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COMMENTARY AND DISCUSSION ARTICLE

Conditions for the broad application of prospective life cycle inventory databases

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1 Introduction

Major technological transitions are necessary to avoid the catastrophic consequences of climate change and other environmental damage (IPCC 2021). However, many of the technologies needed to achieve net zero greenhouse gas emissions by 2050 are still in the early stages of development (IEA 2021a). The implementation of these technologies is expected to occur once they are mature enough to enter the market. Some technologies will require significant capital and time to develop. Therefore, a good understanding of these technologies' potential environmental impacts and guidance to minimize these impacts before such investments are made are crucial to meet environmental targets.

Prospective LCA (pLCA, similar terms are ex-ante and anticipatory LCA) assesses the potential environmental impacts of products and services of future technologies and guides their development (van der Giesen et al. 2020). Assessing the environmental impacts of future technologies often requires placing the temporal scope of the analysis in the mid- to long-term future, when the global economy, society, and environment will differ from today (Moss et al. 2010; Riahi et al. 2017; van Vuuren et al. 2011). It has been widely acknowledged that it is crucial to avoid a temporal mismatch between the foreground system (i.e., the technology under study) and the background system (i.e., the economic system the technology operates in) to support sustainable technology design and policymaking (Arvidsson et al. 2018; Buyle et al. 2019; Joyce and Björklund 2021; Knobloch et al. 2020; Thonemann et al. 2020; van der Giesen et al. 2020; Vandepaer et al. 2020).

Although LCA practitioners can typically obtain information on the development of the foreground system from technology developers, capturing systemic changes in the background is more complicated. Therefore, prospective life cycle inventory (pLCI) databases were developed: for example, within the NEEDS project (NEEDS 2009), the THEMIS model (Gibon et al. 2015; Hertwich et al. 2015), and more recently, in the work that led to the *premise* framework (Cox et al. 2020; Mendoza Beltran et al. 2018; Sacchi et al. 2022). These pLCI databases were derived from a combination of the *ecoinvent* database (Wernet et al. 2016) and exogenous scenario data to represent future technology and supply chains in specific sectors. Scenario data sources have included energy system models, input–output models, macroeconomic models, integrated assessment models (IAMs), scientific literature, and expert judgment, depending on the availability of data for different technologies, economic sectors, and world regions.

Despite the importance of considering future scenarios for key economic sectors in pLCAs, and despite a recent increase in the use of pLCI databases in the academic literature (see Appendix), the use of pLCI databases remains the exception rather than the rule in future-oriented LCAs. This situation involves several issues relating to how pLCI databases are being generated, shared, and used. For example, pLCI databases remain difficult to obtain and use in standard LCA software. Furthermore, guidance for practitioners regarding content and the appropriate usage of pLCI databases is scarce. Also, the technological, sectoral, regional, and environmental coverage remains limited. Finally, a broader discussion to reach a consensus on the models and data sources pLCI databases should be based on has not yet occurred. Recent literature has discussed some of these issues. For example, Adrianto et al. (2021) highlight

