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Data Hub for Life Cycle Assessment of Climate Change Solutions—Hydrogen Case Study

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Abstract: Life cycle assessment, which evaluates the complete life cycle of a product, is considered the standard methodological framework to evaluate the environmental performance of climate change solutions. However, significant challenges exist related to datasets used to quantify these environmental indicators. Although extensive research and commercial data on climate change technologies, pathways, and facilities exist, they are not readily available to practitioners of life cycle assessment in the right format and structure using an open platform. In this study, we propose a new open data hub platform for life cycle assessment, considering a hierarchical data flow starting with raw data collected on climate change technologies at laboratory, pilot, demonstration, or commercial scales to provide the information required for policy and decision-making. This platform makes data accessible at multiple levels for practitioners of life cycle assessment, while making data interoperable across platforms. The proposed data hub platform and workflow are explained through the polymer electrolyte membrane electrolysis hydrogen production as a case study. The climate change environment impact of 1.17 ± 0.03 kg CO_2 eq./kg H_2 was calculated for the case study. The current data hub platform is limited to evaluating environmental impacts; however, future additions of economic and social aspects are envisaged.

Keywords: life cycle assessment; scientific and technology dataset; life cycle inventory datasets; data hub

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1. Introduction

Nature and engineered-based negative emission technologies are pursued to reach net-zero targets [1]. Several carbon accounting tools based on product life cycle assessment (LCA) have been developed [2]. With the requirements of certification and more accuracy in net-zero plans, there is more scrutiny on transparency in methodology and data used. Open and commercial LCA tools are currently used to quantify environmental impacts, including carbon footprint [3]. In the context of climate change mitigation efforts, GHG emissions accounting is often subject to contradicting reporting due to the lack of traceability and transparency on the datasets used [4]. This situation is even more critical for other environmental indicators with fewer dataset inventories available.

LCA methodological framework has been outlined in ISO 14040 [5] and 14044 [6] standards, in which the principles, framework, and guidelines for conducting LCA have been proposed. Stages of LCA methodology include goal and scope definition, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA), and interpretation. Typical life cycle stages of a product include raw material production, product assembly, product use, and end-of-life. Datasets required for LCA are developed as LCIs, a standardized

data format, which includes inputs and outputs of a specific process and supporting meta-data [7]. LCIA results are typically used as decision-making data to evaluate the alignment of environmental criteria and also in communication report formats such as environmental product declarations (EPD) [8]. LCIs are developed based on data collected from existing industrial processes, process simulations, and other types of estimations and models. There are already several commercial [3,9] and open-source [10] LCI databases available. However, underlying scientific and technical data used for the generation of LCIs are rarely made available as part of LCI databases, making the LCA practitioners using LCI datasets heavily rely on scant meta-data documentation of LCIs. This makes it challenging to choose representative and suitable LCI datasets that are aligned with the goal and scope of the LCA study.

Although the focus is on LCI data, there are many types of datasets that are relevant to LCA as indicated in Figure 1. In fact, there is a hierarchy of different types of data that can be used for LCA-supported decision-making. Here we differentiate between raw datasets often collected using instruments in laboratories, pilot, demonstration, and/or commercial scale processes, which are at the bottom of the hierarchy, and high-level data used for decision-making at the top of the hierarchy. Scientific datasets are often only accessible to a limited audience with specialized skills and they are usually not accessible to LCA practitioners [11].

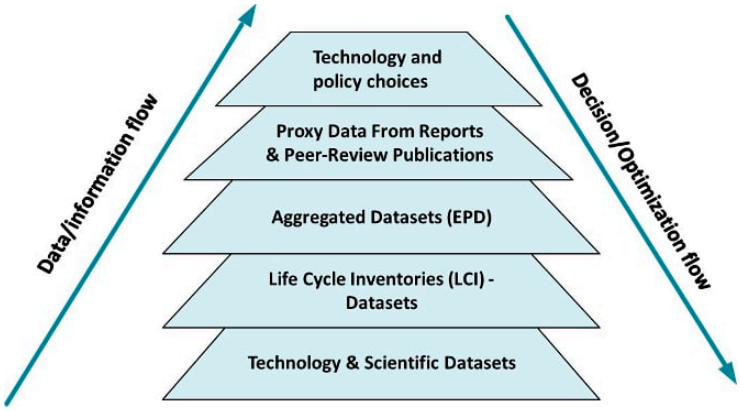

Figure 1. Hierarchy of datasets used on life cycle assessment and associated decision-making processes.

After the LCI datasets, the next level of environmental performance data are reported as EPDs (shown in Figure 1). It is worth noting that EPDs enable data and information reporting by specifying the details of the LCA study and its results as selected environmental impacts [8]. The fourth type of dataset is related to proxy datasets often built on an ad-hoc basis from literature and other means. These proxy datasets focusing mainly on environmental impacts, such as carbon footprint, often less transparent, are used to address gaps in high-level data required for organizational decision-making [12]. Often, different groups develop these data types, with little harmonization effort to build consistency and traceability among different datasets and assessments [13]. This makes technology and policy choices challenging and may lead to poor decision-making. Thus, there is a need to improve data flow from raw scientific/technology datasets to technology/policy choices, which requires multiple steps with different hierarchies of data inputs.

There have been several efforts to improve the transparency and traceability of LCA data flow in the literature. Bellon–Maurel et al. [14] streamlined the LCI data generation using data collected from information and communication technologies (ICT) used in viticulture operations. They guaranteed the traceability of data used in LCIs using a conceptual framework that maps the data flows from ground-level operations to LCIs. Similarly, Ferrari et al. [15] proposed a dynamic LCA framework by integrating the enterprise resource planning (ERP) system and smart digitized manufacturing systems with a custom LCA tool. Typically, industrial manufacturing environments have digitized tools for data acquisition and management, making it easier to integrate technology and scientific datasets with LCI,

providing traceability. However, such systems can be highly specific to the application and include confidential data, less suitable for open-source platforms. Data confidentiality is a key issue that is hindering the efforts to build consistency in data flow traceability towards primary technology and scientific datasets [16]. Blockchain solutions [17] and secure data spaces [18] have been proposed address data confidentiality issues. Current open-source platforms managing non-confidential LCI data also do not have adequate linkages to primary technology and scientific datasets [10]. Such data are often described as meta-data documentation, which is often scant or non-existent as part of the LCI dataset.

LCA-related datasets are not limited to primary scientific and technology data and LCI datasets. The impact assessment result datasets, EPD data, and high-level decision-making data are also a part of the hierarchy of LCA data. A large number of decision-making platforms focusing on buildings [19], building materials [20], waste management [21], wastewater treatment [22], sustainable packaging [23], biorefineries, and transportation [24,25] have been proposed in the literature. Each of these platforms, however, focuses on specific LCA tools and decision-making criteria rather than the identification and management of data required for LCA-based decision-making and communication tools such as EPDs. In particular, previous proposals focusing on open-source platforms allowing the linkage of scientific and technology datasets, LCI datasets, environmental impact results, EPDs, and high-level decision-making data are limited. Such platforms should facilitate access to the data for multiple levels of stakeholders including engineers, lab technicians, LCA practitioners, and managers while providing transparency, traceability, and sufficient meta-data documentation among datasets.

In this study, we propose an open-source data hub platform incorporating a hierarchical data structure that ensures transparency and linkage among datasets, integrates multiple data sources, and ensures that relevant data are collected to evaluate environmental indicators required for decision-making. The data hub platform is then validated using a hydrogen production case study. This case study features the harmonized life cycle assessment-based methodology developed by our team, including critical aspects such as life cycle inventory datasets generation, data quality evaluation, and data curation through data interoperability and accessibility.

