CLEAN SKY 2
JTI-CS2-2020-CFP11-THT-13: Sustainability of Hybrid-Electric Aircraft System Architectures

GAUGING THE ENVIRONMENTAL SUSTAINABILITY OF ELECTRIC AIRCRAFT SYSTEM

D3.1 Guidance document for LCI data collection

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About project GENESIS

In a global context, where modern societies need to move towards more environmental sustainability, the aviation sector has an important role to play. Transition to reduce its environmental footprint (i.e. impacts on ecosystems, human health and natural resources) stemming from activities in the entire value chain of aircraft, has become high on political and industrial agenda. This transition must go hand in hand with the technological transformation of aircraft systems, moving away from the use of fossil-based fuels to alternative energy sources, like biofuels, hydrogen or electricity via batteries.

Project GENESIS, funded by the EU Commission under the Clean Sky 2 Programme, aims to tackle some of these challenges. GENESIS stands for “Gauging the environmental sustainability of electric and hybrid aircraft”. Its main purpose is to develop a technology and sustainability roadmap to support the ambitions of the European aviation industry for transitioning towards environmentally sustainable and competitive electric and hybrid aircraft systems. Several powertrain technology alternatives are explored, including conventional, batteries, fuel cells and hybrid combinations of them, all with three time perspectives over the period 2020-2050.

Organized around a multidisciplinary and complementary expertise of its consortium members, GENESIS has the following key objectives (each reflecting the WP1-3 structure of GENESIS):

1. Develop a conceptual design, associated with top level aircraft requirements and scenarios, for all-electric and hybrid 50 PAX regional class aircraft.
2. Perform technology foresight analyses on key elements of the aircraft system, focusing on the powertrain architecture and energy storage alternatives.
3. Build life cycle inventories for each relevant technology processes within the aircraft life cycle (from resource extraction, through manufacturing and use, up to end-of-life), and use them to perform prospective life cycle assessment of future aircraft system configurations and scenarios.

Overview and role of this deliverable within GENESIS project

This deliverable provides a summary of the data collection procedure proposed by DTU (as WP3 and task leader) to collect data that can support the building of life cycle inventories (LCI) for the aircraft life cycle systems encompassed within the project scope. The procedure and associated guidance are primarily targeted to the different technology experts involved in the GENESIS project, but also cover data gaps, which will be filled by DTU. Eventually the collected data will be used to build LCI bricks that altogether will enable LCA modelling of the aircraft life cycle, accommodating different possible scenarios (i.e. different time horizons, technologies, etc.).

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Executive Summary

To enable the conduct of life cycle assessment and gauge the environmental sustainability of aircraft systems in a future oriented perspective, it is necessary to develop time- and technology-specific life cycle inventories (LCIs). These LCI are specific to a process or activity in the aircraft life cycle systems (e.g. "production of 1 kg of battery with xx specifications"). They are accounts of input and output flows, including waste, materials, energy, emissions, etc. Combined with impact assessment methods, these LCIs can be used to model a specific aircraft life cycle system and perform prospective and comparative life cycle assessments (LCAs) for different scenarios of electric and hybrid aircraft deployment.

This document provides a summary and description of the procedure proposed by DTU to collect the data needed to build LCI from the different partners involved in the GENESIS project.

The starting point was the identification and mapping of all the different technologies considered within the scope of the project and link them to their respective GENESIS expert partner.

LCI building blocks for each technology and component of the aircraft system were then outlined and used as a basis to prepare technology-specific templates for the LCI data collection. These templates were produced to facilitate the data collection process between the technology experts in GENESIS consortium and DTU, thus acting as main interface for data exchange. It was also designed to facilitate the documentation of LCI datasets and their use in LCA modelling (e.g. for software implementation).

Over the course of the project, an iterative process will be established, with the LCI data collection templates first being individually introduced to the partners responsible for each technology with the purpose to provide a general overview and address any initial questions the experts may have. Experts are then asked to fill the template as completely as possible, and feedback is then collected back by DTU, with subsequent meetings for clarifications and potential re-sending. This iterative approach started early in the project (already initiated with all partners) is expected to enhance the communication among the involved parties and aid in the mitigation of some project risks such as delays due to e.g. unclear instructions or data availability, since it will allow early identification of potential data gaps and potential mitigation solutions.