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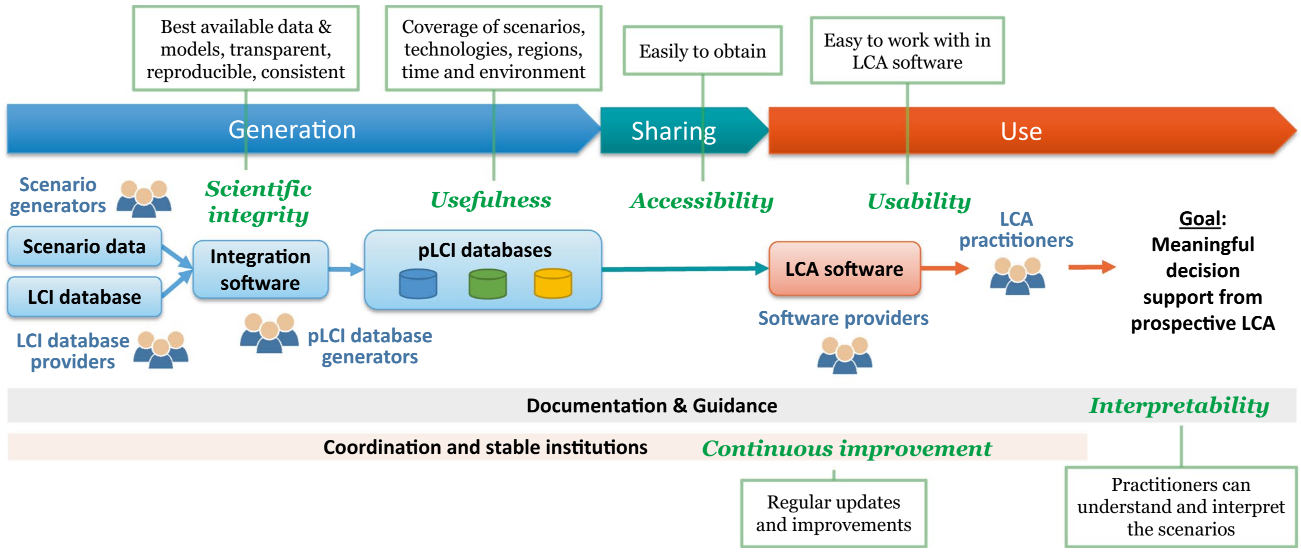

Fig. 1 The generation, sharing, and use of pLCI databases, conditions for the broad application of pLCI databases (green italic), and the involved stakeholders (blue)

the need to streamline the process of including future background scenarios in pLCA. Bisinella et al. (2021) also stress the need for improved guidance when using future scenarios. Therefore, these issues need to be addressed to foster the more widespread use of pLCI databases.

To support these efforts, we provide an overview of the generation, sharing, and use of pLCI databases in this paper. We then discuss the conditions for a broad application of pLCI databases with the ultimate aim of improving environmental guidance for future technologies. Finally, we prioritize the challenges to be addressed to enable the widespread use of pLCI databases within pLCA.

2 The generation, sharing, and use of pLCI databases

To understand what is needed to achieve a widespread use of pLCI databases, we structure the information chain leading up to the use of pLCI databases in pLCAs into three distinct stages: the generation, sharing, and use of pLCI databases (Fig. 1).

During the *generation* stage, scenario data that describe potential future developments for key technologies and supply chains are integrated into an existing LCI database to yield a set of pLCI databases that reflect different scenarios and reference years. The relevant stakeholders during this stage are scenario generators, who develop scenarios and implement them in models (e.g., IAMs), LCI data providers, and pLCI database generators. pLCI database generators generate pLCI databases using dedicated integration software, such as *premise* (Sacchi et al. 2022), which is a Python package that integrates IAM data into the ecoinvent database to generate pLCI databases.

During the *sharing* stage, pLCI databases are made available to LCA practitioners. Solutions for an improved sharing of pLCI databases are still evolving but may, in the future, include stakeholders, such as scenario generators, LCI database providers, and software providers.

During the *use* stage, LCA practitioners use pLCI databases as background data in pLCAs. This use requires LCA software solutions that facilitate the handling of pLCI databases, as well as guidance and documentation, to ensure practitioners can understand what pLCI databases represent and how they should be used.

3 Conditions

Although this information chain depicted in Fig. 1 already exists, it needs further development to enable the broad application of pLCI databases. We identified six conditions that will, in our opinion, determine to which degree pLCI databases will be adopted by LCA practitioners (see also Fig. 1):

1. Scientific integrity: pLCI databases need to be based on state-of-the-art scientific models and data, relying on consistent scenarios, narratives, and assumptions. The generation of pLCI databases needs to be transparent and reproducible.

2. Usefulness: pLCI databases need to cover relevant scenarios for socio-economic developments in sufficient technological, regional, temporal, and environmental detail.
3. Accessibility: pLCI databases need to be easy to obtain for LCA practitioners.
4. Usability: pLCI databases need to be easy to use in LCA software.
5. Interpretability: sufficient guidance and documentation need to be available for LCA practitioners to understand scenarios and their implementation in pLCI databases, and to interpret corresponding LCA results.
6. Continuous improvement: the continuous improvement of all conditions requires coordination and stable institutions.

We now describe essential aspects for each condition, including the current state of development, challenges, and avenues for improvement.

