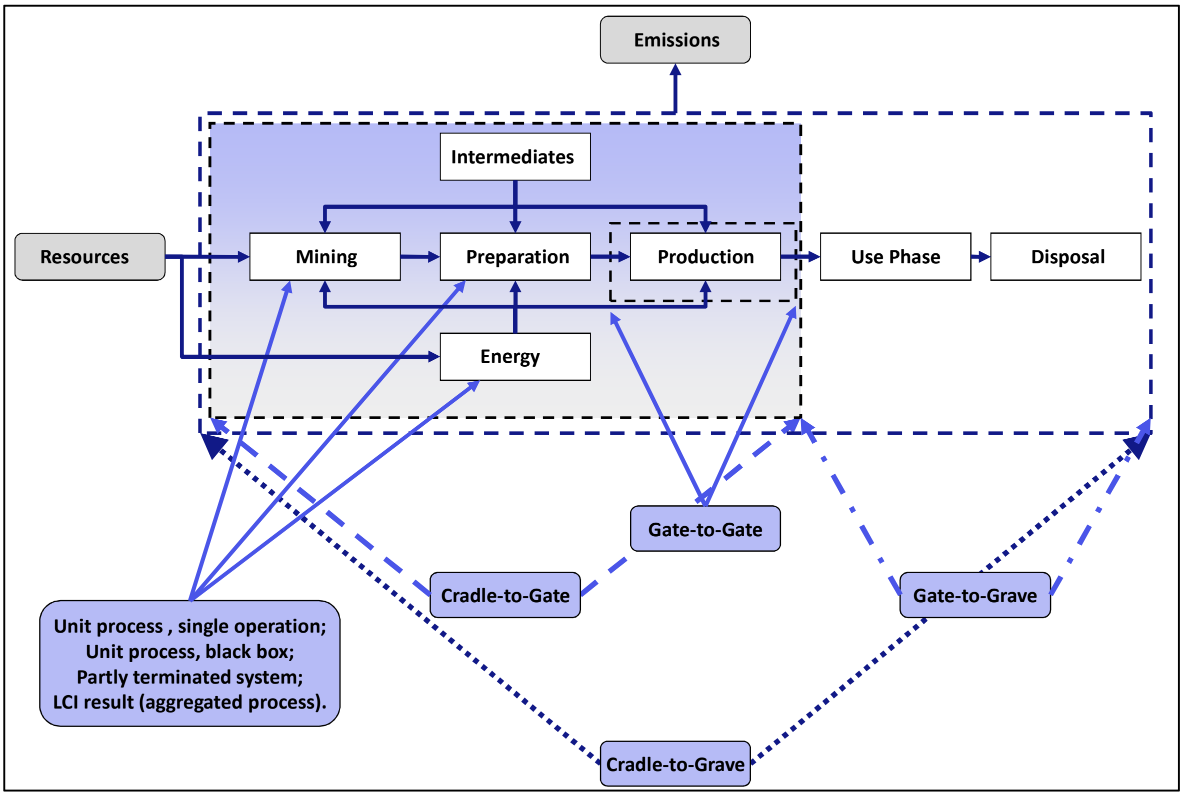

Figure 9: Possible system boundary in the life cycle

Figure 9 shows an overview of how different system boundary can be defined. Generally the system boundary of a LCA on hydrogen production has to be defined according to the actual product system. The main process steps of the hydrogen production (gate-to-gate assessment of the production site) have to be included. The related infrastructure (construction and dismantling of the production plant) can be considered. Commonly a “cradle-to-gate” view is applied to analysis of H_2 production. Cradle-to-gate means that the production unit (e.g. steam reforming) is assessed as well as all preliminary steps. All relevant flows crossing the system boundary have to be included (definition of flows see section 6.3.2).

Data sets on upstream processes such as energy carriers and material supplies are available in existing databases with secondary data sets. All important upstream processes must be included in the LCA study. It is mandatory to use as secondary data already existing data sets from the European Reference Life Cycle Database (ELCD) or from the data network of the International Reference Life Cycle Data System (ILCD) as the first choice (JRC 2010d), (JRC 2010e). Data sets from these databases comprise complete upstream processes (e.g. “EU-27 natural gas, consumption mix at consumer” or DE electricity grid mix, consumption mix at consumer, 230V), including the infrastructure. If the requested data are not available in these two sources, high quality data sets from consistent databases using the ILCD format, ILCD nomenclature and ILCD conventions are recommended to be used. A detailed list of the available databases can be found in the LCA directory of the European Platform on LCA (http://lct.jrc.ec.europa.eu/).

Downstream processes, like the compression and distribution of hydrogen, as secondary data may also be found and used from the above mentioned data sources.

The infrastructure of the system under investigation (e.g. construction and dismantling of vessels, pipes, etc.) may be included.

Time limitations

The primary data used for the LCA, whether measured, calculated or estimated, must be valid for the reference year or reference period that is defined. The time (or time period) of measuring the primary data has to be stated. In the case of calculation or estimation of the data, the time (or time period) to which the assumption refers has to be stated as well. If secondary data are used, especially for the background system, the year of the data and therefore the time-representativeness has to be documented and to be suitable for the study.

Limitation within the life cycle

LCA studies on hydrogen production are mostly carried out as a cradle-to-gate assessment, starting from the extraction of raw materials (e.g. mining) to the production of the hydrogen itself. Further steps in the life cycle, e.g. compression and on-site storage can be included in the assessment. The distribution may be included if the goal of the study makes it necessary. For instance, if the study compares different production systems and the method of distribution such as decentralised production and distribution by tube trailer or central production and distribution by ship, the distribution is part of the system. However, the results excluding the distribution are supposed to be stated if possible. In addition to the analysis of the cradle-to-gate hydrogen production system, the analysis can be expanded by looking at the whole life cycle if this is appropriate.

Boundary towards other technical systems or nature

There are different flows and substances entering from other systems and leaving the hydrogen production system towards other systems. They have to be declared within the study and thus also evaluated. To show the system boundary towards other systems, a flow chart such as that shown in Figure 10 has to be included. However it is recommended that the flow chart shows a higher level of detail.

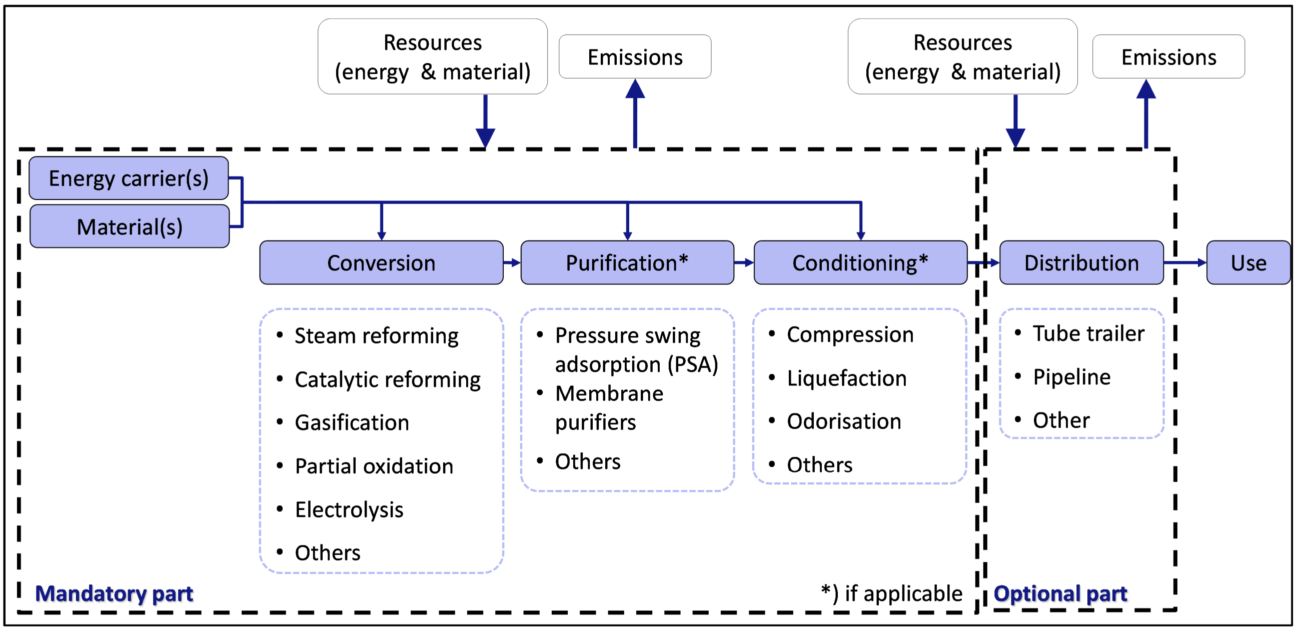

Figure 10: System boundary towards other systems and to nature

Provisions 15: System boundary

Shall: The system boundary shall be consistent with the goal of the study (ISO 2006a).

Shall: Show the chosen system boundary in a flow chart.

Shall: In case of partly terminated systems, selected processes are deliberately foreseen to be excluded from the system boundary. The corresponding product and/or waste flows are meant to stay in the final inventory after aggregation i.e. cross the system boundary in the provided data set. This shall be shown in the system boundary diagram. When later using the data set in another system, the system model has to be completed also for these products and waste flows.

Should: The system boundary of a LCA on hydrogen production should be defined according to the product system under assessment. In the case of a hydrogen production system, a “cradle-to-gate” approach is commonly used.

6.3.2. Definition of relevant (energy, material and elementary) flows

A flow is an input or output from a process or product system. There are several types of flows.

Elementary flows are defined in ISO 14040 as “material or energy entering the system being studied that has been drawn from the environment without previous human transformation, or material and energy leaving the system being studied that is released into the environment without subsequent human transformation" (ISO 2006a). This means that an elementary flow is, for example, crude oil or hard coal resource as an input, or CO_2 emission released to air as a non-further treated output.

Hydrogen produced in the electrolysis would be called a product flow.

Which product flows within the H_2 production process are relevant, depends on which kind of H_2 production is assessed. If e.g. electrolysis is taken into consideration, it is obvious that the most important product flow entering the system is electricity. The most important product output is hydrogen. In the case of steam reforming, the relevant product input flows include natural gas and electricity and again H_2 as a product output. In general all product flows having a significant environmental impact regarding the whole product system are relevant.

The product flows of electricity used, fuel used and hydrogen produced are necessary for all hydrogen production technologies. While it is not possible to show other relevant product flows for all existing H_2 production technologies, Table 2 gives an overview for common technologies used for commercial H_2 production.

Technology	Input	Output
Steam reforming	Natural gas	Hydrogen
	Liquified Petroleum Gas (LPG)	Exhaust gas
	Refinery gas	Cooling water
	Cooling water	Steam
	Tap water	Waste water
	Electricity	Miscellaneous waste
	Operating supplies and spare parts	
	Operating supplies for the de-sulphurisation	
	Operating supplies for the de-ioniser	
Electrolysis	Electricity	Hydrogen
	Tap water	Oxygen
	Supply material (e.g. potassium hydroxide for electrolyte)	
	Operating supplies and spare parts	
Chlorine-alkali electrolysis	Electricity	Hydrogen
	Sodium chloride	Chlorine
	Tap water	Sodium hydroxide
	Operating supplies and spare parts	
Partial oxidation	Fuel (fuel oil, coal, bitumen, natural gas, etc.)	Hydrogen
	Electricity	Heat
	Operating supplies and spare parts	Exhaust gases

Table 2: Relevant flows of different hydrogen production pathways (Faltenbacher et al. 2002)

Product inputs and outputs to and from the hydrogen production system under investigation to and from other technical systems have to be included. Data used have to reflect the technology actually used. For the input flows, the actual production system, depending on the region where they are purchased, is to be considered. If data are not available, comparable, i.e. generic data, have to be used. If secondary data for closing data gaps are used, as described in section 6.3.1, it has to be described in the LCA report.

All resources from nature and emissions to nature of the hydrogen production system have to be taken into account. Exceptions are permitted in accordance with the cut-off criteria (section 6.3.3).

Provisions 16: Relevant Flows

Shall: Consider the following points:

- All flows considered (or not) shall be stated
- Product inputs and outputs to and from the hydrogen production shall be included
- Describe generic and secondary data used for data gaps
- All resources from nature (elementary input flows) and emissions to nature (elementary output flows) of the hydrogen production system shall be taken into account.

6.3.3. Cut-off criteria (completeness)

In practice, accounting for 100 % of all inputs and outputs (both elementary and product flows) is sometimes not achievable since the effort required to acquire the data would be very high. If the additional data would only give a negligible gain in accuracy, the additional effort would not be justified. The ISO standard takes account of this effect by defining cut-off criteria.

The ISO 14040 defines cut-off criteria as "specification of the amount of material or energy flow or the level of environmental significance associated with unit processes or product system to be excluded from a study" (ISO 2006a). In other words, all inputs that contribute more than a pre-defined percentage of the total product system's environmental impacts have to be considered in the study. These cut-off criteria can also be used for outputs such as emissions to the environment.

Choosing several cut-off criteria as described above is very helpful to assess the environmental burdens or impacts. Criteria based on mass alone for example could omit important inputs and outputs (both elementary and product flows), because the magnitude of the burdens/ impacts is not proportional to the mass of inputs, but depends on the individual materials. The cut-off rules imply that the total amount is approximated, because if the total is known, there would not be any need for applying cut-offs. The higher the percentage of cut-offs, the greater is the overall uncertainty of the result. The cut-off rules applied have to be carefully specified in the report and the expected uncertainty within the results has to be stated. Systems could have significantly less environmental impact if a high cut-off is applied.

Inputs and outputs (both elementary and product flows) of each process step can partly be ignored if the overall results are not affected significantly for each environmental impact category under investigation. The sum of all cut-offs regarding inputs and outputs has to be less than 5 % in each pre-selected environmental impact category. If the cut-off is too high the system boundary (section 6.3.1) might need to be reconsidered.

Provisions 17: Cut-offs

Shall: Adopt a 5 % cut-off value on each relevant environmental impact category. Any different value shall be justified and its effects on the final results shall be checked through a sensitivity analysis.

Should: Show which flows are cut-off or excluded from the study.

6.4. Life Cycle Impact Assessment methods and categories

Life Cycle Impact Assessment (LCIA) aims at "understanding and evaluating the magnitude and significance of the potential environmental impacts" (ISO 2006a). Here inputs and outputs of elementary flows that have been collected and reported in the Life Cycle Inventory are translated into impact indicator results related to human health, natural environment and resource depletion. The results of LCIA are not intended to be interpreted as a prediction of actual environmental effects but rather as potential environmentally relevant impact indicators.

The impact assessment phase consists of mandatory (classification and characterisation) and optional (normalisation, grouping and weighting) elements. ISO 14044 specifies in section 4.1 that "It should be recognized that there is no scientific basis for reducing LCA results to a single overall score or number" (ISO 2006b). Grouping and weighting is based on subjective assessments rather than scientific findings and is therefore generally not recommended and not permitted when LCA results are to be used for comparisons. For guaranteeing an impact assessment free of value choices and assumptions, non-normalised, non-grouped and non-weighted results have to be shown.

From the practical point of view the impact assessment does not involve the LCA practitioner directly, but indirectly by choosing the impact categories, the LCIA methods to be applied, and - if included – the normalisation and weighting sets. However it must be emphasised that normalisation, grouping and weighting is not recommended. See section 8.1 for more detail.

Choice of relevant impact categories and impact assessment methods

An impact category is defined as a “class representing environmental issues of concern to which Life Cycle Inventory analysis results may be assigned” (ISO 2006b). This definition means that various emissions are assigned to an impact category e.g. “Global Warming Potential”.

When referring to impact categories it has to be clarified whether mid- or endpoint categories are being used (**Fehler! Verweisquelle konnte nicht gefunden werden.**). Categories at midpoint level require modelling the impact using an indicator located along the mechanisms, but not at the end. Examples include Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Photochemical Ozone Creation Potential (POCP), Human-Toxicity (cancer and non-cancer related), Respiratory Inorganics, Ionising Radiation, Eco-Toxicity, Land Use, Water Footprint, and Resource Depletion.

Category endpoints are defined as an “attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern” (ISO 2006b). Categories at the endpoint level require modelling all the way to the impact on the entities described by the Area of Protections (AoP) i.e. on human health, on the natural environment and on natural resources. This extensive modelling then allows for cross-comparison of different impact categories within AoPs on a natural or social science basis, and possibly taking into account all substance-specific differences.

The endpoint categories are more easily understood, because they are closer to what ultimately matters to society. The major uncertainties associated with modelling from midpoint to endpoint, however, represent a drawback that has to be considered. Conversely, midpoint categories are in line with the current environmental policy theme and can be modelled quite accurately. Moreover, the midpoints allow easier identification of the contribution of different processes, as the result is not completely aggregated.

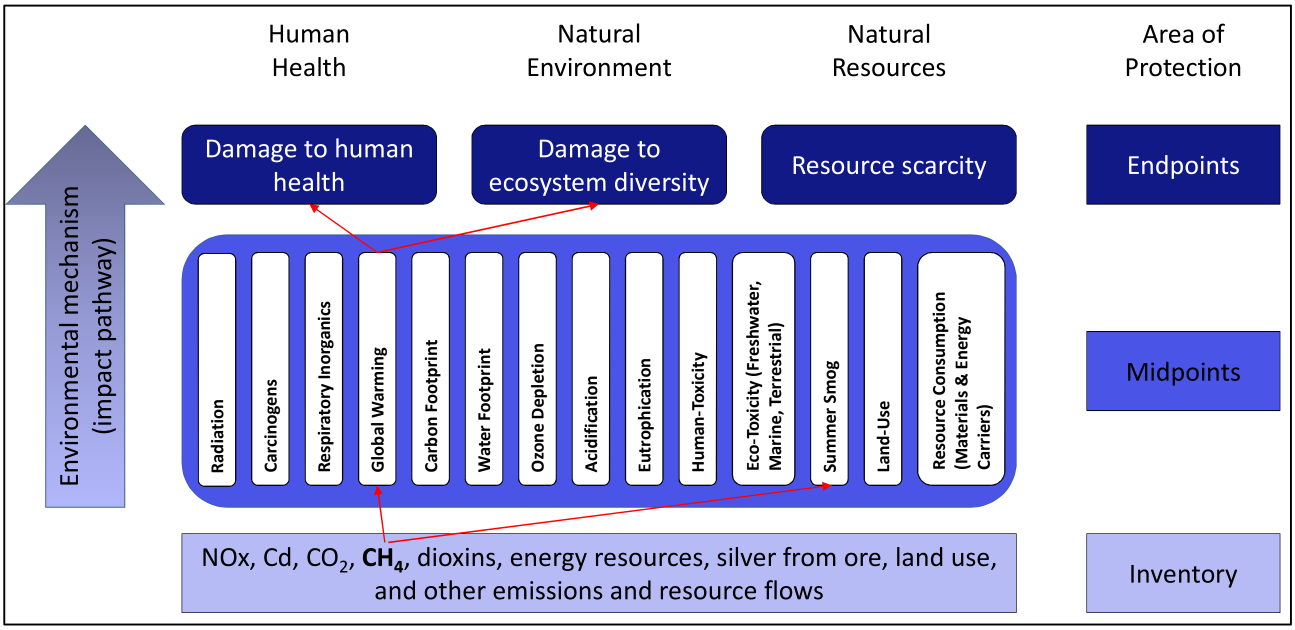

Figure 11: Schematic steps from Life Cycle Inventory to impact category (JRC 2010a) (modified)

In general, impact assessment categories are to be chosen using an approved methodology, in conjunction with the scientific literature and general European policy goals.

The European Parliament and Council published “The Sixth Environment Action Program of the European Community 2002-2012” (European Parliament 2002) that forms the basis for the choice of the impact categories considered. The environmental priorities within this program are:

- Climate change,
- Nature and biodiversity,
- Environment, health and quality of life, and
- Natural resources and wastes.

Global Warming Potential (GWP) is a globally accepted impact category for describing climate change. The main greenhouse gas emissions related to hydrogen production come from energy carrier production, transportation, and conversion. To consider the varying greenhouse gas effects, a time horizon of 100 years is chosen, also known as “GWP100”.

The protection of the environment from harmful pollutants is the primary goal with regard to the priority of nature and biodiversity. The “Acidification Potential” (AP) and “Eutrophication Potential” (EP) are chosen to address this priority. The key pollutants relevant for these impact categories are SO_2 and NO_X which have been in the past, and in many cases still are, the main sources of damage to forests and soil (EC 2002).

The protection of human health and the improvement of the quality of life are amongst other measures addressed by controlling ground level ozone levels. The impact category “Photochemical Ozone Creation

Potential" (POCP) addresses the issue of summer smog formation, especially in densely populated urban areas.

Resource depletion has to be recorded for resources consumed during the production of hydrogen. For many energy carriers, primary energy demand correlates well with the depletion of abiotic resources. Since the product system under investigation in this study is an energy carrier, it is appropriate to refer to primary energy only, without further reference to non-energetic resources. The corresponding inventory quantity focusing on energy resources is called "Primary Energy Demand" (PED) and describes the energy embodied in all flows entering or leaving the product system. Energetic resources are separated into renewable and non-renewable energy carriers. Fossil fuels like coal, crude oil and natural gas are non-renewable energy carriers. Wind, hydro, geothermal, solar and etc. energy is captured in the renewable energy category.

The use of secondary energy carriers, such as electricity, has to be documented separately. Aside from primary energy, other resources like water and Land use are recommended to be addressed as well. Water use is mainly important in areas where water is scarce. Nevertheless assessing the water footprint is recommended, using methodologies already developed. Land use is an impact category currently being developed. It will likely comprise several indicators addressing implications of different Land use types (Beck 2010) and can be used when development has been completed.

Biodiversity (endpoint) is also one of the major topics from a policy perspective. Biodiversity is not calculated directly but represented by those midpoint categories that affect biodiversity negatively, pre-dominantly Eco-Toxicity, Acidification Potential, Eutrophication Potential, Global Warming Potential, Ozone Depletion Potential and Land use. Methodology addressing biodiversity directly is under development. As soon as this methodology becomes available it is recommended to use it for LCA studies on hydrogen production systems.

Provisions 18: Impact categories to be used

Shall: Use midpoint categories for studies on hydrogen production

Shall: Use the following impact categories:

- Global Warming Potential (GWP)
- Acidification Potential (AP)
- Eutrophication Potential (EP)
- Photochemical Ozone Creation Potential (POCP).

Shall: In addition to these environmental impact categories use the following environmental indicators:

- Non-renewable Primary Energy Demand (PED non-renewable)
- Renewable Primary Energy Demand (PED renewable).

Should: The following impact categories could be used additionally

- Ozone Depletion Potential (ODP)
- Human-Toxicity Potential (HTP)
- Respiratory inorganics
- Ionising radiation
- Eco-Toxicity (freshwater, marine, terrestrial) Potential
- Land use
- Resource depletion
- Water footprint.

Shall: For the results of the LCA study on hydrogen production, the following key figures shall be prepared:

- GWP per MJ H_2 (e.g. **XX** kg CO_2 eq. / 1 MJ H_2 @ **YY** bar, **ZZ** °C)
- AP per MJ H_2 (e.g. **XX** kg SO_2 eq. / 1 MJ H_2 @ **YY** bar, **ZZ** °C)
- EP per MJ H_2 (e.g. **XX** kg PO_4^- eq. / 1 MJ H_2 @ **YY** bar, **ZZ** °C)
- POCP per MJ H_2 (e.g. **XX** kg C_2H_4 eq. / 1 MJ H_2 @ **YY** bar, **ZZ** °C)
- PED (non-renewable) per MJ H_2 (e.g. **XX** MJ PED / 1 MJ H_2 @ **YY** bar, **ZZ** °C)
- PED (renewable) per MJ H_2 (e.g. **XX** MJ PED / 1 MJ H_2 @ **YY** bar, **ZZ** °C).

The LCIA methods to be applied shall be defined when the LCA study is being scoped. Different Life Cycle Impact Assessment methods exist which are either midpoint or endpoint oriented. These include CML, ReCiPe, LIME and IMPACT 2002+ etc.. These methods are presently under evaluation by the JRC-IES, through the European Platform on LCA. A guidance document is being developed which will provide recommendations on methods that should be used. [8]

In general terms, the following criteria have been defined for selecting the LCIA methods:

- The scientific robustness, which also takes into account the level of uncertainty
- The development that has occurred over time
- The method's application in LCA practice
- The European environmental policy goals.