1. Introduction

1.1. Life Cycle Assessment and Life Cycle Inventories

Life Cycle Assessment (LCA) is an important decision-support tool to assess environmental impacts of products, technologies or systems at large, and its utilization by companies from all trades has increased over the last decades in absolute terms (Stewart et al. 2018). LCA attempts to perform a quantitative assessment of a broad range of environmental impacts associated with the life cycle of a product or system (object of the study), i.e. from the necessary raw materials extraction, through production and use up to recycling and end-of-life. This life cycle thinking has multiple applications across different areas and it is essential in supporting decision making where sustainability is a concern (Hauschild et al. 2018).

LCA is an ISO-framed methodology with the ISO 14044:2006 standard. The ISO requirements are also further developed in authoritative textbooks and reference documents, including the ILCD Handbook detailed LCA guidance, which is also the foundation for the Product Environmental Footprint guidance in Europe (EC 2010, 2012).

The LCA methodology includes 4 phases (ISO 2006):

- Goal and Scope Definition
- Life Cycle Inventory Analysis (LCI)
- Life Cycle Impact Assessment (LCIA)
- Life Cycle Interpretation

An LCA starts with the definition of the goal and scope. In this phase, the reasons, objectives and the intended application and audience for the study are outlined. Based on the goal of the study, the scope is determined and a precise definition of the object of study, its different life cycle stages and a description of the system boundaries are documented (Hauschild et al. 2018).

In the LCI phase, the data collection and modelling of all processes involved in the entire life cycle of the product or system occurs. For each process, input and output material and energy data are collected and subsequently modelled into LCI building blocks. These are used to build the LCA model, linked to each other to represent the product life cycle system under study. This phase is data intensive and requires an effective structural process to meet the LCA goals appropriately (ISO 2006; EC 2010).

In the LCIA phase, the life cycle inventory data (mainly characterized by pollutant emissions and resource use) are translated into environmental impact indicator scores. These indicators cover a large variety of environmental problems (ideally all relevant ones), incl. climate change, particulate matter formation impacting human health, photochemical ozone formation, toxicity of chemical releases on ecosystems and human health, land use, water availability, metals and fossils resource availability, etc. (Verones et al. 2020). Additional steps can also help understand and evaluate the magnitude and significance of the potential environmental impacts associated to the product or system under study throughout its life cycle.

In the interpretation phase, the results obtained during the study (LCI analysis, LCIA or both) are summarized and discussed, also in relation to the uncertainties underlying in the study. The main objective is to reach conclusions and recommendations based on the results of the study and/or to assist in decision-making in accordance to the goal and scope definition. If not achieved, new iterations of one or more of the LCA methodological phases/steps may be required. (ISO 2006; Hauschild et al. 2018).

1.2. Objectives of LCA – and LCI – in GENESIS

GENESIS will explore and compare different powertrain technologies for a 50PAX regional aircraft across three different time perspectives over the period 2020-2050. These technologies include conventional powertrain (ICE), batteries, fuel cells and hybrid combinations of them. Prospective LCA will be performed to gauge the environmental sustainability of full electric and hybrid aircraft systems by comparing different technology and time-frame scenarios and identifying environmental hotspots to identify the magnitude and sources of largest impacts. The aircraft systems thus will be assessed in a life-cycle based and foresight perspective to support the development of a technology roadmap for transitioning towards sustainable and competitive electric aircraft systems.

To enable prospective LCA studies, LCI building blocks need to be developed, with relevant time- and technology-specific differentiations. To build those LCIs with as much efficiency, completeness and consistency as possible across the different technologies and members of the projects (i.e. data suppliers), a structured approach for data collection is needed. It can also facilitate the later processing of the data into LCI building blocks and their integration into the LCA model. Such approach catered to the needs of GENESIS is detailed in Section 2.

2. Methodology and current status

The different technological components were first identified in relation to the aircraft life cycle and mapping of the expertise within the GENESIS consortium was then applied to identify potential data sources (Section 2.1). Specific LCI requirements were then defined (Section 2.2) before developing LCI data collection templates catered to the expertise of each technology-partner (Section 2.3). Section 2.4 reports the procedure elaborated to ensure data exchanges between DTU (WP3) and the other GENESIS members. Section 2.5 reports the current status in GENESIS in relation to that procedure.

