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JRC TECHNICAL REPORT

Life Cycle Assessment of Hydrogen and Fuel Cell Technologies

Inventory of Work performed by Projects funded under FCH JU

Melideo, Daniele

Ortiz Cebolla, Rafael

Weidner, Eveline

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Contact information
Name: Daniele Melideo
Address: P.O. Box 2, NL-1755 ZG Petten - The Netherlands
Email: daniele.melideo@ec.europa.eu
Tel.: +31 (0)224565112

EU Science Hub
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FUEL CELLS AND HYDROGEN
JOINT UNDERTAKING

Abstract

This report is the public version of the deliverable B.3.7 "Life cycle assessment of Hydrogen and Fuel Cell Technologies - Inventory of work performed by projects funded under FCH JU"; it provides an overview of the progress achieved so far and a comprehensive analysis on Life Cycle Assessment (LCA) for various hydrogen technologies and processes. The review considers 73 Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) funded projects: for some of those the LCA study was requested in the call topic, while other projects decided to perform the LCA study on a voluntary basis.

The LCAs have been assessed regarding the adherence to guideline recommendations (e.g. reported properties, system boundary definitions, goal and scope definitions), methodology and overall quality of the work. Methodology is a critical issue for the comparability of results, as this is only possible if all LCAs follow the same guidelines; in addition, LCAs were often only partially fulfilling the selected guideline requirements. It is recommended that future FCH 2 JU call topics asking for environmental analysis to be performed are setting out some minimum requirements, such as the guidelines to be used and the impacts to be assessed.

Based on the outcome of this analysis, a harmonisation effort in the approach to LCA for the FCH JU funded projects is proposed; in particular a Life Cycle Inventory (LCI) database useful for the projects is required togheter with the identification of a reference cases to be used as benchmark for future LCAs.

1 Introduction

Life Cycle Assessment (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 14040]

One of the key drivers for the energy transition is reducing the emission of greenhouse gases (GHGs). There are other harmful emissions produced during combustion such as mono-nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), volatile organic compounds (VOCs), and particulate matter (PM). Fuel cells and hydrogen technologies have the potential to reduce emissions of greenhouse gases and air pollutants. They can also facilitate the use of renewable energy sources and thereby contribute to a more sustainable energy system. However, the complete fuel cell and hydrogen technology value chain needs to be assessed in order to determine the environmental impacts of these technologies. The appropriate method for this is LCA.

LCA is a structured and internationally standardised method to quantify all relevant emissions and consumed resources. It is meant to assess all the related environmental and health impacts and resource depletion issues that are associated with any good or service ("products") [1]. LCA covers the whole chain from the extraction of resources, through production, use, and recycling, up to the disposal of the remaining waste. A comprehensive approach is needed in order to assess the environmental benefit of any new emerging technology. To achieve sustainable production and consumption patterns, the environmental impact of the entire life cycle of products from "cradle to grave" should be considered.

The Council Regulation (559/2014) establishing the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH 2 JU) has set out a number of overarching objectives for the programme. These objectives do not directly address environmental impacts, but the reduction in the use of EU-defined 'critical raw materials' relates to the development of a circular economy, which is seen as one of the key aims for the programme.

According to the FCH JU Multi-Annual Work Programme (MAWP), "it is expected that LCA will be performed at both project and programme levels" [2], in order to enable an assessment of the environmental impact of FCH technologies with a tool that is already used by industry and policy sectors. The MAWP also states the intention to target emissions reduction and resource conservation at all stages of the life-cycle [2].

To prepare for a consistent methodology, the Annual Implementation Plans of 2008 and 2009 contained call topics designed to develop a framework for LCA dedicated to FCH technologies, with the goal to provide guidance on how to conduct LCA. The FC-HyGuide project delivered detailed technical guidance, providing information on how to deal with key methodological aspects of LCA (such as definition of a functional unit, system boundary, allocation rules, relevant impact categories, etc.). This methodology was to be applied subsequently to the LCA performed in FCH JU funded projects [3, 4] (referred to as LCA deliverables in the following sections).

Meanwhile a large number of projects under both FCH JU and FCH 2 JU have performed work on LCA for various technologies and processes. This report is the public version of the deliverable B.3.7 "Life cycle assessment of Hydrogen and Fuel Cell Technologies - Inventory of work performed by projects funded under FCH JU"; it is meant to provide the FCH 2 JU with an overview of the progress achieved so far in this field, and contains an in-depth analysis on LCA methodology aspects. Following a description of the JRC approach to the evaluation of LCA deliverables in Section 2, an inventory is provided in Section 3, containing basic information on the deliverables such as the technologies covered. The methodological choices made in the various deliverables are reviewed in Section 4. This analysis is structured according to the LCA framework as depicted in

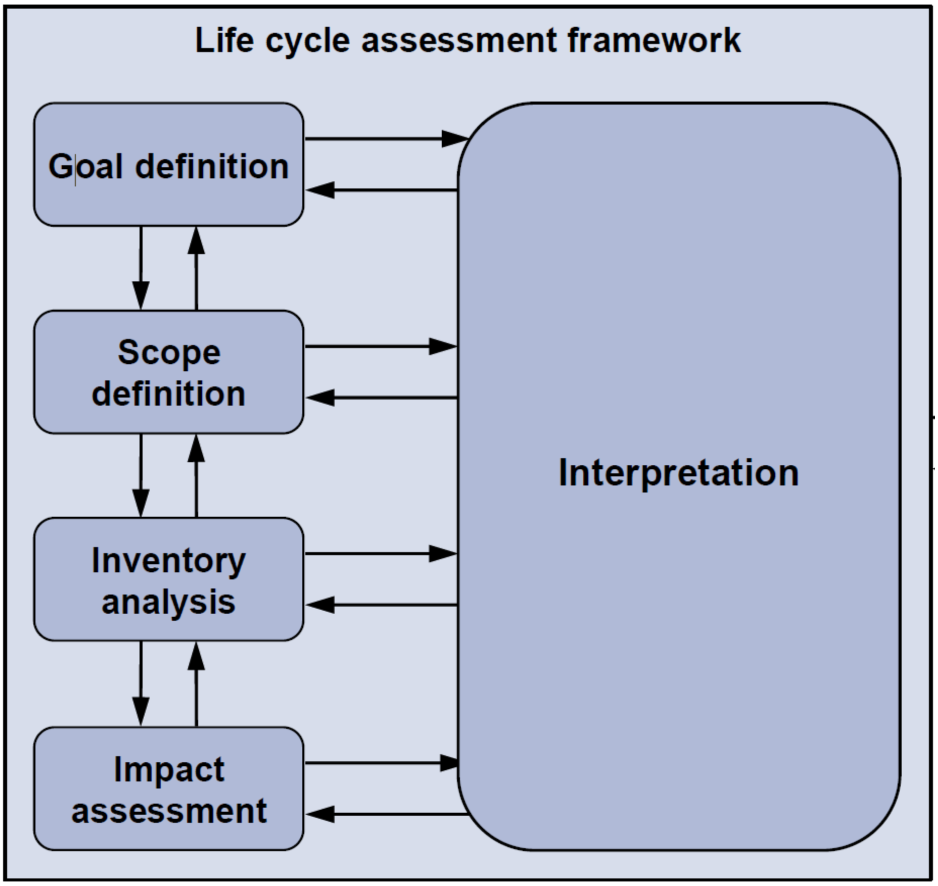
Figure 1 (i.e. goal definition, scope definition, inventory analysis and impact assessment). Conclusions are drawn in Section 5, and recommendations for the FCH JU programme are provided.

The basis of the LCA guidance documents delivered by the FC-HyGuide project are the above mentioned LCA ISO standards. The ISO standards describe the two key elements of an LCA:

- the assessment of the entire life cycle of the investigated system;
- the assessment of the set of environmental impacts.

According to ISO standards, LCA consists of four main steps (Figure 1). An LCA begins with the Goal and Scope Definition. Here, the product or process, the data sources, the functional unit - i.e. the reference for all related inputs and outputs and system boundaries are described. The selection criteria for input and output flows or processes have to be specified, and most importantly the impact categories are provided. In the Inventory Analysis, the data collection and calculation procedures are described. The relevant input and output flows should consider the entire life cycle, usually consisting of a number of stages such as: materials extraction, processing and manufacturing, product use, and product disposal. The potential impacts of these inputs and outputs are then determined by the Impact Assessment, which considers impact categories such as e.g. the global warming potential.

Figure 1 Framework for life cycle assessment [1]



2 Approach to evaluation of LCA deliverables generated within FCH JU projects

The first step of the evaluation of the LCA (or alternative environmental assessments) deliverables consisted in identifying and collecting the LCA work performed by FCH JU funded projects. The deliverables considered in this report have been identified by screening all the Annual Implementation/Work Plan (AIP/AWP)[1] call topics for keywords such as LCA, sustainability or environmental assessment in order to draw up a list of projects which may have produced LCAs. An overview of the call topic requests considered is found in Section 4.1. The corresponding deliverables were then analysed further. Some projects decided to perform the LCA study on a voluntary basis. The JRC has become aware of these deliverables during the course of Programme Review activities[2]. In order to be able to give an overview of all LCA work, these deliverables have been included in the evaluation; however, it cannot be certain that all "voluntary" deliverables have been identified.