2. Materials and Methods

2.1. High-Level Data Hub Architecture

The proposed data hub platform consisting of two cloud-based systems is currently being developed at the National Research Council Canada (NRC) (as shown in Figure 2). One system is dedicated to collecting and curing scientific and technology datasets and LCI datasets. We refer to this below as the "materials and technology data warehouse (m-DW)". A second system is dedicated to high-level environmental assessment data and results including EPD data, proxy data from reports, and high-level decision-making data. This second system is referred to by the term "sustainability webserver (s-WS)".

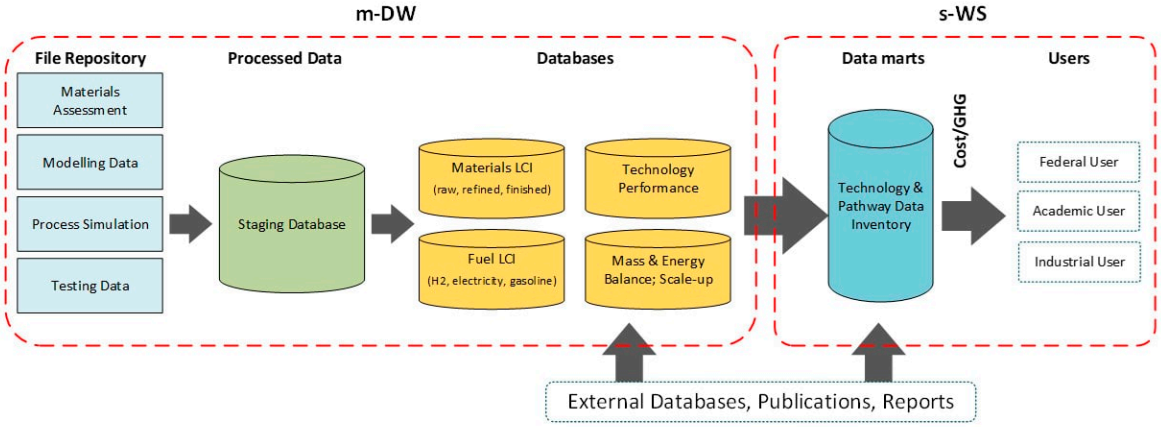

Figure 2. Data hub infrastructure in relation to LCSA.

Undertaking an LCA study is resource-intensive and often incomplete for a lack of data. Inaccessibility or timely availability of these data in the right format are the main issues. The materials and technology data warehouse system (m-DW) and sustainability webserver (s-WS) address this gap with the following key characteristics.

- Build a comprehensive scientific/technical data information architecture to enable efficient data integration from different sources, data analytics, and impact assessments.
- Provide an adaptive architecture to integrate existing databases within and outside the federal labs.
- Provide a dynamic and secure environment for existing and new data to enable faster decision-making for both policymakers and researchers.

Figure 3 shows the overall high-level IT representation of the NRC data hub. Recent developments in data analytics and secure cloud servers support building a reliable information system for structured and unstructured data flow, enabling transparent/secure data sharing and trustworthy environmental assessment.

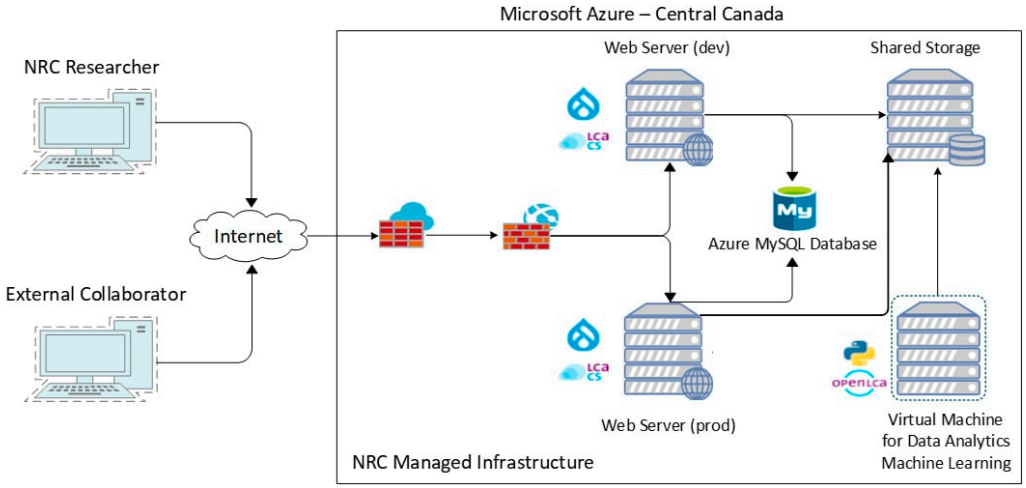

Figure 3. High-level IT infrastructure of NRC data hub and openLCA CS implementation.

Building on the effort of GreenDelta's openLCA platform [26], we have implemented a collaboration server (CS) to enable collaborative LCI dataset development as part of the data hub, which is accessible to registered users at this URL: https://eeecc.nrc-cnrc.gc.ca/openlca (accessed on 1 July 2024). The CS includes repositories of LCI datasets that can be accessed either through an online interface or openLCA desktop software (version 2.2), an open-source LCA software. The local databases in openLCA desktop software can be connected with CS repositories, allowing a number of users to work on developing LCI datasets simultaneously.

The NRC data hub has been built within a secured environment allowing NRC researchers and external collaborators to connect to the openLCA CS web application through a network firewall and a web application firewall. The web application interacts with an internal MySQL database server for data management and network storage for storing and analyzing LCI data. For development and maintenance purpose, the web application server is duplicated into a production server accessible by external users, and a development server accessible only by the NRC development team. Additionally, an internal data analytics server would receive external user requests submitted using a web form, then perform data analysis on a set of LCI data accordingly, and return results to the user.

2.2. Hierarchy of Data and Data Linkages in Data Hub

A key characteristic of the data hub is that it stores and connects a hierarchy of datasets including scientific and technology data, LCI data, proxy data from EPDs, scientific and technology reports, and high-level decision-making data. Linking scientific data with

LCI improves the application of context-specific and up-to-date data, and promotes the precision, robustness, and transparency of LCA assessments. The linkage allows for a deeper understanding of the results of environmental impacts associated with each life cycle stage and identifies hotspots and opportunities for improvement that help decision-makers make informed decisions.

Figure 4 shows a concrete example of the usage of a data hub platform to generate scientific and technology data using process simulation, curate data to generate LCI, validation, and use the data in the environmental assessment to generate data required for high-level decision-making. As with any LCA study, the assessment starts with the definition of goal and scope. This step defines the system under study, and the type of data that should be collected or generated. Depending on the product system, the next step is to define the flow diagram to identify whether data needs to be collected from the actual operating facility and/or generated using process simulation. Then, a process simulation is developed, if required, to generate input and output data to build LCI. The collected or generated (using simulation) data are then validated for overall mass and energy balances and as required for elemental balances. Also, the meta-data describing the process of LCI datasets are also collected. Then, the inputs and outputs are normalized per reference flow of the LCI dataset and appropriate elementary flows and technosphere flows are assigned (further described in Section 3.3). At this point, the data curation is complete and the dataset is integrated into the openLCA collaboration server platform. The LCI datasets can then be used for environmental impact assessment.

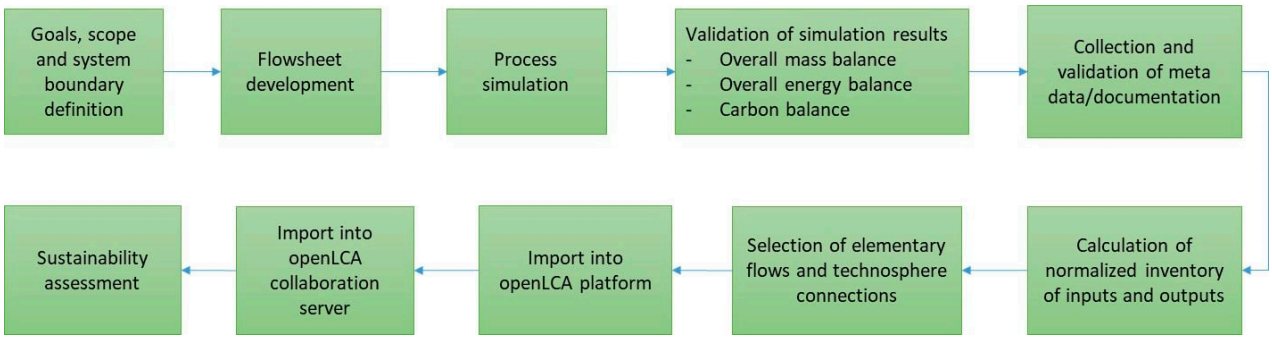

Figure 4. An example of data generation using process simulation, LCI generation, validation, openLCA collaboration server, and environmental indicator assessment using data hub platform.