2.1. Technology mapping

The first step was to understand and scope the life cycle of a typical aircraft system (object of study) and to identify its different components following a top-down approach.

Figure 1 depicts the life cycle of the aircraft system, in which three subsystems can be identified. These are the life cycle of the airplane itself, the life cycle of the airport and that of the fuel, which are needed to support the use/operation stage of the airplane. We further differentiate the life cycle of the airplane into three additional elements: the airframe, the power electronics & drives and the propulsion system (Figure 1). The different fuels and propulsion technologies, which will be assessed, are also indicated therein.

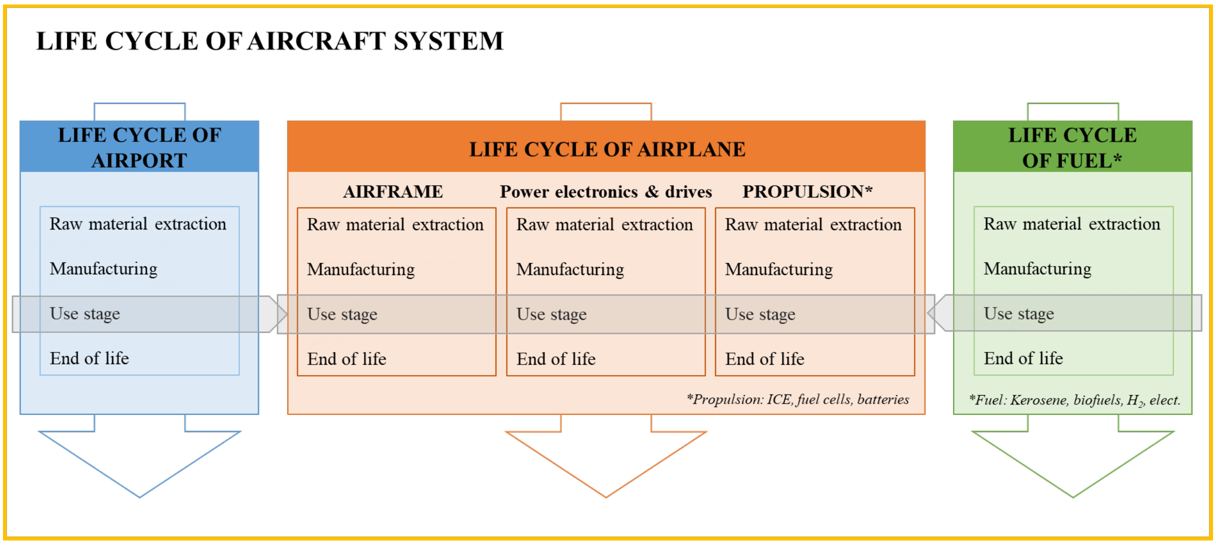

Figure 1. Conceptual representation of the Life Cycle of Aircraft System

Table 1 summarizes the different technologies that were identified as part of the different subsystems considered within the life cycle of the aircraft system (Figure 1). The table also shows the technology expert(s) within the consortium, who will be assisting and providing the LCI data for each particular technology. In some cases, alternative data sources will be used, relying on literature data and secondary data from LCI databases (like ecoinvent).

Table 1. Mapping of the different technologies involved in the life cycle of the aircraft system with its respective technology expertise within the consortium

Life cycle	Technology	Technology expert/data source
Airport	*Airport*	Subcontractor
	Battery charging station	FAU-LEE, BFH, subcontractor
Aircraft	*Airframe*	TU Delft
	Conventional power module (ICE, gearbox, propellers)	UNINA, SMARTUP
	Battery	BFH
	Battery end of life	ACC
	Fuel cell (SOFC)	BFH
	Fuel cell (PEMFC)	PMFC
	On-board H2 storage system	MHT
	Power electronics and drives	FAU-LEE
Fuel	Fuel production (kerosene, biofuels, LNG…)	Alternative data sources
	Hydrogen production & supply (electrolysis pathway)	DTU (alternative data sources), MHT, BFH, PMFC, subcontractor
	Electricity production	Alternative data sources

2.2. LCI data requirements

As described in Section 1.1, LCIs relate to input (material and energy use) and output (products, byproducts, emissions…) data throughout the entire life cycle of the product or system under consideration. Figure 3 illustrates the data needs of a LCI of a product or system across its different life cycle stages.