In order to guarantee the comparability among the LCA studies on hydrogen production systems, it is necessary to define one impact assessment method for the impact categories selected. It is recommended that the latest development of the midpoint CML method (CML 2011) has to be applied. This recommendation is based on the following pragmatic reasons, and not because the method is considered to be inherently superior:

- It adequately meets the criteria described above
- It is implemented in most (if not all) the LCA software available
- It has been widely used for the last 20 years.

Provisions 19: Choice of impact assessment methods

Shall: Select the appropriate impact method based on the following:

1. Select the relevant environmental impact categories from the ILCD Handbook "Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment" available at http://lct.jrc.ec.europa.eu/. (currently in draft version).
2. Use the CML impact methods (CML 2011) if no other method is considered more appropriate.

Note: Until the "Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment" is published, use the CML impact method (CML 2011).

[8] A comprehensive list of Life Cycle Assessment methods is given in the document "Recommendations based on existing environmental impact assessment models and factors for Life Cycle Assessment", available in a draft version at http://lct.jrc.ec.europa.eu/.

6.5. Type, quality and sources of required data and information

The quality of the data determines the quality of the whole study.

In general there are two types of data used in a LCA study. Primary inventory data is recommended to be used for the main processes, i.e. input and output data of an H_2 production system. Examples of these would be amount of energy consumed and amount of hydrogen produced.

Secondary data will also be needed e.g. the inventory of the electricity consumed in the production of an intermediate material.

The data have to be representative for regular operation of the process(es). For example, if unusually frequent start-up and shut-down of the production unit due to the development stage of the technology are included in the operation data, it might lead to non-representative energy consumption figures. In any case, the origin of the data used must be fully documented so that the representativeness of the data can be assessed. For example is it measured or calculated data? If they were measured, over which period of time were they measured? It also has to be clarified if the data are representative for a small scale prototype or a large scale production facility. In some cases seasonal or geographical influences e.g. cryogenic transport of hydrogen in summer/winter or in hot/cold climate, might need to be considered.

Provisions 20: Type, quality and sources of data and information

Shall: Data used and information detailed must take into account the following points:

- Include all inputs and outputs to and from the foreground system to other technical systems
- Take into account all resources from nature and emissions to nature of the foreground and background system. Exceptions are allowed in accordance with the cut-off criteria (section 6.3.3)
- Use data reflecting the technology actually used and in the region where the process occurs
- Describe the closing of data gaps using comparable data in the LCA report.

6.6. Data quality requirements

Data quality requirements consist of Technological representativeness (TeR), Geographical representativeness (GR), Time-related representativeness (TiR), Completeness (C), Precision / uncertainty (P), Methodological appropriateness and consistency (M) (JRC 2010a).

In terms of hydrogen production, the data quality refers to how the data are measured. It is recommended that a long term measurement is undertaken. If this is not possible, it is recommended to measure the same value several times and calculate an average. If the measured data are averaged it has to be stated how often they were measured and how precise the measurements are. This will include stating if all the measured values were close to each other, if not, how wide the deviation is. These aspects have to be considered when planning the data collection (section 7.2). Data quality assessment has to focus on primary data and - for the overall LCA results - relevant secondary data.

Especially for secondary energy data, EU-27 mix data (average data) has to be used. The inventory data for the supply of 1 kWh of grid electricity can vary a lot from country to country depending on the electricity grid (energy carriers used) and in addition on the power plant technology (direct/combined heat and power (CHP), efficiency, applied flue cleaning technologies etc.). For instance, a country with a high share of hydropower has generally less harmful emissions than a country with coal based electricity generation. These differences can result in totally different results when assessing the same electrolyser. For the sake of comparability among studies using this guide, the EU-27 mix is mandatory for secondary data. In addition to the EU-27 electricity grid mix, further mixes, e.g. national grid mixes or energy specific electricity generation data sets, such as electricity from hydro power, may be used.

Since other energy carrier mixes, such as natural gas, also vary from country to country, EU-27 mixes also have to be used here.

Provisions 21: Data quality requirements

Shall: Define the data quality requirements according to the goal and scope of the study

Shall: If the study is intended to be used in comparative assertions to be disclosed to the public, apply all the quality requirements listed in clause 4.2.3.6.2 of ISO 14044

Shall: Use primary data for the foreground system

Shall: Use the European mixes (EU-27) for electricity, natural gas and other energy carriers

Should: In addition to the EU-27 mixes, specific mixes (country, company etc.) regarding electricity, natural gas and other energy carriers can be used, but not as an alternative to the EU-27 mixes.

Should: Secondary data, e.g. production of materials should reflect the European average (see section 7.3 for more details)

Should: Use primary data for the related infrastructure (if the infrastructure is assessed)

Semi-quantitative data quality indicators from the ILCD Handbook

When LCI data sets resulting from the LCA study are produced and they have to be made available to the ILCD Data Network, further requirements on data quality have to be fulfilled (JRC 2010a). The following data quality indicators, described in Table 3, have to be used: Technological representativeness (TeR), Geographical representativeness (GR), Time-related representativeness (TiR), Completeness (C), Precision / uncertainty (P), Methodological appropriateness and consistency (M).

For ILCD compliance it is mandatory to use a semi-quantitative formula to calculate a “Data Quality Rating (DQR)” based on the above mentioned data quality indicators. The following section regarding the DQR calculation was taken from the ILCD Handbook, section 12.3 data quality indicators” page 329 to 333 (JRC 2010a).

Data quality indicators (taken from the ILCD Handbook)

The ILCD data quality indicators relate directly to those key characteristics of LCI data sets that describe their quality[9]. These are:

- Technological, geographical and time-related representativeness,
- Completeness of environmental impacts covered by the inventory,
- Achieved precision of the data, and
- Appropriate and consistent application of LCI methodologies (the latter especially on the system level)

Table 3 describes the concept of the ILCD data quality indicators / components in more detail.

Table 3: Overall inventory data quality (validity) and its main 6 aspects

Indicator / component	Definition / Comment
Technological representativeness (TeR)	"Degree to which the data set reflects the true population of interest regarding technology, including for included secondary data sets, if any." Comment: i.e. of the technological characteristics including operating conditions.
Geographical representativeness (GR)	"Degree to which the data set reflects the true population of interest regarding geography, including for included secondary data sets, if any." Comment: i.e. of the given location / site, region, country, market, continent, etc.

[9] This is a different approach compared with generic quality indicators that attempt to capture data quality by proxy-indicators such as type of used, and data sources that are used to estimate the quality by overlaying an uncertainty factor to each proxy-indicator (e.g. age of data). The approach chosen here better reflects the case-specific relevance of the aspects: e.g. are data that are four years old may be fully representative for technologies that change slowly with time (e.g. basic materials industry), while they would be quite out-dated for most IT products.

Time-related representativeness (TiR)	"Degree to which the data set reflects the true population of interest regarding time / age of the data, including for included secondary data sets, if any." Comment: i.e. of the given year (and - if applicable – of intra-annual or intra-daily differences).
Completeness (C)	"Share of (elementary) flows that are quantitatively included in the inventory. Note that for product and waste flows this need to be judged on a system's level." Comment: i.e. degree of coverage of overall environmental impact i.e. used cut-off criteria.
Precision / uncertainty (P)	"Measure of the variability of the data values for each data expressed (e.g. low variance = high precision). Note that for product and waste flows this needs to be judged on a system's level." Comment: i.e. variance of single data values and unit process inventories.
Methodological appropriateness and consistency (M)	"The applied LCI methods and methodological choices (e.g. allocation, substitution, etc.) are in line with the goal and scope of the data set, especially its intended applications and decision support context. The methods also have been consistently applied across all data including for included processes, if any." Comment: i.e. correct and consistent application of the recommended LCI modelling framework and LCI method approaches for the given Situation A, B, or C.

It should be noted that the components “Completeness” and “Precision” can be quantified (e.g. “90 % completeness/cut-off criterion for overall environmental impact” and “+-10 % LCIA results for Climate change[10], +-20 % for Acidification, etc.”).

However the other components are of a qualitative nature, and the quality achieved is to be judged semi-quantitatively by experts e.g. during a critical review.

[10] This percentage refers to the stochastic uncertainty of the inventory values only, excluding the uncertainty of the LCIA characterisation factors.

The following quality levels of Table 6 and definitions of Table 4 should be used for documenting what has been achieved for the final data and for each of the data quality indicators:

Table 4: Quality levels and quality rating for the data quality indicators, and the corresponding definition (for the three representativeness and the methodological appropriateness and consistency criteria) and quantitative completeness and precision / uncertainty ranges in %.

Quality level	Quality rating	Definition	Completeness overall environmental impact	Precision / uncertainty overall env. impact (relative standard deviation in %)[11]
Very good	1	"Meets the criterion to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality."	≥ 95 %	≤ 7 %
Good	2	"Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality."	[85 % to 95 %)	(7 % to 10 %]
Fair	3	"Meets the criterion to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality. "	[75 % to 85 %)	(10 % to 15 %]
Poor	4	"Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality."	[50 % to 75 %)	(15 % to 25 %]

[11] This does exclude the uncertainty of the LCIA method, the normalisation basis, and the weighting set, but only of the LCI results, however in view of the overall environmental impact. For log-normally distributed results, the confidence intervals shall be used that are obtained with the percentages given in the table and under normal distribution.

Very poor	5	"Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality."	< 50 %	> 25 %
Additional options, not being quality levels:				
Not evaluated / unknown	5	"This criterion was not judged / reviewed or its quality could not be verified / is unknown."	n/a	n/a
Not applicable	0	"This criterion is not applicable to this data set, e.g. its geographical representativeness cannot be evaluated as it is a location-unspecific technology unit process."	n/a	n/a

By this way of classifying the achieved overall quality and its components of the developed e.g. unit process or LCI result data set, a structured communication and identification (e.g. sorting/filtering of suitable data e.g. in the ILCD Data Network) is supported.

Overall data quality and three data quality levels for LCI data sets In addition to the more differentiated quality levels, for orientation it is useful to label data sets with different levels of overall LCI data quality. The overall quality of the data set can be derived from the quality rating of the various quality indicators / components. As said earlier, the weakest of the quality indicators generally weakens the overall quality of the data set.

The overall data quality has to be calculated by summing up the achieved quality rating for each of the quality components. The rating of the weakest quality level is counted 5-fold. The sum is divided by the number of applicable quality components plus 4. The Data Quality Rating result is used to identify the corresponding quality level in Table 5. Figure 12 provides the calculation provision:

$$DQR = \frac{TeR + GR + TiR + C + P + M + X_w * 4}{i + 4}$$

Figure 12: Semi-quantitative formula for data-quality assessment

- DQR : Data Quality Rating of the LCI data set; see Table 5
- TeR, GR, TiR, C, P, M : see Table 3
- Xw : weakest quality level obtained (i.e. highest numeric value) among the data quality indicators
- i : number of applicable (i.e. not equal "0") data quality indicators.

Table 5: Overall quality level of data set according to the achieved overall data quality rating

Overall data quality rating (DQR)	Overall data quality level
≤1.6[12]	"High quality"
>1.6 to ≤3	"Basic quality"
>3 to ≤4	"Data estimate"

Accuracy, precision and completeness of LCI data, LCIA results and LCA studies

Accuracy, precision and completeness of LCI data should be assessed on the system level. This in addition needs to be done in view of the respective LCIA results, per impact category, but disregarding the (additional) uncertainties and limited accuracy of the characterisation factors (and any eventually applied normalisation and weighting factors) as the focus here is on the requirements to the inventory data.

Entry-level requirements exist and can be applied during the first few years of building up the ILCD Data Network. These are simplified/less demanding compared to full ILCD-compliance. The reader shall refer to the document "Compliance rules and entry-level requirements" (available at http://lca.jrc.ec.europa.eu/lcainfohub/datasets/html/external_docs/ILCD-Data-Network-Compliance-Entry-level-Version1-March2010.pdf) for details.

6.7. Comparisons between systems

LCA can also be used to compare between systems. The ISO standards are fully applicable, but some additional aspects have to be considered.

In the case of hydrogen production, the application might be comparisons between different hydrogen production systems. All systems under investigation have to be evaluated in the same way for the comparison to be valid. This means e.g. that the reference flow has to be similar. It is not valid to compare two systems where one delivers hydrogen at 99.999 % purity and one at 96 % purity, as the function is different.

Comparative studies are aimed at evaluating the superiority, inferiority or equality of the compared alternatives. In the comparison among different types of hydrogen production systems, some limitations due to scale factors and to differences in the operational conditions (e.g. fuel used) have to be considered.

For these reasons, the following aspects have to be taken into consideration:

- The equivalence of the functional unit of compared alternatives

[12] This means that not all quality indicator need to be "very good", but two can be only "good". If more than two are only good, the data set is downgraded to the next quality class.

If some of the aspects of the reference flow differ between the systems, it has to be ensured that the functions are still seen as sufficiently comparable by the main stakeholders affected by the LCA study and the product users

- The selection of the compared alternatives
  In selecting alternatives, existing or widely used alternatives that may perform environmentally better than the compared ones must not be left out
- Durability
  The technical life-time of the alternatives must be considered.
- Methodological assumptions and data consistency
  Consistency has to be assured in functional unit and reference flow definition, selection of system boundary, requirements on data (technological, temporal, geographic representativeness), allocation principles, and LCIA methods).

Provisions 22: Comparison of different systems

Shall: If different systems are compared, the definitions made in the scope phase have to be addressed consistently:

- The LCI model shall be constructed analogously using the same rules for system boundary, LCI modelling principles and methodological approaches
- Methodological and data assumptions shall be analogously
- Completeness, accuracy and precision of the data (data quality aspects) shall be sufficiently similar.

Shall: If different systems are compared, harmonise the following aspects:

- Comparisons between systems shall be made on the basis of the same function(s), quantified by the same functional unit(s) in the form of their reference flows
- Uncertainty calculations shall be made either as best/worst case scenario or as stochastic uncertainty and accuracy calculation
- The cut-off shall be the same for mass and energy, additionally to the overall environmental impact
- Identical parts can be excluded of all models, similar but not identical parts shall remain in the model
- A LCIA shall be performed
- A critical review shall be undertaken (section 6.8).

6.8. Identification of critical review needs

The critical review is defined as a "process intended to ensure consistency between a Life Cycle Assessment and the principles and requirements of the International Standards on Life Cycle Assessment" (ISO 2006a). This definition means that the LCA is cross checked by a third party (independent external expert) guaranteeing consistent and reliable results. An independent external critical review panel has to be undertaken in order to meet ISO standards if the hydrogen study compares systems and the results will be disclosed to the public. LCA studies for internal use only do not require a critical review but it is recommended. Hence, whether a critical review is necessary or not depends on the items defined in the goal and scope phases:

- The intended application and decision-context
- The reason for carrying out the study
- The intended target audience (internal or external, technical or non-technical).

The type of critical review is also determined by whether a study is performing a comparative assertion or not. Comparative assertion is defined as an: "environmental claim regarding the superiority or equivalence of one product versus a competing product that performs the same function" (ISO 2006a). In the case of hydrogen production systems a comparative assertion would be comparing two or more different hydrogen production technologies and stating an explicit recommendation afterwards. If such a comparative study is conducted a review panel is necessary to undertake the critical review.

It is useful to make the decision to have external review at an early state of the study, to ensure that single steps in the study such as data collection, documentation or reporting correspond with the requirements of the review.

A concurrent independent critical review process of the study can be performed. The concurrent review allows the reviewer to comment on the project from the beginning, which could avoid mistakes at an early stage and possibly additional work at the end of the project. A concurrent review also improves the credibility of a study.

More details on critical review and its procedure can be found in section 11.

Provisions 23: Identification of critical review needs

Shall: A critical review by an independent reviewer is necessary if the study is intended to be disclosed to the public.

Shall: A critical review by an independent review panel is necessary if the study is comparative and intended to be disclosed to the public.

Shall: The panel shall consist of an independent expert acting as a chairperson and at least two other independent experts, selected by the chairperson.

Shall: For comparative studies, open invitations shall be extended to additional interested parties to be involved in the review process (e.g. governmental agencies, non-governmental organisations or affected industries).

Shall: The opinion of these “additional interested parties” is to be considered in the review and be included in the review report.

Shall: Assure the independence, qualifications and experience of the reviewers. The reviewer(s) shall be experienced in LCA methodology, verification and audit practice and shall have technical expertise related to the hydrogen production system under analysis.

Should: For internal studies a critical review is not mandatory, but recommended.

Should: For reviewer qualification, refer to the document “Reviewer qualification for Life Cycle Inventory data sets” (JRC 2010c).

6.9. Intended reporting

Reporting is the step of the LCA in which the results, data, methods, assumptions and limitations have to be reported completely and accurately and without bias. Moreover, they are to be presented in sufficient detail to ensure reproducibility of the results and to provide the required information to reviewers to judge the quality of the results and appropriateness of conclusions and recommendations.

The report has to be adjusted depending on the intended application and audience of the report, such as companies, trade associations, government agencies, environmental groups, scientific/technical communities, and other non-governmental organisations, as well as the general public / consumers. Three levels of reporting exist, depending on the final purpose of the study:

- For internal use

- Third party use (i.e. an interested party other than the commissioner or the LCA practitioner performing the study)
- Report on comparative studies to be disclosed to the public.

The third party report is likely to be the most commonly undertaken as it documents the results in an appropriate and clear manner.

Provisions 24: Intended Reporting

Shall: Decide which form of reporting shall be used:

- Detailed report
- Data set
- Data set plus detailed report
- Non-technical executive summary.

Shall: Decide which level of reporting shall be used:

- Internal
- External (but limited, well defined recipients)
- Third-party report, publicly accessible
- Report on comparisons, publicly accessible.

Shall: Documentation of the methods, assumptions and data sources used shall be sufficiently to enable a LCA practitioner to reproduce any conclusions or recommendations drawn.

Should: It is recommended that the third party report should document the results in an appropriate and clear manner. Even though this level of reporting does not require the inclusion of confidential information, this information has to be made available for reviewers, but as a separate document under a confidentiality agreement.

7. Life Cycle Inventory analysis of the study on hydrogen production

After the goal and scope definition, the next main phase within the LCA is the Life Cycle Inventory (LCI) analysis. It is defined as the "phase of Life Cycle Assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle" (ISO 2006a). This definition means that the data collection, the data processing and modelling is done during the LCI.

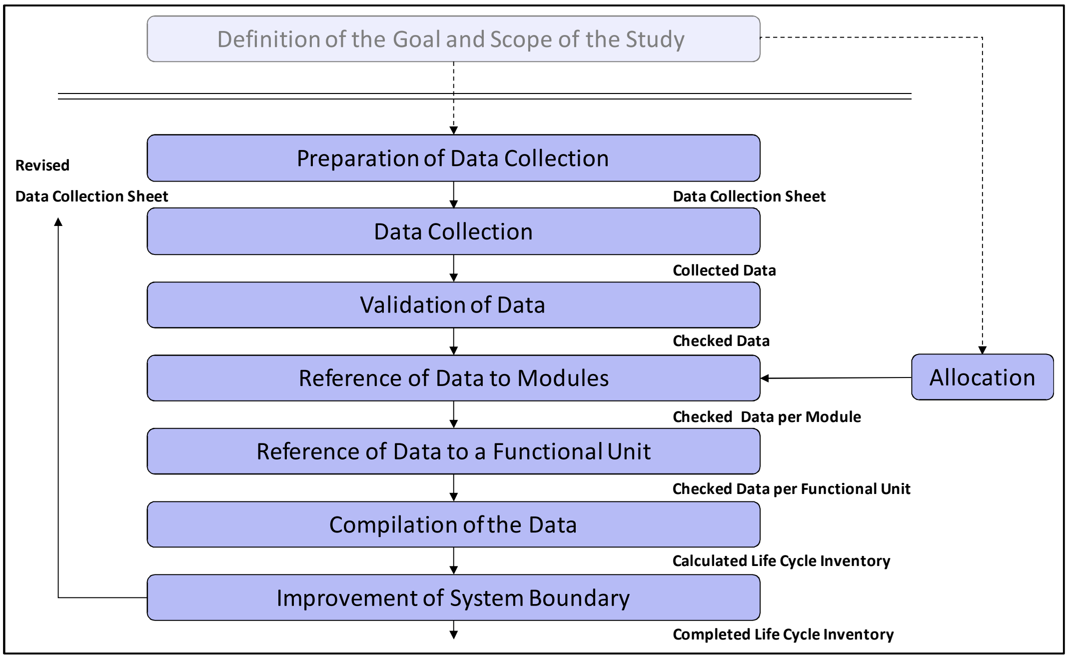

Figure 13: Simplified procedures for inventory analysis (ISO 2006b) (modified)

Figure 13 shows the steps for inventory analysis according to the ISO 14044. Data collection is planned after the definition of goal and scope (section 5 and 6).

The first step is to define which data are needed. The next step is validating the data with e.g. existing secondary data. As a preliminary step for the modelling, the data are processed by referencing them to the functional unit. A model is created using these processed data. This is commonly completed using LCA software systems. A detailed list of the available software can be found in the LCA directory of the European Platform of LCA (http://lct.jrc.ec.europa.eu/). The software system compiles the Life Cycle Inventory based on the data entered. The LCI might be calculated several times following refinements of the data and the LCI model itself, reflecting the iterative nature of LCA.

The Life Cycle Inventory analysis comprises several procedural steps and methodological aspects which are described below. These steps are the definition of the system boundary, the handling of multi-functional processes, the data collection and the modelling.

7.1. Identifying processes within the system boundary

If the LCA study evaluates a system that consists of more than one single process, quantitatively relevant processes within the system boundary have to be included. To identify all of the processes, start with the core/ main process and then identify all processes connected (described in technical terms) to the core process. For hydrogen production, the core process is the hydrogen production process itself.

In the next step all processes connected to the hydrogen production process have to be identified. This can be processes such as natural gas for steam reforming, or electricity to run a water purifier within the electrolysis product system. The best approach is to cover the whole supply chain of the system under investigation.

Provisions 25: Identifying processes within the system boundary

Shall: The following things shall be undertaken for identifying processes:

- Always identify processes using electricity, fossil and/or renewable resources
- Define which foreground and background processes are taken into account in the LCA
- Identify the foreground processes following supply chain logic. For the hydrogen production system they include e.g. production of energy carriers
- Include the important upstream processes such as raw material extraction.

Should: The related infrastructure may be included in line with the cut-off criteria (section 6.3.3). It is recommended to use existing secondary data e.g. from ELCD, which comprises complete upstream processes (including their infrastructure) for instance energy carrier supply

7.2. Planning data collection

Data collection is a very important step within the LCA. The quality of the data determines the quality of the whole study. Therefore the data collection must be done with care and precision. It can be time consuming and resource intensive to assure the data quality. It is strongly recommended to establish a data collection system as a set of procedures as laid out in the provisions at the end of this section (Weidema 2003).

As stated in section 6.5, there are two types of data used in a LCA study. Primary inventory data is recommended to be used for the main processes and secondary (average) data for the background system. Data collection issues mainly concern the foreground system, since this is the core part of the study under investigation. It is recommended that the data collected cover the regular operation of the facility, which means that it has to be representative of normal operation.

If possible the operating data measured cover one year of operation to maximise the chance of any irregularities being averaged. Data covering a shorter period of time may also be used if considered representative for regular operations. If limited or no measured data are available, design data may also be used.

It is important that the origin of, and time period covered by the data are documented in the report. The parts of the facility which have been included during the measurement must also be documented. Generally, everything directly related to the hydrogen production must be included. For example, with an electrolyser not only the stack is to be taken into account, but also the supporting components such as the rectifier converter AC/DC, membranes and electrodes. Again, all parts that were included must be mentioned in the report.

The data are to be measured separately for every unit process. If not, subdivision is recommended, by splitting the black box process into several processes. If some process steps are metered together, virtual subdivision is suggested. Virtual subdivision means to use the nominal power as an allocation factor. This virtual subdivision and hence separation of the unit processes is helpful for indicating significant issues in the results. If possible all data measured are to be referenced to the same circumstances. An example of data referencing is that the demand (e.g. electricity, auxiliaries) and the hydrogen produced is supposed to be measured at the same production unit, within the same period of time. If this measure is taken, there is no need for extra data processing.

If the circumstances are not the same, the data for the modelling has to be calculated. However, this increases the uncertainty. For example if the H_2 production is measured over one year and the auxiliary demand is only for 6 months then the measured figures have to be converted into the annual demand. If such conversions are done they have to be mentioned in the report.

A data reporting template has been prepared to provide better guidance to the workflow. This template is available in Annex I.

No specific requirements apply for hydrogen production systems for the collection, documentation and inventory of data related to emissions and resources (e.g. how to inventory future long term emissions, whether or not inventorying sum indicators like AOX or COD),. Thus, for full ILCD-compliance, the provisions listed in the ILCD Handbook, sections 7.4.3 to 7.4.5 have to be applied, together with those on "Nomenclature and other conventions", given in the respective separate guidance (JRC 2010f).