2.2.1. Scientific and Technology Data

Significant amounts of data are generated by researchers working on early-stage technologies or performing tests on specific components of a larger system. However, these data are either incomplete or not reported in the literature. For example, when publishing results on a new materials synthesis, details on energy use or the different waste streams are not recorded and/or reported. Similarly, the technology data can be collected from industrial processes and plants as well as process simulations that mimic large-scale operations. Figure 5 shows the type of data sources including industrial, simulation, and laboratory data, file storage repositories, and integration of the data to create LCIs.

As shown in Figure 5, the data hub first acts as a data file repository, in which any type of data file including spreadsheets, simulation data files, measurement data files, and data files from data acquisition systems can be stored. Then, relevant data in the scientific and technology data files are transferred to either MySQL-type structured database or a spreadsheet-type document database. A few examples are compiled mass and energy balances from a process simulation, efficiency parameters from an industrial process, or an experimental setup.

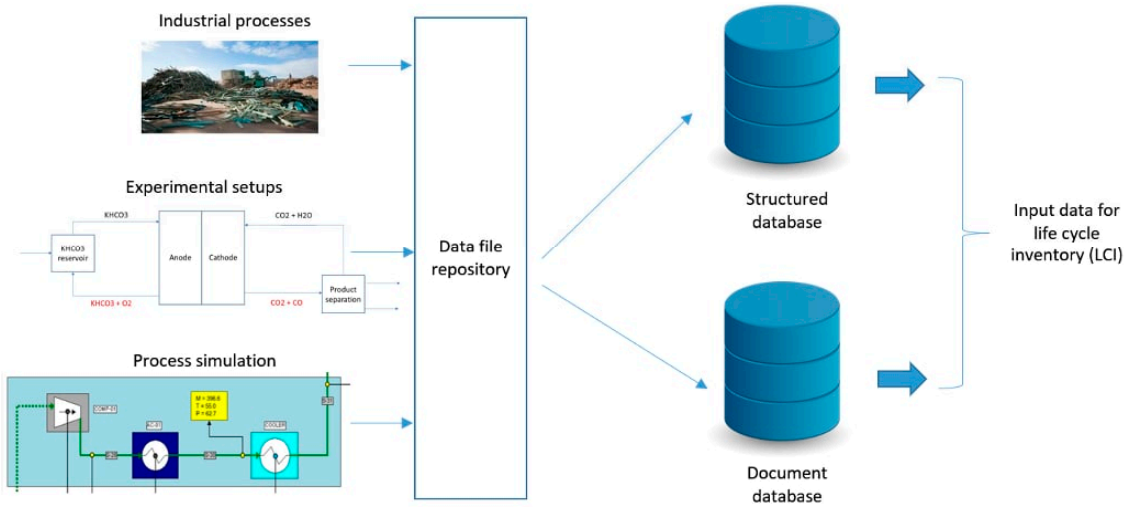

Figure 5. Types of scientific and technology data, file repositories, and structured data.

The upward flow of data and information defined in Figure 1 requires appropriate linkage between different levels of data categories. The first step in such linkage is the generation of LCI datasets based on relevant and sector-specific scientific and technical data. Scientific data such as laboratory data and analyses, empirical measurements, and research findings can provide valuable information about the performance of specific production processes or technologies from an environmental perspective.

2.2.2. LCI Data and Framework

A standardized framework for generating and organizing LCI datasets was developed including a general LCI format (shown in Figure 6). This framework focuses on the LCI format, which includes types of data that are stored as LCI, and also linkages of LCI with collected/generated raw data and data transformations. An LCA study typically involves multiple LCI datasets to build the required product system. A general rule followed is to model LCIs as granular as possible until further sub-division is not possible due to the presence of complex interactions such as recycle or heat integration between unit process LCIs. Figure 6 shows the granularity of unit processes specific to a case study in hydrogen production, which include feedstock production, hydrogen production, and hydrogen compression.

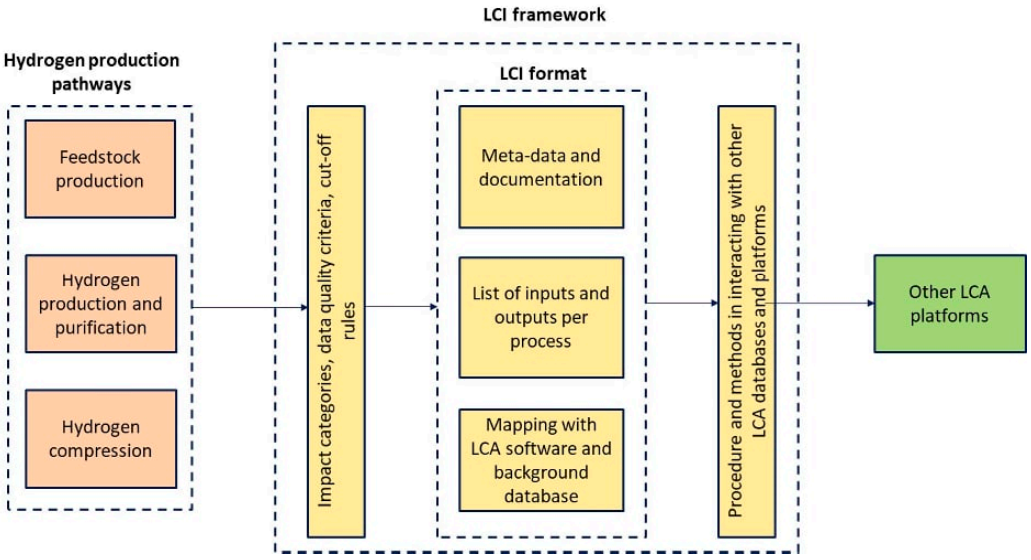

Figure 6. Overview of LCI framework and format used in the data hub related to hydrogen production pathways.

Once the identification of the product system is complete, the goal and scope of the study are then reviewed to define the requirements of LCI datasets. They typically include life cycle impact categories, data quality requirements, cut-off criteria, and allocation. Also, LCI development must collect the required data needed for chosen environmental indicators with sufficient quality. Hence, the generated data from process simulation are transferred to LCI using a set of rules, which include the transfer of appropriate data exchanges to model the required environmental indicators, validation of the quality of the data, and application-defined cut-off rules. The collected data then can be arranged according to the LCI format to include meta-data, inputs and outputs, and mapping data with elementary flows and background databases.

Figure 7 elucidates the data stored in each category of the LCI format. The first category, meta-data and documentation, includes a description of the LCI dataset, data quality in terms of representativeness (technological, time, and geographical), completeness and accuracy, supported sustainability indicators, data sources, and review details. The second category of data includes the numerical values of inputs and outputs of the process and type of the flow (elementary versus technosphere). Elementary flows represent the direct interactions with the environment including resource inputs such as water and emissions to air, water, and soil. Technosphere flows are connections with other unit processes such as electricity or natural gas production and delivery. The third category, mapping with LCA software and background database, ensures the proper mapping of elementary flows and technosphere flows with LCA software and background processes. Proper mapping with elementary flows, as used in LCA software and impact assessment methods, is important in facilitating the assessment or calculation of environmental impacts. Also, mapping the technosphere flows with appropriate background database processes aligning with the specifications of each process is important as well. Furthermore, it increases the interoperability of LCI datasets among different LCA platforms. Hence, this information is included in the LCI format.