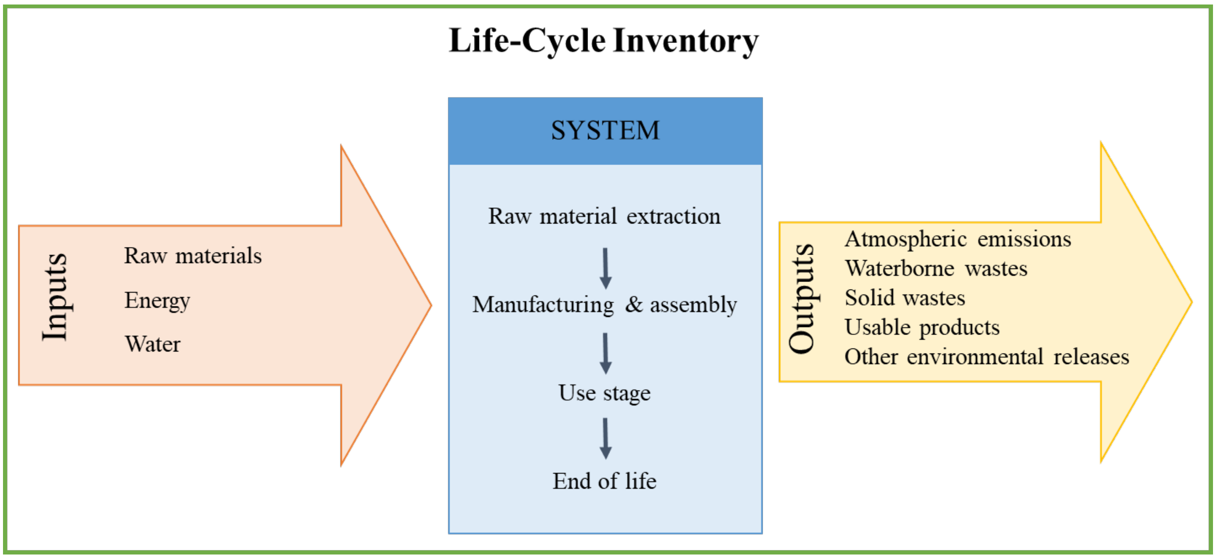

Figure 2. LCI input & output data of system across its different life cycle stages (adapted from Babu, 2006)

For the aircraft system, the LCI data requirements for each technological component of the aircraft system (for all 3-time horizons of the project scope) are presented below.

Raw material extraction

This stage encompasses all the activities required to obtain the raw materials from the lithosphere (Vigon et al. 1994) and that will be needed (after processing) in the manufacturing or the aircraft system. It also includes the transportation of these materials to the manufacturing or production site (Babu 2006). Secondary data from LCI databases and literature will be used to model these processes, thus no data will be collected from the technology experts for this stage.

Manufacturing / production

This life cycle stage includes all the activities required to process basic materials (e.g. steel) into intermediate materials/products and/or into the end product(s)/ component(s) of the system of study (Vigon et al. 1994; Babu 2006). Information collected for this stage include:

- Material inputs: bill of materials (raw materials, auxiliaries and intermediate products) needed in the manufacturing or production of each component of the aircraft system
- Energy inputs: energy (electricity and heat) needed in the manufacturing or production of each component of the aircraft system

- Characterization of the manufacturing process (performance, process efficiency, capacity, maturity…), process description (e.g. process steps, temporal and geographical representativeness, what is included and what is not…) and flow diagram
- Outputs: main product(s)/component(s) of the aircraft system and the byproducts, material waste and emissions (air, water and soil) generated during its manufacturing
- Recyclability of the materials (inputs and waste derived from inputs) involved in the manufacturing process
- Insight of waste management routes (e.g. reuse, recycling, incineration, landfilling…) for the waste generated during the manufacturing of each component of the aircraft system
- Location of manufacturing sites

Use stage

Data covers all the activities in which the product or system is used or operated as well as activities pertaining to reconditioning, maintaining or servicing to extend its useful life (Vigon et al. 1994). They include (non-exhaustive list):