Provisions 26: Important factors regarding the data collection

Shall: The data collection shall be done considering the following factors:

- One start-up and shut-down sequence should be included
- Regular maintenance shall be included
- Auxiliaries such as pressurised air, etc. shall be included
- If seasonal influences exist they shall be included (either measured or estimated) and balanced out
- The period measured shall be long enough to cover business as usual operations without irregularities.

Shall: Collect site specific primary data regarding the hydrogen production system valid for the reference year or the reference period.

Shall: The European mix (e.g. EU-27) shall be used for energy carriers (electricity and fossil fuels e.g. natural gas).

Should: In addition to the above mentioned European mixes for energy carriers, region/country specific data can be used.

Should: Secondary data may be site specific if available. Data on the production of materials should reflect the geographical region from where they are acquired.

Shall: State the time (or time period) primary data were measured. In case of calculation or estimation, the time (or time period) of the data to which the assumptions refer have to be stated as well. As most of the secondary data available are only valid for a certain time period, the reference year of the data used, and therefore the time-representativeness, has to be documented and shall be suitable for the study.

Shall: Document data which are not attributable to regular operations.

Should: Establish a data collection system:

1. Identification of the data that need to be collected
2. Planning when, where, and how data are to be collected and by whom
3. Identification and treatment of data gaps
4. The actual data collection (measurement or retrieval from book, experience, expert, etc.)
5. Documentation of the resulting data, together with possible sources of error, bias or lack of knowledge
6. Validation of the data collection system, the data collected and their documentation
7. Communication of the data and their documentation.

7.3. Selection of secondary Life Cycle Inventory data

Aside from the primary inventory data as described in the sections above, secondary data are needed for items such as energy carriers consumed or auxiliary materials such as nitrogen, to enable the LCA studies to be relevant to normal business. These secondary data can usually be taken from existing (often established and differently reviewed) databases (section 6.5). For example data for electricity supply are usually taken from the national/regional grid. In this way a secondary data set which covers the country/regional specific average (e.g. EU-27) on electricity generation, distribution and transmission losses can be used to improve time-efficiency.

Depending on the power plant technology (direct/combined heat and power (CHP), efficiency, applied flue cleaning technologies etc.) and the energy carriers used, the inventory data for the supply of 1 kWh of grid electricity can vary a lot from country to country. For example a country with a high share of hydropower has generally less harmful emissions than a country with coal based power generation. Due to this difference using different power grid mixes for assessing the same electrolyser can produce totally different results. For the sake of comparability among studies using this guide, the EU-27 electricity mix is mandatory.

In the same way other secondary data can be applied for a variety of processes and materials that are frequently used. Depending on the technology assessed, these data could be the fossil fuel supply, electricity, thermal energy supply, auxiliary materials, catalyst material or transport processes etc.

Criteria for selecting process data

The processes selected have to be appropriate for their application as processes are usually designed for a certain application. For example a process covering a small delivery truck below 7.5 t, is not representative for the carriage of heavy goods. Another example is electricity supply where the voltage level has an impact on transmission/transformation losses. The lower the voltage levels the higher the losses.

Provisions 27: Selection of secondary data

Shall: Consider the following criteria for selecting secondary data:

- The data shall be representative for the applied technology, and for geographical and temporal coverage
- The data supplier and the quality of the secondary data shall be known
- The data shall be modelled consistently i.e. the processes used shall be modelled using the same methodology and the same system boundary for similar processes
- The secondary data shall be consistent with the primary data collected.

List of databases

There are multiple databases available that offer Life Cycle Inventory data with varying coverage and quality.

It is mandatory to use already existing secondary data sets from the European Reference Life Cycle Database (ELCD) or from the data network of the International Reference Life Cycle Data System (ILCD) as the first choice (JRC 2010d), (JRC 2010e). Data sets from these databases comprise complete LCI results, also known as secondary processes (e.g. "EU-27 natural gas, at consumer" or "EU-27 electricity grid mix, at consumer, 230V"). If data are not available from these two sources, high quality data sets from consistent databases using the ILCD format are recommended. A detailed list of the available databases can be found in the LCA directory on the European Platform of LCA (http://lct.jrc.ec.europa.eu/).

Provisions 28: Choice of databases for secondary data

Shall: Use the following database for secondary data:

1. The European Reference Life Cycle Database (ELCD)

If there are no applicable data available in this Database, data sets shall be selected from the following sources in the order 2, 3, 4, 5:

2. ILCD compliant data sets, e.g. from the International Reference Life Cycle Data Network
3. ILCD entry level data sets, e.g. from the International Reference Life Cycle Data Network
4. Databases using the ILCD format (databases are listed under the webpage: http://lca.jrc.ec.europa.eu/lcainfohub/databaseList.vm).
5. If the data needed are not available in databases using ILCD format, the following sources can be used: other LCA databases than those listed above; recipes and formulations; patents; stoichiometric models; legal limits; data of similar processes, etc., but the data has to at least fulfil the ILCD flow nomenclature and conventions.

Shall: In case of comparative assertions to be disclosed to the public, the choice of databases used in the two studies shall be consistent. Any deviation shall be documented.

Dealing with data gaps

A suitable data set may not exist in any of the above mentioned databases. In this case it is recommended a literature search is undertaken to fill the data gap(s).

Other options are available if it is not possible to carry out a literature search due to factors such as time restrictions. One option is to use secondary data similar to the data set needed. If, for instance, a data set for a certain alloy is not available, than a data set for a similar alloy might be used even though they have a slightly different material composition.

Another option for dealing with data gaps is to ask the manufacturers or technical experts/process operators directly for information.

Provisions 29: Filling data gaps

Shall: If data gaps arise, state in the report how they are filled.

Shall: Check the relevancy of initially missing data in the following way and, if possible, relevant gaps shall be filled as detailed below:

- **Should:** Identify relevance of initially missing data by using conservative estimation in a first screening
- **Should:** Dealing with relevant initially missing data if the screening shows relevance, focus on try to get better data
- **Shall:** Filling data gaps with estimates of defined and minimum quality. Documentation should be done in a transparent and consistent way. Data gaps shall generally be filled with methodologically consistent data. Only data that increases the overall quality of the final inventory of the analysed system shall be used to fill data gaps.

Shall: If data estimates cannot be made available that would meet above requirements, the data gaps shall be kept and documented on missing quality instead:

Should: Use the following methods for filling data gaps:

- Literature research
- Secondary data that are similar regarding the environmental profile
- Information gained from manufacturers
- Information gained from technical experts or process operators.

7.4. Dealing with multi-functional processes

As mentioned in section 6.2.1 there is a hierarchy on how to deal with multi-functionality. Subdivision is the first choice if possible. If not the system expansion method has to be chosen. The third choice is the allocation method.

The flow chart of the processes under investigation (section 7.1) can be used to identify possibilities of dealing with multi-functionality.

Sub-division is in most cases not applicable for the hydrogen production systems. If steam or heat is used by external processes, system expansion has to be used. In the case that these two methodological approaches are not applicable, allocation is to be applied. The allocation factor has to be applied in the following order: energy content, mass, market value.

Provisions 30: Hierarchy for solving multi-functionality

Shall: Use the following hierarchy for multi-functional processes:

1. Sub-division (e.g. production unit that can be split into several separated production routes)
2. System expansion (e.g. steam reforming, if heat is technically used, system expansion can be applied by giving credit for the heat produced by another suitable (using the same fuel) heat production process)
3. Allocation (e.g. chlorine-alkali electrolysis).

Shall: If allocation is used the following hierarchy of allocation factors shall be used:

a. Physical relationships between the products
    i. Energy (net calorific value)
    ii. Mass
b. Other relationships
    i. Market value.

7.5. Consideration of re-use, recycling, and energy recovery

As hydrogen is an energy carrier, re-use and recycling is not a topic to be addressed explicitly since it is of minor relevance. Energy recovery must be taken into account during the use phase of hydrogen, which is not considered in this guidance document on hydrogen production systems. If the infrastructure is included in the system boundary (section 6.3) then the re-use and recycling of the infrastructure materials, e.g. steel, stainless steel, may be taken into account.

7.6. Calculation of Life Cycle Inventory results

It is currently common practice to conduct a LCA with professional LCA software systems. Using these software systems facilitates faster and easier modelling of a product system. The software system will commonly also provide a very clear and comprehensive graphical display of real-life systems. The model can closely reflect the structure of the real system (Figure 10) and provide an overview of systems which can include hundreds, and even thousands of processes. Furthermore, using an appropriate LCA software system reduces errors done by manual data handling.

Being able to create hierarchical models allows the reproduction of complex systems and allows the practitioner to keep track of the complete process chain in an unambiguously documented manner. It also eases the work flow for the Life Cycle Inventory and Life Cycle Impact Assessment analysis of the system, as the results are given according to the model structure i.e. the contribution of different parts of the system is presented according to the pre-defined model structure.

Software functionality also commonly enables modelling of physical process chains using a Sankey diagram editor, parameterised modelling, advanced LCI results analysis (including significant issue analysis) and comprehensive analysis functions such as parameter variation, scenario analysis, sensitivity analysis and Monte-Carlo analysis. For details regarding the usage of different software solutions, contact the individual publishers of the software.

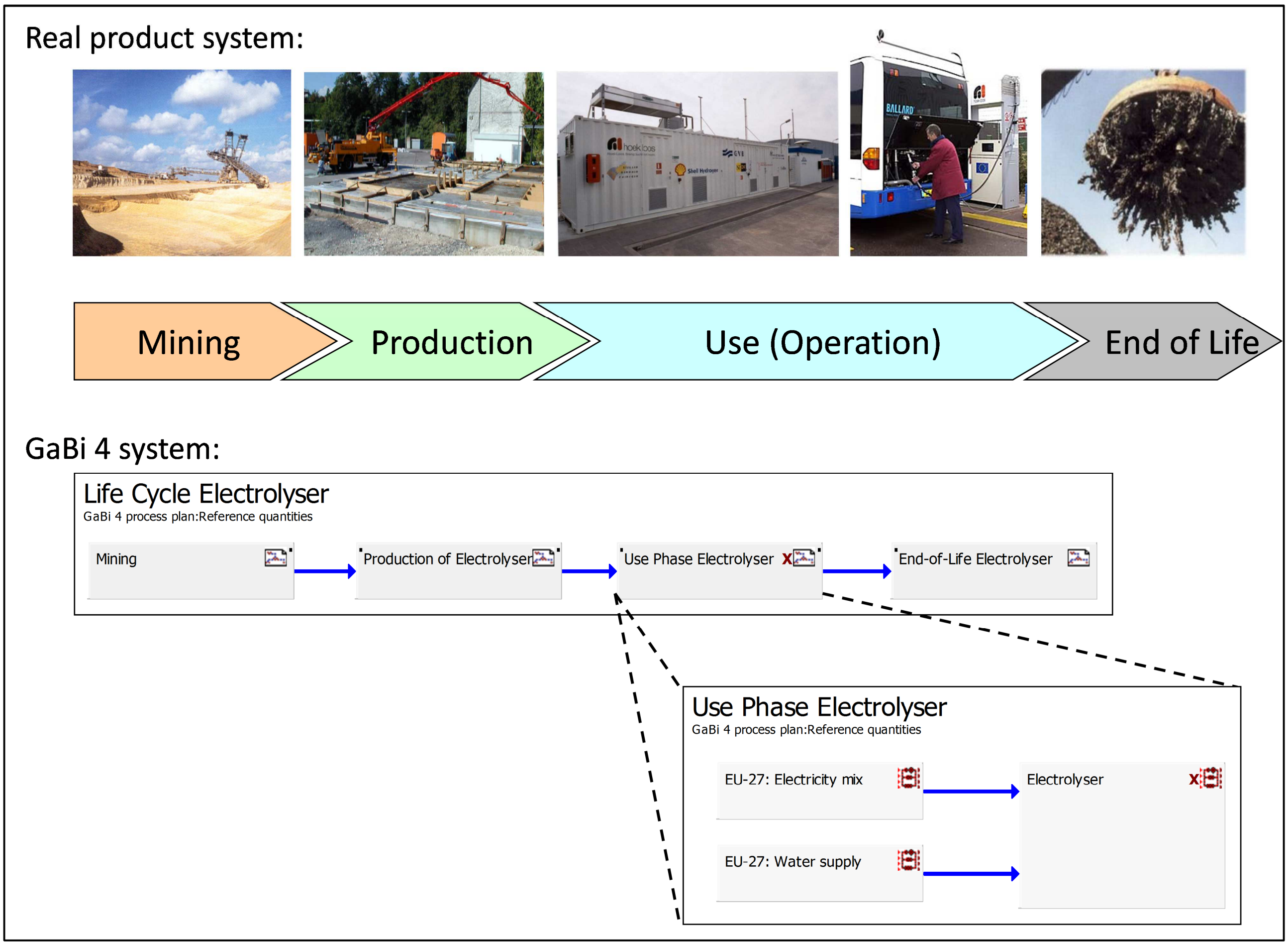

Figure 14: Hierarchical system for real-life modelling in the GaBi software system (LBP, PE 1992-2011) (modified)

Provisions 31: Calculation of LCI results

Shall: Determine for each process within the system boundary how much of its reference flow is required for the system to deliver its functional unit and/or reference flow; scale the inventory of each process accordingly.

Shall: Keep track of the inventory that is not aggregated for the identification of significant issues.

Should: Aggregate the scaled inventories of all processes within the system boundary for that system.

8. Life Cycle Impact Assessment of the study on hydrogen production

Life Cycle Impact Assessment (LCIA) forms the fourth phase of LCA. The LCIA aims at “understanding and evaluating the magnitude and significance of the potential environmental impacts” (ISO 2006a). The impact assessment does not involve the LCA practitioner directly, but indirectly through the choice of impact categories. The choice of the impact categories has been addressed in section 6.4. The classification and characterisation methodology is explained in this section as well as the optional elements of LCIA: normalisation, grouping and weighting.

8.1. Classification and characterisation

Classification and characterisation are mandatory elements in the LCIA.

Classification is the assignment of the various emissions into impact categories. Emissions can be assigned to one or more impact category. For example, methane has an impact on global warming as well as on summer smog (Photochemical Ozone Creation Potential). Therefore during the classification the emissions are assigned to both impact categories.

Characterisation means defining how much impact an emission has with regard to a pre-defined reference substance of an impact category. This is carried out after classification. The impact is expressed by means of a characterisation factor.

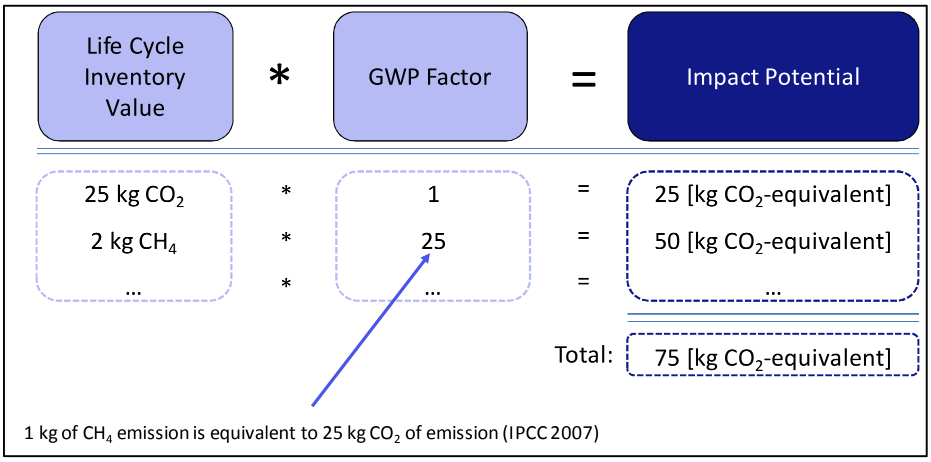

Figure 15: Characterisation of methane

Figure 15 displays an example of the characterisation of methane for GWP according to the IPCC (IPCC 2007). Methane has an environmental impact on GWP that is 25 times higher compared to CO_2. As the GWP is calculated in kg CO_2 equivalents, the characterisation factor of methane is 25.

In this element of the LCIA the practitioner need only to apply the impact assessment method selected in the previous phase (section 6.4). By using an appropriate software system, the impact assessment will be done automatically by multiplying the inventory results by the characterisation factors.

Provisions 32: Classification and Characterisation

Shall: Evaluate the following impact categories previously identified in the scope phase:

- Global warming potential
- Acidification potential
- Eutrophication potential
- Photochemical ozone creation potential.

Shall: When available, use the methods, models and characterisation factors identified in the Guidance document under preparation by the JRC-IES, through the European Platform on LCA. Until this Guidance document is available, use the most up-to-date CML impact assessment methodology. This methodology is implemented in all the major software tools available. If the assessment is performed with spread sheets in Excel, the list of characterisation factors is available at http://cml.leiden.edu/software/data-cmlia.html.

Shall: In addition to these environmental impact categories, use the following environmental indicators:

- Non-renewable Primary Energy Demand (PED non-renewable)
- Renewable Primary Energy Demand (PED renewable)

Should: The following impact categories could be used additionally:

- Ozone Depletion Potential (ODP)
- Human-Toxicity Potential (HTP)
- Respiratory inorganics
- Ionising radiation
- Eco-Toxicity (freshwater, marine, terrestrial) Potential
- Land use
- Resource depletion
- Water footprint.

Should: Do not perform a comparison across the impact categories.

Should: Do not perform a summing up across impact categories.

8.2. Normalisation (optional)

Normalisation means to “calculate the magnitude of category indicator results relative to reference information” (ISO 2006b). It is an optional element of the ISO standard.

As the absolute values of the environmental indicators are of different order of magnitudes, the results may be shown relative to some reference information such as country wide emissions. After normalisation the results can be given relative to the reference e.g. XX % GWP of the reference system, such as EU-27, YY % AP. In this way the results of a hydrogen production system can be compared with the environmental impact indicator of the chosen reference system (e.g. total EU-27 or an individual European member state such as Italy). Normalised environmental impact indicator results can be displayed in one graph. In the case of the determination of the environmental profile of hydrogen production systems, normalisation is not needed.

Provisions 33: Normalisation

Should: Normalisation as an optional element of LCIA is not recommended in the case of hydrogen production systems. However, it may be applied to support the interpretation of the results of the study.

Shall: If normalisation is undertaken, document the decision in the scope definition and report it transparently.

Shall: If normalisation is applied the following points shall be included:

- Show the non-normalised results as well
- Do not aggregate the normalised results
- Different reference systems (e.g. EU-27, DE etc.) have to be used for normalisation.

8.3. Grouping and Weighting (optional)

Grouping is defined as “the assignment of impact categories into one or more sets as predefined in the goal and scope definition, and it may involve sorting and/or ranking” (ISO 2006b). Grouping is an optional element to either sort impact categories on a nominal basis, or rank the impact categories in a given hierarchy (based on value choices).

Weighting is “the process of converting indicator results of different impact categories by using numerical factors based on value-choices” (ISO 2006b). This optional process means that all impact categories are summed up into one figure – a single point.

Weighting steps are based on value-choices and are not scientifically based. Different individuals, organizations and societies may have different preferences; therefore it is possible that different parties will reach different weighting results based on the same indicator results or normalised indicator results. In a LCA it may be desirable to use several different weighting factors and weighting methods, and to conduct sensitivity analysis to assess the consequences on the LCIA results of different value-choices and weighting methods. In comparative studies for release to a third parties or the public, weighting is not permitted.

In the context of this specific guidance document on hydrogen production systems, grouping and weighting is not recommended for environmental evaluations.

Provisions 34: Grouping and weighting

Shall: Do not use grouping and weighting in studies leading to comparative assertions intended to be disclosed to the public.

Shall: If grouping and weighting is undertaken, the following provisions apply:

- Document the decision in the scope definition and report it transparently
- To obtain weighted LCIA results, multiply the (typically normalised) LCIA results by the weighting set. This shall be done separately for each impact category.
- The resulting weighted LCIA results can be summed up across the impact categories
- Show also the non-grouped and weighted results.

Should: The grouping and weighting elements are not recommended in hydrogen production systems.

9. Interpretation and quality control of the study on hydrogen production

The life cycle interpretation phase is defined as the "phase of Life Cycle Assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations" (ISO 2006a). Using this definition the interpretation phase serves several different purposes.

One role of the interpretation phase is to check the results of the LCA. The results of the study are used to critically check the goal and scope definition and, if necessary, to reconsider it as part of the iterative character of LCA. For example, the completeness check of the LCA might reveal that some environmental profiles have not been taken into account. The goal and scope definition would therefore need to be reconsidered or the profiles would need to be completed. If the goal and scope definition had to be reconsidered this has to be stated in the section about limitations (section 5.2).

There is also a risk of inappropriately claiming comparability of alternatives, such as when comparing hydrogen production system producing hydrogen with different purities. A good practice to avoid these mistakes is to state the reasons for the differences together with the results and recommendations.

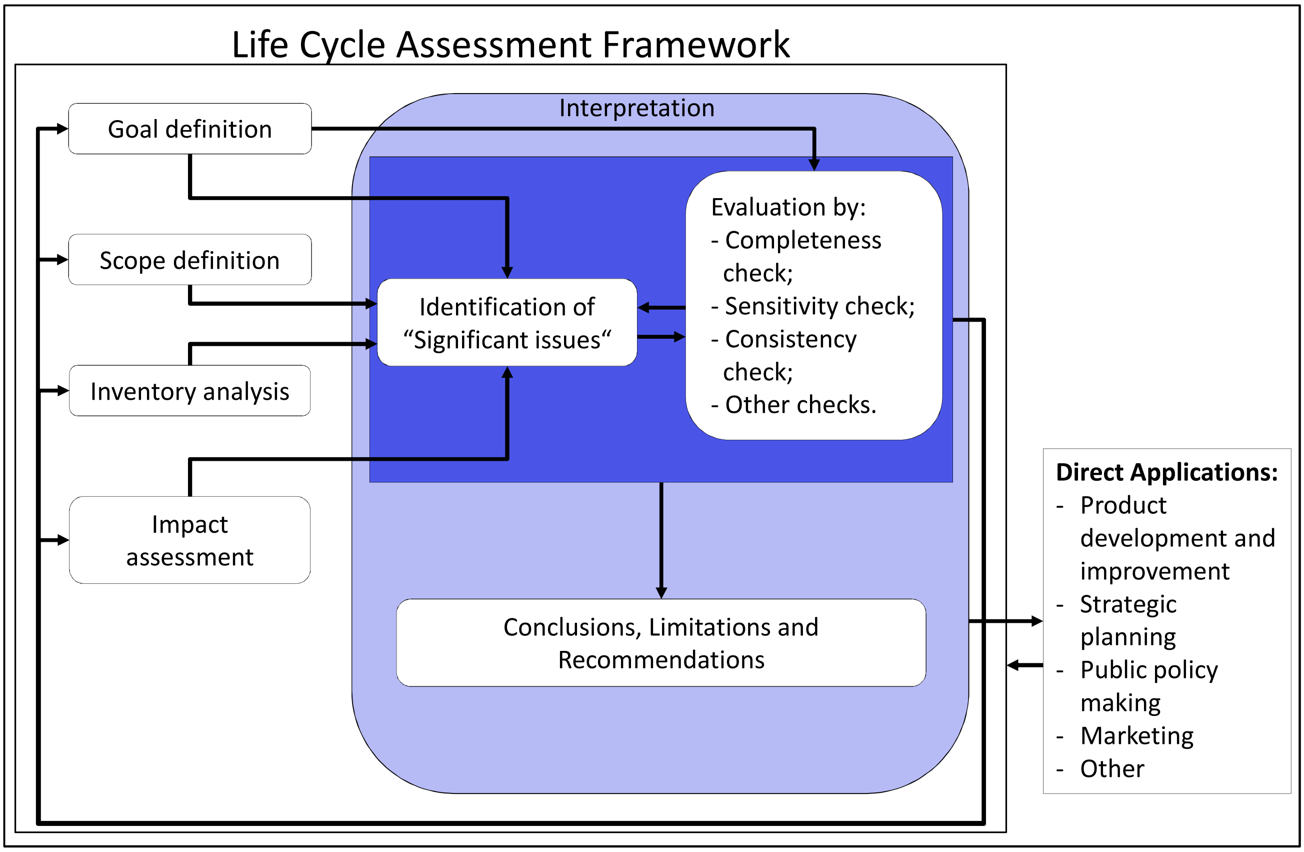

Figure 16: Relationship between elements within the interpretation phase and other phases of LCA (ISO 2006b) (modified)

Figure 16 shows the relationships between the different elements within the interpretation phase and other phases of LCA. It shows the sequence of the different steps during interpretation, as well as the iterative relationship of reconsidering not only the goal and scope definition, but also, potentially, the inventory analysis and the impact assessment. Most importantly, the interpretation includes a sensitivity check of the results taking into account assumptions and sensitive key parameters in the model to ensure robust results.