As a starting point, general information about the relevant deliverables has been collected, such as the status (i.e. final, preliminary, not submitted, not yet submitted) and the dissemination level. The following technology categories have been considered for the evaluation: production, storage, distribution, purification and use, in accordance with the life cycle stage as defined in FC HyGuide [3, 4]. The inventory of LCA deliverables in Section 3 is meant to provide some basic statistics on the portfolio of work.

The evaluation has been performed by analysing information regarding methodological choices of the LCA deliverables. The in-depth evaluation reported in Section 4 starts out with the analysis of the guidelines adopted for the LCA analyses (e.g. FC-HyGuide, ILCD, etc.). The methodological choice has a high impact on the outcome and comparability of the results (e.g. [5]), therefore a detailed analysis has been performed.

According to the ISO 14040 [6] standard, and as shown in Figure 1, LCA consists of several steps, such as goal, scope (including method, assumptions, impact limitations and reasons for carrying out the study), inventory analysis and impact assessment. All these steps have been evaluated and statistics are provided showing how the individual deliverables take these various steps into consideration.

The LCA deliverables have also been reviewed in terms of the results of the environmental assessment, in order to highlight some key findings.

[1] Both AWP and AIP are referred to as AWP in the following. To align with the general H2020 nomenclature, the former Implementation Plans (Annual or Multi-Annual, AIPs and MAIP) have been succeeded by Work Plans (Annual or Multi-Annual, AWPs and MAWP).
[2] Since 2017, the JRC was entrusted with the programme review as part of its activities under the multiannual Framework Contract between FCH JU and JRC.

3 LCA deliverables inventory

In 2008, FCH JU published a call topic for the elaboration of practical guidance for the performance of LCA. No proposals were submitted hence a similar call topic was launched in 2009. On this occasion, two projects (Hyguide and H2FC-LCA) were chosen to perform this task. These two projects later merged into a single project (FC-Hyguide), delivering two LCA guides in mid-2011: one for hydrogen production systems [3] and the other for fuel cell systems [4].

From the first Annual Implementation Plan (AIP) in 2008, until the Annual Work Plan (AWP) 2016, 68 call topics requested environmental assessment of some form. Among those call topics, 43 specifically requested life cycle assessment. This section presents an overview of LCA deliverables performed during the execution of FCH JU funded projects. The deliverables have been classified according to the technical choices made, in terms of life cycle stage and other categories used by FCH JU.

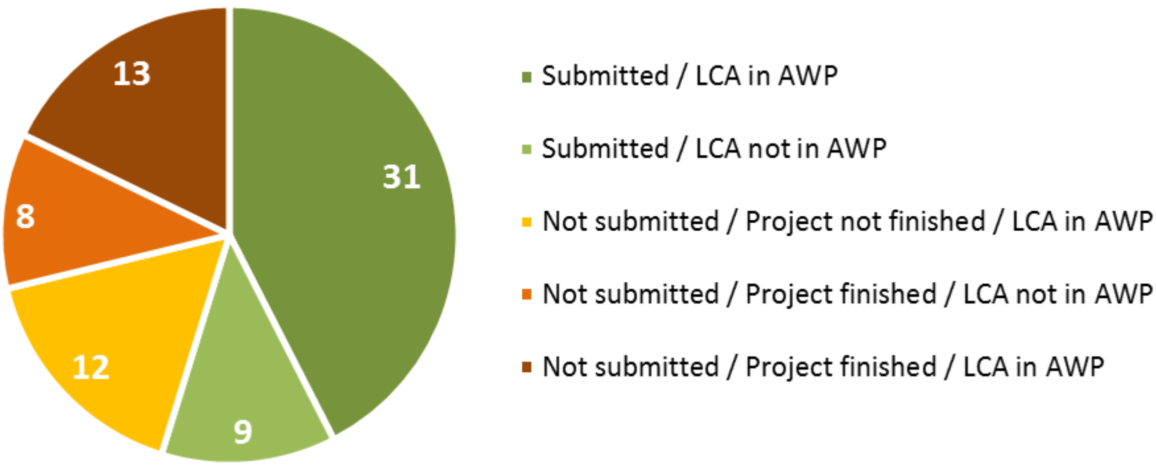
3.1 LCA deliverable status

In total, 73 projects stated in their respective DoW that they would provide a LCA deliverable. In some cases, the LCA study was requested in the call topic whilst other projects decided to perform the LCA on a voluntary basis. As reported in Figure 2, 40 projects submitted an LCA study (i.e. project deliverable). Of those, 31 projects had to perform LCA as requested by the call topic, while 9 projects voluntarily performed the analysis.

There are also LCA deliverables pending from 33 projects:

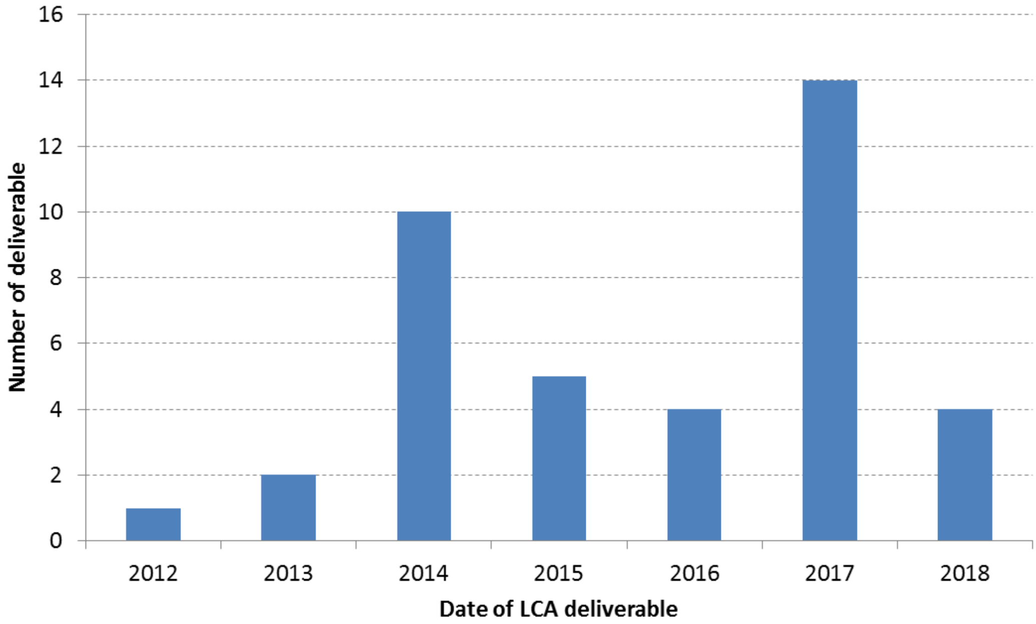
- 13 finished projects had to perform an LCA study according to the call topic, but the deliverable is not yet submitted;
- 8 finished projects did not yet submit an LCA deliverable that had been planned initially in the Description of Work (DoW), without an LCA being requested in the call topic;
- 12 projects are not yet finished and the deliverable has not yet been submitted.

Figure 2 Status of LCA deliverables



The LCA deliverables per the year of submission are reported in Figure 3

Figure 3 Number of LCA submitted deliverables per year[3]



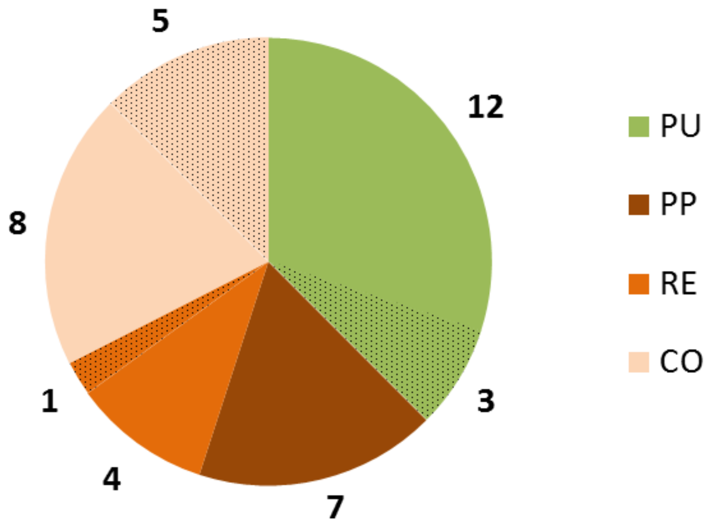
It should be mentioned that in some cases projects have delivered more than one LCA studies.

3.2 LCA deliverable dissemination level

Figure 4 reports the dissemination level of the LCA deliverables among those actually performed; the dotted segment represents the LCA deliverables not requested in the AWP, i.e. the LCA analysis has been performed on voluntary basis. The majority (i.e. 62.5%) of the deliverables are confidential, with several degrees of confidentiality: 7 are restricted to other programme participants (PP), 5 are restricted to a group specified by the consortium (RE) and 13 are Confidential, only for members of the consortium (CO)[4]. The remaining 37.5% of the deliverables are public (PU): 3 of those deliverables have been performed voluntarily.

[3] Cut-off date is 22/06/2018.
[4]PP, RE and CO include the Commission Services.