- Specific time perspective in which the use of that technology/ component will be applicable
- Data linkage to main aircraft system (e.g. number of spare parts or total parts needed of the technology/ component per aircraft when the main system is being used)
- Performances of the technology/ component
- Lifetime of the technology/ component
- Efficiency of the technology/ component
- Emissions produced during use of the technology/ component
- Maintenance requirements of the technology/ component
- Production volume of the technology/ component
- Technology and manufacturing readiness level of the technology/ component
- Other technical specifications relevant to the use of the technology/ component
- Location(s) where the technology will be used

End of life

This stage includes all the activities after the product has served its intended purpose (i.e. lifetime) and will either directly enter waste management systems or enter a new system through reuse or recycling (Vigon et al. 1994). They include (non-exhaustive):

- Efficiency in the collection of the technology/component to be decommissioned
- Insight into disposal route of the technology/component to be decommissioned
- Characterization of the end of life treatment process of each technology/component (performance, efficiencies, maturity, percentage of material recovered…), process description (e.g. process steps, temporal and geographical representativeness, what is included and what is not…) and flow diagram
- Inputs: material and energy requirements during the treatment process
- Outputs: materials recovered during treatment process, byproducts and emissions (air, water and soil) generated during the treatment process, along with details on the subsequent use of by-/co-products.

- Location of waste management sites

2.3. Developing the LCI excel template structure

Once the technologies were identified and mapped to the respective technology experts, LCI building blocks for each technology component and subcomponent of the aircraft system were outlined. This was done by starting from the finished product and working backwards through the supply chain and/or by zooming into the product, to further differentiate the subcomponents needed for its manufacturing. Each subcomponent, represented by an individual building block, is linked together according to its relative contribution to the technology and subsequently to the aircraft system in such a way that omissions and double-counting do not occur. The level of differentiation of the subcomponents took into account the scope of the project, which considers different powertrain configurations and different time perspectives as well as other specific considerations involved in the manufacturing/assembly process of each product. For example, for the production of batteries, it is foreseen that the chemistry used in the cell will vary with time. Thus within the battery cell, the anode, cathode and electrolyte were differentiated to be able to capture the changes in the materials needed for the different battery chemistries considered across the time horizons. Another example is the airframe components, in which the fuselage, wings, empennage and landing gears were differentiated to allow for capturing the airframe manufacturing process. In practice, the components of the airframe are manufactured separately by different companies specialized on each part. When the components of the airframe are produced and ready for integration, these are transported to the aircraft final assembly site (typically the original equipment manufacturer, OEM).

Literature search was performed to better understand the aircraft system and the different technologies considered within the project, thus feeding into the process of outlining the different LCI building blocks. These building blocks provided the foundation for the preparation of the LCI data collection templates. The templates help to identify the information that must be obtained at each step in an inventory and are used to direct the collection of data (Vigon et al. 1994). They are therefore the main interface of data exchange between the project partners and the LCI building team. For each component or technology (listed in Table 1, italic items in the 2nd column), a template was prepared in Microsoft Excel, giving a total of eleven LCI data collection templates. In the templates, the building blocks are represented in several tables, with each collecting specific data relevant for LCI.

Data scarcity is a common issue when performing conventional LCAs but it becomes more challenging when conducting prospective LCAs as the technologies are studied and modeled in a future-oriented perspective (Thonemann et al. 2020). Data quality or data suitable for a specific application is also of concern. To address this issue several authors have proposed the use of the pedigree matrix (Igos et al. 2019; Thomassen et al. 2019; Thonemann et al. 2020), in which the reliability, completeness, temporal, geographical and technological correlation for each collected data point is judged on a scale from 1-5. The values determined by the matrix can be translated into uncertainty factors and be used for uncertainty analysis using Monte Carlo simulations (Igos et al. 2019; Thonemann et al. 2020). Since the LCI in GENESIS will be used to conduct prospective LCAs it is important to have an estimation of the uncertainty and reliability of the LCI data to be collected. For this purpose, dedicated data fields were included in the tables of the LCI data collection templates to estimate quantitatively (e.g. through confidence intervals, ranges, SD…) or qualitatively (e.g. via Pedigree matrix) the uncertainty on the data provided.