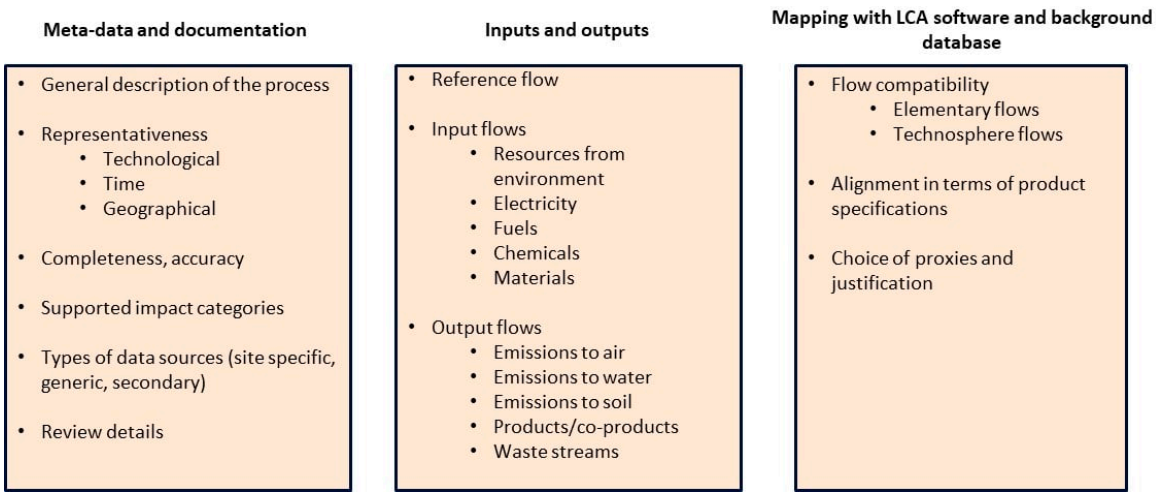

Figure 7. Types of data that are stored as part of LCI format categories.

There are already multiple platforms to conduct LCA and quantify environmental impacts. It is likely that different platforms will be used for the quantification of carbon footprints and other indicators for environmental certification and labeling purposes. Hence, it is important to develop guidelines and procedures to transfer the LCI dataset among different platforms, ensuring data interoperability. As shown in Figure 8, this involves transforming LCI datasets into different versions of LCI datasets that are compatible with other LCA software and background databases. Transformation involves mapping the elementary and technosphere flows of two platforms, adjustment of units, and elimination of data to harmonize on LCA platform scopes. The NRC data hub currently maps data to the FuelLCA platform [27].

Figure 8. Overview of developing data interoperability among LCA platforms and databases.

2.2.3. Environmental Product Declarations (EPD)

EPDs are standardized documents that convey information on the LCA methodology followed and the environmental impacts of a certain product, developed according to requirements of product category rules (PCR). Linking LCI with EPD can establish a standardized approach to improving the transparency and communication of EPDs. However, providing the specific LCI is not considered a mandatory option in PCR; hence, it is often neglected in public EPD documents. By linking LCI with EPDs and improving the transparency of EPDs, LCA researchers and practitioners can improve the credibility, transparency, and comparability of the LCA results. Such efforts, however, require recording and storing data fields relevant to EPDs as shown in Figure 9.

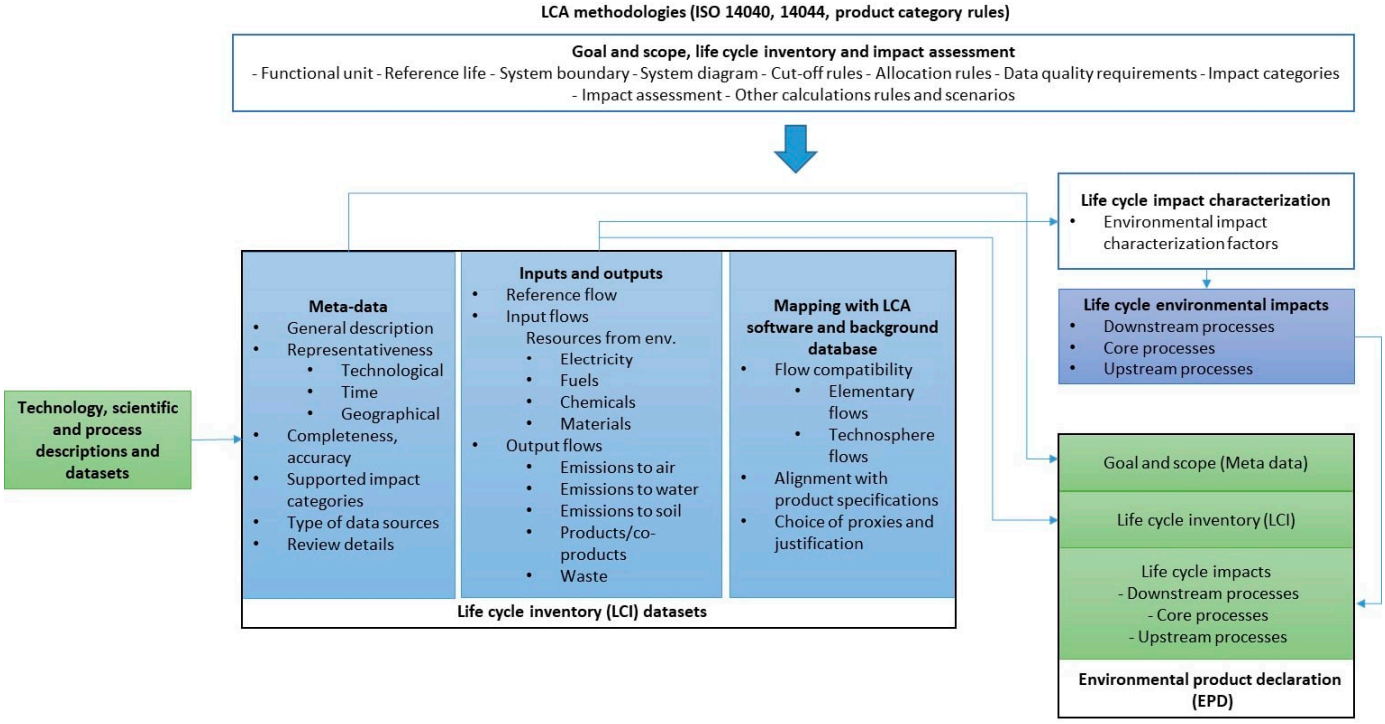

Figure 9. An overview of environmental product declaration (EPD) data fields and its connections with life cycle inventory (LCI) datasets and life cycle assessment (LCA) methodological aspects including ISO standards [5,6].

As the goal and scope definition-related meta-data of an EPD, the following detailed data are stored in the data hub including product category definition, geographical region, validity, PCR used, functional unit, system boundary, life cycle stages, system diagram, cut-off rules, allocation rules, and data quality requirements. Although it is not mandatory to publish LCI datasets with EPD, the inclusion of LCI and its meta-data improves transparency and traceability of the EPD. It is likely that an EPD requires a number of LCI datasets to be used as upstream, core, and downstream processes to represent the system boundary under study. Hence, linking LCI with EPD requires the LCI to follow a specific set of requirements in reporting. The linkages of EPD with LCI datasets and LCA methodological aspects are shown in Figure 9.

Results of the environmental impact assessment data are stored as part of the EPD dataset to be used as environmental performance results. The data are currently stored in Excel format with the ability to fetch by the web interface included in the sustainability web server (s-WS).