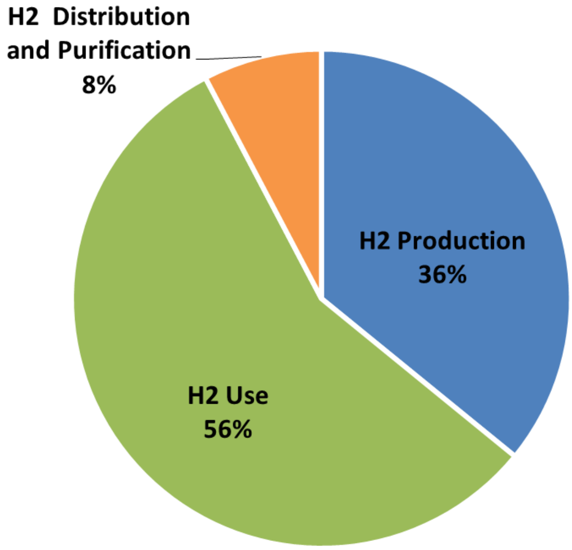
Figure 4 Deliverable dissemination levels (segments with dots represent the LCA deliverables not requested in the AWP)



3.3 LCA deliverable technical choice according to life cycle stage

The LCAs usually consist of a number of stages. Based on FC-HyGuide, the stages are H_2 production, H_2 distribution, H_2 use and H_2 purification. The LCA deliverables analysed have been grouped by those specific stages within the system's boundary. The system boundaries determine which unit processes have to be included in an LCA study; defining system boundaries is partly subjective, made during the scoping phase when the boundaries are initially set. The technical choices made by the projects for their LCA deliverables are reported in Figure 5.

Figure 5 Technical choices according to the life cycle stage

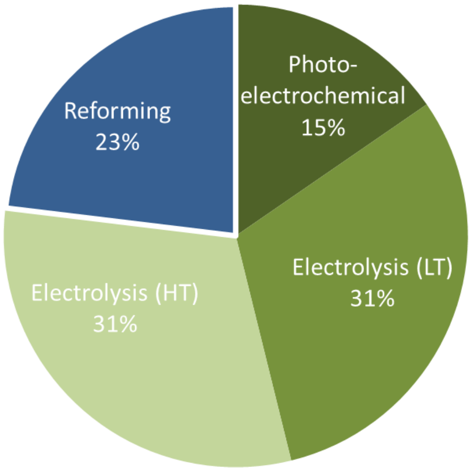


In the following sections, the categories and the relevant number of deliverables (i.e. H_2 production and H_2 use) are described in more detail.

3.3.1 H_2 Production

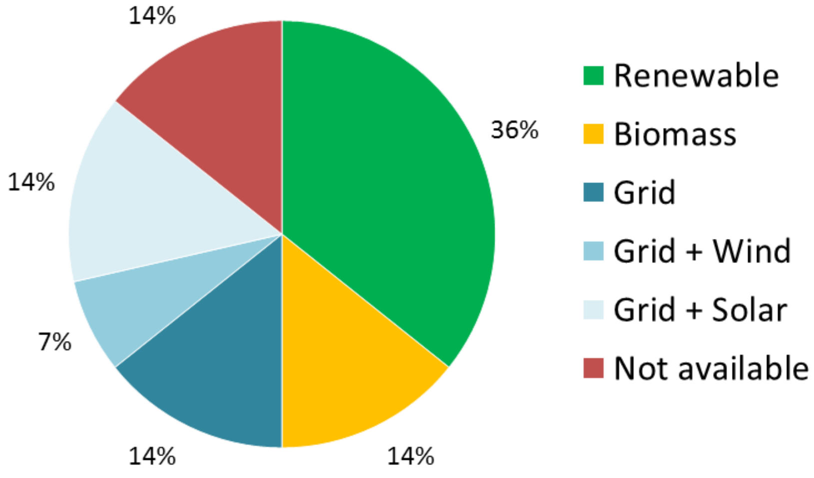
The technologies considered by the deliverables focused on H_2 production are shown in Figure 6. 77% of the analisys are based on electrochemical production (including photo-electrochemical, high temperature (HT) electrolysis and low temperature (LT) electrolysis*)*.

Figure 6 H_2 production: percentage of cases for each sub-category



Key aspects determining the life cycle performance of hydrogen production systems are the source of energy driving the hydrogen production process and the raw material that contains hydrogen. The electrochemical category is widely dominated by case studies of water electrolysis. In general, the environmental performance of this type of system strongly depends on the energy source of the electricity. Figure 7 shows the choice of power source in "H_2 production" case studies. Whilst 36% of the studies relate to energy from renewable sources, a significant percentage of non-renewable sources are covered (35%), mainly because most of the studies carry out comparisons between renewable and non-renewable hydrogen energy systems. Electricity (grid) mixes are generally considered non-renewable regardless of the share of renewables in the grid mix. In addition, 14% of the cases used biomass as a power source and 14% of the cases did not report any information about the power source considered for the LCA analysis.

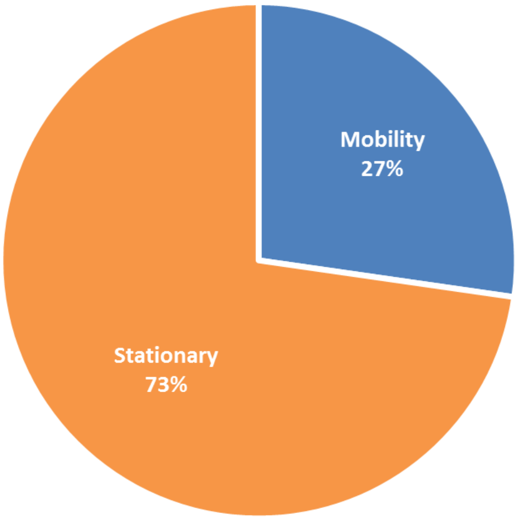
Figure 7 Choice of power source for H_2 production studies



3.3.2 H_2 Use

The technologies considered by the deliverables which focused on H_2 use are shown in Figure 8. The "Mobility" category includes: maritime, auxiliary power unit (APU), bus, fuel cell electric vehicle (FCEV) and micro hydrogen vehicle (MHV). The "Stationary" category includes: industrial size (i.e. with installed power bigger than 400 kW), commercial size (i.e. with installed power between 5 and 400 kW), micro combined heat and power (m-CHP) applications (with installed power lower than 5 kW) and off-grid and back-up applications.

Figure 8 H_2 use: number of cases for each sub-category



4 Evaluation of methodological choices made in LCA deliverables

This section presents the results of an evaluation analysis on the different LCA reports provided by the FCH JU funded projects. This analysis is focussed on the methodology used as reported in the LCA deliverables. The methodological approach to the LCA was assessed by evaluating the adherence to guideline recommendations, such as those set out in FC-HyGuide. It should be noted that the request to perform LCA was phrased in various manners in the call topics, with implications on the scope. In addition, the request to follow the FC-HyGuide methodology has not always been made. This aspect was considered when performing the overall evaluation assessment of the LCAs under study.

4.1 Evaluation of adherence to LCA guidelines

The leading standards for LCA are ISO 14040 [6] and ISO 14044 [7]. These international standards focus mainly on the process of performing an LCA. ISO 14040 describes the principles and framework for LCA including:

- definition of the goal and scope of the LCA,
- the life cycle inventory analysis (LCI) phase,
- the life cycle impact assessment (LCIA) phase,
- the life cycle interpretation phase,
- reporting and critical review of the LCA,
- limitations of the LCA, the relationship between the LCA phases,
- conditions for use of value choices and optional elements.

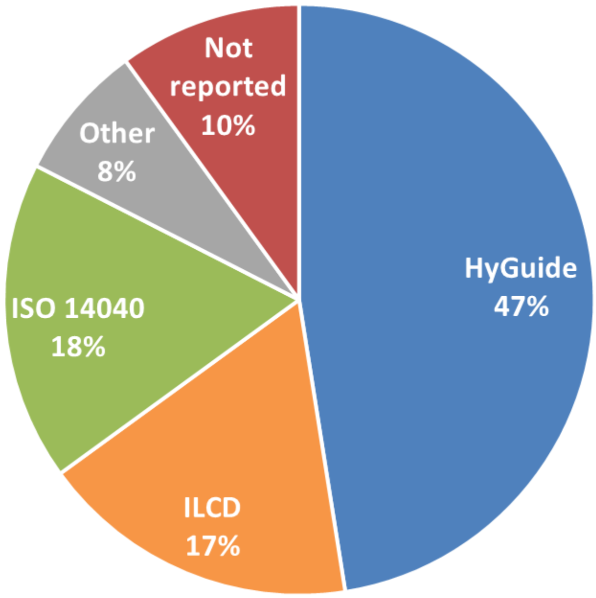
On the other hand, ISO 14044 covers life cycle assessment (LCA) studies and life cycle inventory (LCI) studies; it does not describe the LCA technique in detail, nor does it specify methodologies for the individual phases of the LCA.