3.1 Scientific integrity

The scientific integrity of pLCI databases and the surrounding information chain are paramount for the credibility and quality of the support for environmental decision-making. The relevant aspects of this condition are the following.

3.1.1 State-of-the-art models and data

Significant craftsmanship is involved when developing pLCI databases, and it is part of scientific integrity to ensure that the generation of pLCI databases relies on state-of-the-art scenario and LCI data. However, it should be acknowledged that the perfect data sources for scenario and LCI data do not exist. For example, in recent efforts to generate pLCI databases, IAMs play an important role as scenario data sources, but IAMs also suffer from certain limitations, e.g., incomplete coverage of sectors and life cycle stages (Pauliuk et al. 2017). IAMs, just like LCI databases, also have their own release cycles, and may not always include the latest data. More coordination will, therefore, be necessary to ensure a well-synchronized and continuously improved information chain that delivers pLCI databases based on the best data sources in a landscape of dynamically developing models, data, and scenarios.

3.1.2 Consistency

pLCI databases should provide internally consistent data. However, this consistency may be difficult to achieve in practice for a complex modeling exercise such as the generation of pLCI databases.

Currently, neither scenario models nor LCI databases can provide 100% internally consistent data sources at a high technological, regional, and temporal resolution. For example, IAMs have detailed representations of sectors relevant to climate change, such as electricity production. Still, they fall short for other sectors (e.g., agriculture, chemical production, and material cycles (Pauliuk et al. 2017)). LCI databases have limited coverage of emerging technologies that may become relevant in the future, as their focus is to provide background data for current technology (Wernet et al. 2016). To close such data gaps, IAM-based pLCI databases have been complemented with LCI and scenario data from additional sources (Sacchi et al. 2022). Although this approach increases the representation of specific sectors, technologies, or regions, it may introduce inconsistencies (Mendoza Beltran et al. 2018; Sacchi et al. 2022). Eventually, an optimal compromise between data consistency, coherence, and coverage will have to be identified. We believe using additional data sources to improve pLCI databases is a practical solution in the short term. In the longer term, solutions should be identified to increase coverage and consistency of pLCI data, e.g., by extending IAMs to include more LCA-related data.

Another important aspect to consider in the context of consistency is technological maturity. pLCI databases that are meant to represent average technologies at a future point in time should consider how emerging technologies (e.g., at lab or demonstrator scale) would operate at a commercial scale after their market introduction (see, e.g., Arvidsson et al. 2018; Thonemann et al. 2020; van der Giesen et al. 2020).

3.1.3 Transparency and reproducibility

To ensure scientific integrity, pLCI databases should be documented so the underlying data and the generation process are transparent (see detailed suggestions in Sect. 3.5.2). The generation of pLCI databases should also be reproducible. To ensure reproducibility, the FAIR principles (findable, accessible, interoperable, reusable; (Wilkinson et al. 2016)) should be followed. Further transparency and reproducibility can be achieved via open-source software. These conditions are, in principle, met by recent efforts to generate pLCI databases (e.g., Mendoza Beltran et al. 2018; Sacchi et al. 2022). Furthermore, the underlying software is open-source (i.e., *premise*; (Sacchi et al. 2022), which builds on *wurst* (Mutel 2020) to conduct systematic transformations of LCI databases, which builds on the *brightway* LCA framework (Mutel 2017). Transparency and reproducibility could also be further improved by introducing a clear versioning system to ensure a specific pLCI database can be reproduced from specific versions of the underlying data sources and integration software.

3.2 Usefulness

The usefulness of pLCI databases is strongly determined by their representation of scenarios, economic sectors, time, and geography, as well as the coverage of data for different environmental concerns.

3.2.1 Coverage of scenarios and models

For pLCI databases to serve as future background data in pLCA studies, they should represent well-accepted and commonly used scenarios based on a broad and comprehensive view of potential future socio-economic and technological developments. Important examples of such scenarios are the shared socio-economic pathways (SSPs; (O'Neill et al. 2014)) and their implementations in IAMs (e.g., Stehfest et al. 2014), or scenarios developed by the International Energy Agency (IEA 2021b).