Provisions 35: Interpretation

Shall: Interpretation shall be done according to ISO 14040/14044

Shall: If the goal and scope definitions were not met either change the goal and scope definitions or report it.

Should: Prepare graphs for the significant issue identification. Stacked bar or pie charts are commonly used.

9.1. Identification of significant issues in the Life Cycle Inventory analysis results

Identification of significant issues is important for the analysis of the system and to be able to give recommendations about possible improvement potentials. One simple way to identify significant issues is to display the LCIA results in a graphical way such as in stacked columns or pie charts. The key information is which process or flow contributes to which impact, to what extent and why. For example, electricity supply would be expected to have a high share on the impacts of electrolysis.

In addition to the analysis of the LCIA, the potential significant issues must be kept in mind. Depending on assumptions or methodological choices (e.g. allocation), different or additional significant issues might be highlighted if different choices are made. These potential significant issues have to be identified by detailed analysis.

Provisions 36: Identification of significant issues

Shall: Identify significant issues.

Should: Use graphs (e.g. stacked bar or pie charts) to identify the greatest contributors.

Should: Be aware of potential significant issues that might be cut-off or allocated to another system.

9.2. Evaluation of results

The evaluation of the results helps to indicate their robustness and reliability. Usually the evaluation of the results is conducted concurrently with the identification of the significant issues (section 9.1).

9.2.1. Completeness check

The completeness check is a "process of verifying whether information from the phases of a Life Cycle Assessment is sufficient for reaching conclusions" (ISO 2006a). In general, the completeness check is based on the law of conservation of mass and energy which states that the mass and energy going into the system is the same as the mass and energy going out of the system. It is important to note that there might be non-measured mass flows, such as exhaust gases, during hydrogen production.

The application of the cut-off rules as defined in section 6.3.3 are to be controlled through the completeness check. According to the ILCD Handbook the cut-off rules apply to environmental impacts. According to ISO 14044 the cut-off for comparative assertion has to be met also by mass and energy in addition to environmental impacts (ISO 2006b).

Provisions 37: Performing the completeness check

Shall: To perform the completeness check, the following has to be undertaken:

- Report the degree of completeness achieved
- Add a justification if the excluded flows and processes satisfy the cut-off criteria
- If incompleteness is found either try to solve it (use additional or higher quality data) or adjust the Goal and Scope.

Should: Use the law of conservation for the completeness check regarding:

- Mass (be aware of potential non-recorded mass flows, e.g. exhaust gases)
- Energy (be aware of potential non-recorded energy flows, e.g. waste heat).

9.2.2. Sensitivity check

A sensitivity check is conducted in LCA to assess the final results and conclusion. It is defined in the ISO 14040 as “systematic procedures for estimating the effects of the choices made regarding methods and data on the outcome of a study” (ISO 2006a). In general it is an additional check for the stability of the results enabling the reliability and consistency of the whole study and results to be verified.

The sensitivity analysis underlying the sensitivity check is performed by doing a parameter variation to see the potential impacts of different parameters on the results. For example, with an electrolyser the input parameters electricity and water used can be varied within certain limits. One possibility to determine the limits is to use possible maximum or minimum values. For instance the electricity demand could be varied between idle and full load of the system. If no limits can be derived, standards such as plus or minus 10 % of the value are helpful for a simple check.

The parameters applied in this step are used to derive limits regarding the results. Regarding the hydrogen production a check regarding energy flows is recommended. This means e.g. to vary the electricity or fossil fuel input by e.g. ±10 %.

If a sensitivity analysis shows highly variable results due to estimation resulting from data gaps, the data collection effort has to be intensified.

A sensitivity check has to be done when a LCA is used to compare products and is intended to be disclosed to the public or allocation is used for solving multi-functionality.

Provisions 38: Sensitivity check

Shall: A sensitivity check has to be done if the study is comparative or if system expansion or allocation is used for solving multi-functionality.

Should: For performing the sensitivity check the following steps are recommended:

1. Define different parameters which might have high impact on the results (e.g. significant issues)
2. Define certain limits of the parameters according to expected minimum and maximum values
3. Vary the parameters and record their impact on the results.

Should: Using the Monte-Carlo Simulation for the sensitivity check:

- Instead of performing the parameter variation manually the Monte-Carlo Simulation might be used (several parameters are varied at the same time → measure of the stability of the model).

9.2.3. Consistency check

The consistency check is defined as the "process of verifying that the assumptions, methods and data are consistently applied throughout the study" (ISO 2006a). This means verifying that the methods and assumptions in the goal and scope definition are applied properly throughout the study. In most cases the consistency check can be done while performing the study. For comparative studies the consistency check is especially important because the methods and assumptions made in the different systems are compared. Examples for hydrogen production systems are the use of the net or gross calorific value in the energy calculations, or the exclusion of some impact categories.

Provisions 39: Consistency Check

Shall: Perform a consistency check.

Shall: For comparative studies, check whether differences in data quality are consistent with the goal and scope of the study.

Should: Additionally check the following points

- Check whether the impact assessment elements have been consistently applied and are in line with the goal and scope
- Evaluate the relevance of any inconsistencies identified for the results and document them.

9.2.4. Uncertainty check

Uncertainty in a LCA study is related to several aspects, among which are data, methodological choices and models used in the impact assessment. In this document only the aspects related to data/parameters are addressed in relation their precision, since the others have been addressed under the “sensitivity check”. The uncertainty check is defined as a “systematic procedure to quantify the uncertainty introduced […] due to cumulative effects of model imprecision, input uncertainty and data variability” (ISO 2006a).

Uncertainty in parameters results from incomplete knowledge about the true value of a parameter and it is generally due to measurement errors in input data. Several techniques exist to evaluate this uncertainty, such as Monte-Carlo Analysis, Bayesian statistics, and analytical uncertainty propagation methods.

As an example, Monte-Carlo Simulation is a mathematical stochastic simulation which allows many factors to be varied at the same time and calculation of the overall resulting uncertainty (JRC 2010a). This ability to concurrently vary multiple parameters is the difference between this simulation and parameter variation within the sensitivity analysis. However it does mean that the resulting impacts shown through Monte-Carlo simulation cannot be linked to a particular parameter.

It is important to remember that the quantitative precision of the data is an important component. However structural and modelling aspects of both the LCI and the LCIA play an important and often dominant role, which cannot be addressed directly or quantitatively in uncertainty calculations.

LCA software systems which will allow sensitivity analyses as well as Monte-Carlo analyses at a push of a button are available.

Provisions 40: Uncertainty Check

Should: Perform an uncertainty check:

- Perform uncertainty calculation of data/parameters according to the available techniques
- Report findings of the uncertainty check.

9.3. Conclusions, limitations and recommendations

The conclusions of the study can be developed in an iterative way taking into account the results of the completeness, sensitivity, consistency and uncertainty checks. The conclusions must also take into account the significant issues identified (section 9.1) in the study. Furthermore they have to be in line with the requirements and limitations of the goal and scope phases (JRC 2010a).

The first step is to produce graphs showing the different fractions contributing to e.g. the Global Warming Potential. Based on the graphs, the main contributors are to be defined and named. It is important to do the interpretation for all impact categories considered since the same process step does not always have similar relevance for the different impact categories.

The next step after deriving conclusions is to point out limitations. In general all known limitations within the goal and scope of the study have to be reported. These limitations might be self-imposed limits such as limiting the study to carbon footprint only. It might also be that some flows are either not recorded correctly or, if recorded, not modelled correctly as there are no data available. This situation sometimes occurs, for example, with rare materials or special chemicals.

The recommendations are supposed to be logical, reasonable and plausible, and based on the conclusions. The ILCD Handbook points out common mistakes to be avoided (JRC 2010a).

Examples of recommendations:

- Focus your improvement activities at the electrolysis e.g. on the electricity consumption (is one of the most significant issues which contributes to the overall impact in a significant share)t;
- Replace a supplier by another supplier with a less impactful production system or supply chain.

Provisions 41: Conclusions, limitations and recommendations

Shall: Analyse and report the results obtained with the corresponding worst and best case assumption scenarios.

Shall: Report complete and accurate results and conclusions of the LCA study without bias to the intended audience using the report template given in Annex I of this document.

Shall: Avoid the following common mistakes, while deriving conclusions:

- Exaggerating small or insignificant differences
- Deriving general conclusions from specific case studies
- Being too confident about differences based on assumptions or uncertainties.

Shall: While deriving conclusions on comparisons consider the differences within the different systems.

Shall: Recommendations shall be made conservatively.

Shall: Use the report template when reporting about the hydrogen production system.

Shall: Document sources used for the foreground and background data, in line with scientific standards.

Shall: Take into account additional environmental information (if available) that has not been evaluated within the LCA study.

Shall: Report the validity of the study.

Should: Limit the validity to maximum of 5 years, due to the pace of improvements in hydrogen production technology. Revise the study whenever a major modification to hydrogen production systems occurs.

10. Reporting of the study on hydrogen production

Reporting is the step of the LCA in which the results, data, methods, assumptions and limitations have to be reported completely and accurately without bias. The results have to be presented in sufficient detail to ensure reproducibility of the results and to provide the required information to reviewers to judge the quality of the results and appropriateness of conclusions and recommendations.

As already mentioned in section 6.9 the report has to be adjusted depending on the intended application and audience of the report. The third party report is recommended as it documents the results in an appropriate and clear manner. This level of reporting does not require the inclusion of confidential information, which however needs to be made available for reviewers. This can be done as a separate document under a confidentiality agreement.

The report consists of four parts:

- Executive Summary
- Technical Summary
- Main content
- Annex.

A confidential section could be included as a fifth part. This would contain the data and information that are confidential or proprietary and cannot be made available externally. This information is, however, necessary for a critical review and has to be provided to the reviewer (details on critical review see section 11).

Reports of assertive and non-assertive comparative studies (section 6.8) on hydrogen production intended to be disclosed to the public have to fulfil some additional requirements. These additional requirements include an analysis of the material and energy flows, justifying their inclusion or exclusion, or the assessment of completeness and representativeness as well as the description of the equivalence of the compared system (JRC 2010a).

The LCA report templates given in Annex I of this guidance document provide the report structure for LCA studies on hydrogen production in detail, including main report, third party review report and a report for comparative studies.

Provisions 42: Important parts in reports

Shall: Use the report template in Annex I.

Shall: Include the following parts in the report:

- *Executive Summary*, for non-technical audience. It shall give decision-makers brief information about the goal and scope, the results and recommendations.
- *Technical Summary*, for technical audience and LCA practitioners. It condenses the major information of the report for LCA practitioners in a more technical manner.
- *Main content*, documents the procedure of a LCA study and thus includes detailed information on goal and scope (description of the system under analysis, methods applied, system boundary and cut-off criteria, functional unit, comparison between systems etc.), inventory analysis (information about all inputs and outputs, description of the foreground system, calculation of LCI results, etc.), impact assessment (LCIA results calculated, impact categories considered,

normalisation and weighting factors, etc. if applicable) and interpretation and quality control (interpretation of significant issues, sensitivity checks, conclusions and recommendations, etc.).

Should: Include the following parts in the report:

- *Annex*, which includes elements that would interrupt the reading flow of the main part of the report and are also of a more technical nature. It could include a data collection template, or overview of all assumptions made.

Shall: Report for comparative studies: Reporting on assertive and non-assertive comparative studies intended to be disclosed to the public, the following additional reporting shall be done in addition to the requirements to reports for internal use and third party reports (ISO 2006b):

- Analysis of material and energy flows to justify their inclusion or exclusion;
- Assessment of the precision, completeness and representativeness of data used;
- Description of the equivalence of the systems being compared in accordance with ISO 14044 and related provisions in this document
- Description of the critical review process;
- Evaluation of the completeness of the LCIA;
- Statement as to whether international acceptance exists for the selected environmental categories and a justification for their use;
- Explanation for the scientific and technical validity and environmental relevance of the category indicators used in the study;
- The results of the uncertainty and sensitivity analyses;
- Evaluation of the significance of the differences found.

11. Critical review of the study on hydrogen production

The critical review is defined as the "process intended to ensure consistency between a Life Cycle Assessment and the principles and requirements of the international standards on Life Cycle Assessment" (ISO 2006a). It is aimed at ensuring whether the methods used to carry out the LCA are consistent with the ILCD Handbook (and thereby also with ISO 14040 and 14044) and scientifically and technically valid; the data used are appropriate and reasonable in relation to the goal of the study; the interpretations reflect the limitations identified and the goal of the study, and the study report is transparent and consistent (JRC 2010c). This means that the LCA is cross checked by a third party who is an independent external expert that has not been involved in the performance of the LCA study, guaranteeing consistent and reliable results.

Whether a critical review is necessary or not, depends on the goal and scope definition as described in section 6.8. A critical review has to be done if the study compares systems, or will be disclosed to the public. If the study involves a comparison and is intended to be published, a critical review conducted by a review panel of at least 3 persons has to be done. LCA studies for internal use only do not require a critical review, and this phase is optional.

The independence, qualification and experience of the reviewers have to be assured (JRC 2010c). The reviewer(s) needs experience in LCA methodology, verification and audit practice, and must have technical expertise related to the hydrogen production system analysed.

An additional important point to note is that for studies with comparative assertions as mentioned in section 6.8, the independent external review panel has to involve interested parties (e.g. government agencies, non-governmental organisations or affected industries) in the review process by open invitation. Their opinion is to be considered in the review and could be included in the review report, compiled by the chairperson of the review panel.

The review report template to be used is shown in Annex IV.

Provisions 43: Critical review

Should: For internal studies a critical review is not mandatory, but recommended.

Should: For internal studies an independent internal review is recommended if an external review is not planned.

Shall: A critical review is necessary if the study is intended to be disclosed to the public

Shall: A critical review panel (at least 3 reviewers) is necessary if the study is comparative and intended to be disclosed to the public

Shall: For comparative studies, involve additional interested parties (e.g. governmental agencies, non-governmental organisations or affected industries) in the review process by open invitation.

Shall: If a critical review is conducted the reviewer shall be:

- Independent
- Experienced in LCA methodology
- Experienced in verification and audit practice
- Have technical expertise related to the hydrogen production system under analysis.

Should: If one reviewer does not have all the above mentioned experience, it is possible to replace the reviewer by a review team.

Should: The reviewer may be integrated in the study from the beginning.

12. References

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JRC 2010c: European Commission – Joint Research Centre – Institute for Environment and Sustainability: International Reference Life Cycle Data system (ILCD) Handbook – Review schemes for Life Cycle Assessment. First edition March 2010. Luxembourg. Publications Office of the European Union; 2010

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Annex I LCA study reporting template on hydrogen production

Executive Summary	Provide a short summary for non-technical audience.
Technical Summary	Provide a short summary for technical audience. Address the system such as ISO 14040/14044 and/or ILCD with which the study complies.
Main Part	
1. Product group	
1.1. Product information requested and standards to use	Provide information about the hydrogen properties and quality. Mandatory: purity, aggregate state, pressure, temperature Optional: impurities, quantity produced per year
1.2. Producer's information requested	Provide information about the hydrogen producer: Mandatory: Overall H_2 production capacity, number of sites, production technology used, geographical coverage by region. Provide information about the hydrogen production system: Mandatory: Production technology used, year of construction, on-site electricity or heat production (if existing), production capacity, flow diagram Optional: location of the site; technical service life, type of production site (laboratory, commercial…), type of storage.
2. Goal of the Life Cycle Assessment study on hydrogen production	
2.1. Intended application(s)	Describe the intended application(s), e.g.: Evaluation of a hydrogen production system, carbon footprint, comparison of different hydrogen production systems….
2.2. Method, assumptions and impact limitations	Detail any assumptions or limitations.

2.3. Reasons for carrying out the study	Unambiguously state the reason for carrying out the study.
2.4. Target audience	Describe the target audience, e.g.: Technical / non-technical audience; decision-makers etc..
2.5. Comparisons intended to be disclosed to the public	State whether the study is comparative State whether the study is intended to be disclosed to the public.
2.6. Commissioner of the study	Specify the commissioner of the study, (co)financier and/or other actors having direct/indirect influence on the study.
3. Scope of the Life Cycle Assessment study on hydrogen production	
3.1. Functional unit / Reference flow	State a hydrogen purity standard or complete the gaps in the reference flow below: MJ of hydrogen (net calorific value (NCV)) with __ % purity and __ bar @ __ °C.
3.2. Multi-functionality	If multi-functionality occurs state which method is chosen to solve multi-functionality.
3.3. System boundary	Describe the system boundary and show it graphically through a Flow chart. List the flows taken into consideration.
3.4. Cut-off criteria	State the flows which are cut-off or excluded and the expected impact of the cut-off.
3.5. LCIA methods and categories	State which impact categories are chosen and if there are any limitations.
3.6. Type, quality and sources of required data and information	Describe the quality and the sources of the data and information required. Describe the closing of data gaps using comparable data.
3.7. Data quality requirements	Describe the data quality.

3.8. Comparisons between systems	If there are comparisons between systems, describe the differences (reference flow, scope definitions, assumptions etc.)
3.9. Identification of critical review needs	State whether a critical review is required or not, according to ILCD specifications
4. Life Cycle Inventory Analysis of the study on hydrogen production	
4.1. Identifying processes within the system boundary	Describe the processes being evaluated.
4.2. Data collection	Describe the data collection, e.g. how long the data were measured, in which way, etc.
4.3. Selection of secondary LCI data	List the secondary data used and the underlying database or source
4.4. Dealing with multi-functional processes	If multi-functionality occurs, show the influence of solving the multi-functionality. If allocation is used, show the results of the usage of different allocation factors.
4.5. Consideration of re-use, recycling and energy recovery	State whether there is any re-use, recycling and/or energy recovery.
4.6. Calculation of LCI results	Describe how the LCI results are calculated (e.g. Excel, LCA software). If a LCA software is used indicate which one.
5. Life Cycle Impact Assessment of the study on hydrogen production	
5.1. Impact assessment, classification and characterisation	Replace the "**XX**", "**YY**" and "**ZZ**" by your results and graph the results. GWP per MJ H_2: **XX** kg CO_2 eq. / 1MJ H_2 @ **YY** bar, **ZZ** °C AP per MJ H_2: **XX** kg SO_2 eq. / 1MJ H_2 @ **YY** bar, **ZZ** °C EP per MJ H_2: **XX** kg PO_4^{-} eq. / 1MJ H_2 @ **YY** bar, **ZZ** °C POCP per MJ H_2: **XX** kg C_2H_4 eq. / 1MJ H_2 @ **YY** bar, **ZZ** °C PED (non-renewable) per MJ H_2: **XX** MJ $PED_{non\text{-}renewable}$ / 1MJ H_2 @ **YY** bar, **ZZ** °C PED (renewable) per MJ H_2: **XX** MJ $PED_{renewable}$ / 1MJ H_2 @ **YY** bar, **ZZ** °C

5.2. Normalisation	State whether normalisation is applied or not. If applied, document it unambiguously.
5.3. Grouping and Weighting	State whether grouping and/or weighting are applied or not. If applied, document it unambiguously.
6. Interpretation and quality control of the study on hydrogen production	
6.1. Identification of significant issues	List and describe the significant issues. Show graphs of the significant issues if available
6.2. Completeness check	Report the degree of completeness achieved
6.3. Sensitivity check	Detail the results of the sensitivity check.
6.4. Consistency check	Detail the results of the consistency check.
6.5. Uncertainty check	Detail the results of the uncertainty check.
6.6. Conclusions, limitations and recommendations	State and explain the conclusions, limitations and recommendations.
7. Critical Review of the study on hydrogen production	
7.1. Critical Review	State and explain the results of the critical review or attach the report of the reviewer.

Annex II Documentation of the resulting data set according to ILCD

If the LCA study on hydrogen production produces an ILCD entry level or ILCD compliant data set, the following meta documentation fields of the ILCD format have to be filled out within the data set. Note that a data set in the ILCD format consists of the meta documentation (item 1-15) and the input/output flows (item 16). Data sets in the ILCD format can be prepared by using the ILCD editor Tool, available at http://lca.jrc.ec.europa.eu/ or by commercial software systems providing this functionality.

1. Process information	
1.1. Key data set information	
1.1.1. Base name	Naming conventions of the "ILCD - Nomenclature and other conventions" document shall be applied.
1.1.2. Treatment standard routes	Naming conventions of the "ILCD - Nomenclature and other conventions" document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.1.3. Mix and location types	Naming conventions of the "ILCD - Nomenclature and other conventions" document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.1.4. Quantitative product or process properties	Naming conventions of the "ILCD - Nomenclature and other conventions" document shall be applied. If the field has no entry, enter a blank (" "). This should occur very rarely.
1.2. Classification information	
1.2.1. Name	The classes of the file ILCDClassification.xml shall be used. Classes of additional classification systems can be added only via separate "Classification" field sets.
1.2.2. Unique class identifier	The classes of the file ILCDClassification.xml shall be used. Classes of additional classification systems can be added only via separate "Classification" field sets.

2. Quantitative reference	
2.1. Type of quantitative reference	Recommended to be of the type “Reference flow(s)”.
2.2. Reference flow(s)	If "Type of quantitative reference" is "Reference flow", at least one reference flow is to be identified among the input/output product or waste flows.
2.3. Functional unit, Production period, or Other parameter	Required ("C"), if field "Type of quantitative reference", is of a type other than "Reference flow(s)". However, also if of a type "Reference flow(s)", it is recommended to also give one or more functional units for the reference flow(s). If the data set is anticipated to be used in comparative studies, this step might be a formal requirement.
3. Time representativeness	
3.1. Reference year	
3.2. Data set valid until:	
3.3. Time representativeness description	
4. Geographical representativeness	
4.1. Location	Must use one of the locations that are specified in the ILCDLocations.xml or other file, as referenced in the field <processDataSet@locations>. Empty if geography-unspecific such as technology-model data set i.e. do only enter "GLO" if the data set represents worldwide average data.
4.2. Geographical representativeness description	
5. Technological representativeness	
5.1. Technology description including	

background system	
5.2. Technical purpose of product or process	
5.3. Flow diagram(s) or picture(s)	System boundary diagram should also be placed here. Technical flow charts are recommended to improve documentation of most data sets.
6. Mathematical model	
6.1. Model description	This entry is required ("C") only for parameterised LCI data sets, i.e. if at least one field "Name of variable" is in use.
6.2. Name of variable	This entry is required ("C") only for parameterised LCI data sets, for at least one set of "Variable / parameter" fields.
6.3. Formula	This entry is empty if the "Name of the variable" is a parameter that is defined by the "Mean value" given, i.e. a formula should be entered only if it actually is a variable that is calculated by a formula.
6.4. Mean value	This entry is required ("C") only for parameterised LCI data sets, if a "Name of variable" is given. If this is a variable, the "Mean value" is the calculated result of the "Formula" field with the given parameterisation i.e. with the default parameter settings.
6.5. Comment, units, defaults	This entry is required ("C") only for parameterised LCI data sets.
7. LCI method and allocation	
7.1. Type of data set	Note the differences between "LCI result" and "Partly terminated system" data sets.
7.2. LCI method principle	Ensure that the entry is consistent with the approach stated in the section “Compliance declarations” and the entry/ies in the field “LCI method approaches”. Note that for data sets for Situations A, B, C1 or C2 of the ILCD Handbook, this information is to be entered in the field "Compliance declarations".
7.3. Deviation from	Enter "None", if no deviations.

