European Commission

JRC CONFERENCE AND WORKSHOP REPORTS

# Workshop on Lifecycle analysis of Fuel Cell and $H_2$ Technologies

*Summary of the main outcomes*


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2020

Joint Research Centre

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**EU Science Hub**
https://ec.europa.eu/jrc

JRC118195

PDF ISBN 978-92-76-12583-9 doi:10.2760/459675

Luxembourg: Publications Office of the European Union, 2020

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How to cite this report: Melideo, D., Ortiz Cebolla, R. and Weidner, E., *Workshop on Lifecycle analysis of Fuel Cell and H2 Technologies: Summary of the main outcomes*, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-12583-9, doi:10.2760/459675, JRC118195.

# Contents

# Abstract

This report provides a summary of the main outcomes of a workshop on Life Cycle Assessment (LCA) for Fuel Cells and $H_2$ Technologies organised by the Fuel Cells and Hydrogen 2 Joint Undertaking (FCH JU) and the Joint Research Centre of the European Commission (JRC). The goal of the workshop was to identify critical requirements, to discuss a common approach to LCA of Fuel Cells and $H_2$ Technologies and to propose the creation of a Life Cycle Inventory (LCI) database useful for the projects performing LCAs.

# 1 Introduction

Life Cycle Assesment (LCA) is a structured - and often internationally standardised - method to quantify relevant releases and consumption of natural resources. It is meant to assess the environmental and health impacts and resource depletion issues that are associated with any good or service ("products") [1]. LCA covers the chain from the extraction of natural resources, through production, use, and recycling, up to the disposal of any remaining waste. Such a comprehensive approach is needed in order to assess the environmental costs and benefits of emerging technologies. To achieve sustainable production and consumption patterns, the environmental impact of the whole life cycle of products from "cradle to grave" should be considered.

According to the Fuel Cells and Hydrogen 2 Joint Undertaking FCH JU Multi-Annual Work Plan (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 and applications 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 Joint Undertaking's 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 certain methodological aspects of LCA (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] and [4] (referred to as LCA deliverables in the following sections).

In 2018, the Joint Research Centre (JRC) of the European Commission (EC) delivered the report "Life cycle assessment of Hydrogen and Fuel Cell Technologies - Inventory of work performed by projects funded under FCH JU" [5]: it provides an overview of the progress achieved so far and an analysis on LCA for various hydrogen technologies and processes. The review considers 73 FCH JU funded projects. For some of these the LCA study was requested in the call topic, while other projects decided to perform the LCA study on a voluntary basis.

These LCAs have been assessed regarding adherence to guideline recommendations (e.g. reported properties, system boundary definitions, goal and scope definitions), methodology and overall quality of the work.

Based on the outcome of this analysis, a consistent approach on how to carry out LCAs in the frame of projects funded by the FCH JU is proposed. A workshop with 11 experts (the list of experts is reported in Annex 3) in the field of LCA was organised by FCH JU and JRC in June 2019. The workshop enabled a discussion of how LCA is contributing to the assessment of the environmental performance of technologies in the fuel cells and hydrogen field. The experts reported on their experience on performing LCAs 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 was to find commonalities and 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, it was discussed:

- to harmonise the approach to LCAs to facilitate the comparison between systems under study;
- to identify reference cases to be used as benchmarks for future LCAs; these should refer to competing technologies (e.g. electrolysis vs steam reforming) but

also to state-of-the-art systems when the purpose of the comparison is to analyse the environmental impact of a new design;
- to create a Life Cycle Inventory (LCI) database useful for projects performing LCAs.

A questionnaire was sent to the experts before the workshop. The goal of the questionnaire was the identification of gaps and suggestions regarding LCA on Fuel Cells and $H_2$ Technologies. The results were discussed during the workshop and are summarized in Annex 1.

The outcomes of the workshop are summarised in the following chapters. Chapter 2 summarises the main points of the presentation about the identification of potential updates to the FC-HyGuide guidance provided by Alessandro Agostini (ENEA - Italian National agency for new technologies, Energy and sustainable economic development) and Till Bachmann (EIFER – European Institute for Energy Research). A harmonized approach for facilitating the comparison of the LCAs was proposed and presented by Javier Dufour (IMDEA - Madrid Institute of Advanced Studies); the main points of the presentation are reported in Chapter 3. The presentation given by Mitja Mori (University of Ljubljana) addressed the challenges related to databases for FCH technologies, which are summarized in Chapter 4. During the workshop, a discussion took place on other aspects not strictly related to LCA, but necessary to LCA methodology: these are reported in chapter 5.

# 2 LCA methodology for fuel cells and hydrogen technologies: FC-HyGuide

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 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 requirements 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 more detailed technical guidance. The ISO 14040 and 14044 standards provide a 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 assure quality. The ILCD has therefore been developed to provide guidance for consistent and quality assured LCA data and studies. The ILCD Handbook is applicable to a wide range of different decision-contexts and sectors. It needs, however, to be translated into product-specific criteria, guidelines and simplified tools to support LCA applications in specific sectors.

The FC-HyGuide project responded to this need by providing a guidance document on how to perform each step of an LCA for hydrogen production [3] and fuel cell technologies [4]. The guidance document is intended 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.

During the workshop Alessandro Agostini (ENEA - Italian National agency for new technologies, Energy and sustainable economic development) and Till Bachmann (EIFER – European Institute for Energy Research) presented *"LCA of fuel cell and hydrogen technologies in the FCH JU: Identifying potential updates to the FC-HyGuide guidance"*; they discussed major issues and proposals regarding the FC-HyGuide documents ([3] and [4]), summarized in the following sub-chapters.

## 2.1 Major challenges and proposed improvements

### 2.1.1 Functional unit and reference flow

Currently, the functional unit (FU) and the reference flow (RF) are defined differently for hydrogen production and fuel cell technologies in [3] and [4]. In the fuel cell technologies guideline document two functional units are defined: one for stacks (capacity of the fuel cell, measured in kW of energy) and one for systems (production of useful energy). During the workshop, it was proposed to define two functions instead: "manufacturing" and "operation"; following that new classification, the recommended FUs would be a fuel cell of a given capacity (e.g. 1 kW based on the LHV of the fuel) for "manufacturing" and production of one unit of energy for "operation". Regarding the RFs, according to the new classification, one stack of one fuel cell system is the proposed RF for "manufacturing", while one stack or one fuel cell system meeting a given demand (taking into account lifetime, degradation, and parts replacement) is the proposed RF for "operation".

In the hydrogen production guideline document, the current RF is 1 MJ $H_2$ (LHV) with XX% purity and YY bars at ZZ °C; it is recommended to define the level of purity, the pressure and the temperature, because different values of those parameters provide different functions.