Currently, efforts are being made to use IAMs (e.g., IMAGE and REMIND) to generate pLCI databases (e.g., Mendoza Beltran et al. 2018; Sacchi et al. 2022). Future work should focus on increasing the coverage of scenarios in pLCI databases, covering, for example, the core scenarios used by the Intergovernmental Panel on Climate Change (see, e.g., IPCC 2021) or International Energy Agency (IEA) scenarios (IEA 2021b). However, the number of existing scenarios and models is large, which has led to divergent results (IPCC 2021; Monier et al. 2018). Although variations reflect the range of possible future developments, a proliferation of pLCI databases complicates the comparison of pLCAs and is not ideal from a harmonization perspective. Therefore, coordination between pLCI database generators and related stakeholders (Fig. 1) is necessary to discuss which scenarios, models, and data sources should ideally be used to generate pLCI databases. In this context, focusing efforts on a smaller set of well-developed and, ultimately, well-accepted pLCI databases might be the best option.

A driving force in the opposite direction is the fact that the LCA community distinguishes several modes of LCA, e.g., attributional versus consequential LCA, that can be used for answering different kinds of questions (Guinée et al. 2018). Each mode differs in modeling choices, such as system boundaries or solutions to multi-functionality (e.g., allocation versus substitution), and LCI database providers have provided LCI databases for different modes, also known as system models (Wernet et al. 2016). Likewise, pLCI database generators may have to generate databases for different modes of LCA from different underlying LCI databases to cater to the needs of LCA practitioners in different contexts. This is already happening as pLCI databases have been generated based on attributional (e.g., Mendoza Beltran et al. 2018; Sacchi et al. 2022) as well as consequential system models (Maes et al. 2023).

3.2.2 Technological and sectoral coverage

The usefulness of pLCI databases to practitioners depends on the technological and sectoral coverage. pLCI databases should provide inventory data for environmentally relevant sectors expected to change in the future (e.g., energy and raw material supply, transportation, alternative fuels, cement, steel, and chemicals). It is also essential to consider the improvement of existing technology and the introduction of emerging technology.

Currently, IAMs have a good representation of climate-relevant technologies in key economic sectors. However, not all sectors are represented, or at least not at the level needed to inform the generation of pLCI databases. Other models, such as energy system models, cover only specific sectors, but in greater detail. The representation of future technologies in a pLCI database depends on the scenario data sources used. pLCI database generators face the challenge of finding data sources that are both comprehensive and detailed. Historically, most efforts to generate pLCI databases have focused on the electricity sector. More recently, efforts were made to close data gaps by complementing IAM-based pLCI databases with additional LCI and scenario data from other sources: for example, for fuels (Watanabe et al. 2022), transportation (Sacchi et al. 2021), steel, ammonia (Boyce et al. in preparation), cement (Müller et al. in preparation), cobalt (van der Meide et al. 2022), and other metals (Harpprecht et al. 2021). The main challenge will be to increase the usefulness of pLCI databases for pLCA while building a relatively consistent information chain that can be updated.

3.2.3 Regional coverage

There are substantial regional differences in how products are produced (e.g., using different technologies, raw materials, or energy sources), and therefore essential differences in the related environmental impacts.

Existing LCI databases, IAMs, and other data sources relevant for the generation of pLCI databases do capture regional differences, albeit with limitations. The ecoinvent database, for example, has a country-level resolution for certain products (e.g., electricity mixes), but a regional- or even global-level resolution for others. In IAMs, the regional coverage is the same for all products and sectors but is typically limited to certain world regions (e.g., 26 in IMAGE (Stehfest et al. 2014) and 13 in REMIND (Aboumahboub et al. 2020)). Therefore, IAMs can be used to disaggregate supply chains further with a low regional resolution in ecoinvent. However, this process is not reciprocal; country-specific supply chains in ecoinvent may also have to be aggregated to match IAM world regions, yielding, for example, regional- instead of country-specific electricity mixes. As with technological coverage, energy system models offer a higher geographical resolution than IAMs but are usually limited to a specific world region. Therefore, while accounting for region-specific differences in pLCI databases is crucial, important gaps remain for the regionalization of pLCI databases, which should be addressed in future work (Hellweg and Canals 2014).