2.2.4. Proxy Data and High-Level Decision-Making Data

Life cycle impact assessment results or EPD reporting can be, in some cases, directly used as decision-making data. But in most cases, environmental indicators will be evaluated against a plethora of other criteria including capital costs, profitability, technological maturity, government policy and regulations, and social aspects and engagement. The data hub does not intend to include all the high-level decision-making data related to a certain technology pathway, but does offer flexibility to include necessary parameters as a part of s-WS (shown in Figure 2).

LCA studies based on the attributional approach typically show a snapshot of environmental impacts valid for a given time period and region. However, changes in energy mixes, technology improvement, and supply chain decarbonization require LCA impact assessment results, EPDs, and other high-level decision-making criteria to be updated regularly to reflect current real-world conditions. Such periodic updates are, however, difficult and time-consuming. Hence, tools and IT infrastructure that facilitate automatic and semi-automatic updates to high-level datasets with the change of LCI and technology characteristics are critical. Hence, we propose the infrastructure below, which combines openLCA CS, a datamart or pre-calculation module, and a web-based interface as part of s-WS.

Many internal and external stakeholders, who would use data hub for high-level decision-making, are non-LCA experts or do not have the required software installed in their respective computers. Such stakeholders require simplified high-level LCA tools, preferably web-based, to calculate key LCA impacts and view underlying LCI data and assumptions. Hence, a web-based high-level LCA calculation tool for NRC and its stakeholders with validated traceability and transparency of datasets would be built upon the current NRC openLCA CS platform as shown in Figure 10.

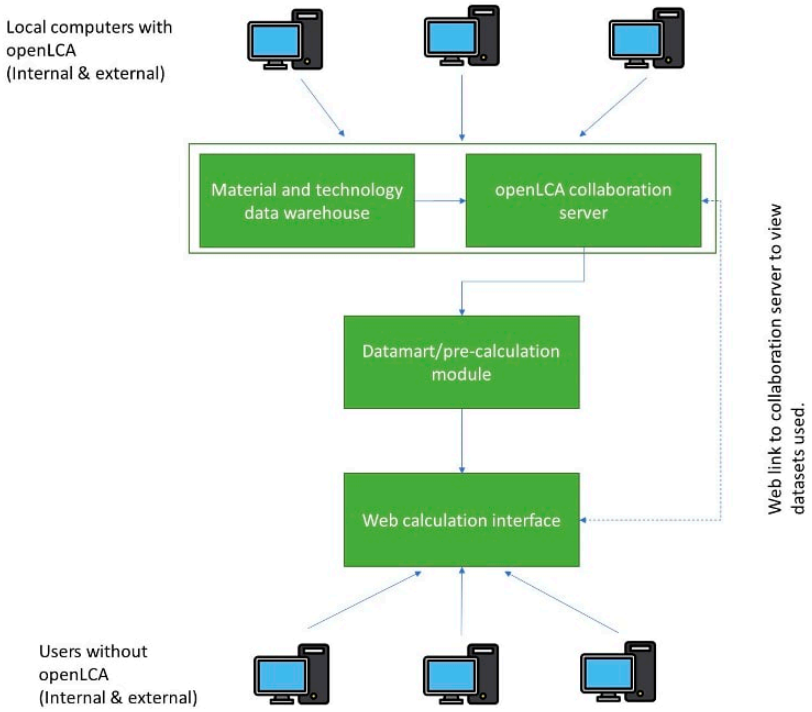

Figure 10. A web-based LCA tool for NRC and its stakeholders with validated traceability and transparency of LCI datasets.

3. Results and Discussion

3.1. Case Study—Hydrogen Production Using PEM

The electrolysis process converts water into hydrogen and oxygen by applying electrical energy:

$$H_2O \rightarrow H_2 + ½\, O_2$$

The produced hydrogen gas (H_2) is usually at a high purity of 99.99%, and the oxygen gas (O_2) can be sold as a marketable by-product if not released into the atmosphere. Among the different electrolysis technologies, low-temperature electrolysis, including alkaline and proton-exchange membrane (PEM), could commercially compete against fossil fuel-based technologies [28].

3.2. Overview of LCA Methodology

An LCA-based methodology that aims to quantify H_2 production carbon intensity by using an attributional LCA with a "well-to-gate" system boundary has been developed by our team [29]. The life cycle inventory data for the foreground system comes from modeling and simulation results of H_2 production processes. While the net GHG emissions are the focus of their proposed life cycle-based framework, other impact factors, including ozone depletion, acidification, and eutrophication could also be quantified using the same framework. The three main components of the LCA-based methodology include:

- Goal and scope definition, which state the aims for performing the LCA study and include the scope (product system, system boundary, functional unit, and others as the type of hydrogen production pathway, and geographical scope).
- Life cycle inventory, which comprises a literature review, collection of (primary) data, building a hydrogen LCI database, and data quality evaluation.
- Life cycle impact assessment, which considers the calculation of carbon intensity for a hydrogen production pathway [29].

Each component is described below in the context of H_2 production using PEM.

3.2.1. Goal and Scope

In our case study, the goal is to perform an LCA of hydrogen production via PEM electrolysis and quantify its carbon footprint. The product system and functional unit are defined as 1 kg of compressed gaseous hydrogen with a purity of 99.9%, a compression of 6.4 MPa, and an energy content (LHV) of 119.9 MJ/kg [29]. The "well-to-gate" system boundary considers a foreground system with three subsystems: (i) feedstock that includes electricity and deionized water; (ii) hydrogen production and purification; and (iii) hydrogen compression [29]. The geographical scope considers that the hydrogen production facility is located in the Canadian Province of Quebec, Ontario; thus, the grid electricity from the Quebec electricity system is used in the hydrogen production system.

3.2.2. Life Cycle Inventory

The development and implementation of an LCI of the H_2 production pathway via PEM electrolysis considers the steps as follows.

- Step 1. Literature review to collect existing LCI datasets, and identify the preliminary process flow diagram, key parameters, and assumptions.
- Step 2. Undertake the process simulation. In this step, a process flow diagram, mass–energy balance, and the initial LCI are obtained.
- Step 3. LCI datasets are finalized, which include LCI data gap, validation, and data quality assessment.
- Step 4. LCI data are transformed into potential environmental impacts using life cycle impact assessment methods.

Collection of primary LCI data

Due to the lack of accessible primary data from the industry, process simulation results are taken as data sources to generate primary data. The main source of data for H_2 LCI datasets is the mass–energy balance, the targeted results of the process simulation procedure [29].

On the basis of the collected process parameters and information from the literature review, the PEM process was designed based on the most state-of-art technologies, and the entire H_2 production plant was modeled using commercial process simulation software (such as Aspen Plus or ProSim). Either a built-in model (if it existed) or a customized model of the PEM stack was developed for the process simulation. A customized model was built based on the developed model found in literature that was already validated through test data of commercial PEM stack unit. All the mass and energy flows in and out of the product system's boundary were simulated, where the mass and energy data were ensured to be balanced.

To generate primary LCI data, the inventory template developed using the results of identified input and output flow names from the literature review's second screening step will be filled with the amounts calculated from primary data sources [29]. Specifically, for the PEM process, the raw mass and energy balance data generated from process simulation, as shown in Table 1**,** were used to calculate the amounts of required electricity and deionized water to the system and the amounts of hydrogen and oxygen flow out of the system. This calculation was realized in an Excel template.

Table 1. Data template of raw flow data from process simulation of a PEM-based hydrogen plant.

Input/Output	Value	Unit
Main inputs to the process		
Water	3595.7	kg/h
Electricity consumption—Electrolyzer	20,000	kW
Electricity consumption—BoP	290.61	kW
Main outputs from the process		
Hydrogen output		kg/h
- Hydrogen	396.5	kg/h
- Water	0	kg/h
- Oxygen	0.1	kg/h
Purge		kg/h
- Hydrogen	1.2	kg/h
- Water	2.4	kg/h
- Oxygen	0	kg/h
Oxygen output		kg/h
- Hydrogen	0.6	kg/h
- Water	23.5	kg/h
- Oxygen	3161.7	kg/h
Residual vapor		kg/h
- Hydrogen	0	kg/h
- Water	9.4	kg/h
- Oxygen	0	kg/h

Building a hydrogen LCI database

The primary LCI of the PEM process, as included in the foreground system, was obtained from the mass–energy balance results of the simulation and optimization process. The scope three emissions from capital goods of the system are excluded [29]. In this PEM-based hydrogen use case study, there is no background system required when the cooling water is not counted. Both electricity and deionized water production were counted in the foreground system. As it is described in [29], a conversion of the LCI results to unit process data was performed using an Excel template.