### 2.1.2 Life Cycle Inventory

Both guidelines recommend the use of International System of Units (SI) for Life Cycle Inventory (LCI) modelling: it should be made clear whether this refers to the SI base units or also includes the so-called coherent derived units[1].

Two main LCI modelling principles are in use in LCA practice: attributional and consequential modelling (see Figure 1). They represent fundamentally different perspectives in the assessment of the analysed system (e.g. a product) [1]:

- the attributional life cycle approach depicts the actual or forecast average supply-chain plus its use and end-of-life value chain; the existing or forecast system is embedded into a static techno-sphere;
- the consequential life cycle approach depicts the generic supply-chain as it is theoretically expected in consequence of the analysed decision; the system interacts with the markets and those changes are depicted that an additional demand for the analysed system is expected to have in a dynamic techno-sphere that is reacting to this additional demand.

**Figure 1 The attributional and consequential modelling approach** [1]

<table>
<tr><td rowspan="4">Decision support?</td><td rowspan="3">Yes</td><td colspan="2">Kind of process-changes in background system / other systems</td></tr>
<tr><td>None or small-scale</td><td>Large-scale</td></tr>
<tr><td>Situation A<br>"Micro-level decision support"<br>ATTRIBUTIONAL</td><td>Situation B<br>"Meso/macro-level decision support"<br>CONSEQUENTIAL</td></tr>
<tr><td>No</td><td colspan="2">Situation C<br>"Accounting"<br>(with C1: including interaction with other systems, C2: excluding interaction with other system)<br>ATTRIBUTIONAL</td></tr>
</table>

### 2.1.3 Cut off criteria

Both guidance documents (i.e. fuel cell and hydrogen production), recommend a cut-off criterion[2] of 2% and 5%, respectively. The cut-off values are based on values of the

[1] A coherent derived unit is defined as a derived unit that, for a given system of quantities and for a chosen set of base units, is a product of powers of base units with no other proportionality factor than one.

[2] 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.

input variables, and not on their output. It is proposed not to use cut-off but to clearly state which parts of the inventory are included and excluded and to interpret properly the results and discuss limitations.

### 2.1.4 Impact categories

The impact categories recommended by FC-HyGuide differ slightly for hydrogen production systems and fuel cells systems. Global Warming Potential (GWP), Acidification Potential (AP), Eutrophication Potential (EP), Non-renewable Primary Energy Demand (PED non-renewable) and Renewable Primary Energy Demand (PED renewable) are to be reported according to both documents; but Abiotic depletion (AD) and water footprint are only to be reported for hydrogen production systems. It was proposed that global warming and resources depletion (both fossil and elements) should be reported as a minimum requirement, and that other impact categories are included into the analysis depending on the goal of the LCA study (e.g. respiratory inorganics or eutrophication when compared with conventional cars or biomass-based CHP). In addition, it was proposed that the impact categories should be aligned with those recommended in the Product Environmental Footprint Category Rules Guidance (PEFCR).

### 2.1.5 Choice of impact assessment methods

According to the FC-HyGuide guideline documents, the impact assessment methods and characterization factors from the CML methodology are to be taken as long as there is no recommendation from the ILCD handbook [1]. It was proposed that the latest recommendations provided by the European Commission should be adopted. Currently the Impact Assessment methods recommended in the framework of the Environmental Footprint programme (EF) (2013/179/EU) should be followed which can be found at https://ec.europa.eu/jrc/en/publication/supporting-information-characterisation-factors-recommended-ef-life-cycle-impact-assessment-methods.

### 2.1.6 Data quality requirements

The LCA study performed in the framework of the ene.field project has shown that the electricity replacement mix is of utmost importance for the environmental performance of fuel cells (as for any other kind of CHP, micro or not). Requiring an average electricity mix to be used will therefore not assess the specific merits of this technique in a given setting. Using true replacement mixes applicable to different parts of Europe will increase the degree of realism; this will also concern the electricity with which hydrogen is produced. It was clarified also that the electricity mix, or any other alternative energy system, can be used only to present the results and put them into context, but assuming the perfect substitution of any arbitrarily chosen system is misleading.

### 2.1.7 Identifying processes within the system boundary

In the fuel cell guideline document, it is stated that the use phase of the fuel cell in a specific application (e.g. on-site electric power for households and commercial buildings, supplemental or auxiliary power to support car, truck and aircraft system, etc.) shall be excluded. However in the LCA study performed in the framework of the ene.field project, the fuel cells use phase turned out to be one of the life cycle stages with the highest environmental impacts. Therefore, the results would considerably change if this stage was excluded. It has also been suggested to make clearer what is meant by “in specific applications”.

## 2.2 More general remarks

In a recent publication [9], the following more general remarks and recommendations were made:

- A clear identification of the goal and scope of the analysis is essential to properly perform the interpretation phase. It is necessary to clearly state which question is at stake and how it is planned to answer it.
- Different impact assessment methods have different meanings, thus the methods used for the impact assessment need to be understood and explained. For example, climate impacts can be measured with different metrics at different time horizons: GWP100 is a cumulative metric on the radiative forcing in 100 years, while GTP20 is the earth surface temperature change in 20 years from the emissions; often many climate forcers are neglected (e.g. albedo, aerosols). The same for other impact categories, there are several methods which answer different questions.
- In general, even if input data are highly uncertain or scarcely known (i.e. impacts deriving from the extraction of some rare materials), it is recommended to use the best available data, or a proxy, and carry out a sensitivity analysis. It is better to be approximately right than precisely wrong (e.g. omitting uncertain aspects altogether).
- If allocation is used, the rationale supporting the chosen allocation methods should be explained and assessed via a sensitivity analysis.
- The intended use and audience of the study should be clearly identified and reported.
- Limitations should be clearly identified and reported. Care should be taken to identify the limitations relative to the [modelling] approach chosen and all the subjective choices taken (allocation or system expansion, system boundaries, sustainability aspects and environmental impacts analysed, systems definition, etc.).
- Conclusions must be drawn only on the impact categories analysed, respecting the following order: sustainability assessment includes social, environmental and economic aspects; environmental sustainability assessment encompasses all the relevant areas of environmental concern; climate change impact assessment includes all the climate forcers; Greenhouse Gas (GHG) emissions assessment includes all well mixed GHG.