LCI method principle / explanations	
7.4. LCI method approaches	Ensure that the entry fits with the approach stated in the section “Compliance declarations” and the entry/ies in the field “LCI method principle”.
7.5. Deviations from LCI method approaches / explanations	Enter "None", if no deviations.
7.6. Modelling constants	
7.7. Deviation from modelling constants / explanations	Enter "None", if no deviations.
8. Data sources, treatment, and representativeness	
8.1. Data cut-off and completeness principles	Ensure that the cut-off and completeness requirements as defined for the data quality level stated in sub-section “Validation/Data quality indicators” and the section “Compliance declarations” are met.
8.2. Deviation from data cut-off and completeness principles/explanations	Enter "None", if no deviations.
8.3. Data selection and combination principles	Ensure that the method requirements as defined for the data method type and quality level stated in the section “Compliance declarations” are met. For “LCI results” and “partly terminated systems” data sets also check the “Included processes”.
8.4. Deviation from data selection and combination principles / explanations	Enter "None", if no deviations.
8.5. Data treatment	Ensure that the technological, geographical and time representativeness

and extrapolations principles	requirements as defined for the data quality level in sub-section "Validation/Data quality indicators" and the section "Compliance declarations" are met. Also check with entries given in the respective "... representativeness" sections.
8.6. Deviation from data treatment and extrapolations principles/explanations	Enter "None", if no deviations.
8.7. Data source(s) used for this data set	Provide citations/reference of all relevant data sources, including for the relevant ("key") processes included in the background system, if any.
8.8. Percentage supply or production covered	Consider which market-relevant technologies are actually and explicitly addressed/included in the inventory of this data set., especially for secondary data sets,
8.9. User advice for data set	
9. Completeness	
9.1. Completeness product model	Ensure that the cut-off and completeness requirements as defined for the data quality level in sub-section "Validation/Data quality indicators" and the section "Compliance declarations" are met.
9.2. Supported impact assessment methods	Usability of this field pending finalisation of the implementation of the "LCIA method data set". If primary data sets are unavailable, a reference to an empty default "LCIA method data set" can be entered.
9.3. completeness type	
9.4. value	
10. Validation	
10.1. Type of review	Ensure that the review type meets the requirements of the "review compliance" in section "Compliance declarations". The ILCD generally requires an independent review for externally provided data sets; for details see "ILCD compliance" documentation.

10.2. Scope name	Ensure that the review scope meets the requirements of the “review compliance” in the section “Compliance declarations”.
10.3. Method name	Ensure that the cut-off and completeness requirements as defined for the data quality level in sub-section “Validation/Data quality indicators” and the section “Compliance declarations” are met. Ensure that the review methods meet the requirements of the “review compliance” in the section “Compliance declarations”.
10.4. Name of data quality indicator	Ensure that the data quality indicator matches the requirements of the ”quality“, ”method“, „nomenclature“, ”documentation“, and ”review“ compliance in the section ”Compliance declarations“.
10.5. Value of data quality indicator	Ensure that the data quality indicator matches the requirements of the “quality”, “method”, “nomenclature”, “documentation”, and “review” compliance in the section “Compliance declarations”.
10.6. Review details	
10.7. Reviewer name and institution	
10.8. Other review details	
11. Compliance declarations	
11.1. Compliance system name	Must reference the corresponding source data set of the most recent version of the ILCD compliance system. • For the definitions for use in the ILCD Data Network see the separate document "ILCD Data Network: • Compliance rules and entry-level requirements". For general ILCD-compliance requirements for LCI data sets see also the "Specific guide for LCI data sets". Other compliance systems e.g. of specific EPD schemes, can be also be referenced.

11.2. Approval of overall compliance	Ensure that the overall requirements for ILCD related compliance are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.3. Quality compliance	Ensure that the quality requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.4. Nomenclature compliance	Ensure that the nomenclature requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.5. Methodological compliance	Ensure that the method requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.6. Review compliance	Ensure that the review requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
11.7. Documentation compliance	Ensure that the documentation requirements for ILCD related compliance systems are met. For an overview and specific settings for the ILCD Data Network, see the separate document "ILCD Data Network: Compliance rules and entry-level requirements".
12. Commissioner and goal	
12.1. Commissioner of data set	Detail the commissioner of the study, (co) financier and/or other actors having influence on the study.
12.2. Intended applications	Ensure that this is consistent with the ”LCI method principle“, ”Compliance declarations“, any specific requirements on reporting stated in ISO 14044, the ILCD Handbook (e.g. "third-party report"), and the ”Type of data set“.

13. Data set generator / modeller	
13.1. Data set generator / modeller	
14. Data entry	
14.1. Data entry by:	
14.2. Official approval of data set by producer/operator:	Used only if official approval is given by the goods producer or service operator of the product represented by the data set. If it is not given, insert a reference to an empty default contact data set with a "No official approval" text entry.
15. Publication and ownership	
15.1. Data set version	This is typically automatically generated, but may need to be manually adjusted.
15.2. Date of last revision	
15.3. Owner of data set	
15.4. Copyright?	
15.5. License type	
15.6. Access and use restrictions	
16. Inputs and Outputs	
16.1. Reference to flow data set	
16.2. Exchange direction	
16.3. Mean amount	
16.4. Resulting	

amount	
16.5. Data source type	Required ("C") for unit process data sets only. (For other secondary data set types, the entry will almost always be “Mixed primary/secondary” and is hence non-informative).
16.6. Data derivation type / status	Required ("C") only if "Type of data set" is “unit process, etc.”. Recommended also for other data set types.

Annex III Data collection template on hydrogen production

AGGREGATE DATA NEEDED FOR THE PREPARATION OF A LIFE CYCLE INVENTORY OF HYDROGEN PRODUCTION		
note: the questionnaire need to be adapted in case of application to different production technologies		
Please fill out the questionnaire with the requested data and send it back to the following e-mail address:		info@fc-hyguide.eu
Legend:		
cells to be filled out with requested data are white (mandatory)		
cells to be filled out with additional information are purple (optional)		
Comments and explanations are given in italic		
Part I: General information on hydrogen production should be filled out. The other parts (II-VII) are specialised for main production technologies. Please fill out the appropriate part. If no part applies fully, please complete the one that best fits, and add additional rows if necessary.		
The specialised parts (II-VII) are relative apply to the production of hydrogen. Please enter the energy and material resources which are necessary for the production of:		
"1 MJ of hydrogen (net calorific value (NCV) with XX % purity and YY bar @ ZZ °C)"		
Part I: General information on hydrogen production		**unit**
Please attach an additional sheet including a system functioning scheme and system's basic components		
Hydrogen related information		
[please add rows and other fields if needed]		
Purity of the hydrogen (XX %)		%
Aggregate state (liquid or gaseous) of the hydrogen		
Pressure of the hydrogen (YY bar)		bar
Temperature of the hydrogen (ZZ °C)		°C
Impurities (please state them below, if known)		%
Type of Impurities		
Amount		%
Quantity produced by volume		Nm³/h or Nm³/year
Quantity produced by mass		kg/h or kg/year
Description of hydrogen producer (general information on the producer)		
[please add rows and other fields if needed]		
Overall hydrogen production capacity (of the production company)		m³
Number of hydrogen production sites		No.
Hydrogen production technologies used (e.g. steam reformer, electrolysis etc.)		
Geographical coverage by region (where are the major production locations of the producer)		country or region
Description of the product system under investigation		
[please add rows and other fields if needed]		
Hydrogen production technology used		
Location of the production site		country or region
Year of construction		
Is there electricity produced on-site used		yes/no
Amount of electricity produced on-site used (if applicable)		kWh/MJ hydrogen
Type of electricity production on-site (if applicable)		
Is there heat produced on-site used in the production of H_2		
Type of heat production on-site, e.g. gas boiler, oil CHP etc. (if applicable)		
Amount of heat production on-site (if applicable)		MJ/MJ hydrogen
H_2 production capacity per day		Nm³/year or MJ/year
H_2 production capacity per year		Nm³/year or MJ/year
Technical service life of H_2 production		
Scale of production site (laboratory, pre-commercial, commercial scale)		
Type of storage (including e.g. liquefaction facility or other device)		

Figure 17: Data collection template for the general information

Part IV: Hydrogen production by partial oxidation	**amount (per unit of product)**	**unit**
Hydrogen production - Functional unit is "1 MJ of hydrogen (net calorific value (NCV) with XX % purity and YY bar @ ZZ ℃)"		
[please add rows and other fields if needed]		
Input		
Fuel (fuel oil, coal, bitumen, natural gas, etc.)		
Type		
Amount		kg/MJ hydrogen
Calorific value		MJ/kg
Electricity		kWh/MJ hydrogen
Process gases (e.g. off gas from H_2 purification) (please specify if applicable)		m³/MJ hydrogen
Net calorific value of the process gas used (if applicable)		MJ/m³
Composition of the process gas (e.g.% H_2, % CO_2 etc.) (if applicable)		
Operating supplies for the desulphurisation (e.g. kg catalyst per year)		
Operating supplies and spare parts (e.g. catalysts)		
Output		
Heat		MJ/MJ hydrogen
CO_2		kg/MJ hydrogen
NO_x		kg/MJ hydrogen
CO		kg/MJ hydrogen
Amount of H_2 losses during purification		%
Are the H_2 losses used as process gas? (if yes please specify in process gas column above in inputs)		yes/no
Other emissions (please specify)		kg/MJ hydrogen

Part V: Hydrogen production by catalytic reforming	**amount (per unit of product)**	**unit**
Hydrogen production - Functional unit is "1 MJ of hydrogen (net calorific value (NCV) with XX % purity and YY bar @ ZZ ℃)"		
[please add rows and other fields if needed]		
Input		
Fuel (fuel oil,biomass, coal, bitumen, natural gas, etc.)		
Type		
Amount		kg/MJ hydrogen
Calorific value		J/kg
Electricity		kwh/MJ hydrogen
Cooling Water		m³/MJ hydrogen
Process gases (e.g. off gas from H2 purification) (please specify if applicable)		m³/MJ hydrogen
Net calorific value of the process gas used (if applicable)		MJ/m³
Composition of the process gas (e.g.% H2, % CO2 etc.) (if applicable)		
Operating supplies for the desulphurisation (e.g. kg catalyst per year)		
Operating supplies and spare parts		
Output		
Refinery gas		m³/MJ hydrogen
LPG		m³/MJ hydrogen
Reformate		m³/MJ hydrogen
Amount of H_2 losses during purification		%
Are the H_2 losses used as process gas? (if yes please specify in process gas column above in inputs)		yes/no
Other emissions (please specify)		kg/MJ hydrogen

Figure 18: Data collection template for the specific hydrogen production types.

Figure 17 and Figure 18 show examples of a data collection template. For ease of use the template is prepared in Excel format, and separated into different parts for general and specific information.

Annex IV LCA review reporting template on hydrogen production

The results of the verification should be reported in a “Review report – Judgment table” that has to follow the scheme of table below.

1. Life Cycle Assessment and LCA applications

REVIEW REPORTING			
General information			
Project name			
Review commissioner(s)			
Reviewer name(s)			
Review type applied			
Date of completion of review (DD/MM/YYYY)			
Compliance system name			
Reviewer assessment:			
Aspect	**Yes**	**No**	**Comments**
Quality compliance			
Method compliance			
Nomenclature compliance			
Documentation compliance			
Review compliance			
Compliant with ISO 14040 & 14044			
Reproducibility and Transparency			

In order to express a judgment on each of the items listed above, the following items have to be considered:

- For **quality conformity** all items under Life Cycle Inventory and Quality control

- For **method conformity** all items under goal and scope definition, LCIA and interpretation
- For **nomenclature conformity** all items throughout the study because it represents a transversal judgment. It is considered transversal as there is a specific nomenclature for all the LCA phases (e.g. for input and output flows, processes, etc.)
- For **documentation conformity** all items under reporting
- **Review conformity** represents a judgment on the possibility to perform a complete review on the basis of the requirements for verification

The reviewer has to tick "yes" if the LCA study fulfils the requirements for the conformity and "no" if the LCA study does not reach this fulfilment.

In the "comments" field the reviewer has to insert references and examples in order to justify non-conformity judgments.

The Judgment table has to be appended to a full review report. In the full report the following issues have to be covered:

- Items verified
- Methods used
- Criteria for choice of samples
- Reasons for exclusions
- Analyzed data flows
- Main results
- Suggestions for improvements

2. Life Cycle Inventory data set (ILCD Data Network - Entry-level requirements)

The review findings are to be documented in the LCI data set. The specifically applied scope and methods of review are also to be documented in the data set.

The - for Independent External Reviews optional - separate review report would carry e.g. responses of the Commissioner to the reviewer comments and further details.

REVIEW REPORTING	
General information	
Data set name	
Data set UUID and version number	

Data set locator (e.g. URI, URL, contact point, database name and version, etc.)			
Data set owner			
Review commissioner(s)			
Date of completion of review			
Reviewer name(s)			
Review type applied			
Date of review (DD/MM/YYYY)			
Compliance system name	**ILCD Data Network - Entry-level**		
Reviewer assessment:			
Aspect	**Yes**	**No**	**Comments**
Quality compliance			
Method compliance			
Nomenclature compliance			
Documentation compliance			
Review compliance			
Compliant with ISO 14040 & 14044			
Reproducibility and Transparency			

All the following items should be explicitly addressed. It should be noted the findings/comments on all items are part of the "Review details" text field. Some items are also represented by separate data quality indicators, and in the validation section of the data set.

ITEMS	**Quality values***	**Comments**
Correctness and appropriateness of the data set documentation		
An overall quality statement on the data		

Geographical representativeness of Inputs and Outputs		
Technological representativeness of Inputs and Outputs		
Time representativeness of Inputs and Outputs		
Completeness of Inputs and Outputs		
Precision of Inputs and Outputs		
Completeness of coverage of the relevant impact fields (environmental, human health, resource use)		
Plausibility of data		
Appropriateness of system boundary,		
Appropriateness of cut-off rules,		
Appropriateness of LCI modeling choices such as allocation,		
Consistency of processes included and of LCI methodology.		
If the data set comprises pre-calculated LCIA results, the correspondence of the Input and Output elementary flows (including their geographical validity) with the LCIA method(s) applied.		
Others		

Note*

Quality Values	Meaning
Very good	Meets the criterion to a very high degree, having or no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.

Good	Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Fair	Meets the criterion to a sufficient degree, while having the need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Poor	Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Very poor	Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to an ideal situation.
Not evaluated / unknown	This criterion was not reviewed or its quality could not be verified.
Not applicable	This criterion is not applicable to this data set, e.g. its geographical representative cannot be evaluated as it is a location-unspecific technology unit process.

If intended/foreseen, the responses of the commissioner of the study to the reviewer comments can be reported using this template:

ITEMs	Reviewer Comments	Response from commissioner
Correctness and appropriateness of the data set documentation		
An overall quality statement on the data		
Geographical Representativeness of Inputs and Outputs		
Technological representativeness of Inputs and Outputs		
Time representativeness of Inputs		

and Outputs		
Completeness of Inputs and Outputs		
Precision of Inputs and Outputs		
Completeness of coverage of the relevant impact fields (environmental, human health, resource use)		
Plausibility of data		
Appropriateness of system boundary,		
Appropriateness of cut-off rules,		
Appropriateness of LCI modeling choices such as allocation,		
Consistency of processes included and of LCI methodology.		
If the data set comprises pre-calculated LCIA results, the correspondence of the Input and Output elementary flows (including their geographical validity) with the LCIA method(s) applied.		
Others		

Annex V Example from case studies on hydrogen production

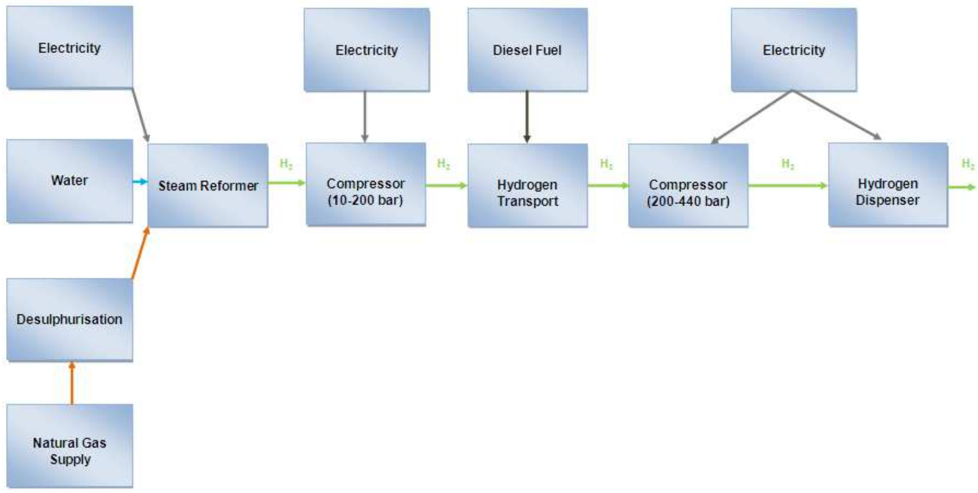
Within the FC-HyGuide project two case studies on hydrogen production systems are performed. One case study is analysing the hydrogen production via centralised steam reforming. The other cases study is evaluating the gaseous hydrogen production via decentralised water electrolysis. Those case studies are investigating the whole hydrogen supply chain well-to-tank.

The indented application of the case study is mainly to demonstrate the applicability of the guidance document rather than the environmental evaluation of the hydrogen production system. The LCA inventories are not to be used for any further analysis or study!

Steam Reformer example

Executive Summary	*[Provide a short summary for non-technical audience.]* The study was carried out to test the applicability of the guidance document developed in the FC-HyGuide project, funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). It evaluates the environmental impacts and the primary energy demand of the production of compressed hydrogen by centralised steam reforming. The case study is documented following the LCA reporting template, developed in the FC-HyGuide project. In addition to this documentation a meta documentation of the LCI result (for demonstration purpose only) is provided. This meta documentation and the LCI results will be uploaded to the ILCD data network as an example for demonstration purposes only.
Technical Summary	*[Provide a short summary for technical audience. Address the system such as ISO 14040/14044 and/or ILCD with which the study complies.]* The study is an LCA of centralised steam reforming production of gaseous hydrogen at 440 bar @ 85°C temperature (350 bar @ ambient temperature) for mobile applications as used by end consumers at the hydrogen filling station. The analysis covers the whole hydrogen production chain from well-to-tank. It includes the manufacturing, operation, and end of life of all hydrogen production and supply units. Therefore also all burdens and credits associated with the recycling of the hydrogen production facilities are considered. The analysis is based on situation A (minor level) as defined in the ILCD Handbook. The study is compliant to ISO 14040, 14044 and to ILCD rules (whenever the study is not compliant to ILCD due to the case study character, it is highlighted in the report).
Main Part	

1. Product group	
1.1. Product information requested and standards to use	*[Provide information about the hydrogen properties and quality.* *Mandatory: purity, aggregate state, pressure, temperature* *Optional: impurities, quantity produced per year]* • Hydrogen, 99.995 % purity, gaseous, 440 bar @ maximum 85°C • Quantity produced: 50,000 Nm³ H_2 per hour
1.2. Producer's information requested	*[Provide information about the hydrogen producer:* *Mandatory: Overall H_2 production capacity, number of sites, production technology used, geographical coverage by region.* *Provide information about the hydrogen production system:* *Mandatory: Production technology used, year of construction, on-site electricity or heat production (if existing), production capacity, flow diagram* *Optional: location of the site; technical service life, type of production site (laboratory, commercial…), type of storage.]* • Generic study about hydrogen production via centralised steam reforming • Overall production capacity: Since several production sites from different manufacturers were averaged, the overall production capacity of all producers is unknown. • Number of sites: Hydrogen production is based on primary data from two European steam reforming sites, completed by literature data. • Production technology used: Centralised steam reforming of natural gas. • Breakdown of technologies used in hydrogen production system: Desulphurisation of natural gas, steam reforming unit itself, Pressure Swing Adsorption (PSA) for purification, distribution by 200 bar tube trailers, an on-site compression system to 440 bar @ 85°C temperature prior to dispensing. • Geographical coverage: The hydrogen production system represents average European boundary conditions. • Year of construction: Reference years of steam reforming data are 1992-2003. • Actual production: not known, assumed 95 % utilisation. • Production capacity: 50,000 m³ H_2 per hour. • On-site electricity or heat production: Steam produced as co-product. • Location of the production site under evaluation: average Europe. • Technical service life: 20 years. • Type of production site: Commercial. • Type of storage: On-site 3 band storage system with a capacity of 50-500 kg hydrogen. • Total market share: Since several production sites from different manufacturers were averaged, the total market share of all producers is unknown.

	• Flow diagram of production route: 

2. Goal of the Life Cycle Assessment study on hydrogen production

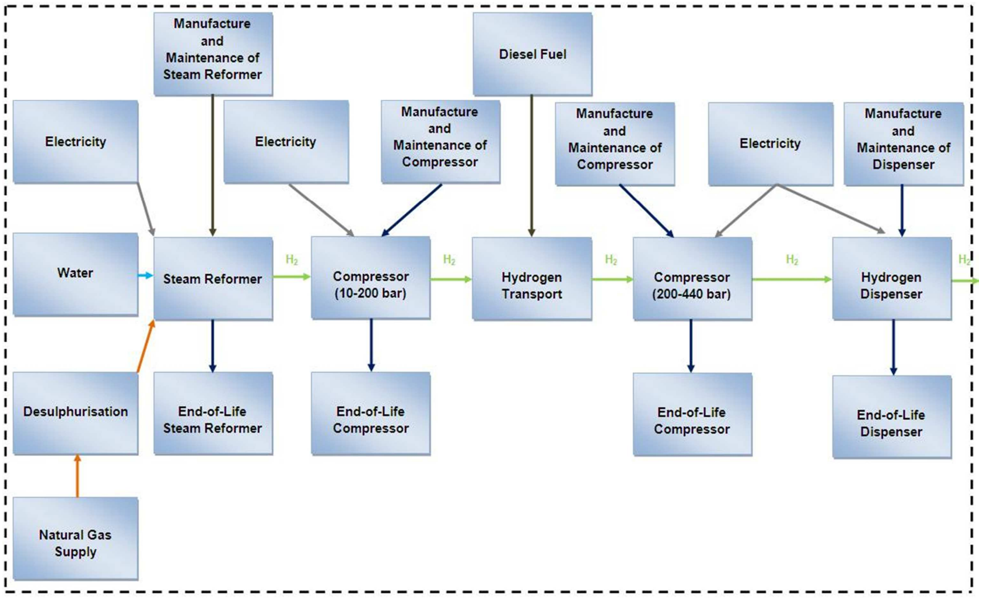
2.1. Intended application(s)	*[Describe the intended application(s), e.g.:* *Evaluation of a hydrogen production system, carbon footprint, comparison of different hydrogen production systems….]* The indented application of the case study is first to demonstrate the applicability of the guidance document itself and second the environmental evaluation of a natural gas steam reforming production system. However, the key application is to check the applicability of the hydrogen guidance document.
2.2. Method, assumptions and impact limitations	*[Detail any assumptions or limitations.]* A "standard" evaluation (according to ISO 14044) of the environmental impacts and the primary energy demand (divided in renewable and non-renewable) of the product system is undertaken. The used impact method is based on CML (CML 2011). Investigated midpoint categories for the environmental and primary energy demand evaluation are: • Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Non-renewable Primary Energy Demand ($PED_{non-renewable}$) • Renewable Primary Energy Demand ($PED_{renewable}$) Endpoints are not investigated.

2.3. Reasons for carrying out the study	*[Unambiguously state the reason for carrying out the study.]* The case study is based on ILCD "situation A" to evaluate environmental impacts and the primary energy demand of hydrogen production by centralised steam reforming of natural gas. Again, focus of this generic desktop study is to check the applicability of the hydrogen guidance document.
2.4. Target audience	*[Describe the target audience, e.g.:* *Technical / non-technical audience; decision-makers etc...]* The target audience of this study is LCA practitioners and technical experts; therefore the focus is on technical aspects and details.
2.5. Comparisons intended to be disclosed to the public	*[State whether the study is comparative* *State whether the study is intended to be disclosed to the public.]* This is a non-comparative study. It is intended to be disclosed to the public as an example case study.
2.6. Commissioner of the study	*[Specify the commissioner of the study, (co)financier and/or other actors having direct/indirect influence on the study.]* Commissioner: FC-HyGuide project team, funded by the European Commission Fuel Cells and Hydrogen Joint Undertaking (FCH JU). Practitioner: PE International AG and University of Stuttgart, Chair of Building Physics, Department Life Cycle Engineering.
3. Scope of the Life Cycle Assessment study on hydrogen production	
3.1. Functional unit / Reference flow	*[State a hydrogen purity standard or complete the gaps in the reference flow below:]* Functional unit: 1 MJ of hydrogen (net calorific value (NCV)). Reference flow: 1 MJ of hydrogen (net calorific value (NCV)) with 99.995 % purity and 440 bar @ 85°C maximum temperature (350 bar @ ambient temperature)
3.2. Multi-functionality	*[If multi-functionality occurs state which method is chosen to solve multi-functionality.]* Since subdivision is not applicable, system expansion shall be applied. However for this case study allocation is chosen to solve multi-functionality. This approach is chosen to demonstrate different allocation rules and related procedures, which have to be done when applying allocation (sensitivity check for instance). The approach is acceptable because of the character of being an example demonstrating the applicability of the guidance document only. Steam is produced as a co-product. It is allocated by net calorific value (NCV).