The LCI dataset of H_2 production via PEM technology was generated by transferring the normalized LCI datasets in Excel format (see Table 1 below) to the LCI dataset in OpenLCA format. Then the final LCI dataset generated in the OpenLCA desktop environment is committed to the OpenLCA collaboration server [29]. The resulting LCI datasets regarding the total electricity demand and water consumption were confirmed to be reasonably within the ranges found from the literature, i.e., 56.9 ± 9.8 kWh/kg H_2 and 9.5 ± 0.6 kg/kg H_2, respectively. Hydroelectricity generation, dominant in the Canadian province of Quebec, was used as the electricity source for electrolysis.

Data quality evaluation

An interim quality control of the preliminary LCI dataset was conducted to check completeness, sensitivity, and consistency [29]. First, the preliminary LCI dataset values obtained from process simulation are compared with the LCI dataset with the range and average values from secondary sources. The preliminary LCI dataset of the PEM electrolysis process was found to be within the range of values obtained from the secondary sources and be comparable to the average value.

Then, an LCI data quality evaluation is focused on the key data sources used to select the PEM electrolyzer's input parameters in the process model. The evaluation of critical parameters that are used to model the PEM process is described below:

1. The most important parameters (electrolyzer stack efficiency) that affect the electrolyzer electricity consumption were obtained from literature [30]. This technoeconomic assessment study analyzes the H_2 production costs of a state-of-the-art PEM electrolyzer. Technical data from four independent electrolyzer companies were obtained through questionnaires, and an engineering system performance model was developed from these inputs to create a generalized electrolyzer system engineering design consistent with the diverse industry input from electrolyzer manufacturers. Hence, these parameters can be considered primary data valid until 2020.
2. The anode and cathode pressures are based on literature [31], which is a review paper on high-pressure PEM water electrolyzers. The data are sourced from the average pressure of commercial PEM based on a market survey result of 11 active manufacturers marketing large-scale PEM electrolyzer systems.
3. Heat losses and hydrogen diffusion to the anode were based on literature [32], which is a process simulation of alkaline electrolysis operation and experimental validation study using a 10 kW bench scale setup.
4. The thermal management and cooling system parameters of the PEM electrolyzer were based on literature [33]. This study models heat generation and its management for a PEM electrolyzer. The models are based on state-of-the-art technology at the time of the study (2019) and hence can be considered secondary data.
5. Faradaic efficiency of hydrogen production was obtained from literature [34]. The data are sourced from an experimental lab-scale PEM electrolysis setup of 0.4 kW.
6. The majority of data sources used to model the PEM electrolysis plant are from 2019–2022.

The data quality of process flows is assigned based on a pedigree matrix that evaluates the data in terms of multiple criteria [35]. Data quality assessment provides a measure of the representativeness of the unit process being studied, and results are typically included as metadata along with LCI. In some cases, data quality assessment is used to achieve

certain data quality goals required by the analysis. The following data quality indicators (DQI) are typically used in measuring the data quality of each flow in a unit process dataset.

- Reliability
- Completeness
- Time-related appropriateness
- Geographical appropriateness
- Technological appropriateness

Each DQI is given a score of 1 to 5 upon evaluation of data quality. Reliability indicates the quality of data collection and validation methods. Completeness evaluates the robustness of sampling methods and the amount of data points collected. Time-related and geographical appropriateness measures representativeness in terms of correct geography, such as country or region and the age of the data. Technological appropriateness measures the gap between the goal and scope of the LCA study and the actual represented technology. In addition to the data quality of the flows, the complete process data quality is evaluated based on guidelines developed by the US EPA [35]. They include the following DQI.

- Process completeness
- Process review

Table 2 shows an example of the key values of unit process datasets of water electrolysis, including flow names, units, quantities, and data quality parameters.

Table 2. Life cycle inventory of hydrogen production using PEM water electrolysis process.

Flow Name	Value	Unit	Data Quality (Flows)	Data Quality (Process)
Input flows				(1, 4)
Deionized water required	9.1	kg	(3, 5, 1, 3, 2)	
Electricity required	55.2	kWh	(3, 5, 1, 3, 2)	
Output flows				
Hydrogen produced	1	kg	(3, 5, 1, 3, 2)	
Oxygen produced	8.0	kg	(3, 5, 1, 3, 2)	

3.2.3. Life Cycle Impact Assessment

The calculation of carbon intensity of H_2 produced via PEM technology was done using openLCA and selecting an impact assessment method, IPCC (GWP-100), 2013. Also, additional impact indicators were calculated using ReCiPe midpoint method [36]. The resulting carbon intensity of hydrogen, 1.17 ± 0.03 kg CO_2/kg H_2, was compared with identified values from the literature, i.e., 30.01 ± 0.85 kg CO_2/kg H_2. The large difference in the mean value is due to the fact that our case study used hydroelectricity for the electrolysis process and studies in the literature used fossil-fuel-dominant electricity sources. Hence, it is safe to conclude that there can be a statistically significant difference in hydrogen carbon intensity based on electricity source.

Thereby, the LCA-based methodology is statistically validated by evaluating accuracy and reliability from a comparison of the carbon intensity and input flow with great significance with the mean and standard deviation of a group of LCA studies with similar LCA elements such as system boundary, hydrogen technology, and functional unit.

Also, results for other impact categories calculated by the ReCiPe method are shown in Table 3.

Table 3. Life cycle impact assessment results using ReCiPe midpoint environmental indicators for hydrogen production using PEM electrolysis.

Environmental Impact Catogory	Result	Unit
Mineral resource scarcity	0.00975	kg Cu eq
Human non-carcinogenic toxicity	1.3809	kg 1,4-DCB
Human carcinogenic toxicity	0.15429	kg 1,4-DCB
Freshwater ecotoxicity	0.26103	kg 1,4-DCB
Water consumption	1.13287	m^3
Marine ecotoxicity	0.32041	kg 1,4-DCB
Stratospheric ozone depletion	3.62×10^{-6}	kg CFC11 eq
Land use	0.55658	m^2a crop eq
Ionizing radiation	0.60945	kBq Co-60 eq
Freshwater eutrophication	0.00018	kg P eq
Terrestrial ecotoxicity	8.24127	kg 1,4-DCB
Marine eutrophication	2.58×10^{-5}	kg N eq
Terrestrial acidification	0.00316	kg SO_2 eq
Fine particulate matter formation	0.00123	kg PM2.5 eq
Ozone formation, terrestrial ecosystems	0.00218	kg NOx eq

3.3. Implementation of H_2 Production Datasets in the Collaboration Server

Figure 11 shows the organization of foreground data and background data in the openLCA CS. The H_2 production unit process datasets, reference flow system, and data quality systems were implemented as an online CS repository. The background LCIs are not a part of the CS online repository. However, foreground and background LCIs share the same reference flow system so that background LCIs can remain in the local database of each respective user. This implementation eliminates the need to host large background databases in the CS.