# 3 Harmonised approach to LCAs for facilitating the comparison / identification of reference cases to be used as benchmark for future LCAs

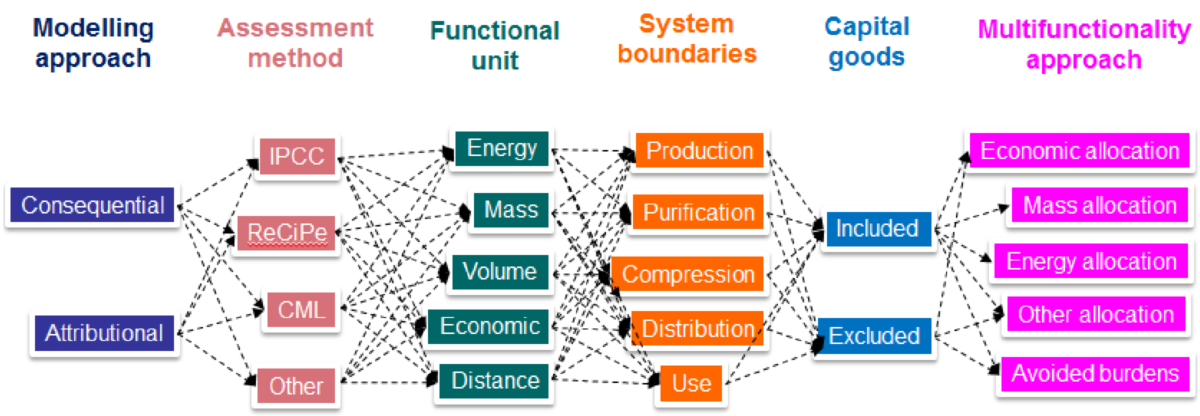
LCA provides information about the environmental impact of a specific product or system. It can be used to identify which life cycle stage or process contributes the most to a given environmental impact for the product under study (e.g. manufacturing process or use phase) but it also helps to compare which technology performs better from an environmental point of view through the comparison of the results of the individual LCAs. This comparison could serve to justify the funding of specific technologies with a better environmental footprint.

However, this comparison is usually not straightforward; aspects such as application of the technology, size (small scale or large scale) or the methodology followed to perform the LCA have to be considered when comparing the results.

Javier Dufour (IMDEA) presented the work done by his working group. They performed a literature review on LCA on hydrogen energy systems where they observed a big disparity in the methodological approaches and environmental impacts reported. Based on the outcome of that review they decided to make an effort to harmonise the results of the different studies. With that purpose, they have developed a software tool (GreenH$_2$armony) that should help to harmonise the results of different LCAs and facilitate their comparison. This tool is still in beta phase and only available for hydrogen production technologies. In the future, it could include, in addition to other hydrogen technologies, other aspects such as economic or social indicators. The development of this tool requires huge efforts and the IMDEA team will welcome any suggestions.

The tool addresses the challenges of performing comparisons between LCAs of similar or competing hydrogen production technologies (e.g. different electrolysers or electrolyser vs steam methane reforming). When performing an LCA there are many methodological choices (see Figure 2) among which LCA performers have to select such as the [modelling] approach (Consequential vs Attributional), assessment method (e.g. CML [10]), functional unit, system boundaries or in decisions regarding allocation, the results obtained will be influenced by these methodological choices. Therefore, if the LCAs to be compared have not been performed by the same methodological approach, it is highly probable that their results cannot be compared.

**Figure 2 The attributional and the consequential modelling approach**




Following the presentation, the discussion focused on the importance of LCA comparability to assess the environmental benefits of FCH technologies and the need of reference cases. To overcome the comparison challenges mentioned above, the approach proposed by IMDEA can be followed.

According to the workshop participants, this methodology for comparison is more feasible for hydrogen production technologies than in the case of hydrogen use technologies, particularly when the FC is part of a bigger system (e.g. FCEV).

In the case of hydrogen use technologies, comparison must consider the specific application in which the technology is used. Apparently the most challenging application is the mobility one. If we consider comparing the outcomes of LCAs for BEV and FCEV, it has to be considered whether those vehicles are able to provide the same service. In these cases the common functional unit is the distance travelled, but this functional unit cannot consider that the BEV does not usually have the same range as FCEV, so its use is less feasible in certain applications. This is a critical factor when performing the comparison, since its final goal is to establish which technology has a lower environmental impact for a specific application.

Regarding reference cases, there was a common consensus on their usefulness to benchmark, validate and verify the methodology followed. Reference cases could refer to conventional technologies so that the FCH technologies could be compared against them (e.g. Steam reforming vs Electrolysis), but also to a state-of-the-art FCH technology that could help to identify the environmental benefit of a specific modification (e.g. reduction of platinum in a FC or modification of BoP in an electrolyser). As explained above, reference cases are easier to be defined for hydrogen production technologies than for hydrogen use technologies. To partially address this problem, a solution could be to define reference cases referring to the device and not to systems (e.g. FC instead of FCEV) so the specific application of the technology is not relevant. In this case, it has to be clearly stated the limitations for comparability purposes of such reference case. The general agreement among the participants was that further discussion is needed to define reference cases and identify limitations in their applicability.

Definition of an electricity source that could serve as a reference for comparability purposes was a request from the participants. Electricity has an important role in the final environmental impact of hydrogen production technologies (e.g. electrolysers) or in system with auxiliary equipment that relies on electricity (i.e. compressor in HRS), but also it is important when performing comparison among, for instance, a CHP system against the electric grid.

Another aspect discussed during the workshop was the comparison between well-established technologies and technologies in their earlier stage of development. Manufacturing processes, performance and durability are aspects that could improve for technologies in their earlier stage of development and they could have a significant impact on the environmental footprint of a particular technology. A possible approach to perform a fairer comparison against more developed technologies could be the use of learning curves.  The values included in these learning curves should be agreed among experts of each specific technology and shared with LCA practitioners in a reference document.

The inclusion of additional indicators such as noise level or space requirements was also discussed.

# 4 LCA databases for FCH technologies

The performance of an accurate LCA requires precise information on the different materials and energy sources used during the lifetime of the product/technology under analysis, which is called Life Cycle Inventory (LCI). Once the LCI is elaborated it is possible to perform the environmental impact assessment using such an inventory (LCIA).

The presentation given by Mitja Mori (Univeristy of Ljubljana) addressed the challenges of availability of accurate and complete databases for FCH technologies. He presented experience gathered during the HyTechCycling project. One of the goals of this project was the development of new technologies and strategies applied to FCH technologies in the phase of recycling & dismantling and LCA analysis considering critical, expensive and scarce materials inventory. Despite the fact the project was focused on the end-life of the technology, they gathered information on the whole chain of the technology, which includes manufacturing and the operation. The project analysed several FCH technologies: Solid oxide fuel cell (SOFC), Proton exchange membrane fuel cell (PEMFC), Proton exchange membrane water electrolyser (PEMWE), Alkaline water electrolyser (AWE) and Balance-of-Plant components. Within these technologies the focus was on components such as electrolyte, cathode, anode or sealants. The project established a methodology to identify the criticality of the materials involved. This classification was based on price, scarcity and hazardousness of the material.