3.2.4 Temporal coverage and representation

pLCAs typically use time horizons between five and 30 years in the future, and even longer for long-lived products (e.g., in the building sector (Fnais et al. 2022; Su et al. 2019)). pLCI databases should, therefore, cover these time horizons to provide temporally consistent background data.

Scenarios developed by the IPCC, IEA, or IAMs often extend to the year 2100 or beyond to consider long-lived products, such as building materials, and climate change effects on vegetation and ocean currents. Therefore, from a temporal perspective, these data sources are suitable for generating pLCI databases. However, not all data sources extend so far into the future, limiting the inclusion of specific sectors from other models. Moreover, the likelihood of any scenario to happen as described is going to be smaller the longer the considered time horizon, which is an important limitation that LCA practitioners should keep in mind when interpreting results.

A central reason for the development of pLCI databases is to reduce temporal inconsistencies between foreground and background data in prospective LCAs. While pLCI databases add value in *covering* data for future reference years, they lack, just like conventional LCI databases (Beloin-Saint-Pierre et al. 2014; Levasseur et al. 2010), a real representation of time. For example, in reality, the production, use, and disposal of an electric vehicle all happen in different years. In (p)LCI databases, there is no such temporal representation and, therefore, all life cycle stages happen "at once," i.e., at the same time within the same economic system. This means, to stick with the example, that the LCA of an electric vehicle in 2030 is most likely more accurate when using a pLCI database for the background system of 2030, yet, it fails to consider the changing impact of electricity over the lifetime of the vehicle. Thus, pLCI databases do not solve the aspect of *temporal representation* of LCI data. Nevertheless, the availability of pLCI databases for different reference years provides a stepping stone in this direction. For example, the LCA practitioner could manually model the production, use, and disposal of the vehicle using pLCI databases for different reference years. Another solution is the generation of temporal average datasets that represent, for example, the electricity supply over a specific decade, as proposed within the *premise* framework. However, these approaches are no silver bullets, and further developments are needed to better represent time in LCA (see, e.g., Beloin-Saint-Pierre et al. 2017; Cardellini et al. 2018; Pinsonnault et al. 2014).

3.2.5 Environmental coverage

pLCA should be used to provide a holistic environmental perspective by considering a broad range of impact categories. Therefore, pLCI databases should include inventory data relevant to these impact categories.

In practice, the focus has been on generating pLCI databases with data relevant to climate change, and much less for other impact categories. This approach has mainly been due to the sources used for deriving pLCI databases (e.g., IAMs) focusing on climate change and excluding sectors and environmental interventions relevant to other impact categories -- for example, the use of pesticides for the production of biofuels. Although some IAMs project a large increase in biofuel production, no information pertaining to the use, fate, or toxicity of pesticides is provided. Consequently, pLCI databases generated from such data sources disregard future developments for pesticides. Therefore, the scores for toxicity-related indicators (e.g., human-, terrestrial-, or ecosystem toxicity) should be regarded as highly uncertain (Sacchi et al. 2022).

Such data gaps should be filled to maintain the strength of LCA to identify burden shifts from one environmental indicator to another in the future. This point also applies to resource-related indicators. For example, energy transition policies often lead to an increased use of metals due to the large-scale development of renewables (Vandepaer et al. 2020) or the electrification of vehicle fleets (Dirnaichner et al. 2022). Increased recycling could counteract resource depletion and mitigate environmental impacts related to extractive activities. Representing stocks and flows of metals and other resources that can be recycled is a desirable feature for IAMs as it would facilitate the integration of future recycled content rates in pLCI databases.

3.3 Accessibility

pLCI databases should be easily accessible by LCA practitioners. Although this is currently not the case, inspiration can be drawn from existing sharing models for LCI databases.

3.3.1 Data sharing

At least four solutions for providing practitioners access to pLCI databases can be distinguished:

1. Via LCA software providers: most LCA practitioners obtain LCI databases through LCA software.
2. Via LCI database providers: LCI databases may also be available for download from LCI database providers, and can then be imported into LCA software.
3. Via pLCI database generators: similar to (2), pLCI database generators could make pLCI databases available online. However, this solution may not be possible if any of the underlying data are under a restrictive license. Although a license check could be performed, there is no such system in place for pLCI databases.
4. Via local generation: the local generation of pLCI databases on the practitioner's computer can overcome the data license issue. Data and software under an open license (e.g., scenario data and the integration software) are provided publicly to users. Data under license are not provided, but if the LCA practitioner has access to these data, pLCI databases can be generated locally (a system currently used by *premise*). This solution may be more sophisticated than the first three, depending on the implementation. On the other hand, this solution also opens up possibilities for practitioners to customize the pLCI generation process further (e.g., by adding specific scenario data for specific sectors).