Collecting data through inventory templates in excel spreadsheets has the advantages that the data collected can be stored electronically, can allow for flexibility to provide numerical correlations and formulas and can facilitate subsequent data handling (e.g. calculations, filtering, other data processing, etc.). Although it is not the ideal format for capturing long texts or descriptions, it was decided to keep using a single file and add text boxes next to each table to enable technology experts to provide a detailed description of the process or process step that the corresponding table/block is representing. Technology experts are also encouraged to provide any visual aid (e.g. process flow chart, bill of materials, etc.) that complements the inputs in the file.

The LCI data collection templates, made as Excel files include several worksheets, of which a brief summary is provided below (for additional information, please contact the authors of this deliverable):

0. *Read Me* worksheet.
   Contains detailed instructions, definitions and guidelines on how to complete and navigate the LCI data collection template.

1. *Overall parameters* worksheet.
   Collects overarching information, typically centered on the "use stage" of the technology (e.g. efficiencies, performance, material and energy inputs, emissions, technology and manufacturing readiness level and other technical specifications). This worksheet also collects data about the time perspective in which the technology will be valid and defines the relationship(s)/linkage of the technology to the main aircraft system during its use.

2. *[Technology]_prod* worksheet.
   Collects the data related to the production and assembly of the technology and its main subcomponents (organized in several tables feeding into one another). For example, bill of materials, energy needs, byproducts, emissions, process description, waste production and its management routes are included therein.

3. *Economic information* worksheet.
   The economic assessment is also an important and relevant part of the objectives in GENESIS. Thus through this worksheet, expenditures associated with each technology/component of the aircraft system are collected. These values will be fed into economic analyses performed over the main system in a later stage of the project.

4. *[Technology]_EoL* worksheet.
   This worksheet collects the information related to the recycling and end of life of the technology/component of the aircraft system. The partners are requested to provide any insight about the end of life of the technology for example the way the technology to be discarded is collected, or the efficiency during the collection and recycling processes. Only one of the partners in the consortium specializes in waste management and modelling assumptions and proxies will be needed during the development of LCI for the disposal stage.

This will be done using literature search and expert judgement from the project- members. Sensitivity analysis on different waste management scenarios will also be anticipated to accommodate for the uncertainties in this life cycle stage.

5. *References* worksheet.
   As previously mentioned, LCI data stem from many different sources e.g. production data, experimental data, measurements, calculations, patents, scientific papers etc. In this sense, it is important to document all the references and sources reviewed in order to ensure complete transparency and reproducibility. This worksheet is intended for that purpose.

2.4. LCI data collection process

The proposed procedure to carry out the LCI data collection process is illustrated in Figure 4. When a given technology-specific LCI data collection template is ready (Section 2.3), an introductory meeting is organized with the partner having expertise on that technology (tep 2 in Fig. 4). An iterative process then ensues (Steps 3-4-A), with the partner filling the template and DTU providing feedback and seeking for refining the data collection until the LCI building block can be developed using primary data from the partner and relying on gap-filling assumptions/procedures agreed with the expert partner (Steps 5 and 6 going out of the iterative process).