The project found gaps and challenges regarding the availability of information on materials. The information needed to perform LCA could either be provided by the manufacturer of the technology (primary data) or it can be found in scientific literature, commercial catalogues or LCA databases (secondary data). The first type of data is not always available, as manufacturers are not usually keen to disclose the materials used in their technologies and the amount of each of them since they prefer to keep this information from their competitors. Another reason for not sharing this information could be that, for those technologies that are less developed and still relying on funding, the comparison with other technologies could show that their technology has a worse environmental performance and this could mean a reduction in funding opportunities. Still another reason could be that some manufacturers are only system integrators, i.e. they buy the cells or stacks and make commercial FCH systems out of them. In that case, they might not (be allowed to) know the composition of the cells or stacks.

Secondary data do not only come with an issue of their broad availability, as said above, but also one of quality, because there is no guarantee on their being up-to-date. Many FCH technologies are still under development, and their performance in many aspects (i.e., efficiency, reduction of precious materials…) has been improving along the years. This problem is less important in well-established technologies since they do not usually have significant and recent improvements. Using outdated information while performing LCA will lead to results that do not represent the current situation.

An additional difficulty associated with secondary data is that, due to confidentiality issues, the presence and environmental impact of some materials is reported together, for instance PGM (Platinum Group Metals) or TM (Transition Metal) materials. Therefore it is dificult to extrapolate that information to individual materials.

Another important piece of information that is not usually found in the literature and that also the manufacturers are not willing to provide, is regarding the different manufacturing processes involved in the elaboration of the product. Energy and material flows of these processes are needed to for an accurate LCA.

Not only manufacturing processes are important, but operational modes and end-of-life processes should be considered in the performance of an LCA. Unfortunately there is a lack of information on these two aspects. The operational mode often considered in LCAs refers to operation at nominal conditions but this can be far from reality in some sytems (notably FCEV). The operational conditions will completely modify the efficiency with which the system is working and therefore its emissions. End-of-life processes are gaining importance in a world where generation and managment of waste and raw material sourcing is becoming a main concern. In principle, they should reduce the environmental impact of any particular product, but still there is a lack of information of the different EoL process and their environmental consequences.

HyTechCycling has faced an additional challenge: the lack of information on the characterisation factors of the environmental impacts of certain materials present in the technologies under study. The case of SOFC was especially remarkable, as this technology uses several complex ceramic compounds for which these characterisation factors cannot be found in commercial databases. There is also a lack of information regarding doped alloys. A possible approach to solve this problem is to find substitution materials or to separate these complex compounds in more simple compounds for which this characterisation factors are available in commercial databases. However, this approach will bring uncertainty to the LCA results, but this problem could be tackled by means of, for instance, sensitivity analysis.

During the round-table discussion proposals were made on how to resolve these issues of data availability. It was clear that there is need to build, maintain and periodically review a FCH technology database. This database could be filled with data provided by FCH JU projects. Another source of data should be the FCH industry, but one needs to find a motivation for them to share that information, and means of aggregating or anonymising the data should be discussed. This information should not only be limited to material composition, but also to manufacturing and end-of-life processes. Several proposals were made regarding who should be the keeper of this database, with suggestions that FCH JU or JRC or a small group of experts under the mandate (contract) of the FCH JU.

The lack of information on the characterisation factors of environmental impacts of certain materials used in FCH technologies is limiting the accuracy of LCIA for these technologies. It was agreed that this is a gap that has to be filled, but the actions to solve this issue were not clear. It seems to be in the hands of the companies that produce and sell the databases of this characterisation factors.

# 5 Other topics

In this session, the discussion revolved around other aspects not strictly related to LCA but that are seen as necessary to improve the overarching approach of the LCA methodology. The topics under discussion referred to critical raw materials, life cycle cost and sustainability assessment. The main outcomes of the discussion are shown below.

Critical raw materials (CRM) are those raw materials which are economically and strategically important for the economy, but have a high risk associated with their supply. These materials are currently identified, but this list is periodically updated (in Europe, every 3 years) according to the parameters mentioned above. The materials included in this list will depend on the country/region issuing it. Their criticality is not related with their environmental impact but with geo-political and economic aspects. However, during the LCA process all the materials involved in the manufacturing and operation of a certain product/technology are identified (by means of the LCI). From this list, it is easy to point out which are critical raw materials present in the technology/product under analysis just by cross-checking with the most recent critical raw materials list. In the case of Europe, such list can be found in Table 1. This identification of CRMs could help to understand the impact and the limitations of the use of such technology/product from critical materials point of view.

Table 1. List of critical raw materials (CRMs) in Europe

| **2017 CRMs (27)** | | | |
|---|---|---|---|
| Antimony | Flourspar | LREEs | Phosphorus |
| Baryte | Gallium | Magnesium | Scandium |
| Beryllium | Germanium | Natural graphite | Silicon metal |
| Bismuth | Hafnium | Natural rubber | Tantalum |
| Borate | Helium | Niobium | Tungsten |
| Cobalt | HREEs | PGMs | Vanadium |
| Coking coal | Indium | Phosphate rock | |

Life Cycle Costing (LCC) would identify the different costs associated to a certain product/technology during its lifetime. The workshop participants agreed on the fact that a methodology is needed and that an analysis should be performed according to same scenarios and assumptions as for the LCA, to facilitate comparison. The maturity of a specific technology can be an issue when comparing with more established technologies, therefore the use of learning curves was proposed as a solution, to align the current costs of new technologies to the expected value when these technologies are more established.

Life Cycle Sustainability Assessment (LCSA) is a new approach to assess the sustainability of a certain technology. In addition to the environmental aspects it also addresses social and economic aspects. This would be the most overarching assessment of a technology since it would merge LCA, LCC and social impact. It is still under development, especially the social part. The social indicators should be defined and databases of these indicators would need to be generated. An example of possible social indicators could be fair salary, child labour or health expenditure. In this kind of assessment, there could be a stronger link with critical raw materials.

It was suggested that an actions roadmap could be the first step in the establishment of a LCSA methodology. Since the purpose of the LCSA is going beyond FCH technologies, it was agreed that FCH JU should not put efforts on developing any global methodology for LCSA. However, the FCH JU could support and fund projects including objectives related to LCSA methodology development that could be relevant for FCH technologies. Nevertheless, the agreement on this point was not general among the participants.