In response to the commitments in the Integrated Product Policy communication of the European Commission [8], the Joint Research Centre prepared the International Reference Life Cycle Data System handbook (ILCD) [1]. The ILCD Handbook was published in 2010. It is based on ISO 14040 and ISO 14044, but provides much more detailed technical guidance. The ISO 14040 and 14044 standards provide the indispensable framework for Life Cycle Assessment (LCA). This framework, however, leaves the individual practitioner with a range of choices, which can affect the results of an LCA. While flexibility is essential in responding to the large variety of questions addressed, further guidance is needed to support consistency and quality assurance. The ILCD has therefore been developed to provide guidance for consistent and quality assured LCA data and studies. The ILCD consists primarily of the ILCD Handbook and the ILCD Data Network. The ILCD Handbook is a series of technical documents providing guidance for good practice in Life Cycle Assessment in business and government. It is supported by templates, tools, and other components. The ILCD Handbook 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 support 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 production [3] and fuel cell technologies [4]. The guidance document is foreseen to be applied to all projects funded by the FCH JU requiring LCA in the field of H_2 production and fuel cell technologies. By providing information on how to deal with key methodological aspects of LCA (e.g. definition of a functional unit, system boundary, allocation rules, relevant impact categories, etc.), the guidance document allows each hydrogen production and fuel cells technology developer to assess their own technology, and make the information available in the ILCD Data Network.

The guidelines adopted for the LCA analyses, are shown in Figure 9. The majority of the projects used FC-HyGuide to perform the LCA study, followed by ILCD and ISO 14040.

Figure 9 Guidelines used for the LCA deliverables



The scope of work as presented in the AWP for all the projects analysed is reported in Table 1.

Table 1. Work description of analysed projects in AWP

Scope of work as presented in the AWP	Project
Well to wheel analysis	HyFIVE, IDEALHY
Assessment of performance in terms of CO_2 footprint and cost per produced amount of H_2	BIONICO
Environmental sustainability assessment by means of Life Cycle Assessment studies should be carried out according to the requirements in the FC-HyGuide guidance document	FLUIDCELL, fitup, HyTechCycling, BIOROBUR, POWER-UP, STAGESOFC
Environmental sustainability assessment by means of Life Cycle Assessment studies carried out according to the International Life Cycle Data System (ILCD) Handbook requirements	REFORCELL, SOFT-PACT, UNIFHY, Don Quichote, FluMaBack, sofcom, TriSOFC
The Project activities shall focus on LCA according to developed guidelines	CATION, MEGASTACK
Estimate a full file cycle cost and revise periodically this estimate	ene.field
Show the potential for efficient, reliable, environmentally friendly and economically feasible production of hydrogen	HELMET, SOPHIA, ELECTRA
Life Cycle Assessment (LCA)	CHIC
To carry out life cycle analysis of the developed technologies in order to estimate their feasibility to meet the EU target cost of 5 €/kg hydrogen produced by sustainable technologies	PECDEMO
Investigate the CO_2 performance (through Life Cycle Analysis techniques) of current marine powertrain solutions and demonstrate the specific emissions saving that can be achieved by replacing conventional technology	MARANDA
Assessment of technical issues and cost-benefit analysis of using higher capacity trailers, including impact on energy efficiency and GHG emissions	DELIVERHY
Comparative Life Cycle Assessment studies carried out according to the practice guidance developed by the FCH JTI	NEXPEL
Perform a life cycle assessment on the CO_2 to prove the recycling potential of this technology	ECO
Comparative Life Cycle Assessment studies carried out according to the practice guidance developed by the FCH JU	ELYGRID

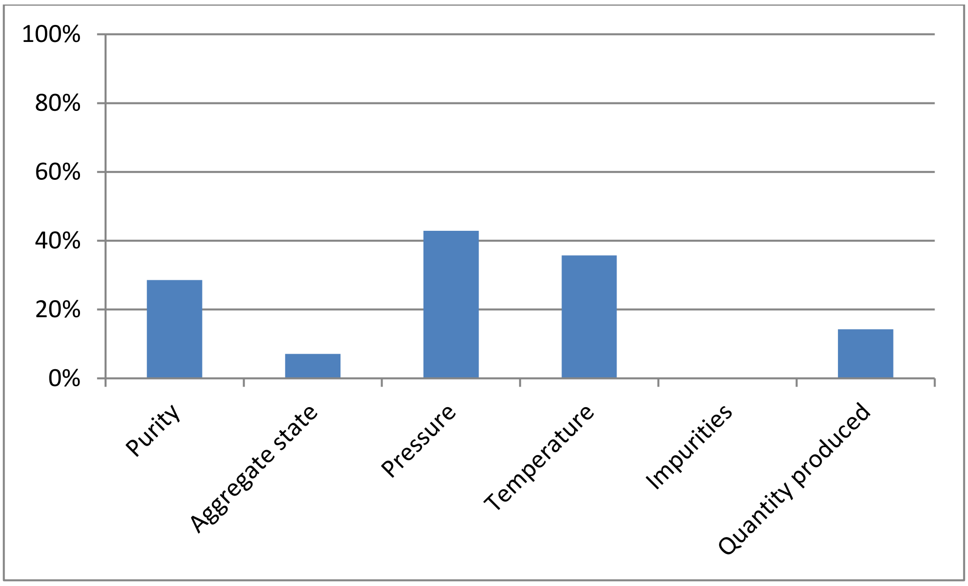
4.2 Evaluation of the product properties reported

Properties of the product under life cycle assessment have to be reported at the beginning of the LCA. The reporting of these properties facilitates comparison among LCAs. FC-HyGuide requests a minimum set of properties; logically, these properties are different for hydrogen production and FC stack/system. For instance, in the case of hydrogen production systems, LCA shall report purity, aggregate state, pressure and temperature of the hydrogen produced. Impurity type and quantity produced by volume and/or mass (e.g. YY Nm^3/h) are also recommended.

Among the LCAs related to hydrogen production, very few projects have reported information about any of the properties mentioned above. Moreover, LCAs assessing hydrogen distribution and purification have not provided any information about properties.

Only one project has provided information about all of the properties as requested by FC-HyGuide. Pressure, followed by temperature, is the most reported property among the LCAs analysed. Aggregate state has been specifically reported just one time, but in most of the cases it can be deduced by the technology used, with the gaseous aggregate state being the most common. On the other hand, impurities have never been reported. Figure 10 shows, for each property, the percentage of LCAs related to hydrogen production reporting them.

Figure 10 Percentage of LCAs reporting the properties requested in FC-HyGuide for hydrogen production



In the case of FC stack/system, FC-HyGuide requests a brief description of the FC system or stack. Information about the major properties needs to be given by stating the FC standard being met, such as:

- IEC/TS 62282-1 - Fuel cell technologies - Part 1: Terminology [9];
- IEC 62282-2 - Fuel cell technologies - Part 2: Fuel cell modules [10] and [11]

If there is no standard applicable, FC-HyGuide requests the following properties to be reported:

- Trade name
- Type of electrolyte used
- Primary functions (production of electricity, heat, etc.)
- Electrical power (rated output)

- Thermal power (if applicable)
- Efficiency
- Rated voltage
- Rated current
- Range of temperatures and operating temperature
- Weight
- Dimensions
- Fuel used and its technical specifications
- Expected service life
- Description of the intended use.
- System boundary definition

The analysis of the properties reported by LCAs of FC stack/systems gave the following results:

- 55% of the LCA reports have been delivered assessing FC stacks/systems
- only one LCA report included all the properties as requested in FC-HyGuide
- electrical power is the property reported most often, followed by system boundary definition and fuel used.

It should be considered that not all the FC stack/systems were intended to be used for CHP purposes, therefore, thermal power was reported fewer times than electrical power. However, the number of LCAs reporting thermal power was lower than the number of LCAs assessing FC stack/systems with heat production. The type of electrolyte was not specifically reported in many cases, however, from the description of the project it was easy to identify what kind of technology (e.g. PEM, SOFC, etc.) was used.

Figure 11 and Figure 12 show, for each property requested by FC-HyGuide, the percentage of the LCAs related to FC stack/system reporting them.

Figure 11 Percentage of LCAs reporting the properties requested by FC-HyGuide for FC stack/system (I)