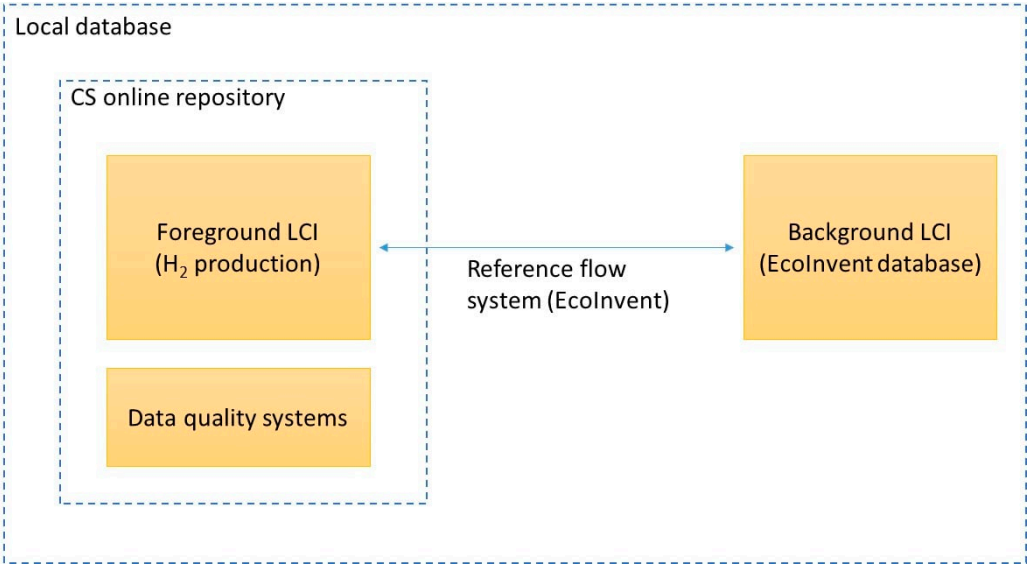

Figure 11. Organization of the foreground and background datasets relating to H2 production.

Each user can fetch the updated foreground LCI data for H_2 production from the CS and establish the linkage between foreground and background data by selecting the

appropriate providers of the unit processes. Table 4 provides suggestions for selecting appropriate background process providers.

Table 4. Flows of foreground system and suggested background system processes from ecoinvent database.

Flow Name	Background System Process
Monoethanolamine	market for monoethanolamine | monoethanolamine {GLO}
Zinc oxide	market for zinc oxide | zinc oxide {GLO}
Aluminium oxide	market for aluminium oxide, metallurgical | aluminium oxide, metallurgical {GLO}
Copper oxide	market for copper oxide | copper oxide {GLO}
Activated carbon	market for activated carbon, granular | activated carbon, granular {GLO}
Wastewater	treatment of wastewater, average, capacity 5E9l/year | wastewater, average {CA-QC}
Steam	steam production, as energy carrier, in chemical industry | heat, from steam, in chemical industry [37]
Nitrogen	market for Nitrogen, liquid [37]
KOH	market for potassium hydroxide | potassium hydroxide {GLO}
Polyacrylic acids	market for Acrylic acid {GLO}
Sulfuric acid	market for Sulfuric Acid {GLO}
Caustic soda	market for Caustic Soda {GLO}
Chlorine	market for Chlorine {GLO}

3.4. Life Cycle Sustainablity Assessment

A life cycle sustainability assessment (LCSA) framework ideally consists of three sustainability pillars: environmental, economic, and social. Often one, two, or three pillars are combined in sustainability reporting depending on if the focus is on viability (economic plus environmental), bearability (environmental and social), or equitability (economic and Social). In the literature, often environmental and social [38] or exclusively social [39] LCA have been performed. The social LCA follows UNEP/SETAC guidelines, which were developed based on the environmental LCA framework, including goal and scope definition, social LCI development, social impact assessment, and interpretation stages [40]. To build consistency in the sustainability reporting, the current proposed data hub platform needs to be extended to social and economic aspects as well. Hence, LCSA considering economic, social, and environmental aspects is a future direction for the data hub.

4. Conclusions

This study emphasized the importance of harnessing open data and developing an open-access data hub for comprehensive life cycle assessments (LCA). For this, data sharing and data interoperability are critical. This will help timely data accessibility to accelerate the deployment of climate change solutions. The use of the LCA framework in conjunction with open platforms, such as the openLCA collaboration server, and the concept of a federated open data platform was introduced. In addition, the integration of a web interface will help facilitate the widespread use of the proposed integrated data hub. The linkage of datasets at different levels will enable traceability and transparency of sustainability assessments and reporting. Future efforts should focus on the further development of the proposed data hub, ensuring that it becomes an accessible and user-friendly platform for LCSA practitioners. This involves the advancement of the IT infrastructure, particularly the creation of a user-friendly web interface platform. Additionally, this platform would benefit greatly from ongoing testing and refinement using diverse case studies to increase its reliability. The design and functionality of the platform should be improved based on user input from

these case studies in order to better serve the larger LCSA community. Training programs should be created that are essential in promoting the wide acceptance and utilization of the platform and ensuring users utilize the platform efficiently. It is crucial to keep in mind that the goal is not only to develop an innovative platform but also to make sure that it can be useful and accessible to the target community.

Limitations

Regarding the hierarchy of datasets presented in this study, LCI and EPD datasets have some standardization on the format and content of the data. However, when it comes to scientific and technological datasets and high-level decision-making/proxy datasets, there are no standard structures or formats. These datasets can vary significantly in terms of data structure, data formats, and size. Although the proposed data hub platform in this study provides high-level linkages and infrastructure for the linkage of scientific/technology datasets and high-level decision-making datasets, further work is required to specify the connections between datasets with varying structures and formats. We suggest achieving this in terms of semantic models, in which the conceptual linkages are modeled depending on the type of data available in scientific/technology datasets.

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References

1. Durack, P.; Eyring, V.; Gillett, N.; Achutarao, K.; Barimalala, R.; Barreiro, M.; Bellouin, N.; Cassou, C.; Kosaka, Y.; McGregor, S.; et al. Human Influence on the Climate System. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V.P., Zhai, V., Pirani, A., Conners, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021.
2. Allen, M.; Axelsson, K.; Caldecott, B.; Hale, T.; Hepburn, C.; Hickey, C.; Mitchell-Larson, E.; Malhi, Y.; Otto, F.; Seddon, N.; et al. *The Oxford Principles for Net Zero Aligned Carbon Offsetting*; University of Oxford: Oxford, UK, 2020; p. 15.
3. Herrmann, I.T.; Moltesen, A. Does it matter which Life Cycle Assessment (LCA) tool you choose?—A comparative assessment of SimaPro and GaBi. *J. Clean. Prod.* **2015**, *86*, 163–169. [CrossRef]
4. Bhaduri, G.; Copeland, L. Going green? How skepticism and information transparency influence consumers brand evaluations for familiar and unfamiliar brands. *J. Fash. Mark. Manag. Int. J.* **2021**, *25*, 80–98. [CrossRef]
5. *ISO 14040*; Environmental Management-Life Cycle Assessment-Principles and Framework. British Standards Institution: London, UK, 2006.
6. *ISO 14044*; Environmental Management-Life Cycle Assessment-Requirements and Guidelines. International Organization for Standardization: Geneva, Switzerland, 2006.
7. De Smet, B.; Stalmans, M. LCI data and data quality: Thoughts and considerations. *Int. J. Life Cycle Assess.* **1996**, *1*, 96–104. [CrossRef]
8. Del Borghi, A. LCA and communication: Environmental Product Declaration. *Int. J. Life Cycle Assess.* **2013**, *18*, 293–295. [CrossRef]
9. Wernet, G.; Bauer, C.; Steubing, B.; Reinhard, J.; Moreno-Ruiz, E.; Weidema, B. The ecoinvent database version 3 (part I): Overview and methodology. *Int. J. Life Cycle Assess.* **2016**, *21*, 1218–1230. [CrossRef]