3.3.2 Data format

Effective access to pLCI databases also requires data formats that can be used by standard LCA software. *Premise* can generate pLCI databases in several data formats (Brightway/Activity Browser, Simapro CSV, sparse matrices text files). In the future, pLCI databases should be provided in other standard data formats to cater to the needs of other LCA software.

3.4 Usability

The ease of use of pLCI databases in LCA software has a large influence on whether LCA practitioners will use them. A major challenge for usability is that, unlike in conventional LCA, in which a single background LCI database is typically used, the practitioner may want to use *multiple* pLCI databases in pLCA to assess a product system in different scenarios and reference years. This approach means LCA software must provide efficient solutions for handling *alternative* background systems.

3.4.1 LCA software to work with pLCI databases

There are several ways LCA software could support the modeling with alternative background systems. One solution could be to offer users the option to specify alternative suppliers for process inputs, so products are sourced from different pLCI databases depending on the scenario and reference year. Another solution is the *superstructure approach* (Steubing and de Koning 2021), where a set of pLCI databases is "compressed" into a single *superstructure LCI database* and a corresponding *scenario difference file*. The latter approach can be used to transform the superstructure database into any of the original scenarios. This approach enables practitioners to use a single LCI database while calculating LCA results for different scenarios and reference years. The superstructure approach is currently only implemented in the Activity Browser (Steubing et al. 2020), but could be implemented in other LCA software. In addition, LCA software should also facilitate the analysis of scenario LCA results (e.g., providing graphs displaying the comparison across scenarios or reference years).

3.5 Interpretability

The "2.16" of pLCI databases is crucial for their effective use by LCA practitioners. Key aspects of this condition include the following.

3.5.1 Guidance

pLCI databases are typically the result of comprehensive modeling exercises. A good understanding of what pLCI databases represent, how they should be used, and what their limitations are is crucial for a meaningful interpretation of pLCA results. Although the scientific literature already provides insights in this respect (e.g., Mendoza Beltran et al. 2018; Sacchi et al. 2022), more specific information should be provided to guide LCA practitioners in working with pLCI databases. For example, for a set of pLCI databases, there should be a clear description of the following:

- The scenario that each pLCI database represents (e.g., socio-economic and climate projections following SSP 1 with RCP 1.9)
- The scenario data sources (e.g., specific versions of IAMs and additional data sources)
- The original LCI database version (e.g., ecoinvent version 3.9, cut-off system model)
- The integration software and version used to generate the pLCI databases
- An executive summary that describes the scenario narratives, the sectoral, technological, and environmental cov-

erage of the scenario data, the most important changes to the original LCI database, key assumptions, limitations, and other information relevant for practitioners to understand and correctly interpret LCA results derived from the pLCI database
- Practical guidance for the effective use of the pLCI database (e.g., naming and modeling conventions and how to document and cite the use of the pLCI databases)
- Links to additional documentation and guidance

Such information could be provided as factsheets, manuals, or other media, including videos and in-software guidance. This information should ideally be complemented by guidance on how to work with pLCI databases in specific LCA software.

Although it may seem trivial, it is important to point out to users of pLCI databases that scenarios of the future are inherently uncertain and that the likelihood for any scenario to occur as described decreases with increased time horizons (e.g., 2050 or 2100). Also, not all scenarios have the same likelihood of occurring in the future (Huard et al. 2022), e.g., if certain scenarios are meant to be extreme scenarios. This should also be mentioned when results of prospective LCAs are interpreted for other audiences in order to avoid that they are misunderstood as predictions, or even worse, facts. Moreover, practitioners should be encouraged to assess multiple scenarios and to test whether their conclusions are robust across these scenarios. When such robustness is not given, it may be interesting to the audience to report under which conditions certain findings are valid.