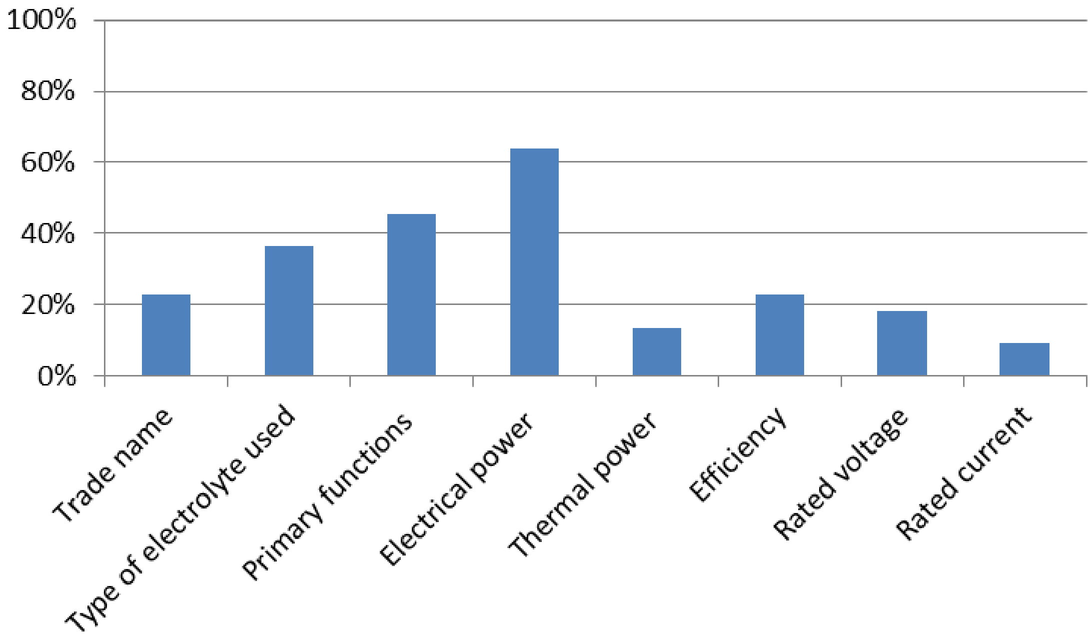
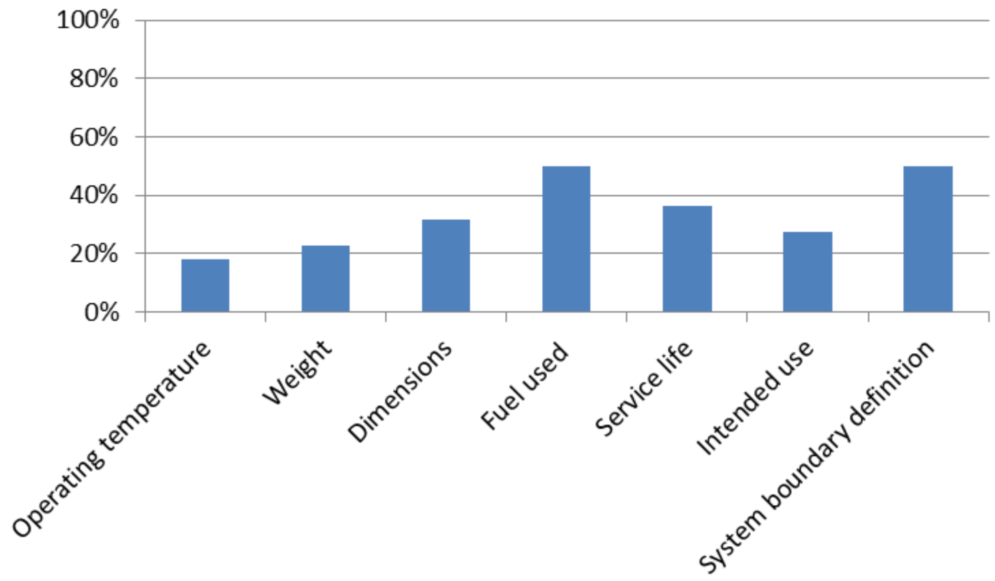


Figure 12 Percentage of LCAs reporting the properties requested for FC stack/system (II)



4.3 Evaluation of LCA goal definitions

Once the properties of the product have been reported, the LCA goal has to be defined. According to ISO 14040 [6], defining the goal of an LCA study includes:

- Intended application(s)
- Method, assumptions and impact limitations
- Reasons for carrying out the study and the 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.

FC-HyGuide requests the unambiguous definition of the goal of the study, according to the goal definition in the ISO 14044 standard. It has been found that 90% of projects have unambiguously defined the goal of the study.

4.4 Evaluation of LCA scope definitions

According to the ILCD handbook, the object of the LCI/LCA study is identified and defined in detail during the scope definition phase. This should be done in line with the goal definition. The main part of the scope definition is to derive the requirements on methodology, quality, reporting, and review in accordance with the goal of the study, i.e. based on the reasons for the study, the decision-context, the intended applications, and the intended audience.

The analysis of the LCA scope definition is focussed on functional unit, system boundaries and performance of comparative study. They have been considered, within this study, as the most relevant items in order to compare results among LCAs of similar technologies. How these items have been reported in the LCAs analysed is shown in the following subsections.

4.4.1 Functional unit

According to ISO 14044:2006 the functional unit is a "quantified performance of a product system for use as a reference unit". Generally, a functional unit shall be precise and quantifiable.

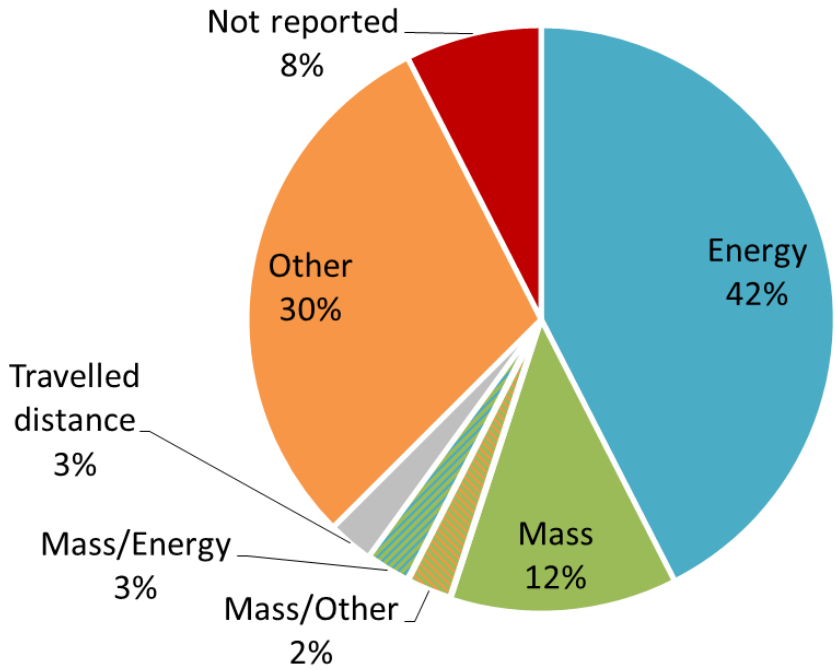
The LCA guides delivered by FC-HyGuide [3] and [4] suggest the use of the following functional units:

- [For fuel cell stacks] The functional unit is the power capacity of the manufactured stack expressed in kW (energy if electricity is the only valuable product, exergy if both electricity and heat are valuable products; in this case the share of electricity and heat shall be declared)
- [For fuel cell systems] The functional unit is the "production of a certain amount of electricity and useful thermal energy in a given number of years", expressed in MJ_{ex}. The share of electricity and heat shall be declared. If the thermal output of the FC is not used, the FU is only the production of electricity, expressed in MJ_{el}.
- [For hydrogen production systems] 1 MJ of hydrogen (net calorific value or lower heating value)

A lack of homogeneity in the functional units that have been used to perform the LCAs analysed is observed. This makes it very difficult to compare results among the LCAs performed in the frame of the FCH JU funded projects.

As already anticipated in section 4.1, 47% of the projects claimed to have used FC-HyGuide as the reference LCA guidelines; of these, only 20% of the projects have used the functional units suggested by FC-HyGuide in their LCA reports. Surprisingly, none of these projects were requested to follow the FC-HyGuide guidelines in their respective call topics. Figure 13 shows the distribution of types of functional units.

Figure 13 Functional units used by projects



4.4.2 System boundaries

ISO 14040 defines the system boundary as a "set of criteria specifying which unit processes are part of a product system". This implies that the process steps to be followed in the LCA study need to be clearly defined. FC-HyGuide requires that the system boundary shall be consistent with the goal of the study and shall be shown in a flow chart.

75% of the LCA reports assessed have defined system boundaries consistent with the goal of the study and 77.5 % of LCA reports have provided the system boundary in a flow chart.

4.4.3 Comparative study

LCA can also be used to compare environmental performance among different systems. Guidelines provided by FC-HyGuide give some indications as to how to perform such comparative studies by means of LCA. All systems under investigation have to be evaluated in the same way for the comparison to be valid.

In the comparison between different types of hydrogen production system, some limitations due to scale factors and to differences in the operational conditions (e.g. fuel used) have to be considered. The same applies for comparison between the different types of FC technologies (temperature, used fuel, power output). For instance, high temperature fuel cells could be fed by methane internally reformed to hydrogen, while low temperature fuel cells are directly fed by H_2 which has been produced externally, thus adding to the difficulty of a direct comparison

For these reasons, the following aspects shall be taken into consideration, according to FC-HyGuide:

- Use of the same rules for system boundaries definition
- Methodological and data assumptions are analogous
- Harmonisation of functional units
- Harmonisation of Life Cycle Inventory Assessment

The majority of the LCA reports have included a comparative study. Some of these comparative studies included several reference systems to be compared with the one under study. However, not all of them have followed the guidelines provided by FC-HyGuide: around 50% of them have adhered to the FC-HyGuide requirements.

4.5 Evaluation of Life Cycle Inventory (LCI) Analysis /data sources

Data sources have to be reported when performing an LCA. 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; they are referred to as primary and secondary inventory data. Primary inventory data is recommended to be used for the main processes (foreground system). Primary inventory data is provided by the owner, manufacturer and/or operator of the system. However, it may be that not all the data needed to perform the LCA is known by the owner, manufacturer and/or operator of the system. In that case, secondary inventory data is needed. Secondary inventory data is also used for the background system. Different data sources can be used for secondary data such as: LCA databases, scientific literature, non-scientific literature, simulations, calculations, assumptions and so on.