As in the case of the LCA, it will be necessary that the results of future FCH JU projects performing LCSA are comparable.

# 6 Conclusions/Recommendations and open questions

## 6.1 LCA methodology for fuel cells and hydrogen technologies: FC-HyGuide

The FC-HyGuide documents ([3] and [4]) have been analysed and discussed and potential updates and improvement needs were identified. New functional units and reference flows have been proposed for the LCA studies on hydrogen production and fuel cell technology. Both guideline documents (i.e. fuel cell and hydrogen production), recommend a cut-off criterion of 2% and 5 %, respectively; it has been proposed not to use cut-off but to clearly state which parts of the inventory are included and excluded and to interpret properly the results and discuss limitations.

Two main LCI modelling principles are in use in LCA practice: attributional and consequential modelling; they represent the two fundamentally different situations of modelling the analysed system: attributional LCA uses normative cut-off rules and allocation to isolate the investigated product system, and by this, it ignores some the physical and economic causalities that are related to the life cycle of a product.

In many processes more than one product is produced, in such cases it is necessary to divide the environmental impacts from the process between the products. It is not straightforward to divide environmental impacts between the product and the co-product, but it can be done choosing either allocation or system expansion methods; the choice between the two methods can have huge impacts on the result of the LCA. If system expansion is used, the type and amount of product replaced is a critical subjective assumption which should be thoroughly assessed via a sensitivity analysis. Uncertainties are always present in complex modelling exercises, if a quantitative uncertainty assessment is not performed, this choice should be clearly mentioned and justified.

The impact categories should be aligned with those recommended in the Product Environmental Footprint Category Rules Guidance (PEFCR). It has been proposed that at least global warming and resource depletion (both fossil fuel and elements) impact categories should be reported as a minimum requirement.

The conclusions of an attributional LCA can only be drawn on the system or amount of energy considered as functional unit, hence in contexts of microscale decision, eco-design or accounting, such as in environmental product declarations or national (or other) inventories. To draw policy relevant conclusions, thus affecting the installed capacities, a strategic assessment shall be carried out; the potential consequences of the policy together with all the related current and expected market mediated effects shall be modelled.

A clear recommendation from the discussion was that any LCA (performed by FCH JU projects) should be verified by a third party, as kind of a quality check.

## 6.2 Harmonised approach to LCAs for facilitating the comparison/ identification of reference cases to be used as benchmark for future LCAs

The most relevant LCA feature for funding bodies as the FCH 2 JU is that it can allow comparability among technologies/systems in terms of their environmental impact. This aspect is crucial to justify funding strategies with environmental objectives. A fair comparison of the LCA results of different technologies/systems requires that the LCAs are performed following the most similar methodology possible. Therefore, when comparison of results is reported, it has to be clearly stated the methodologies followed in the different studies to understand if they are comparable as well as the limitations of such comparison.

Comparability of hydrogen production technologies seems easier than the case of hydrogen use technologies, where the intended use of the system should also be considered. The intended use may not allow the implementation of some solutions (e.g. long range distance vehicles for pure-battery solutions technologies) and therefore the comparison against those technologies should not be performed. To facilitate the comparability for hydrogen use technologies more efforts have to be made to solve the challenge of the intended use.

LCA reference cases of conventional technologies (e.g. steam reforming) or state-of-the-art systems (e.g. commercial alkaline electrolyser) should be defined to facilitate the comparison against alternative technologies or new designs. The LCA reference cases should be clearly described, not only the results obtained, but also the methodology that has been followed for their performance.

Comparison between well-established technologies on one side and early-stage development technologies on the other could lead to misleading results. Supply chains, manufacturing processes and operational performance are usually less optimised in the second case. In these cases, the adoption of learning curves or expert judgment on the potential optimisation at commercial scale are recommended, along with guidelines on when and how to perform such an assessment.

## 6.3 LCA databases for FCH technologies

Accurate inventories of material composition and their amounts in FCH technologies are fundamental to perform a reliable LCA. This also refers to the characterisation factors of environmental impacts of the materials used in such technologies. Unfortunately, the information needed to perform the LCA is often not complete and some materials are missing. Manufacturers, which are the main (and most reliable) source of information for material inventory of their technology, are usually reluctant or not able to share information that they may consider confidential. On the other hand, new technologies may use materials which characterisation factors have not been defined yet (e.g. ceramics in SOFC) and therefore there is no literature available that could help the LCA practitioner to perform the LCIA.

The lack of information is not only related to material inventories but also to the energy demand of manufacturing processes and operational performance. On the latter, usually nominal operation conditions are assumed, however, in many applications a specific system may work at different operational conditions (e.g. FC in a FCEV).

Another important aspect is the update of the data available. It is normal for technologies under development, as FCH technologies, that noticeable progress (e.g. reduction of PGM) is achieved more frequently than in well-established technologies. This progress should be reflected in the databases, therefore a continuous revision and update of these inventories is needed.

It was suggested that FCH JU should look actively for strategies to motivate industry members to provide data. Manufacturers participating in FCH JU projects may be invited to provide information necessary for these databases. This data should be part of a repository where performers of LCA for FCH technologies could have access.

Questions remain open on how to address the lack of information on the characterisation factors of environmental impacts of relevant materials in certain FCH technologies (i.e. complex ceramics in SOFC).

## 6.4 Other topics

The extension of LCA to aspects as critical raw materials, Life Cycle Costing and Life Cycle Sustainability Assessment were discussed.

The definition of critical raw materials is not related to environmental impact. It refers to economic aspects and reliability of their supply. The lack of characterisation factors for these aspects does not allow LCA methodology to assess the criticality of raw materials, however during the performance of LCA it is possible to identify the presence of critical raw materials by means of the LCI.

Life cycle costing (LCC) provides information about the total cost of a technology/system during its lifetime, including the economic, environmental and social costs. It follows a similar methodology as LCA and it has the similar problems as described for LCA regarding comparability and accuracy of the data needed to perform it[3]. As mentioned for the LCA case, comparability of LCC results should be done under the same scenarios and assumptions as for an associated LCA. Learning curves are also recommended to avoid the economic differences that come by default between well-established technologies and the ones in early stage of development. In the case of data, similar to the case for LCA, there is the problem of the lack of cost data for materials. Databases with this information, with a periodic maintenance (review and update) are necessary.

Life Cycle Sustainability Assessment (LCSA) has an overarching approach when assessing a technology/system. It includes environmental and economic aspects but also social indicators (e.g. ethical issues such as child labour). It is still at an early stage of development in terms of the social indicators, while environmental and economic aspects are already covered by LCA and LCC. Work is needed to develop the methodology, indicators and databases. It is not recommended that FCH JU makes efforts in developing a global methodology, however it could support and fund projects that include some methodology development relevant for FCH technologies.