3.3. System boundary	*[Describe the system boundary and show it graphically through a Flow chart. List the flows taken into consideration.]*

The system under investigation is the hydrogen production "well-to-tank" by centralised natural gas steam reforming. The data set considers the entire supply chain from the natural gas production, the natural gas supply, the steam reforming, compression of the produced hydrogen, the transport, a second compression up 440 bar @ 85°C temperature, the dispensing unit.

Thereby manufacturing, maintenance, transport and end of life of the main equipment is considered.



The main processes of this study are the steam reformer, including the desulphurisation of natural gas, the steam reforming itself, the CO-shift conversion and the purification (pressure swing adsorption, PSA) of hydrogen.

Produced hydrogen is compressed in a first stage to 200 bar, transported, and transfer to a second compression (440 bar), before it gets dispensed. All required electricity mixes, as well as the natural gas mix are modelled under European system boundary conditions. These data sets were taken from the European Reference Life Cycle Database (ELCD) (JRC 2010d).

Relevant flows:

Steam Reforming:

Inputs:

- Natural gas (European average)
- Electricity (European average)
- Manufacture and maintenance of system components, auxiliaries

Outputs:

- Hydrogen to compressor

	• Steam and waste heat from steam reforming • End of life steam reformer *Compression:* Inputs: • Electricity (European average) • Manufacture and maintenance of system components, auxiliaries Outputs: • Hydrogen compressed, to second compressor or dispenser • Used oil • Waste heat • End of life compressor *Dispensing:* Inputs: • Electricity (European average) • Manufacture and maintenance of system components, auxiliaries Outputs: • Hydrogen fuel • Used oil • Waste heat • End of life dispenser
3.4. Cut-off criteria	*[State the flows which are cut-off or excluded and the expected impact of the cut-off.]* Coverage of at least 95 % value on each relevant environmental impact category (according to expert judgment). Waste from the desulphurisation unit in the form of zinc oxide was cut-off.

3.5. LCIA methods and categories	*[State which impact categories are chosen and if there are any limitations.]* The following impact categories are chosen: • Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Non-renewable Primary Energy Demand ($PED_{non\text{-}renewable}$) • Renewable Primary Energy Demand ($PED_{renewable}$) The following key figures are prepared: • GWP (kg CO_2 eq. / MJ H_2 @ 350 bar at ambient temperature) • AP (kg SO_2 eq. / MJ H_2 @ 350 bar at ambient temperature) EP (kg PO_4^- eq. / MJ H_2 @ 350 bar at ambient temperature) • POCP (kg C_2H_4 eq. / MJ H_2 @ 350 bar at ambient temperature) • $PED_{non\text{-}renewable}$ (MJ PED / MJ H_2 @ 350 bar at ambient temperature) • $PED_{renewable}$ (MJ PED / MJ H_2 @ 350 bar at ambient temperature). The method used is (CML 2011). Endpoint methods are not investigated in this study.
3.6. Type, quality and sources of required data and information	*[Describe the quality and the sources of the data and information required. Describe the closing of data gaps using comparable data.]* The data for the hydrogen production through steam reforming including the hydrogen supply to the filling station are provided by manufacturers and operators of the units within the CUTE project[13]. Two independent steam reformer sites and their associated hydrogen supply units are selected and modelled. The steam reforming units are averaged by a horizontal approach. The hydrogen supply units are also horizontally averaged. The data sources for the complete product system are fully consistent. The foreground data are supplied by the manufacturers and operators of the hydrogen production and supply units and are of high quality. The background data, including the electricity grid mix, the natural gas mix as well as material data sets for manufacturing, are primarily taken from the European Reference Life Cycle Database (ELCD) (JRC 2010d). Wherever necessary data sets are taken from the GaBi databases (2006) (LBP, PE 1992-2011).
3.7. Data quality requirements	*[Describe the data quality.]* According to the goal and scope definition (demonstrating the applicability of the guidance document) the data quality requirements are low. The data set covers all relevant process steps / technologies over the supply chain of the represented well-to-tank inventory with a good overall data quality.

[13] CUTE: Clean Urban Transport for Europe, funded by European Commission, 2001-2005, see also http://www.fuel-cell-bus-club.com

<table>
<tr><td></td><td>
The inventory is mainly based on industry data and is complemented, where necessary, by secondary data from literature. Data quality for the steam reforming and hydrogen supply units life cycle is very good; direct industry data from steam reformer and hydrogen supply unit producers and operators are available. Material and energy inputs including upstream processes are based on industry data, statistical data and various literature sources.
Natural gas supply is modelled on the basis of European statistical import mixes and detailed information on gas supply including logistics and gas gathering in main natural gas exporting countries. Electricity generation is modelled by European data on the basis of statistical grid mixes, as well as detailed information from power plant operating companies.
Illustration of the main aspects of the data quality rating
<table>
<tr><th>Component</th><th>Achieved quality level</th><th>Corresponding quality rating</th></tr>
<tr><td>Technological representativeness (TeR)</td><td>Poor</td><td>4</td></tr>
<tr><td>Geographical representativeness (GR)</td><td>Good</td><td>2</td></tr>
<tr><td>Time-related representativeness (TiR)</td><td>Poor</td><td>4</td></tr>
<tr><td>Completeness (C)</td><td>Good</td><td>2</td></tr>
<tr><td>Precision / uncertainty (P)</td><td>Fair</td><td>3</td></tr>
<tr><td>Methodological appropriateness and consistency (M)</td><td>Very good</td><td>1</td></tr>
</table>
Using these main aspects calculating the data quality rating of the LCI data set results in an overall data quality rating of 3.2. This is equivalent to “Data estimate”.
</td></tr>
<tr><td>3.8. Comparisons between systems</td><td>
[If there are comparisons between systems, describe the differences (reference flow, scope definitions, assumptions etc.)]
No different hydrogen production systems are compared.
</td></tr>
<tr><td>3.9. Identification of critical review needs</td><td>
[State whether a critical review is required or not, according to ILCD specifications]
Since the study is intended to be disclosed to the public a third party critical review is required by following the guidance document. However, a third party critical review is not performed because of the character being an example demonstrating the applicability of the guidance document only.
Anyway, an internal critical review is performed.
</td></tr>
</table>

4. Life Cycle Inventory Analysis of the study on hydrogen production

4.1. Identifying processes within the system boundary	*[Describe the processes being evaluated.]* The core processes in the hydrogen production by natural gas steam reforming, apart from the natural gas supply, is the desulphurisation of natural gas, the steam reforming process itself, the pressure swing adsorption and the purification of the produced hydrogen. The supply chain is completed by, the compression to 200 bar, the tube trailer hydrogen transport, and the second compression to 440 bar @ 85°C temperature, and dispensing. Thereby manufacturing, maintenance, transport and end of life of the main equipment is considered. The steam reformer process is divided into three steps for the generation of a hydrogen-rich reformate steam from steam-methane. The pre-treatment of the natural gas includes desulphurisation using activated carbon filters. The natural gas is then pressurised, preheated and mixed with process steam. Methane (Natural gas) and steam are converted in the presence of a nickel catalyst to a hydrogen rich reformate stream. After the reforming the synthesis gas is fed into the CO conversion reactor ("CO-shift") to produce additional hydrogen. The last step is the hydrogen purification reaching hydrogen purities higher than 99.995 % by volume and CO impurities of less than 1 vppm achieved by pressure swing adsorption (PSA). Pure hydrogen from the PSA unit is sent to the hydrogen compressor and brought to the filling station where the hydrogen is further compressed to a level of 440 bar @ 85°C temperature. The data set considers the whole supply chain of the natural gas upstream and the manufacture, the maintenance and the end of life of all necessary equipment (steam reformer, compressor, transport and filling station). The natural gas mix used, is modelled under European boundary conditions and is taken from the European Reference Life Cycle Database (ELCD) (JRC 2010d).
4.2. Data collection	*[Describe the data collection, e.g. how long the data were measured, in which way, etc.]* Foreground data or manufacturing data are collected using bill of material information. Data on energy demand for manufacturing, operation and end of life are collected from technical experts using questionnaires, site visits and through interviews. Data gaps were closed in collaboration with the technical experts using expert judgment. The following points can be stated: o Start up and shut down sequences are considered, o Regular maintenance is included, o Auxiliaries like pressurised air, etc. are included, o Down-time of steam reformer is included, o Seasonal influences are not relevant to this study, o "Business as usual" modelling of the steam reformer. For the steam reformer manufacturing, detailed data were only available for small scale steam reforming units (decentralised). For the large scale steam reformer (centralised, considered in this study) it is assumed that the scaling for infrastructure would follow the square root of the capacity factor of 500. As a conservative estimate an additional safety factor of 2 is applied. Under section

	6.3, the sensitivity analysis assumption is checked for relevance. Consumption data are measured between 1992 and 2003.
4.3. Selection of secondary LCI data	*[List the secondary data used and the underlying database or source]* The background data, like the electricity grid mix (EU-27) and natural gas mix (EU-25) as well as the material data sets for manufacturing are primarily taken from the European Reference Life Cycle Database (ELCD) (JRC 2010d). Wherever necessary data sets are taken from the GaBi databases (2006) (LBP, PE 1992-2011). Primary and secondary data are fully compliant.
4.4. Dealing with multi-functional processes	*[If multi-functionality occurs, show the influence of solving the multi-functionality. If allocation is used, show the results of the usage of different allocation factors.]* Steam as a co-product is produced and allocated by net calorific value (NCV) and for the sensitivity analysis by market value.
4.5. Consideration of re-use, recycling and energy recovery	*[State whether there is any re-use, recycling and/or energy recovery.]* The steam reformer, compressor and dispenser consist mainly of metal and a small amount of aluminium and polymers. End of life treatment for those parts is implemented. The assumed recycling rates range between 70 % for plastic and 98 % for steel.
4.6. Calculation of LCI results	*[Describe how the LCI results are calculated (e.g. Excel, LCA software). If a LCA software is used indicate which one.]* All results are calculated using the GaBi software system. In GaBi a parameterised plan system is set up which represents the technical system in an appropriate way. The GaBi model allows manifold analysis like hot sport analysis (significant issues), sensitivity analysis, Monte Carlo analysis etc.

5. Life Cycle Impact Assessment of the study on hydrogen production

5.1. Impact assessment, classification and characterisation

*[Replace the "**XX**", "**YY**" and "**ZZ**" by your results and prepare graphs of the results.]*

The method used is (CML 2011).

GWP: **0.106** kg CO_2 eq./MJ H_2 @ 350 bar, ambient temperature

AP: **2.290E-4** kg SO_2 eq./MJ H_2 @ 350 bar, ambient temperature

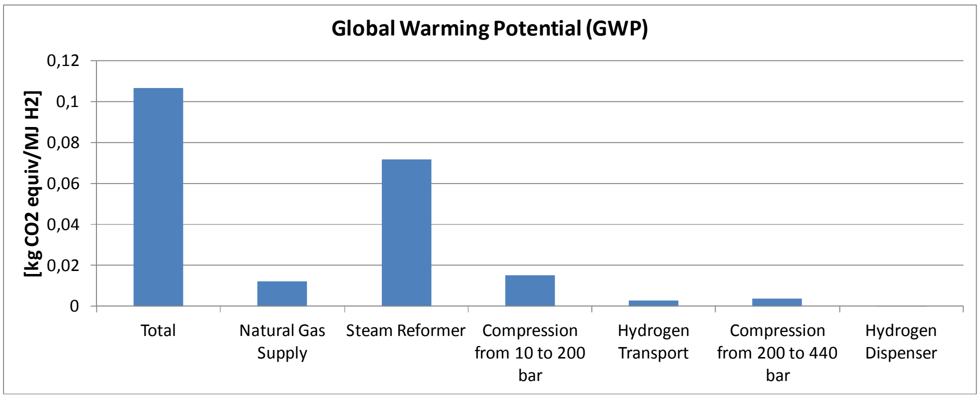
EP: **1.496E-5** kg PO_4^- eq./MJ H_2 @ 350 bar, ambient temperature

POCP: **1.835E-5** kg C_2H_4 eq./MJ H_2 @ 350 bar, ambient temperature

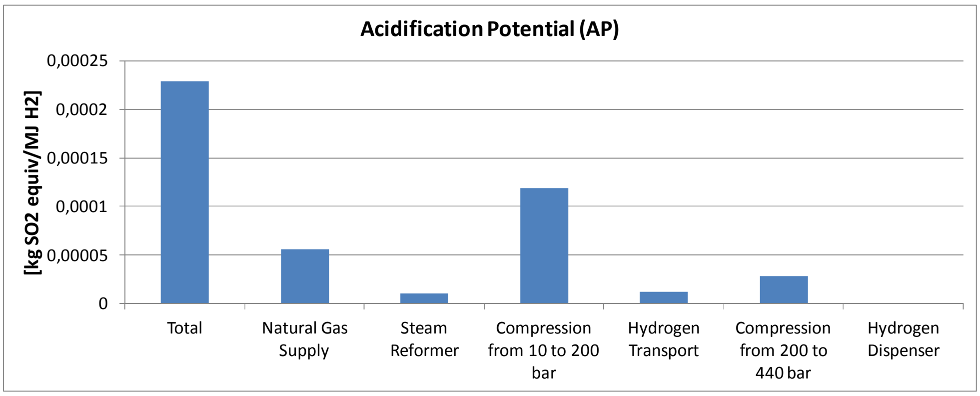
The environmental impact results are based on CML (CML 2011).

$PED_{non-renewable}$): **1.798** MJ/MJ H_2 @ 350 bar, ambient temperature

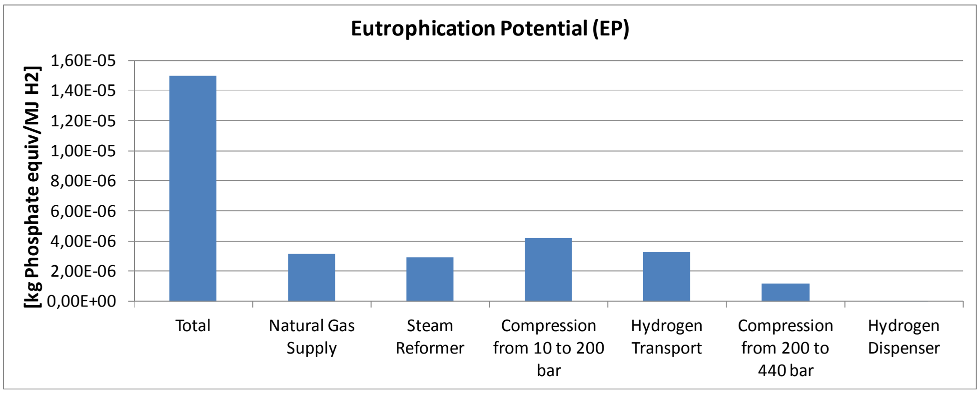
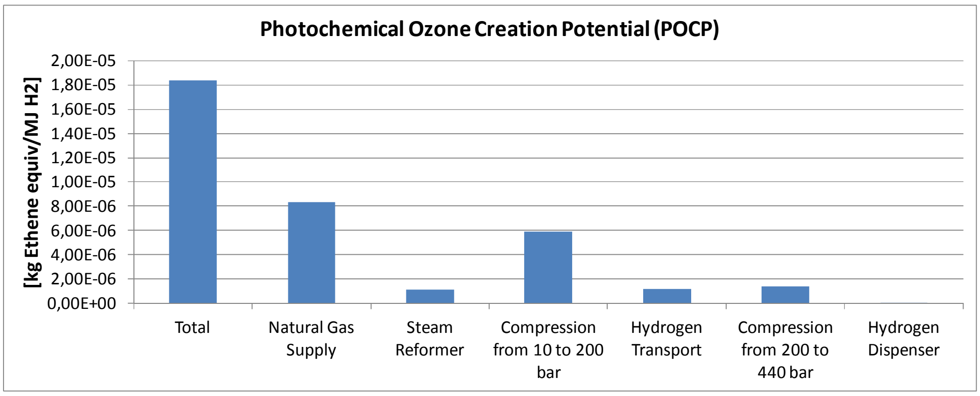
$PED_{renewable}$: **3.320E-2** MJ /MJ H_2 @ 350 bar, ambient temperature



The Steam Reformer contributes the most to the Global Warming Potential with a 67 % contribution to the total. Compression 1 accounts for 14 % and the natural Gas supply with 11 %. The Dispenser has a negligible impact on the Global Warming Potential.



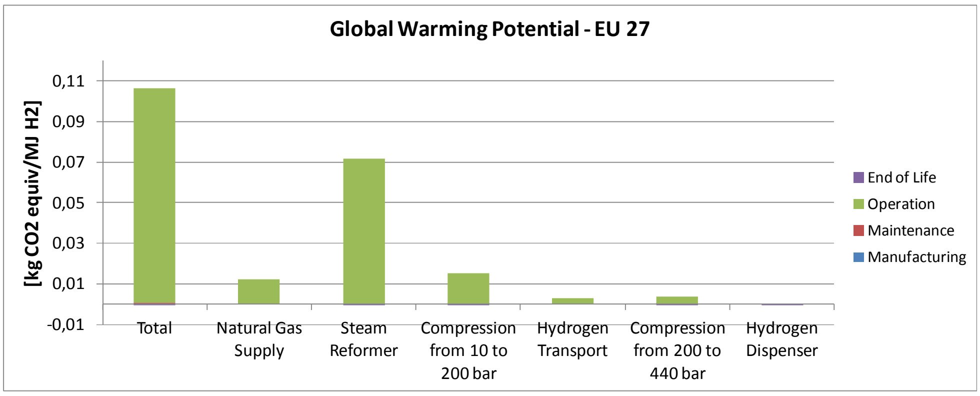
The first Compression stage has the highest impact on the Acidification Potential with a contribution a little over 50 %. Natural gas supply has almost half the impact as Compression (10-200 bar) contributing 25 % of the total. The second

	Compression stage an impact of approx. 12 %.  The Eutrophication Potential is most influenced by the first Compression step at 28 %, closely followed by the Truck transport at 22 %, Natural Gas at 21 % and the Steam Reformer at 20 %.  Natural gas is the highest contributor to the Photochemical Ozone Creation Potential at 46 %, followed by the first Compression step with 32 %.
5.2. Normalisation	*[State whether normalisation is applied or not. If applied, document it unambiguously.]* Normalisation of the LCIA results is not applied.
5.3. Grouping and Weighting	*[State whether grouping and/or weighting are applied or not. If applied, document it unambiguously.]* Grouping and weighting is not applied.

6. Interpretation and quality control of the study on hydrogen production

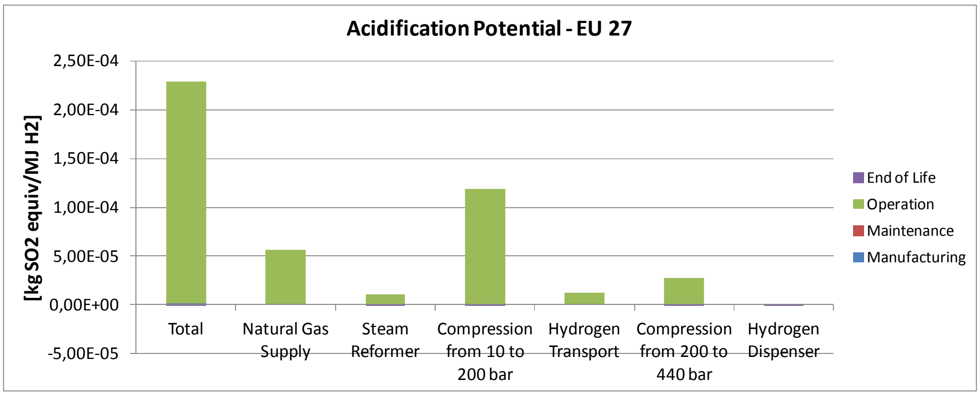
6.1. Identification of significant issues

[List and describe the significant issues. Show graphs of the significant issues if available]



The Operation phase dominates the environmental impacts during the 20 years lifetime of the steam reformer. Practically all of the greenhouse gas impacts occur in the Operation phase. Within the Steam Reformer, over 99 % of the impacts occur during the Operation phase.

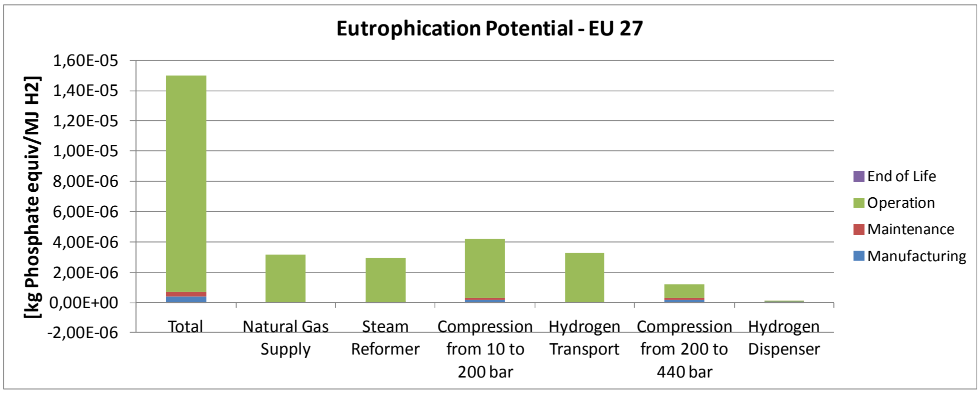
Focusing on the dispenser only, the greatest impact of the Dispenser occurs during Manufacturing, and due to recycling of materials (End of life).



The impact of the Acidification Potential is dominated also by its Operation phase. The Acidification Potential is measured in kg of SO_2 equivalent.

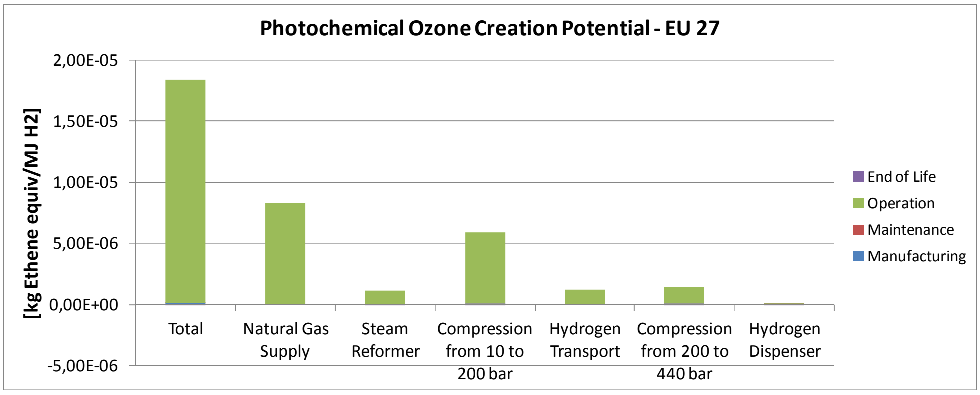
The first Compression stage has the greatest Acidification Potential impact, followed by the Natural Gas Supply. The second Compression stage follows.

Electricity supplied to the first Compressor accounts for 50.9 % of the AP.



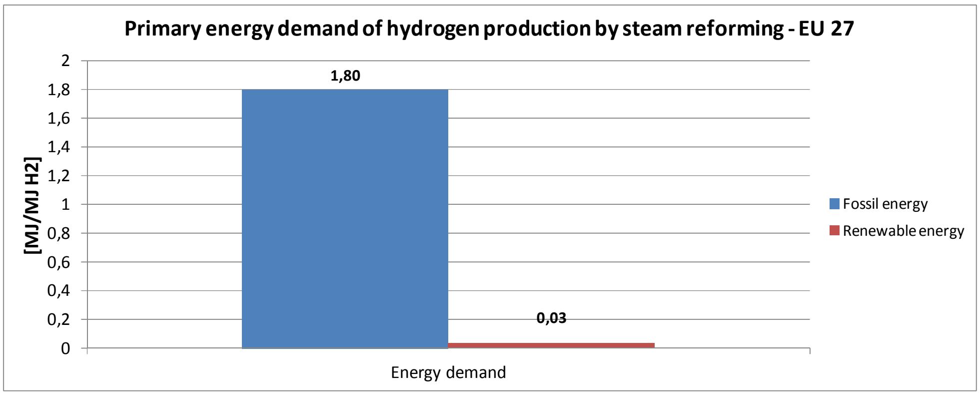
The Eutrophication Potential is also heavily influenced by the Operation phase at 92 %; however Manufacturing (3 %) and Maintenance (2 %) have a slightly greater impact share (left bar). Eutrophication is measured by kg of Phosphate equivalent. The stage with the greatest influence on the Eutrophication Potential is the first Compression stage, but is followed closely by the other stages, except for the second Compressor and Dispenser.