Prior to the selection of data sources, a definition of the foreground and background systems has to be performed. According to FC-HyGuide [3, 4], the foreground system comprises the main process steps and the related infrastructure processes such as manufacturing. The foreground system is supported by the background system which is made up of processes such as the infrastructure for the supply of energy including power plants and power lines. The foreground and the background systems are included in the system boundary. In the case of the LCA reports evaluated, 22 out of 40 have defined the foreground and background system; of these, 19 have used primary inventory data for the foreground system. In addition, there are 3 more reports using primary inventory data without a clear distinction between the foreground and background systems. Since many of the LCA reports are assessing systems under development or prototypes, and the owner, manufacturer and/or operator is a partner in the project, as well as the LCA rapporteur, most of the primary data needed is available. However, it can be that some primary inventory data is not provided to the partner performing the LCA due to confidentiality issues.

More than half of the LCA reports have used secondary inventory data to fill data gaps. Among those LCAs it has been found that several sources of secondary data have been used in each individual LCA report. The most commonly used source of secondary data is LCA databases, followed by scientific literature; commercial catalogues and estimations have also been used in some cases.

Regarding LCA databases, approximately 40% of the LCA reports using secondary inventory data have used the Ecoinvent database (the version of which varies depending on the date when the LCA was performed). The GaBi database has also been used in more than 15% of the LCAs.

4.6 Evaluation of impact assessment methods/impact categories

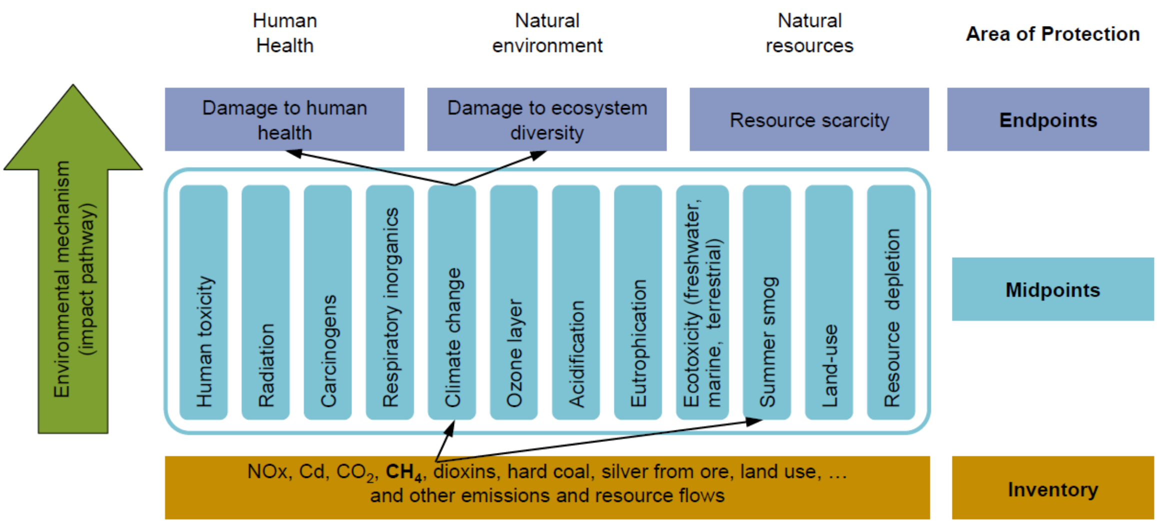
The life cycle impact assessment (LCIA) methods are used to relate the life cycle inventory (LCI) results to the associated environmental impacts, where the LCI results are classified within impact categories, each with a category indicator. Use of a common LCIA method facilitates the comparison regarding environmental impact among different systems.

An impact category is defined as a "class representing environmental issues of concern to which Life Cycle Inventory analysis results may be assigned" [7]; this definition means that various emissions are assigned to an impact category e.g. "Global Warming Potential". These impact categories can be expressed at midpoint level or at endpoint level.

Categories at endpoint level are defined as an "attribute or aspect of natural environment, human health, or resources, identifying an environmental issue giving cause for concern" [7]. Categories at the endpoint level require modelling all the way to the impact on the entities described by the Area of Protection (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 AoP on a natural or social science basis, possibly taking into account all substance-specific differences.

Categories at midpoint level require modelling the impact using an indicator located along the impact pathway, but not at the end. Figure 14 depicts endpoint and midpoint categories and how they can relate.

Figure 14 Schematic steps from inventory to category endpoints [1]



The endpoint categories are more easily understood, because they are closer to what ultimately matters to society. The major uncertainties associated with modelling the impact pathway from midpoint to endpoint, however, represent a drawback that shall 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.

The LCIA methods to be applied shall be defined when the LCA study is being scoped. Different Life Cycle Impact Assessment methods exist (CML [12], ReCiPe, LIME [13] and IMPACT 2002+, etc.) which are either midpoint or endpoint oriented.

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. FC-HyGuide recommended that the latest development of the midpoint CML method [14] be applied, until the ILCD Handbook was published. As the ILCD Handbook was published in 2011, all LCAs performed after that date shall follow its recommendations regarding the impact assessment methods to be used.

Annex 2 provides a summary of the LCIA methods recommended by the ILCD Handbook for each impact category (midpoint categories).

The impact categories (i.e. midpoint categories) which FC-HyGuide recommends should be used are shown in Table 2. The impact categories recommended by FC-HyGuide differ slightly for hydrogen production systems and fuel cells systems. In Table 2, impact categories in bold should appear in the LCIA, according to FC-Hyguide.

Table 2. Impact categories recommended in FC-HyGuide (impact categories in bold should appear in the LCIA, according to FC-Hyguide)

Hydrogen production systems	Fuel cells systems
Global Warming Potential (GWP)	**Global Warming Potential (GWP)**
Acidification Potential (AP)	**Acidification Potential (AP)**
Eutrophication Potential (EP)	**Eutrophication Potential (EP)**
Photochemical Ozone Creation Potential (POCP)	**Abiotic depletion (AD)**
Non-renewable Primary Energy Demand (PED non-renewable)	**Non-renewable Primary Energy Demand (PED non-renewable)**
Renewable Primary Energy Demand (PED renewable)	**Renewable Primary Energy Demand (PED renewable)**
Ozone depletion potential (OPD)	Ozone depletion potential (ODP)
Human-Toxicity Potential (HTP)	Human-Toxicity Potential (HTP)
Respiratory inorganics	Respiratory inorganics
Ionising radiation	Ionising radiation
Ecotoxicity (freshwater, marine, terrestrial)	Ecotoxicity (freshwater, marine, terrestrial)
Resource depletion	Photochemical ozone formation potential (POCP)
Water footprint	Ecotoxicity
Land use	Land use

The results for each impact category should be depicted using the following units (in the case of hydrogen production systems and according to the FC-Hyguide. There is no corresponding information in the LCA fuel cell systems guide).

- 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)

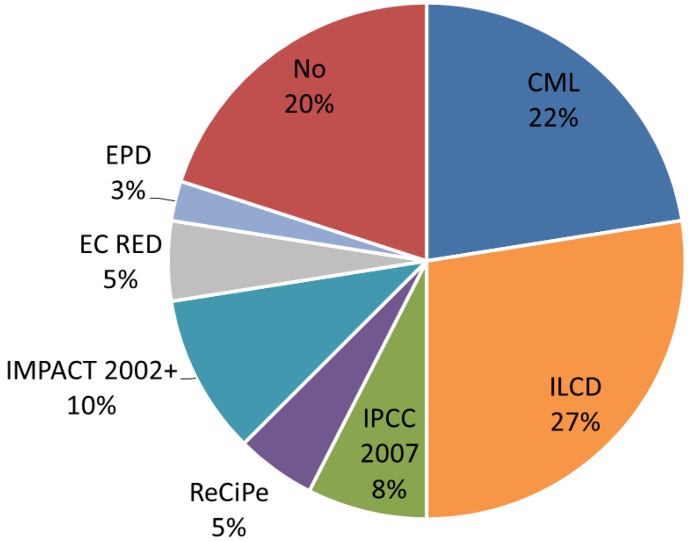
The analysis of the LCA deliverables has led to the following findings (Figure 15):

For the impact assessment methods:

- Several impact assessment methods have been used by the projects delivering an LCA.
- The selection of these methods is directly related to the impact categories reported, e.g. IPCC has been chosen by some projects when reporting about GWP.
- 27% of the projects have followed the recommendations given by the ILCD handbook.
- Some projects not following the ILCD handbook recommendations appear to have used more than one method, according to the results provided. However, they have only reported a single method.
- The CML method is the most commonly used amongst the projects not following ILCD recommendations.

- 20% of the projects have not reported the impact assessment method that they have used in their LCA report.