[3] It has to be noted that Life Cycle Costing if far more complex and uncertain than an economic assessment as it introduces the costs of externalities. Often there is a misunderstanding between LCC and a simple economic analysis. LCC introduces the uncertainties of externalities, which are huge (even for CO2 emission, which are the most studied and where there is a market).

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# Annex 1. Survey results

A survey was circulated among the potential participants of the workshop. This survey aimed at identifying aspects to be improved in the FC-Guide LCA methodology as well as current challenges on the performance of LCA of FCH technologies. The structure of the survey was similar to the one of the workshop. The most relevant questions and the answers to them are presented in this annex. In general, the replies are in-line with the comments and opinions provided by the participants of the workshop. Please note that these answers have been modified in order not to show any confidential information (direct reference to projects)

**- METHODOLOGY**

| ***Which advantages and drawbacks did you find when implementing FC-HyGuide?*** |
|---|
| There are not many advantages or disadvantages. It builds on the ILCD, which builds on the ISO standards. It just tries to harmonize the impact assessment methods, functional units and a little more. |
| The main advantage is the existence of a common guide to perform LCAs.<br>Disadvantages: requirement of sending your information to a private company, no clear comparison with competing technologies |
| We actually didn't find very useful information, except for the system boundaries (no default data for example) |
| It is a good check list to not forget about anything.<br><br>Drawbacks:<br>• Rather than using the ENTSO-E electricity mix, it is more appropriate to use a more realistic production mix that electricity produced by FCs replace. More realistic electricity consumption mixes for electric alternatives (e.g. heat pumps) should also be used.<br>• There is rather little guidance on how to carry out the completeness check according to provision 36. Most notably, the evaluation of the 2% cut-off rule as required by provision 17 is difficult to perform without having a world model.<br>• One requirement of provision 13 refers to the use of "the International System of Units (SI) in the Life Cycle Inventory modelling". In order to avoid confusion, it should be made clear whether this refers to the SI base units or also includes the so-called coherent derived units.<br>• Provision 25 states that the use phase of fuel cells in specific applications should be excluded. The FCs use phase turns out to be, however, one of the life cycle stages with highest environ-mental impacts. The results would consistently change if this stage was to be excluded.<br>• Provision 28 does not directly name ecoinvent in the list of accepted databases for secondary data. It was therefore difficult to verify its validity.<br>• Provision 30 obliges to use exergy in case heat is a valuable product and there are allocation problems. In the a project LCA, however, the environmental burden is not allocated to each of the energy forms provided by the FCs, i.e. heat and electricity. The functional unit was defined as "the satisfaction of the heat and electricity demand of a given home in a specific European setting, defined by the dwelling type (single vs. multi-family home), its age (existing or new/renovated) and climatic |

| |
|---|
| conditions (northern, central and southern), during one year". The FU therefore includes both electricity and heat, without the need of converting to exergy. As a result, there was no allocation problem. It may therefore be useful to define in the FC-Guide guidance document under which conditions allocation problems exist.<br>• Provision 11 suggests assuming a 10% performance degradation without indicating the period during which this fall in efficiency occurs. |
| Advantages: usefulness of having some guidelines and recommendations.<br>Drawbacks: it does not successfully avoid misinterpretation risk in comparative studies. |
| System boundaries approach were applicable, as well as data collection principles. The end of life of the fuel cell system is optional, which is good if there is lack of data of that stage. However, since the technology is often very young when compared to e.g. diesel generators, the impact of the equipment manufacturing may appear to be high, especially if no material recycling in the end of life stage is considered. |
| Drawbacks:<br>• Some missing data in generic databases<br>• No available data from the industry - hard to motivate them to share the data<br>• The lack of EoL approach strategies in end of life |

| **Do you have any suggestions to improve the FC-HyGuide?** |
|---|
| It should be updated on the LCIA methods recommended, and maybe integrate a discussion on the inventory modelling approach. |
| Development of on-line tools where everyone can introduce its information and get results. Clear comparison with other systems |
| • Default data (e.g., average composition of the different elements and infrastructure, average lifespan, etc...)<br>• Additional case studies of comparative LCAs<br>• We found this guide very much oriented toward non-LCA experts that need to perform LCA, but not really for LCA experts that do not know about hydrogen production technologies and fuel cells.<br>• The guide could also be adapted for other type of use of Fuel cells for combined heat and power generation. |
| For the electricity mix that is replace by FC electricity, use the so-called residual mix, i.e. the electricity without guarantee of origin.<br>I will present the specific items at the workshop (see also my answers to the previous question). |
| Online computation of sound indicators for comparative studies.<br>Unification of methodological choices (harmonisation). |
| If it is possible to add clear instructions of how the end of life of the equipment should/could be treated, it could be beneficial. |
| Implement EoL strategies |

| **Why you did not use the FC-HyGuide?** |
|---|
| 1. It did not exist.<br>2. It ignores and violates the Commission's guidelines for novel transport fuels in FQD ("Data requirements and principles for calculating life cycle GHG intensity of novel transport fuels", September 2016), and instead relies on LCA dogma, resulting in some unworkable rules.<br>3. In particular, FCHJU ignores displacement emissions, which often apply to hydrogen, or potential feedstocks for hydrogen, which are diverted from an existing use. However, the 2 examples given are of elastic sources, not rigid ones (read the FQD principles to understand the difference).<br>4. The rules for allocation do not work even for the example of the chlor-alkali process given as an example in the text. However, the steam reforming process is actually irrelevant to the supply of additional hydrogen. As the hydrogen hardly affects the profitability of the chlor-alkali process, it is run at a capacity to satisfy the Cl2 and NaOH demands; so buying hydrogen from an existing chlor-alkali process would actually mean diverting it from an existing use. The emissions from the chlor-alkali plant will not change, but the existing H2 customer has to buy hydrogen from another source. That additional source of hydrogen is very probably steam reforming (under present conditions). Therefore the emissions from steam reforming apply.<br>5. The rule for allocation to exported heat (used in steam-reforming example) is bad. Steam at <150C is of little value, as vast amounts of it are thrown away by industry as there are not enough industrial uses for it. 1MJ heat at 1000C can produce more useful work than 1MJ heat at 200C. So allocation to exported heat should be done by value or exergy, never by energy-content. But it should not be a choice for the producer, and as there is not always a clear market value, exergy is the only method that can always be applied.<br>6. Reporting of the examples is insufficient to check the results (we need an excel sheet of all input data, and all assumptions should be laid out). For example, in NG steam-reforming, we are not even told how much NG is used to make 1 MJ H2. |
| I did't know about its existence. |