Hydrogen transport accounts for 21.8 % of the total EP, but only 6.59 % of the POCP.



Photochemical Ozone Creation Potential is dominated by the Operation phase with an overall share of about 99 %, the rest effectively coming from Manufacturing.

Almost half of the impact of Photochemical Ozone Creation Potential is caused by the Natural Gas supply at 46 %.



The required primary energy is provided by non-renewable energy, which can be expected from natural gas steam reforming. 66.3 % of the total PED from renewable sources is found in the European Electricity Grid Mix in the first

	Compression stage, and 15.9 % of total PED from non-renewable sources comes from the same Electricity Grid Mix.
6.2. Completeness check	*[Report the degree of completeness achieved]* All main processes are considered and have equal (or only slight differences of <5 %) input and output shares of mass and energy hence the law of conservation of energy and mass is met. Excluded flows satisfy the cut-off criteria.

6.3. Sensitivity check	*[Detail the results of the sensitivity check.]*

A) Efficiency and Scale Factor of Manufacturing

For the sensitivity check the efficiency was decreased from 79.8 % to 70 %, and increased to the maximum of 85 %.

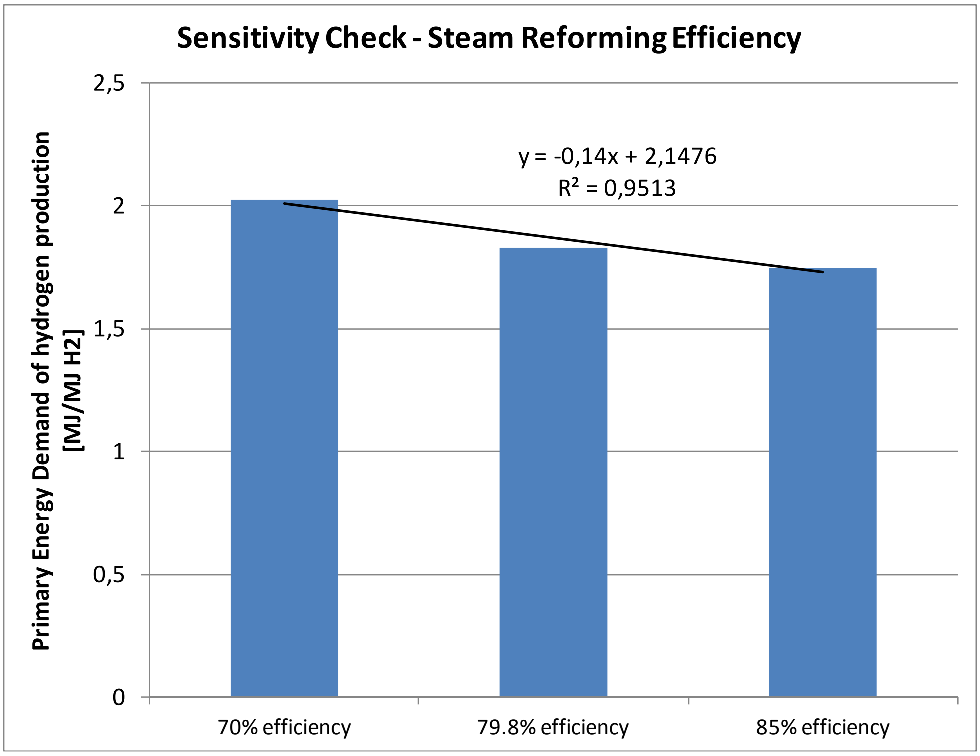
Decreasing the efficiency to 70 % affected the operation of the steam reformer, causing the Global Warming Potential for the steam reformer to increase by 14 % (an overall increase in GWP by 11 %).

Increasing the efficiency to 85 % results in an overall decrease in Global Warming Potential of 5 %, caused by a 6 % decrease in the steam reformer.

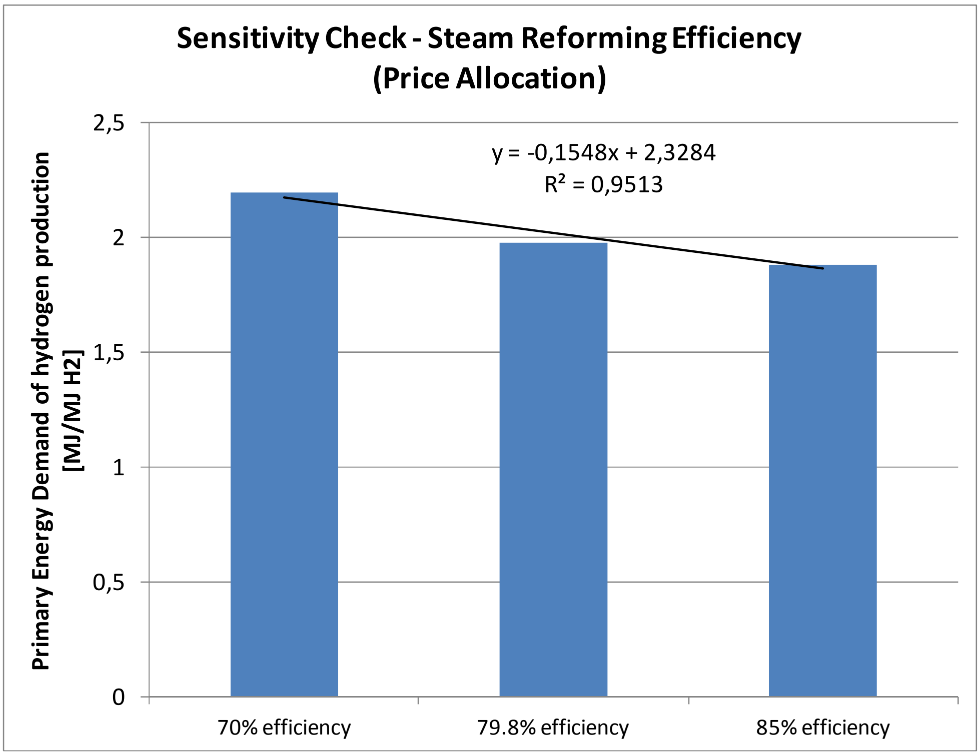
When the efficiency of the steam reformer is at 70 %, the result is a higher primary energy consumption (2 % higher renewable, 11 % higher non-renewable). Altering the efficiency of the steam reformer to the maximum value of 85 % results in a decreased in primary energy consumption (1 % less renewable, 5 % less non-renewable).

Setting the scale factor of the manufacturing to 1, thus representing a small scale steam reforming system, results in a maximum infrastructure impact of 0.006 % (EP). Scaling the model up to a factor of 500, the maximum impact value is 3 % (EP), which is still very small.

At the scale of the large scale centralised steam reformer, scale factor of 25, the maximum impact value is 0.16 % (EP).



B) Allocation

	When the allocation is according to market value rather than energy content, the share of Hydrogen increases from 87 % to 96.2 %, and the share of Steam decreases from 13 % to 3.85 %. The market value of Hydrogen per kg produced is 2.30€ (0.01917 €/MJ) and the market value of Steam per MJ is 0.00511€. Changing the allocation to market value from energy content results in a slightly higher, 8 %, Primary Energy Demand for the hydrogen supply, since a higher share of PED is allocated to hydrogen. 
6.4. Consistency check	*[Detail the results of the consistency check.]* Data, assumptions and methods are consistently applied throughout the study. They are in line with the goal and scope of the study.
6.5. Uncertainty check	*[Detail the results of the uncertainty check.]* No uncertainty check performed.

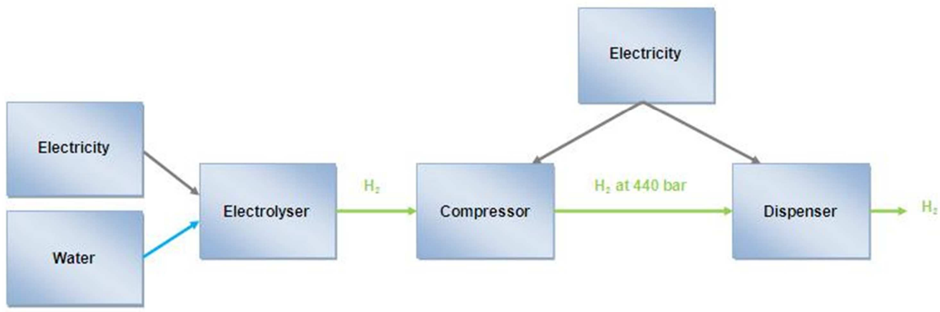
6.6. Conclusions, limitations and recommendations	*[State and explain the conclusions, limitations and recommendations.]* Conclusions: The majority of the environmental impacts during the lifetime of the steam reformer result from electricity and natural gas usage in the Operation phase. Limitations: Only Global Warming Potential, Acidification Potential, Eutrophication Potential, Photochemical Ozone Creation Potential and Primary Energy Demand are considered, and conclusions are drawn from these categories. Recommendations: The Operation phase is the most relevant with the highest impact in each impact category due to the electricity and natural gas used. When the steam reformer performs at a higher efficiency, the energy demand can reduce by as much as 5 %. Hence it is important, that data collected on natural gas and electricity consumed by the steam reforming unit itself as well as at the compressors are of high relevance for the overall results. For a more holistic approach, the study should be repeated with more impact categories such as ADP and HTP. Besides a third party critical review should be undertaken. In this case study a third party critical review was left out. Because the foreground and background data are from the reference years 1992-2003, newer, more current data can be used for more accurate results. The case study shows that the FC-HyGuide guidance document is applicable to LCAs on hydrogen production. The indented application of the case study is mainly to demonstrate the applicability of the guidance document rather than the environmental evaluation of the hydrogen production system. The LCA inventories are not to be used for any further analysis or study.

7. Critical Review of the study on hydrogen production

7.1. Critical Review	*[State and explain the results of the critical review or attach the report of the reviewer.]* An internal critical review is performed. The critical review was checking if the guidance is used in an appropriate way and if the LCA models were set up in an appropriate manner.

Electrolysis example

Executive Summary	*[Provide a short summary for non-technical audience.]* The study was carried out to test the applicability of the guidance document developed in the FC-HyGuide project, funded by the Fuel Cells and Hydrogen Joint Undertaking (FCH JU). It evaluates the environmental impacts and the primary energy demand of the production of compressed hydrogen by decentralised alkaline water electrolysis. The case study is documented following the LCA reporting template, developed in the FC-HyGuide project. In addition to this documentation a meta documentation of the LCI result (for demonstration purpose only) is provided. This meta documentation and the LCI results will be uploaded to the ILCD data network as an example for demonstration purposes only.
Technical Summary	*[Provide a short summary for technical audience. Address the system such as ISO 14040/14044 and/or ILCD with which the study complies.]* The study is an LCA of the decentralized electrolytic production of gaseous hydrogen at 440 bar @ 85°C temperature (350 bar @ ambient temperature) for mobile applications as used by end consumers at the hydrogen filling station. The analysis covers the whole hydrogen production chain from well-to-tank and includes the manufacturing, the operation and the end of life of all hydrogen production and supply units. Therefore also all burdens and credits associated with the recycling of the hydrogen production facilities are considered. The analysis is based on situation A (minor level) as defined in the ILCD Handbook. The study is compliant to ISO 14040, 14044 and to ILCD rules (whenever the study is not compliant to ILCD due to the case study character, it is highlighted in the report).
Main Part	
1. Product group	
1.1. Product information requested and standards to use	*[Provide information about the hydrogen properties and quality. Mandatory: purity, aggregate state, pressure, temperature Optional: impurities, quantity produced per year]* • Hydrogen, 99.995 % purity, gaseous, 440 bar @ maximum 85°C • Quantity produced: 60 Nm^3 H_2 per hour

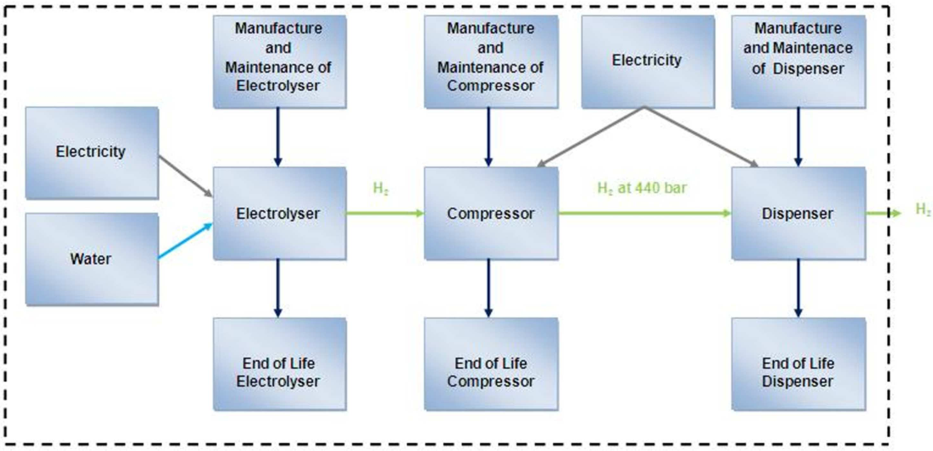
1.2. Producer's information requested	*[Provide information about the hydrogen producer:* *Mandatory: Overall H_2 production capacity, number of sites, production technology used, geographical coverage by region.* *Provide information about the hydrogen production system:* *Mandatory: Production technology used, year of construction, on-site electricity or heat production (if existing), production capacity, flow diagram* *Optional: location of the site; technical service life, type of production site (laboratory, commercial…), type of storage.]* • Generic study about on-site hydrogen production via alkaline water electrolysis. • Overall production capacity: Since several production sites from different manufacturers were averaged, the overall production capacity of all producers is unknown. • Number of sites: Hydrogen production is based on primary data from five European electrolyser sites and their associated hydrogen storage units. The data are completed by literature data. • Production Technology used: decentralised alkaline water electrolysis. • Breakdown of technologies used in hydrogen production system: Alkaline water electrolysis, on-site compression system to 440 bar @ 85°C temperature prior to dispensing. • Geographical coverage: The hydrogen production system represents average European boundary conditions. • Year of construction: Reference year of electrolyser data is 2003. • Actual production: not known, assumed 90 % utilisation. • Production capacity: 60 Nm^3 H_2 per hour. • Technical service lifetime: 20 years. • Type of production site: Pre-commercial. • Location of the production site under evaluation: average Europe. • Electricity is taken from the European electricity grid and in addition to the electricity grid the results are calculated by hydropower electricity supply. • Type of storage: no hydrogen storage in the supply system. • Total market share: Since several production sites from different manufacturers were averaged, the total market share of all producers is unknown. • Flow diagram of production route: 

2. Goal of the Life Cycle Assessment study on hydrogen production	
2.1. Intended application(s)	*[Describe the intended application(s), e.g.: Evaluation of a hydrogen production system, carbon footprint, comparison of different hydrogen production systems….]* The indented application of the case study is first to demonstrate the applicability of the guidance document itself and second the environmental evaluation of an electrolysis hydrogen production system. However, the key application is to check the applicability of the hydrogen guidance document.
2.2. Method, assumptions and impact limitations	*[Detail any assumptions or limitations.]* A “standard” evaluation (according to ISO 14044) of the environmental impacts and the primary energy demand (divided in renewable and non-renewable) of the product system is undertaken. The used impact method is based on CML (CML 2011). Investigated midpoint categories for the environmental and primary energy demand evaluation are: • Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Non-renewable Primary Energy Demand ($PED_{non\text{-}renewable}$) • Renewable Primary Energy Demand ($PED_{renewable}$) Endpoints are not investigated.
2.3. Reasons for carrying out the study	*[Unambiguously state the reason for carrying out the study.]* The case study is based on ILCD “situation A” to evaluate environmental impacts and the primary energy demand of hydrogen production by decentralised water electrolysis with electricity from the European grid mix. Again, focus of the generic desktop study is to check the applicability of the hydrogen guidance document.
2.4. Target audience	*[Describe the target audience, e.g.: Technical / non-technical audience; decision-makers etc.]* The target audience of this study is LCA practitioners and technical experts; therefore the focus is on technical aspects and details.
2.5. Comparisons intended to be disclosed to the public	*[State whether the study is comparative State whether the study is intended to be disclosed to the public.]* This is a non-comparative study. It is intended to be disclosed to the public as an example case study.
2.6. Commissioner of the study	*[Specify the commissioner of the study, (co)financier and/or other actors having direct/indirect influence on the study.]* Commissioner: FC-HyGuide project team, funded by the European Commission Fuel Cells and Hydrogen Joint Undertaking (FCH JU).

	Practitioner: PE INTERNATIONAL AG and University of Stuttgart, Chair of Building Physics, Department Life Cycle Engineering.
3. Scope of the Life Cycle Assessment study on hydrogen production	
3.1. Functional unit / Reference flow	*[State a hydrogen purity standard or complete the gaps in the reference flow below:]* Functional unit: 1 MJ of hydrogen (net calorific value (NCV)). Reference flow: 1 MJ of hydrogen (net calorific value (NCV)) with 99.995 % purity and 440 bar @ maximum 85°C (350 bar @ ambient temperature)
3.2. Multi-functionality	*[If multi-functionality occurs state which method is chosen to solve multi-functionality.]* Since oxygen produced via water electrolysis is technically not used as a co-product, no multi-functionality occurred.

3.3. System boundary	*[Describe the system boundary and show it graphically through a Flow chart. List the flows taken into consideration.]*

The system under investigation is the hydrogen production "well-to-tank" by decentralised small scale water electrolysis. The data set considers the entire supply chain from the electricity supply from the European electricity grid mix respectively from hydropower, the electrolysis, compression of the produced hydrogen and dispensing unit.
Thereby manufacturing, maintenance, transport and end of life of the main equipment is considered.



The main processes of this study are the electrolysis, the compression of the hydrogen from 14 to 440 bar @85 temperature) and the dispensing (350 bar @ ambient temperature) of the hydrogen up to the tanking nozzle. For the three main parts the manufacturing, maintenance and end of life processes are also included.

Relevant flows:

Electrolysis:

- Inputs
  - Electricity (based on European average and hydropower)
  - Tap water for electrolysis
  - Manufacture and maintenance of the electrolyser, auxiliaries
- Outputs
  - Hydrogen to compressor
  - End of life electrolyser

Compression:

- Inputs
  - Electricity (based on European average and hydropower)
  - Manufacture and maintenance of the compressor, auxiliaries like lubricating oil
- Outputs

	o Hydrogen compressed, to dispenser o Used oil o Waste heat o End of life compressor Dispensing: • Inputs o Electricity (based on European average and hydropower) o Manufacture and maintenance of the dispenser, auxiliaries • Outputs o Gaseous hydrogen o Used oil o Waste heat o End of life dispenser
3.4. Cut-off criteria	*[State the flows which are cut-off or excluded and the expected impact of the cut-off.]* Coverage of at least 95 % value on each relevant environmental impact category (according to expert judgment). Oxygen emissions to air, produced at the electrolyser, are cut-off since they are considered to have no associated environmental impacts.
3.5. LCIA methods and categories	*[State which impact categories are chosen and if there are any limitations.]* The following impact categories are chosen: • Global Warming Potential (GWP) • Acidification Potential (AP) • Eutrophication Potential (EP) • Photochemical Ozone Creation Potential (POCP) • Non-renewable Primary Energy Demand ($PED_{non-renewable}$) • Renewable Primary Energy Demand ($PED_{renewable}$) The following key figures are prepared: • GWP: (kg CO_2 eq. / MJ H_2 @ 350 bar at ambient temperature) • AP: (kg SO_2 eq. / MJ H_2 @ 350 bar at ambient temperature) • EP: (kg PO_4^- eq. / MJ H_2 @ 350 bar at ambient temperature) • POCP: (kg C_2H_4 eq. / MJ H_2 @ 350 bar at ambient temperature) • $PED_{non-renewable}$: (MJ PED / MJ H_2 @ 350 bar at ambient temperature) • $PED_{renewable}$: (MJ PED / MJ H_2 @ 350 bar at ambient temperature) The method used is based on (CML 2011). Endpoint methods are not investigated in this study.

3.6. Type, quality and sources of required data and information	*[Describe the quality and the sources of the data and information required. Describe the closing of data gaps using comparable data.]* The data for the hydrogen production through electrolysis including the hydrogen supply to the filling station are provided by manufacturers and operators of the units within the CUTE project[14]. Five independent electrolyser sites and their associated hydrogen supply units are selected and modelled. The electrolysers are averaged by a horizontal approach. The hydrogen supply units are also horizontally averaged. The data sources for the complete product system are fully consistent. The foreground data are supplied by the manufacturers and operators of the hydrogen production and supply units and are of high quality. The background data, like the electricity grid mix as well as the material data sets for manufacturing are primarily taken from the European Reference Life Cycle Data System (ELCD) (JRC 2010d). As second data source, data sets are taken from the GaBi databases (2006) (LBP, PE 1992-2011).
3.7. Data quality requirements	*[Describe the data quality.]* According to the goal and scope definition (demonstrating the applicability of the guidance document) the data quality requirements are low. The data set covers all relevant process steps / technologies over the supply chain of the represented well-to-tank inventory with a good overall data quality. The inventory is mainly based on industry data and is complemented, where necessary, by secondary data from literature. Data quality for electrolyser and hydrogen supply units life cycle is very good; direct industry data from electrolyser and hydrogen supply unit producers and operators are available. Material and energy inputs including upstream processes are based on industry data, statistical data and various literature sources. Electricity generation is modelled by European data on the basis of statistical grid mixes as well as detailed information from power plant operating companies. Illustration of the main aspects of the data quality rating

Component	Achieved quality level	Corresponding quality rating
Technological representativeness (TeR)	Very good	1
Geographical representativeness (GR)	Good	2
Time-related representativeness (TiR)	Poor	4
Completeness (C)	Good	2
Precision / uncertainty (P)	Fair	3
Methodological appropriateness and consistency (M)	Very good	1

Using these main aspects calculating the data quality rating of the LCI data set

[14] CUTE: Clean Urban Transport for Europe, funded by European Commission, 2001-2005, see also http://www.fuel-cell-bus-club.com

	results in an overall data quality rating of 2.9. This is equivalent to “Basic quality”
3.8. Comparisons between systems	*[If there are comparisons between systems, describe the differences (reference flow, scope definitions, assumptions etc.)]* No different hydrogen production systems are compared.
3.9. Identification of critical review needs	*[State whether a critical review is required or not, according to ILCD specifications]* Since the study is intended to be disclosed to the public a third party critical review is required by following the guidance document. However, a third party critical review is not performed because of the character being an example demonstrating the applicability of the guidance document only. Anyway, an internal critical review is performed.

4. Life Cycle Inventory Analysis of the study on hydrogen production

4.1. Identifying processes within the system boundary	*[Describe the processes being evaluated.]* The core processes in the hydrogen production by water electrolysis is the electrolysis itself, followed by compression and concluded with the dispensing. This part of the system is called foreground system. The background processes are the electricity processes, water supply for electrolysis and auxiliaries like lubricants and compressed air for the compression. The core processes require electric power which is provided by the European electricity grid mix respectively by hydropower. Manufacturing, maintenance and end of life is also included for the electrolyser, the compressor and the dispenser, containing the required steel, copper, aluminium, polymer etc. compounds as well as required energy for the assembly of the parts.

4.2. Data collection	*[Describe the data collection, e.g. how long the data were measured, in which way, etc.]* Foreground data or manufacturing data are collected using bill of material information. Data on energy demand for manufacturing, operation and end of life are collected from technical experts using questionnaires, site visits and through interviews. Data gaps were closed in collaboration with the technical experts using expert judgment. The following points can be stated: o Start-up and shut-down sequences are included, o Regular maintenance is included, o Auxiliaries like pressurised air, etc. are included, o Down-time of electrolyser is included, o Seasonal influences are not relevant to this study, o “Business as usual” modelling of the Electrolyser. Reference year of foreground data collection is 2003 and for background data the reference year is 2002.
4.3. Selection of secondary LCI data	*[List the secondary data used and the underlying database or source]* The background data, like the electricity grid mix (EU-27) / hydropower mix (RER) as well as the material data sets for manufacturing are primarily taken from the European Reference Life Cycle Data System (ELCD) (JRC 2010d). As second data source, data sets are taken from the GaBi databases (2006) (LBP, PE 1992-2011). Primary and secondary data are fully compliant.
4.4. Dealing with multi-functional processes	*[If multi-functionality occurs, show the influence of solving the multi-functionality. If allocation is used, show the results of the usage of different allocation factors.]* There is no multi-functionality in the hydrogen production system via water electrolysis (foreground system).
4.5. Consideration of re-use, recycling and energy recovery	*[State whether there is any re-use, recycling and/or energy recovery.]* The electrolyser, compressor and dispenser consist mainly of metal and a small amount of plastic. End of life treatment for those parts is implemented. The assumed recycling rates range between 70 % for plastic and 98 % for steel. According to the manufacturers, the parts have no precious metal compound so precious metal recycling for those is not considered.
4.6. Calculation of LCI results	*[Describe how the LCI results are calculated (e.g. Excel, LCA software). If a LCA software is used indicate which one.]* All results are calculated using the GaBi software system. In GaBi a parameterised plan system is set up which represents the technical system in an appropriate way. The GaBi model allows manifold analysis like hot sport analysis (significant issues), sensitivity analysis, Monte Carlo analysis etc.