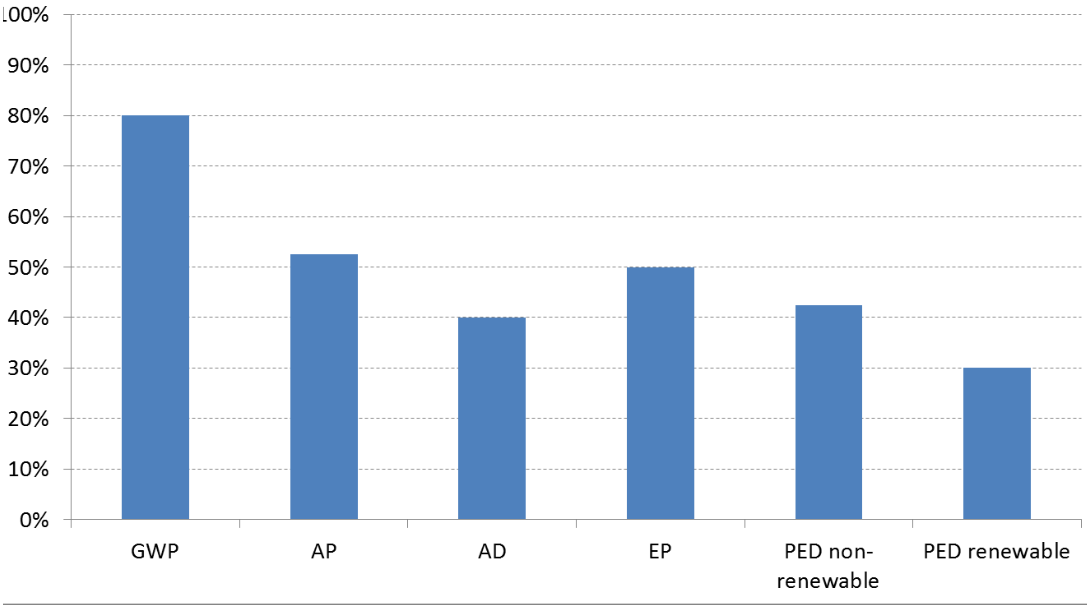
Figure 15 Impact assessment methods used in the LCA deliverables



For impact categories (Figure 16):

- 25% of the projects have reported results for all the impact categories requested by FC-Hyguide.
- No project has reported results for all the impact categories suggested by FC-Hyguide. 80% of the projects have reported about Global warming potential (GWP), making it the most reported impact category.
- Renewable Primary Energy Demand (PED renewable) is the least reported impact category of the ones requested

Figure 16 Percentage of reports including impact categories requested by FC-HyGuide



4.7 Qualitative evaluation of LCA deliverables

All deliverables have been assessed regarding methodology and overall quality of the work. The level of agreement of the portfolio of LCA deliverables to individual guideline recommendations has been analysed. The methodological choices made in the LCA deliverables are reviewed in detail to ascertain whether there is a consistent framework, enabling consistent and comparable results.

A recent study investigated the methodological choices made in the life cycle assessment of hydrogen and fuel cell technologies [5]. It found trends in the methodology applied, which, according to the authors, should be used to further harmonise LCA results. The analysis as reported in [5] is based on 46 publications (237 case studies) from 1998 to 2011 (prior to the publication of FC-HyGuide) and on 51 publications (272 case studies) from 2012 to 2015 (after FC-HyGuide publication).

The review found a positive impact on methodology following the publication of FC-HyGuide, in particular regarding reported properties and system boundary definitions. As recommended by FC-HyGuide, mid-point categories were more often chosen for the impact assessment. The impact category addressed most often was Global Warming Potential (GWP) followed by acidification. A lack of full traceability of results was noted, as well as a reliance on secondary data. In addition, many of the LCAs did not provide any information regarding data quality [5].

In Table 3, the results of the study on methodological choices of the published case studies [5] regarding the level of agreement with a selected set of recommendations based on FC-HyGuide are compared with the results of the analysis performed by JRC on the LCA deliverables. In this table, the level of agreement is ranked as "very high" if more than 90% of case studies (or LCA deliverables) followed the corresponding FC-HyGuide recommendation, "high" (60-90%), "intermediate" (40-60%), "low"(10-40%) and "very low" (less than 10%). The results of the analysis performed in [5] are reported in the columns "before FC-HyGuide" and "after FC-HyGuide", according to the time of publication of the studies assessed, as mentioned above. In the next column, the results of the analysis of the LCA deliverables are presented. The level of agreement observed for the LCA deliverables is also compared to the agreement observed for the LCA case studies in the time period following the FC-HyGuide publication: it can be observed that the level of agreement is quite similar, which means the LCA deliverables followed a similar approach to the published case studies. It should be noted that the use of primary data was assessed as intermediate, which is higher than for the published case studies. Although an even higher level of primary data use would be optimal, this is a strong point of the LCA work performed by FCH JU funded projects. The level of agreement according to the analysis of deliverables regarding the "product system information" (i.e. state hydrogen purity, temperature and hydrogen production capacity) is mainly low. This result needs further investigation to clarify whether the information was difficult to obtain or not considered relevant for the LCA studies.

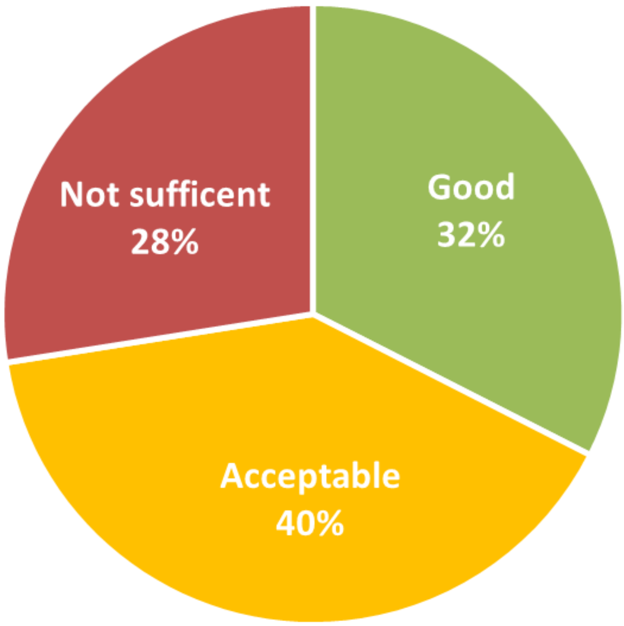
Table 3. Agreement between the observed trends of selected sets of recommendations

Topic	Recommendation from FC-HyGuide	Level of agreement according to [5]		Level of agreement according to the analysis of FCH JU LCAs
		Before FC-HyGuide	After FC-HyGuide	
Product system information	State hydrogen purity	Low	Low	**Low**
	State hydrogen pressure	Intermediate	High	**Intermediate**
	State hydrogen temperature	Very low	Low	**Low**
	State hydrogen production capacity	Low	Intermediate	**Low**
Goal and scope definition	Unambiguously define the goal of the study	Very high	Very high	**Very high**
	Show the chosen system boundary in a flow chart	High	Very high	**High**
	Use "production of a certain amount of hydrogen" as the functional unit[5]	Very high	Very high	**High**
	Use an attributional modelling approach in LCA studies	Very high	Very high	**Very high**
	The system boundary shall be consistent with the goal of the study	Very high	Very high	**High**
	In comparative studies, use the same rules for system boundaries definition	Intermediate	High	**High**
	In comparative studies, methodological and data assumption shall be analogous	Intermediate	High	**High**
	In comparative studies, harmonise FUs	Very high	Very high	**Very high**
	In comparative studies, harmonise LCIA	High	High	**High**
Life cycle inventory analysis	Define the data quality requirements according to the goal and scope	Very low	Very low	**Very low**
	Define foreground and background processes taken into account	Intermediate	High	**High**
	Use primary data for the foreground system	Low	Low	**Intermediate**
	Fill data gaps with secondary data	High	High	**High**
Life cycle impact assessment	Use midpoint categories for studies on hydrogen production	High	Very high	**Very high**
	Use the Global Warming Potential impact category	High	Very high	**High**
	Use the Acidification Potential impact category	Low	Intermediate	**Intermediate**
	Use the Eutrophication Potential impact category	Low	Intermediate	**Intermediate**
	Use the Photochemical Ozone Creation Potential impact category	Low	Low	**Intermediate**
	Use renewable/non-renewable Primary Energy Demand categories	Low	Intermediate	**Low/Interm.**
	Use the CML methods if no other method is more appropriate	Intermediate	High	**Intermediate**

[5] Only for XtoGate case studies

The outcome of the evaluation of the quality of the individual deliverables is shown in Figure 17. The LCA studies have been rated according to quality of information provided: assessment criteria included the adherence to LCA guideline recommendations, comprehensiveness, approach to data sources, level of detail provided and whether a sensitivity analysis was performed. The quality assessment results were grouped into three categories: good, acceptable, insufficient. The quality of the majority of the deliverables was considered acceptable or good, but more than 10 deliverables are considered to be of insufficient quality. Some common negative aspects were: a lack of clarity on the methodology used, missing information, poor data quality and a limited scope as to the impacts assessed. In addition, some LCA did not perform any comparative analysis, which could either be a benchmarking with relevant other technologies or a sensitivity analysis (e.g. comparing with the same technology but modifing some design parameters). For the deliverables where a comparison was made, there is a lack of harmonisation of the reference technologies. The LCA work rated as high quality consisted typically of comparative studies, with detailed information regarding the sources used and the assumptions made, which had also performed a sensitivity analysis on relevant parameters. The knowledge of the project partner performing the LCA had a bearing on the quality of the report, and it is recommended that expertise on LCA be made a requirement in the call topic. In general, it was found that the comparability of results needs to be improved.