10. Kahn, E.; Antognoli, E.; Arbuckle, P. The LCA Commons—How an Open-Source Repository for US Federal Life Cycle Assessment (LCA) Data Products Advances Inter-Agency Coordination. *Appl. Sci.* **2022**, *12*, 865. [CrossRef]
11. Perera, H.; Atmojo, U.D.; Vyatkin, V. Confidentiality Preserving Data Sharing for Life Cycle Assessment in Process Industries. In Proceedings of the 2024 IEEE 29th International Conference on Emerging Technologies and Factory Automation (ETFA), Padova, Italy, 10–23 September 2024; pp. 1–4.
12. Llorenç, M.i.C.; Adisa, A.; Gabor, D.; Donna, J.; Henry, K.; Christopher, M.; Thomas, N.; Anne, R.; Sarah, S.; Heinz, S.; et al. Approaches for addressing life cycle assessment data gaps for bio-based products. *J. Ind. Ecol.* **2011**, *15*, 707–725.
13. Weidema, B.P. Consistency check for life cycle assessments. *Int. J. Life Cycle Assess.* **2019**, *24*, 926–934. [CrossRef]
14. Véronique, B.-M.; Gregory, M.P.; Sonia, C.; Gustavo, F.; Carole, S.; Hernan, O.; Philippe, R.; Michael, D.S. Streamlining life cycle inventory data generation in agriculture using traceability data and information and communication technologies–part II: Application to viticulture. *J. Clean. Prod.* **2015**, *87*, 119–129.
15. Ferrari, A.M.; Volpi, L.; Settembre-Blundo, D.; García-Muiña, F.E. Dynamic life cycle assessment (LCA) integrating life cycle inventory (LCI) and Enterprise resource planning (ERP) in an industry 4.0 environment. *J. Clean. Prod.* **2021**, *286*, 125314. [CrossRef]
16. Kuczenski, B.; Sahin, C.; El Abbadi, A. Privacy-preserving aggregation in life cycle assessment. *Environ. Syst. Decis.* **2017**, *37*, 13–21. [CrossRef]
17. Carrières, V.; Lemieux, A.-A.; Margni, M.; Pellerin, R.; Cariou, S. Measuring the Value of Blockchain Traceability in Supporting LCA for Textile Products. *Sustainability* **2022**, *14*, 2109. [CrossRef]
18. Tao, J.; Yu, S. A Meta-model based Approach for LCA-oriented Product Data Management. *Procedia CIRP* **2018**, *69*, 423–428. [CrossRef]
19. Sandanayake, M.; Zhang, G.; Setunge, S. Estimation of environmental emissions and impacts of building construction–A decision making tool for contractors. *J. Build. Eng.* **2019**, *21*, 173–185. [CrossRef]
20. Barbhuiya, S.; Das, B.B. Life Cycle Assessment of construction materials: Methodologies, applications and future directions for sustainable decision-making. *Case Stud. Constr. Mater.* **2023**, *19*, e02326. [CrossRef]
21. Han, D.; Rajabifard, A. Improving the Decision-Making for Sustainable Demolition Waste Management by Combining a Building Information Modelling-Based Life Cycle Sustainability Assessment Framework and Hybrid Multi-Criteria Decision-Aiding Approach. *Recycling* **2024**, *9*, 70. [CrossRef]
22. Kalbar, P.P.; Karmakar, S.; Asolekar, S.R. Life cycle-based decision support tool for selection of wastewater treatment alternatives. *J. Clean. Prod.* **2016**, *117*, 64–72. [CrossRef]
23. Verghese, K.L.; Horne, R.; Carre, A. PIQET: The design and development of an online 'streamlined' LCA tool for sustainable packaging design decision support. *Int. J. Life Cycle Assess.* **2010**, *15*, 608–620. [CrossRef]
24. Whittle, J.; Callander, K.; Akure, M.; Kachwala, F.; Koh, S. A new high-level life cycle assessment framework for evaluating environmental performance: An aviation case study. *J. Clean. Prod.* **2024**, *471*, 5. [CrossRef]
25. Cihat, N.; Kucukvar, M.; Tatari, O.; Phil, Q. Combined application of multi-criteria optimization and life-cycle sustainability assessment for optimal distribution of alternative passenger cars in US. *J. Clean. Prod.* **2016**, *112*, 291–307.
26. GreenDelta. openLCA Collaboration Server. 2024. Available online: https://www.openlca.org/collaboration-server/ (accessed on 1 December 2023).
27. ECCC. Fuel Life Cycle Assessment Model. 2024. Available online: https://www.canada.ca/en/environment-climate-change/services/managing-pollution/fuel-life-cycle-assessment-model.html (accessed on 1 December 2023).
28. Dash, S.K.; Chakraborty, S.; Elangovan, D. A Brief Review of Hydrogen Production Methods and Their Challenges. *Energies* **2023**, *16*, 1141. [CrossRef]
29. Giovanna, G.-C.; Jianjun, Y.; Jalil, S.; Deces-Petit, C.; Farid, B.; Nima Ghavindel, M.; Cedric Diffo, T.; Maryam, A.; Marzouk, B.; Chen, J. Life Cycle Assessment of Hydrogen Production Pathways in Canada. 2022. Available online: https://nrc-publications.canada.ca/eng/view/object/?id=edf7cdaf-2a77-43b0-a9a4-87ea5cf1773f (accessed on 1 January 2023).
30. Peterson, D.; Vickers, J.; DeSantis, D. Hydrogen Production Cost from PEM Electrolysis. Available online: https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/19009_h2_production_cost_pem_electrolysis_2019.pdf?Status=Master (accessed on 18 September 2024).
31. Salehmin, M.N.I.; Husaini, T.; Goh, J.; Sulong, A.B. High-pressure PEM water electrolyser: A review on challenges and mitigation strategies towards green and low-cost hydrogen production. *Energy Convers. Manag.* **2022**, *268*, 115985. [CrossRef]
32. Sánchez, M.; Amores, E.; Abad, D.; Rodríguez, L.; Clemente-Jul, C. Aspen Plus model of an alkaline electrolysis system for hydrogen production. *Int. J. Hydrogen Energy* **2020**, *45*, 3916–3929. [CrossRef]
33. Tiktak, W.J. *Heat Management of PEM Electrolysis*; Delft University of Technology: Delft, The Netherlands, 2021.
34. Yodwong, B.; Guilbert, D.; Phattanasak, M.; Kaewmanee, W.; Hinaje, M.; Vitale, G. Faraday's Efficiency Modeling of a Proton Exchange Membrane Electrolyzer Based on Experimental Data. *Energies* **2020**, *13*, 4792. [CrossRef]
35. Edelen, A.; Ingwersen, W. Guidance on Data Quality Assessment for Life Cycle Inventory Data. 2016; p. 47. Available online: https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=321834 (accessed on 1 January 2023).
36. Mark, A.J.H.; Zoran, J.N.S.; Pieter, M.F.E.; Gea, S.; Francesca, V.; Marisa, V.; Michiel, Z.; Anne, H.; Rosalie, V.Z. ReCiPe2016: A harmonised life cycle impact assessment method at midpoint and endpoint level. *Int. J. Life Cycle Assess.* **2017**, *22*, 138–147.

37. Swanson, R.M.; Platon, A.; Satrio, J.A.; Brown, R.C. Techno-economic analysis of biomass-to-liquids production based on gasification. *Fuel* **2010**, *89*, S11–S19. [CrossRef]
38. Vinci, G.; Prencipe, S.A.; Ruggeri, M.; Gobbi, L.; Arcese, G. Sustainability performance evaluation in the organic durum wheat production: Evidence from Italy. *Int. J. Life Cycle Assess.* **2024**, 1–19. [CrossRef]
39. dos Reis, R.A.; Rangel, G.P.; Neto, B. Social life cycle assessment of green hydrogen production: Evaluating a projected Portuguese industrial production plant. *Renew. Energy* **2024**, *235*, 121293. [CrossRef]
40. Benoît, N.C.; Traverzo, M.; Neugebauer, S.; Ekener, E.; Schaubroeck, T.; Russo, G.S. *Guidelines for Social Life Cycle Assessment of Products and Organizations 2020*; United Nations Environment Programme: Nairobi, Kenya, 2020.

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