5. Life Cycle Impact Assessment of the study on hydrogen production

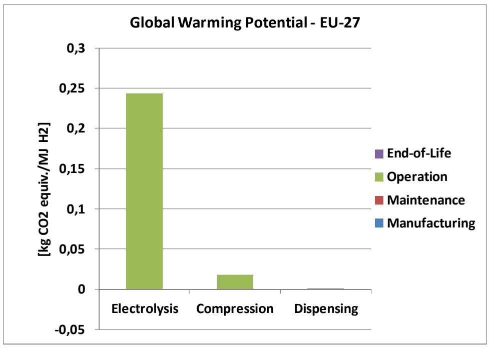
5.1. Impact assessment, classification and characterisation

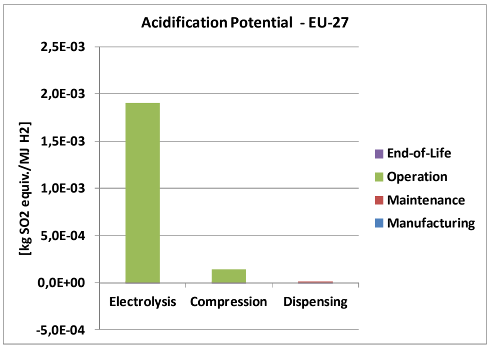
*[Replace the “**XX**”, “**YY**” and “**ZZ**” by your results and prepare graphs of the results.]*

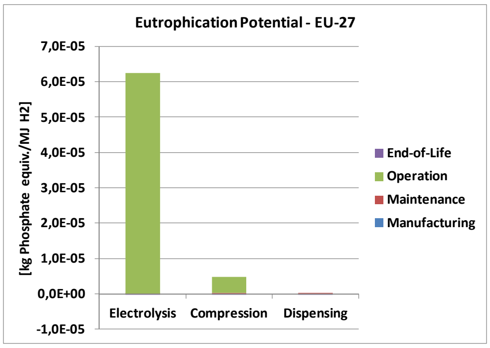
The method used is (CML 2011).

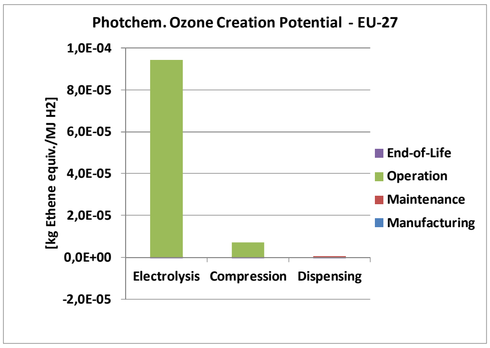
<u>Electrolysis with the European electricity grid mix:</u>

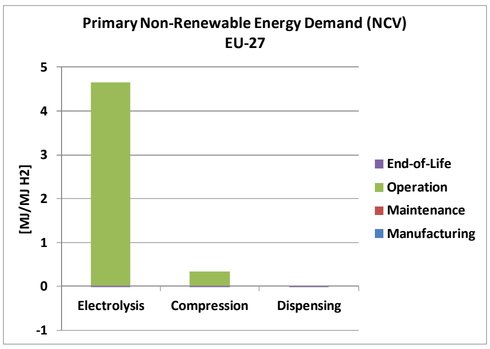
GWP: **0.261** kg CO_2 eq. / MJ H_2 @ 350 bar, ambient temperature
AP: **2.04E-03** kg SO_2 eq. / MJ H_2 @ 350 bar, ambient temperature
EP: **6.74E-05** kg PO_4^- eq. / MJ H_2 @ 350 bar, ambient temperature
POCP: **1.01E-04** kg C_2H_4 eq. / MJ H_2 @ 350 bar, ambient temperature
$PED_{non-renewable}$: **5.0** MJ PED/ MJ H_2 @ 350 bar, ambient temperature
$PED_{renewable}$: **0.385** MJ PED/ MJ H_2 @ 350 bar, ambient temperature

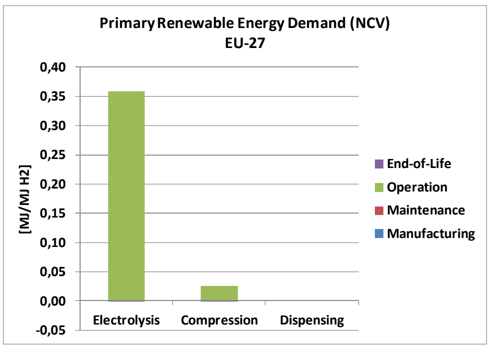












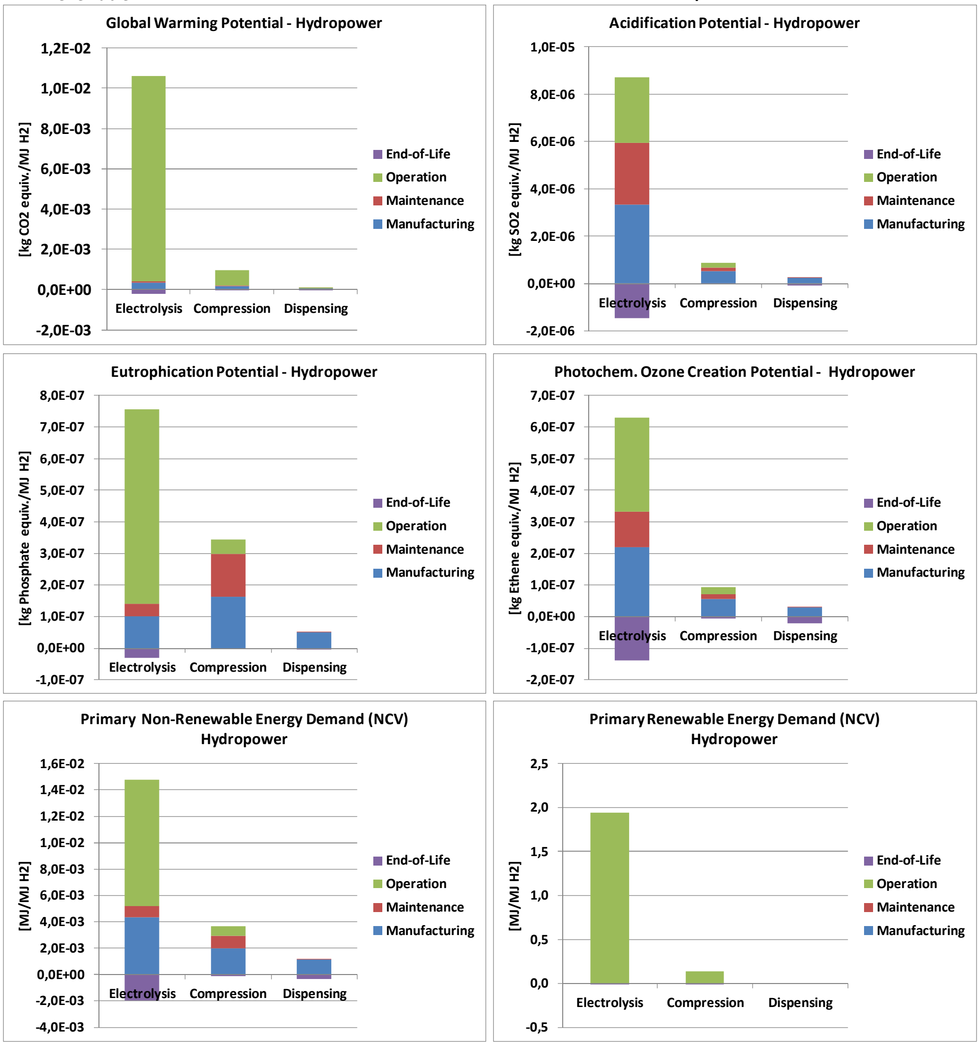
As can be seen, the operation phase is the main contributor. The compression has a share of about 5 % of the total impacts. The dispensing is negligible.

<u>Electrolysis with hydropower:</u>

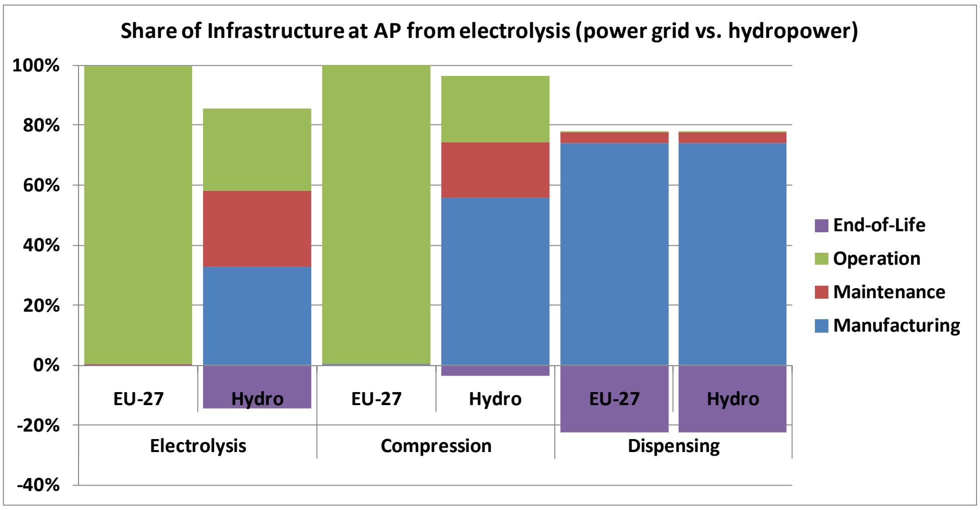
GWP: **0.0113** kg CO_2 eq. / MJ H_2 @ 350 bar, ambient temperature
AP: **8.31E-06** kg SO_2 eq. / MJ H_2 @ 350 bar, ambient temperature
EP: **1.12E-06** kg PO_4^- eq. / MJ H_2 @ 350 bar, ambient temperature

POCP: **5.90E-07** kg C_2H_4 eq. / MJ H_2 @ 350 bar, ambient temperature

$PED_{non\text{-}renewable}$: **0.017** MJ PED/ MJ H_2 @ 350 bar, ambient temperature
$PED_{renewable}$: **2.079** MJ PED/ MJ H_2 @ 350 bar, ambient temperature



For the hydropower the relative share of manufacturing, maintenance and end of life become more relevant. But the total impacts decline drastically. When hydropower is used, primary energy demand from renewables logically increases.

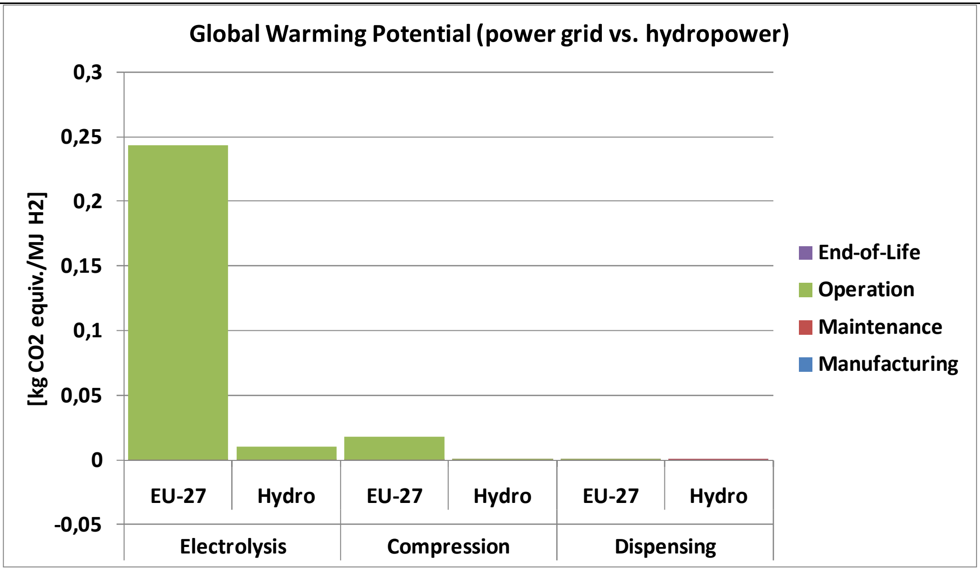


The share of maintenance, manufacturing and end of life becomes significantly more relevant when hydropower is used as can be seen in the upper diagram for AP as an example category.

5.2. Normalisation	*[State whether normalisation is applied or not. If applied, document it unambiguously.]* Normalisation of the LCIA results is not applied.
5.3. Grouping and Weighting	*[State whether grouping and/or weighting are applied or not. If applied, document it unambiguously.]* Grouping and weighting is not applied.

6. Interpretation and quality control of the study on hydrogen production

6.1. Identification of significant issues	*[List and describe the significant issues. Show graphs of the significant issues if available]* • For the water electrolysis the used electricity is crucial for the determination of the environmental impacts. • Main contributor is the operation of the electrolyser itself because of the required electricity. The hydrogen compression has a share of about 7 % (EU-27 grid) in each category of the total impacts, the dispenser is negligible. The share of the compression increases when hydropower is used • Environmental impacts decline drastically when renewable electricity like hydropower is used • Infrastructure becomes environmental relevant when renewable energy is used



The operation phase is dominating the environmental impacts during the lifespan of 20 years for the electrolyser. For the EU-27 grid mix 99.5 % of the greenhouse gas impact occurs in the operation phase. About 93 % of the total impacts for greenhouse gases occur in the electrolysis, the rest occur in the compression. The dispensing is negligible. When hydropower is used instead of the grid mix the global warming potential can be reduced over 95 %. The following tables show the results of the other measured impact categories:

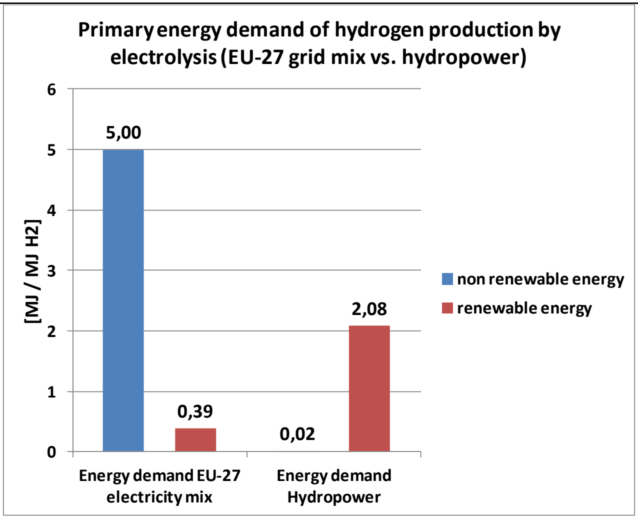
	Electrolysis					Compression				
	EU-27	Hydropower	Hydro/EU-27	% of total EU-27	% of total Hydro	EU-27	Hydropower	Hydro/EU-27	% of total EU-27	% of total Hydro
GWP	2,43E-01	1,04E-02	4,28%	93,09%	91,40%	1,80E-02	9,50E-04	5,28%	6,90%	8,36%
EP	6,25E-05	7,26E-07	1,16%	92,70%	64,92%	4,87E-06	3,43E-07	7,05%	7,23%	30,69%
AP	1,90E-03	7,27E-06	0,38%	93,15%	87,45%	1,40E-04	8,64E-07	0,62%	6,85%	10,40%
POCP	9,42E-05	4,91E-07	0,52%	93,11%	83,28%	6,96E-06	8,77E-08	1,26%	6,88%	14,86%
PED ren.	3,59E-01	1,94E+00	539,83%	93,13%	93,16%	2,64E-02	1,42E-01	538,49%	6,85%	6,83%
PED non ren.	4,65E+00	1,28E-02	0,28%	93,10%	74,36%	3,44E-01	3,54E-03	1,03%	6,88%	20,50%

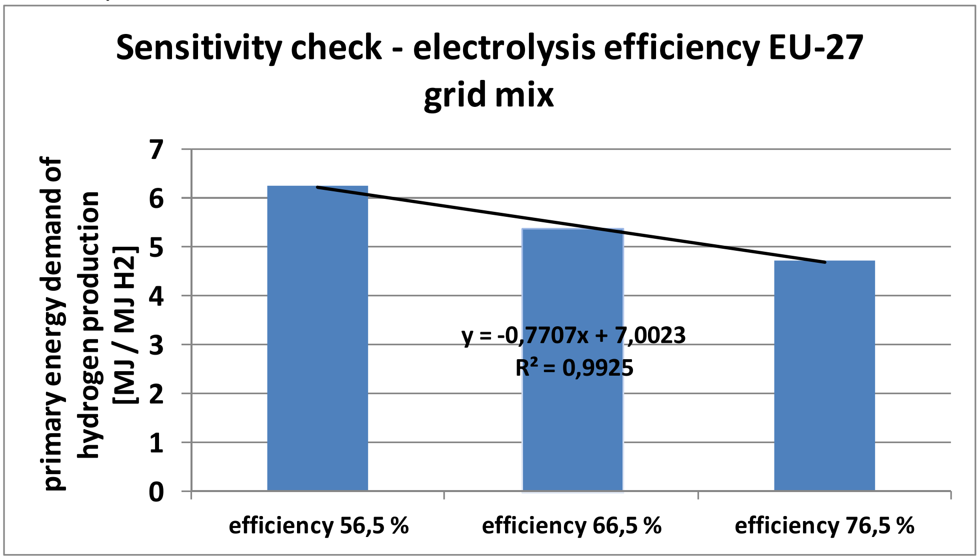
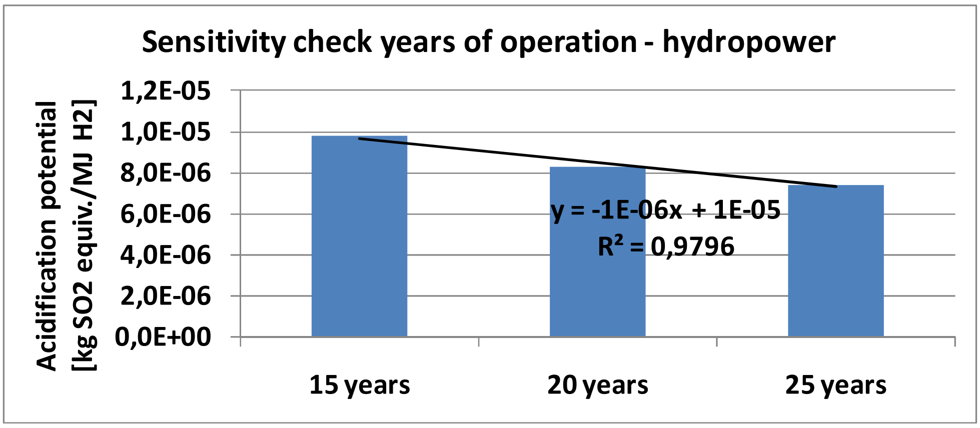
Dispension					Total		
EU-27	Hydropower	Hydro/EU-27	% of total EU-27	% of total Hydro	EU-27	Hydropower	% Hydro/Total
2,78E-05	2,77E-05	99,94%	0,01%	0,24%	2,61E-01	1,14E-02	4,36%
4,91E-08	4,91E-08	99,99%	0,07%	4,39%	6,74E-05	1,12E-06	1,66%
1,79E-07	1,79E-07	99,93%	0,01%	2,15%	2,04E-03	8,31E-06	0,41%
1,10E-08	1,10E-08	99,94%	0,01%	1,86%	1,01E-04	5,90E-07	0,58%
6,35E-05	6,36E-05	100,16%	0,02%	0,00%	3,85E-01	2,08E+00	539,67%
8,87E-04	8,87E-04	99,97%	0,02%	5,14%	5,00E+00	1,73E-02	0,35%

Explanation of Tables:

- % Hydro/EU-27: Hydropower has an X % share of the EU-27 amount in this part.
- % of total EU-27: e.g. the electrolysis contributes to 93.09 % of the total GWP when the electricity grid mix is used.
- % of total Hydro: e.g. the electrolysis contributes to 91.40 % of the total GWP when hydropower is used.

As can be seen in the first table, in every category investigated, over 90 % of the total impacts are associated with the electrolysis process due to the electricity supply. This share declines e.g. for EP to 65 % when hydropower is used. By replacement the significance of the manufacturing and maintenance increases. Hydropower contributes to GWP less than 5 % of the total EU-27 electricity grid impacts, for EP less than 2 %, for AP, POCP and non-renewable primary energy less than 1 %. Renewable primary energy increases significantly when hydropower is used which can be seen in the following diagram:

	 Renewable primary energy demand has a share of about 7 % for the grid mix and more than 99 % for hydropower. The total primary energy demand can be reduced about nearly 60 % when hydropower is used instead of the European grid mix. Non-renewable primary energy demand can be reduced over 99.5 % when hydropower is used.
6.2. Completeness check	*[Report the degree of completeness achieved]* All main processes are considered and have equal (or only slight differences <5 %) input and output shares of mass and energy hence the law of conservation of energy and mass is met. Excluded flows satisfy the cut-off criteria.

6.3. Sensitivity check	*[Detail the results of the sensitivity check.]* **Electrolysis with EU-27 grid mix:** One major parameter of the hydrogen supply by electrolysis is the efficiency of the electrolyser. A sensitivity check has been performed to check the influence of efficiency:  Shows the expected results. Altering the efficiency of the electrolyser +/- 10 % points results in less respectively higher energy consumption with an approximately linear correlation. Other investigated impact categories follow the same correlation. **Electrolysis with Hydropower:** Like previously stated the infrastructure becomes more important when hydropower is used. One parameter which is crucial for the infrastructure is the electrolyser operation life span. A sensitivity check has been performed to check the influence of operation time. Exemplary the results for the Acidification are shown.  Acidification impacts occur in high share in the manufacturing phase. Altering the years of operation of the electrolyser (+/- 5 years) results in less respectively higher AP with an approximately linear correlation. Other impact categories follow the same correlation.

6.4. Consistency check	*[Detail the results of the consistency check.]* Data, assumptions and methods are consistently applied throughout the study. They are in line with the goal and scope of the study.
6.5. Uncertainty check	*[Detail the results of the uncertainty check.]* No uncertainty check performed.
6.6. Conclusions, limitations and recommendations	*[State and explain the conclusions, limitations and recommendations.]* Conclusions: The majority of the environmental impacts during the lifespan of the electrolyser occur from electricity usage in the operation phase. Especially when the European electricity grid mix is consumed. The share of maintenance, manufacturing and end of life becomes significantly more relevant when hydropower is used instead of grid electricity. Nevertheless, the total impacts decline to very small shares in comparison with the electricity grid mix. Limitations: Only Global Warming Potential, Acidification Potential, Eutrophication Potential, Photochemical Ozone Creation Potential and Primary Energy Demand are considered, and conclusions are drawn from these categories. Recommendations: For example greenhouse gasses can be significant lowered when renewable energy (or at least a high share) is used. The use phase (operation) is the most relevant phase in most impact categories due to the dependency on the used electricity. GWP can be reduced over 95 %, and total primary energy demand about 60 % when electricity from the grid is substituted by hydropower. Higher efficiency of the electrolyser can reduce the total primary energy demand clearly (e.g. about 12 % less PED with 15 % more efficiency compared to the case EU-27 grid is used). For a more holistic approach, the study should be repeated with more impact categories like ADP and HTP. Besides a third party critical review should be undertaken – for the case study this has been left out. Because the reference years of the foreground and background data are 2003, it can be considered to collect more up-to-date data for better data quality. The case study also shows that the FC-HyGuide guidance document is applicable to LCAs on hydrogen production. The indented application of the case study is mainly to demonstrate the applicability of the guidance document rather than the environmental evaluation of the hydrogen production system. The LCA inventories are not to be used for any further analysis or study.

7. Critical Review of the study on hydrogen production

7.1. Critical Review	*[State and explain the results of the critical review or attach the report of the reviewer.]* An internal critical review is performed. The critical review was checking if the guidance is used in an appropriate way and if the LCA models were set up in an appropriate manner.