**-BENCHMARKING**

| **What are the difficulties you have found when performing benchmarking (e.g. reference cases, LCA methodology, etc.)?** |
|---|
| We did not have any particular philosophical difficulty in the reference cases for the hydrogen-calculation tasks I was involved in: we calculated the reference cases as well. For hydrogen (or hydrogen-derived liquid fuels) used in transport, we compared EU-average WTW emissions with those of gasoline and diesel cars. |
| Lack of specific datasets on the materials and processes used in FC & H |
| Lack of clear definition of system boundaries, no clear allocation procedures, generally accepted reference cases |
| • Difficult to define the functional unit --> Has a large influence on the results<br>• Difficult to define the dimensioning of the reference case (we first had to define the dimensioning based on the energy production of the m-CHP developed within the project) |
| There are two main challenges:<br>1) FC technologies are still much less mature than conventional alternatives (e.g. ICE in the case of automotive, and gas condensing boilers in case of stationary applications). As a result, one would in principle need to anticipate mature FC technologies, if one wanted to do fair comparisons with conventional alternatives available today.<br>2) Data availability: not only datasets for entire FC or H2 production systems, but also data for components thereof are missing. This concerns for instance PEM membrane production (e.g. Nafion/PFSA) or Yttrium-Stabilized Zirconia (YSZ) and Lanthanum Strontium Manganite (LSM) used for SOFCs. |
| The key point is the lack of transparency (or clear statements) in many of the LCA studies of hydrogen systems available to date. |
| Comparison to diesel generators can be challenging if the systems provide energy with different kWhs. |
| Since there is not precisely prescribed EoL strategy it is hard to compare results in EoL phase. |

| What would you suggest to solve these difficulties? |
|---|
| To buy or to build specific datasets and make them available |
| Development of harmonization protocols |
| Provide examples of functional unit depending on the type of technology assessed<br>Provide examples and default data of reference cases |
| To address the issue of different maturity levels, one would need to find methodologies to make the systems comparable. Learning curves might be one option that I can think of.<br>To address the issue of data availability, effort would need to be made to gather data of individual substances (e.g. nafion, Yttrium-Stabilized Zirconia and Lanthanum Strontium Manganite) and the processes needed for their production. It would presumably be helpful to work together with material scientists (i.e. not only LCA scientists) if help from industry cannot be found. |
| The use of harmonisation protocols (e.g. those currently available for hydrogen production systems). |
| Instructions how to compare generators / fuel cells (both in use stage / manufacturing of the equipment) if they have different power outputs (I'm an LCA expert, not a physicist.) |
| A very precise revision of HyGuide with EoL part strategies added. |

**-DATABASES**

| **Regarding available information in LCI databases, which limitations did you find while performing LCA of hydrogen technologies?** |
|---|
| They tend to share the same problems as FC-Hyguide. They are of no use for new processes. They don't take into account local electricity emissions. They may use different sources than you for electricity or NG upsteam emissions. |
| The lack of specific datasets on rare earths and elements and their processing. |
| Lack of materials and systems |
| • No data on catalysts, fillers, membrane<br>• Types of metals and ceramics are missing<br>• Lack of data for catalyst and membrane synthesis (energy and goods consumption)<br>• Poor quality data for rare metals (e.g., palladium)<br>• Lack of different purity grade of ethanol (used as feedstock for hydrogen production) |
| The ELCD did not contain any data. The datasets in the ecoinvent database were more than dated not only for the FC but also for the gas condensing boiler that was used as the conventional alternative. |
| A significant number of LCIs of relevant H2 production/use systems are still missing. |
| Hydrogen origin itself. |
| Ecoinvent database lacks transparency when using LCI datasets.<br>Some materials used in fuel cell systems may not have LCI data available in Ecoinvent (e.g. carbon fibres, ruthenium). |
| • The lack of industry partners to provide the data in all stages relevant for quality LCI phase<br>• Lack of generic data in specific databases and environments.<br>• Lack of specific EoL processes mainly of more critical materials - we modelled them on the basis of scientific papers but several papers have different recovery ratio that is of main importance by reducing environmental impacts in manufacturing stage |

| **Are there specific technologies where the lack of data does not allow performing an accurate enough LCA?** |
|---|
| Not for us: manufacturers confidentially provided us detailed information on their processes. With the present state of the art, it will be difficult to find the emissions for the electricity actually used by a plant that is not operating continuously. |
| The level of accuracy depends on the goal and scope of the analysis. in general, even if some datasets are missing, some conclusions can be drawn in any case, maybe with a sensitivity analysis to test the robustness |
| End-of-life technologies, SOFC/SOEC, Low scales SMR, new compressors... |
| In our case, we were able to collect data from partners, but they are more representative of the lab/pilot scale, and some data from litterature (very few data in litterature for catalyst and membrane production) |
| PEM FC, SOFC, both of different capacities for both automotive and stationary applications. |
| • There is a significant gap in data for the EoL stage of hydrogen systems.<br>• Depending on the scale, there is also a need for updated and complete inventories of technologies such as SOFCs. |
| Catalyst, bioreactors. |
| Not that I'm aware of, LCA can (almost) always be applied if throughly explained and sensitivity of assumptions is tested. |
| By far the biggest lack is in manufacturing stage:<br>• SOFC critical materials are almost not available in databasesIn operation phase:<br>• Usually just stationary operation is used in LCA models/data<br>• Usually just nominal power operation is used in LCA models/data - no degradation in life time of technology<br><br>End of Life Phase:<br>• For critical materials no recycling processes are available in databases<br>• After manual dismantling of technology no general approach of EoL is standardized |

| What kind of efforts would be needed to reduce these limitations? |
|---|
| Work on marginal electricity emissions as a function of time, work on GHG value of electricity storage; and future projections of these. |
| To build or to buy specific datasets for the materials used in fuel cells and hydrogen |
| Development of specific inventories |
| Default data on above information<br>Improved LCA datasets for rare metals and ceramics |
| There is a problem of data availability. Even within a demonstration project (with a couple of manufacturers, some however only being system integrators), primary data has not become available. So, it is not only an issue of effort (i.e. in terms of resources), but most of all an issue of data availability. One reason is that the manufacturers do not want to unveil data of their own product in order to avoid the risk of an unfavourable result that their product performs worse than that of other manufacturers. We even had a discussion at consortium level whether or not we should compare PEM FC against SOFC The fear being that the less performant type of FC would lose its financial support from the FCH JU/EU. |
| Investments are needed to develop complete LCIs of a wide range of FCH technologies (increased budget in projects, specific call, etc.). |
| More development in LCA adapted to Hydrogen technologies. |
| Publicly available LCI datasets? |
| General approach in EoL stage could be given in few steps so the results could be comparable from different studies.<br>Regarding operation phase, checklist of what to include in the model should be given (operational regime, degradation in time, maintenance, spare parts, etc.). Operation regime is depended of manufacturer, application of technology, regular maintenance, etc, so difference should be emphasised. |