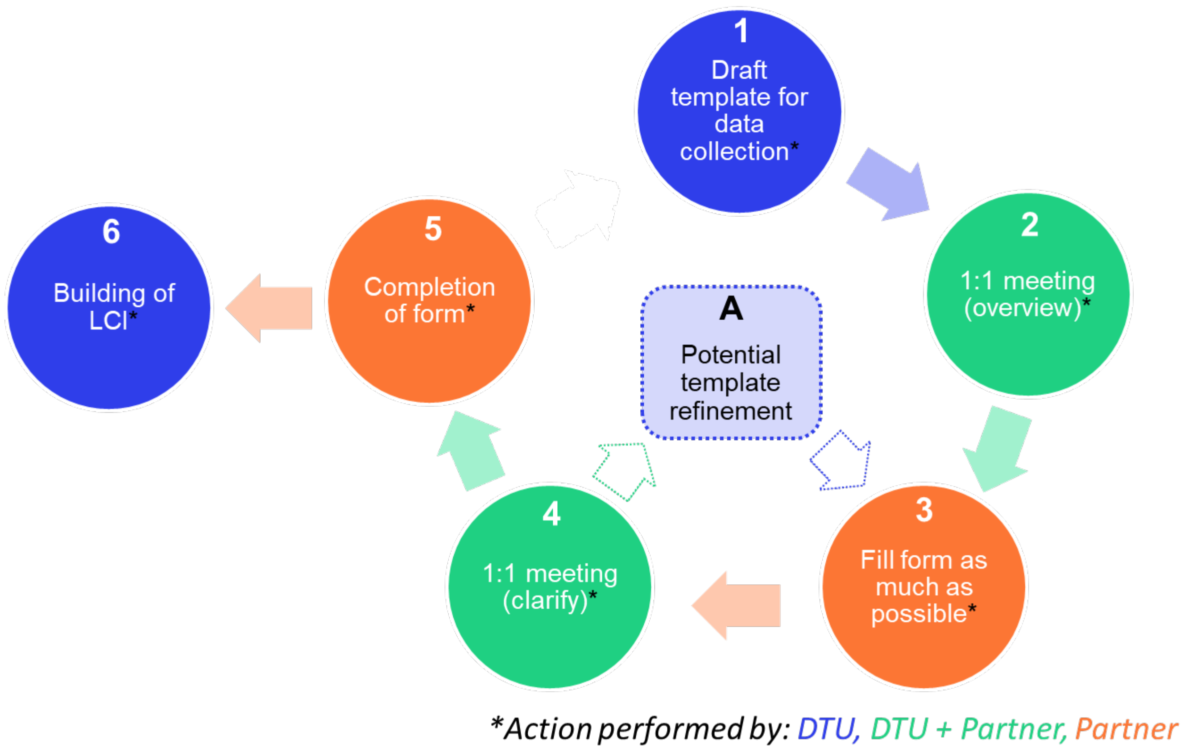

Figure 3. Proposed approach for the LCI data collection process

2.5. Current status

The status on the LCI data collection process for each technology expert is provided in Table 2.

Table 2. Status on the LCI data collection process

System / Technological component	Partner / Data source	Current status (end-June 2021)
Airport	Subcontractor	LCI template to be developed
Battery charging station	FAU-LEE, BFH, subcontractor	LCI template to be developed
H2 production & supply (electrolysis)	DTU, MHT, BFH, PMFC, subcontractor	LCI template to be developed
Airframe	TU Delft	Template ready, introduction meeting to schedule
Conv. power module (ICE, gearbox, propellers)	UNINA, SMARTUP	1st iteration (partner filling the template)
Battery	BFH	1st iteration (partner filling the template)
Battery EoL	ACC	1st iteration (partner filling the template)
Fuel cell (SOFC)	BFH	1st iteration (partner filling the template)
Fuel cell (PEMFC)	PMFC	1st iteration (partner filling the template)
On-board H2 storage	MHT	1st iteration (partner filling the template)
Power electronics & drives	FAU-LEE	1st iteration (partner filling the template)
Fuel production (kerosene, biofuels, LNG…)	Alternative data sources	No template needed (use of existing literature)
Electricity production	Alternative data sources	No template needed (use of existing literature)

3. Conclusions and way forward

To address the LCI needs it was decided to prepare technology-specific LCI data collection templates instead of one generic template to be used across all technologies. This was done in order to better understand all the technologies interacting in the aircraft system and to accommodate the differences in the data needed. The latter relates to e.g. technical specifications (which are different for all), how each technology links to the aircraft given a time scenario and the level of differentiation/disaggregation needed among the components and subcomponents of the technologies when considering different time frames.

The main objectives of the templates are to facilitate and guide the data collection process between DTU and the technology experts in the consortium and to ensure consistent reporting thus facilitating subsequent data review, processing and handling. It was also the intention to prepare the templates as complete as possible in terms of the LCI data needs to understand what information partners can and cannot provide, thus allowing identification of data gaps.

An iterative procedure for the data collection process was developed by DTU along with the templates. This procedure will help refine the LCI templates (if needed), ease the data collection process and enhance the communication between DTU and the technology experts. Furthermore, it will mitigate delays as it permits early clarification of potentially unclear instructions or questions and allow for an early identification of potential data gaps.

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