Figure 17. Evaluation assessment of LCA deliverables



5 Conclusions and recommendations

The FCH JU has supported research on the environmental sustainability of fuel cell and hydrogen technologies. To date, 40 reports on LCA performed on a wide scope of technologies and processes have been submitted. Whereas the work is a significant step forward in understanding and quantifying the performance of the technologies for a number of enviromental impacts, there are still gaps remaining. The majority (62.5%) of these deliverables are confidential, therefore the results will not benefit the FCH community. In terms of scope, while some areas seems to be comprehensively covered (e.g. SOFC), others like storage or purification have not been extensively addressed. There is a lack of information on the environmental impact of certain applications such as storage or purification. Furthermore, few projects dealing with transport and stationary applications have performed an LCA study. Additionally, newer systems in technologies already assessed (e.g. electrolysis) need to be analysed from an environmental point of view. Therefore, it is recommended to continue supporting LCA in all the panels of the FCH JU. The outcomes of these environmental analyses could increasingly be used to shape the programme of the FCH JU, as further research could specifically target areas where a high environmental impact has been found.

The level of agreement with the recommendations from the FC-HyGuide guidance documents ([3] and [4]) found in the LCAs analysed within this report is comparable with that observed in a recent study investigating the methodological choices made in the life cycle assessment of hydrogen and fuel cell technologies [14].

The comparability between the results of the LCAs performed by the FCH JU projects is at present considered rather limited, in spite of the positive trend noted by this report. Methodology is a critical issue for the comparability of results, as this is only possible if all LCAs follow the (same) guidelines. Less than 50% of the LCAs analysed state that they have followed FC-HyGuide. In addition, even if a deliverable purportedly followed FC-HyGuide, the LCA was often only partially fulfilling the requirements.

This has resulted in a portfolio of LCAs following a variety of methodologies, which hinders the comparability of results. The absence of a common guideline has led, for example, to a lack of homogeneity when describing the properties of the system or when defining the functional unit and system boundaries.

Comparative studies have been performed using different reference systems for the benchmarking. In addition, the scenarios considered have differed among the LCAs analysed. Several data sources for secondary inventory data or used to fill gaps in primary inventory data have been applied in the LCAs submitted. These issues bring additional difficulty to the comparison of LCA results.

The selection of different impact assessment methods also challenges the comparability between the results. Moreover, despite the fact that GWP is usually the most important impact to report when dealing with technologies that compete against technologies based on fossil fuels, it is also important to report other impact categories in order to more fully understand the global environmental impact of the system under study and to allow a better comparison of the overall environmental performance between systems.

In summary, the findings on the quality of the LCA performed have led to the following recommendations:

- The methodologies used vary widely, and further guidance would be needed to ensure that the outcomes are comparable, so they can be of actual benefit. It is recommended that future call topics asking for environmental analysis to be performed are setting out some minimum requirements, such as the guidelines to be used and the impacts to be assessed.

- In terms of data sources, it has been noted that primary data has not always been available and secondary sources had to be relied upon. The data generated by the work should be used to construct a database, according to the MAWP [2], published as part of the ILCD (International Reference Life Cycle Data System)[6], and maintained by the industry partners of the FCH 2 JU. This activity has not been pursued by any of the projects according to the information available for the present report.
- It has been noted that the quality of the LCA deliverable is often linked to the level of the LCA performer expertise, therefore it is suggested that a partner with an appropriate background on LCA is included in the consortium.

Based on the outcome of this analysis, a harmonisation effort in the approach to LCA for the FCH JU funded projects is proposed. A workshop with selected experts in the field of LCA should be organised in collaboration with the FCH JU. This workshop should enable a discussion regarding how LCA is currently contributing to the assessment of environmental performance and how it can be used to perform LCAs on the specific technologies in the fuel cells and hydrogen field. Experts should report on their experience about performing an LCA on Fuel Cells and H_2 Technologies (e.g. which type of guidelines were used, why a specific set of guidelines was chosen, difficulties encountered in defining inventory data, etc.). A goal of the workshop is to find commonalities, simplifications and to identify critical requirements that need to be retained and provide a common approach in performing an LCA on Fuel Cells and H_2 Technologies. In particular, the following are required:

- To create a Life Cycle Inventory (LCI) database useful for the projects performing LCAs;
- To harmonise the approach to LCAs to facilitate the comparison between systems under study.
- To identify reference cases to be used as benchmark for future LCAs; these should refer to competing technologies (e.g. electrolysis vs steam reforming) but also to SoA systems when the purpose of the comparison is to analyse the environmental impact of a new design

In order to promote a harmonised approach, the proposed workshop will focus on implementation of LCA on Fuel Cells and H_2 Technologies, current adopted models, the importance of life-cycle inventory data, panel discussions with key professionals on the topic, as well as round table discussions with all participants. Attendees should include practicing engineers, academics, industry professionals, FCH JU representatives, EC-JRC representatives and policy makers.

Future work should include an assessment of the current guidelines addressed in the "Guidance document for performing LCAs on Fuel Cells and H_2 Technologies" (HyGuide deliverable D3.3 [3] and [4]), to discuss possible improvements. As already mentioned, even if HyGuide was used, often not all recommendations were followed. It is proposed to conduct a survey of selected experts to collect input on how the methodology could be adapted and implemented.

[6] "The International Reference Life Cycle Data System (ILCD) Handbook provides governments and businesses with a basis for assuring quality and consistency of life cycle data, methods and assessments. The International Reference Life Cycle Data System (ILCD) provides a common basis for consistent, robust and quality-assured life cycle data and studies."

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Annex 1. Impact assessment method by impact category recommended by ILCD Handbook [1]

	Recommendation at midpoint		
Impact category	**Recommended default LCIA method**	**Indicator**	**Classification**
Climate change	Baseline model of 100 years of the IPCC	Radiative forcing as Global Warming Potential (GWP100)	I
Ozone depletion	Steady-state ODPs 1999 as in WMO assessment	Ozone Depletion Potential (ODP)	I
Human toxicity, cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTU_h)	II/III
Human toxicity, non-cancer effects	USEtox model (Rosenbaum et al, 2008)	Comparative Toxic Unit for humans (CTU_h)	II/III
Particulate matter/Respiratory inorganics	RiskPoll model (Rabl and Spadaro, 2004) and Greco et al 2007	Intake fraction for fine particles (kg PM2.5-eq/kg)	I
Ionising radiation, human health	Human health effect model as developed by Dreicer et al. 1995 (Frischknecht et al, 2000)	Human exposure efficiency relative to U^{235}	II
Ionising radiation, ecosystems	No methods recommended		Interim
Photochemical ozone formation	LOTOS-EUROS (Van Zelm et al, 2008) as applied in ReCiPe	Tropospheric ozone concentration increase	II
Acidification	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, terrestrial	Accumulated Exceedance (Seppälä et al. 2006, Posch et al, 2008)	Accumulated Exceedance (AE)	II
Eutrophication, aquatic	EUTREND model (Struijs et al, 2009b) as implemented in ReCiPe	Fraction of nutrients reaching freshwater end compartment (P) or marine end compartment (N)	II
Ecotoxicity (freshwater)	USEtox model, (Rosenbaum et al, 2008)	Comparative Toxic Unit for ecosystems (CTU_e)	II/III
Ecotoxicity (terrestrial and marine)	No methods recommended		
Land use	Model based on Soil Organic Matter (SOM) (Milà i Canals et al, 2007b)	Soil Organic Matter	III
Resource depletion, water	Model for water consumption as in Swiss Ecoscarcity (Frischknecht et al, 2008)	Water use related to local scarcity of water	III
Resource depletion, mineral, fossil and renewable[6]	CML 2002 (Guinée et al., 2002)	Scarcity	II

The recommended methods are classified according to their quality into three levels: "I" (recommended and satisfactory), level "II" (recommended but in need of some improvements) or level "III" (recommended, but to be applied with caution).

List of abbreviations and definitions

AC	Alternating Current
AEL	Alkaline Electrolyser
AIP	Annual Implementation Plan (FCH JU FP7)
AP	Acidification Potential
AWP	Annual Work Plan (FCH 2 JU H2020)
bar	Metric Unit of Pressure
BoP	Balance of Plant
DC	Direct Current
DoW	Description of Work
ELCD	European Reference Life Cycle Database
EHS	Electrochemical Hydrogen Separation
EoL	End of Life
EP	Eutrophication Potential
FCH JU	Fuel Cells and Hydrogen Joint Undertaking
GaBi	Ganzheitliche Bilanzierung (German for Life Cycle Engineering)
GWP	Global Warming Potential
ILCD	International Reference Life Cycle Data System
IP	Intellectual Property
JRC	Joint Research Centre
kW	Kilowatt
kWh	Kilowatt Hour
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory Analysis
LCIA	Life Cycle Impact Assessment
LPG	Liquefied Petroleum Gas
MHV	Materials Handling Vehicle
MEA	Membrane Electrode Assembly
MJ	Megajoule
Nm^3	Standard Cubic Metre
PCEL	Proton Conducting Electrolyser
PED	Primary Energy Demand
PEM	Polymer Electrolyte Membrane
PEMEL	Polymer Electrolyte Membrane Electrolyser
PEMFC	Polymer Electrolyte Membrane Fuel Cell
RED	Renewable Energy Directive
REFCS	Reformed Ethanol Fuel Cell System
TSA	Temperature Swing Adsorption
V	Volt
VOC	Volatile Organic Compound
W	Watt

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