**- OTHER CHALLENGES**

| **Do you have any other comment regarding challenges when performing LCA for hydrogen technologies that has not been addressed by this survey?** |
|---|
| Apart from shortcomings already mentioned, you will need to address CO2 capture for use in recycled carbon fuels. Both the CO2-capturing plant (such as a steam reformer with CO2 capture) and the producer of the recycled-carbon fuel would like to claim the credit for not releasing the captured CO2. But that would be counting it twice.<br><br>In fact, there is far more CO2 released, even in concentrated form, than industry needs. So the amount used is limited by the demand, not the supply. Increasing the DEMAND for CO2 leads to more CO2 capture. But increasing the SUPPLY by capturing more CO2 in a particular plant will do nothing to reduce global GHG emissions, because without an increase in demand, it will result in another CO2-capture plant shutting down its CO2 capture, and emitting it instead. Therefore the CO2-capture credit must go to the USER of the CO2, not the plant that happens to capture it. (p.s. of course, no-one in industry with any significant demand for CO2 burns fossil fuel just to make CO2, as there is so much already being released). |
| The current information in databases are mostly focused on production and some uses, but full information about the full value chain is missed. For instance, transport is usually addressed with general techniques and not specific for H2. In this way, if the full value chain is taking into account, the geographical scope should be included. |
| • The Guide should very short and summarized, with more information in appendices.<br>• A section is missing on how to treat bio-based materials that are used as feedstock<br>• A section is missing on heat and power cogeneration in fuel cells |
| A key future challenge will be to enlarge the scope of the (harmonised) systems so that the whole supply chain is covered. |

## Annex 2. Workshop agenda

### WORKSHOP ON LIFE CYCLE ANALYSIS OF FCH TECHNOLOGIES: GAPS AND CHALLENGES

### FCH 2 JU, Brussels, 24 June 2019

White Atrium. Common Meeting Room 1
Avenue de la Toison d'Or 56-60, B-1060 Brussels

| | | |
|---|---|---|
| *09.30 - 10.00* | *Registration, coffee* | |
| 10.00 - 10.10 | Welcome & opening | FCH 2 JU |
| 10.10 - 10.15 | Agenda, objectives and organizational remarks | JRC |
| 10.15 - 10.30 | LCA of FCH Technologies:<br>Inventory of work performed by FCH JU projects | JRC |
| 10.30 - 12.00 | LCA methodologies for FCH technologies.<br>Presentation (Alessandro Agostini, ENEA and Till Bachmann, EIfER) & round table | All |
| *12.00 - 13.00* | *Lunch break* | |
| 13.00 - 14.30 | Harmonized approach to LCAs for facilitating the comparison/ identification of reference cases to be used as benchmark for future LCAs.<br>Presentation (Javier Dufour, IMDEA) & round table | All |
| 14.30 - 16.00 | Creation of a LCI database for the projects performing LCAs.<br>Presentation (Mitja Mori, University of Ljubljana) & round table | All |
| *16.00 - 16.15* | *Coffee break* | |
| 16.15 - 17.00 | Round table on other topics:<br>New fields of application, inclusion of social and economic indicators, critical raw materials, Life Cycle Cost. | All |
| 17.00 - 17.15 | Summary of gaps and main challenges. Recommendations | JRC |
| 17.15 - 17.30 | Final Q&A, closing remarks and next steps | FCH 2 JU |
| *17.30* | *End of the meeting* | |

# Annex 3. List of participants

| Name | Company/organisation |
|---|---|
| Alessandro Agostini | ENEA |
| Aikaterini Konti | JRC |
| Diego Iribarren | IMDEA |
| Esperanza Batuecas Fernandez | Politecnico di Torino |
| Javier Dufour | IMDEA |
| Julie Clavreul | Engie |
| Katri Behm | VTT |
| Mitja Mori | University of Ljubljana |
| Oliver Schuller | Thinkstep |
| Pajula Tiina | VTT |
| Till Bachmann | EIfER |

# List of abbreviations and definitions

| | |
|---|---|
| AD | Abiotic Depletion |
| AP | Acidification Potential |
| bar | Metric Unit of Pressure |
| BEV | Battery Electric Vehicle |
| BoP | Balance of Plant |
| CHP | Combined Heat and Power |
| CRM | Critical Raw Material |
| EC | European Commission |
| EIFER | European Institute for Energy Research |
| ELCD | European Reference Life Cycle Database |
| ENEA | Italian National agency for new technologies, Energy and sustainable economic development |
| EoL | End of Life |
| EP | Eutrophication Potential |
| EU | European Union |
| FC | Fuel Cell |
| FCEV | Fuel Cell Electric Vehicle |
| FCH | Fuel Cell and Hydrogen |
| FCH JU | Fuel Cells and Hydrogen Joint Undertaking |
| FU | Functional Unit |
| GaBi | Ganzheitliche Bilanzierung (German for Life Cycle Engineering) |
| GHG | Greenhouse Gas |
| GTP | Global Temperature change Potential |
| GWP | Global Warming Potential |
| HRS | Hydrogen Refuelling Station |
| ILCD | International Reference Life Cycle Data System |
| IMDEA | Madrid Institutes of Advanced Studies |
| JRC | Joint Research Centre |
| kW | Kilowatt |
| kWh | Kilowatt Hour |
| LCA | Life Cycle Assessment |
| LCC | Life Cycle Costing |
| LCI | Life Cycle Inventory |
| LCIA | Life Cycle Impact Assessment |
| LCSA | Life Cycle Sustainability Assessment |
| LHV | Lower Heating Value |
| MAWP | Multi-Annual Work Plan |
| MJ | Megajoule |
| MW | Megawatt |
| PED | Primary Energy Demand |
| PEFCR | Product Environmental Footprint Category Rules Guidance |
| PEM | Polymer Electrolyte Membrane |
| PEMFC | Polymer Electrolyte Membrane Fuel Cell |
| PGM | Platinum Group Metals |
| RF | Reference Flow |
| SI | International System of Units |
| SOFC | Solid Oxide Fuel Cell |
| TM | Transition Metal |

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KJ-02-19-898-EN-N

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doi:10.2760/459675
ISBN 978-92-76-12583-9