3.5.2 Documentation

In addition to such higher-level guidance, detailed documentation of the generation of pLCI databases is necessary to provide further information to LCA practitioners and to ensure transparency and reproducibility. In particular, (i) the inputs to the generation of a pLCI database (e.g., data, assumptions, and models); (ii) the integration process itself (e.g., the integration software code); and (iii) the output (e.g., the changes in the pLCI compared with the original LCI database) all need to be documented.

Various levels of documentation already exist for current pLCI databases. For example, the *premise* framework provides technical documentation[1] of the generation process and data, as well as the source code[2] and associated log files. The scenario difference file used in the superstructure approach (Steubing and de Koning 2021) helps to document and understand the differences between the pLCI and the original LCI database. In addition, Futura software (Joyce and Björklund 2021) can record transformations of the original LCI database in a structured text file called a recipe. Nevertheless, guidance and documentation remain scattered and evolving. Further efforts are necessary to improve and consolidate this information and present it to users.

3.6 Continuous improvement

The previously discussed conditions and aspects relating to the generation, sharing, and use of pLCI databases could be improved, ultimately contributing to well-accepted and regularly updated pLCI databases with an adequate coverage that can be easily obtained, used, and interpreted by LCA practitioners. Achieving this aim will require a continuous improvement process that involves all relevant stakeholders.

3.6.1 Coordination and stable institutions

pLCI databases have been generated as part of research projects by individual research groups. However, the importance of future-oriented background data for LCA means the generation of pLCI databases merits a more concerted effort with stable funding sources and contributing institutions. This approach would enable these institutions to build and maintain the required expertise to deliver high-quality pLCI databases, to coordinate regarding important choices, to release regular updates, and to gain the trust of the wider LCA community. The coordination between stakeholders along the information chain (see Fig. 1), particularly pLCI database generators, scenario generators, and LCI database and LCA software providers, should therefore be strengthened to create a continuous improvement process for the generation, sharing, and use of pLCI databases.

4 Priorities and next steps

We summarize in Table 1 the current state of development for each condition and aspect, as well as the next steps and their priorities. The priorities have been derived from a ranking of each aspect according to importance versus current level of achievement (Fig. 2). The ranking as well as the attempt to suggest and prioritize the next steps represents the view of the authors and is a proposal to steer discussion and action.

Overall, substantial work remains to improve pLCI databases and to make their use more widespread. The most pressing issues (high priority) are a better coverage of environmental data for other impact categories than climate change and a better technological and sectoral coverage, and consistency, as well as LCA software that facilitates

[1] https://premise.readthedocs.io

[2] https://github.com/polca/premise

Table 1 Current level of achievement by condition and aspect, as well as the possible next steps and priorities

Conditions	Aspects	Current situation and challenges	Possible next steps	Priority*
Scientific integrity	Consistency	Good consistency for sectors that are well represented in scenarios and LCI data (e.g., electricity). Potential consistency issues for other industries and impact categories other than climate change. Trade-off between completeness and consistency.	Close data gaps in IAMs by adding techno-regional details and new substances/emissions. Carefully integrate other data sources and check consistency with narratives (e.g., SSPs) and primary data sources (e.g., IAMs).	+ + +
	Transparency and reproducibility	Scenario data, LCI data (for license holders), and integration software are open. Transparency and reproducibility of pLCI databases are given but require expert knowledge and could be improved.	Improve documentation of data, models, and integration software. Introduce a versioning system to ensure the reproducibility of pLCI databases.	+ +
	State-of-the-art models and data	The models used are usually state-of-the-art, but the data they rely on is not always the latest.	Continuous improvement of models and data.	+
Usefulness	Technological and sectoral coverage	Broad representation of technology in scenario data versus detailed representation of processes in LCI database. Large parts of pLCI databases remain unchanged.	Improve sectoral and technological coverage. Focus on energy and resource-intensive sectors.	+ + +
	Environmental coverage	Focus has so far been on greenhouse gas emissions. Data for other impact categories are only partly available from IAMs and have not been fully exploited.	Using data for other impact categories from IAMs or other data sources.	+ + +
	Coverage of scenarios and models	Increasing coverage of scenarios and models (e.g., to additional SSPs and IAMs).	Coverage should be further extended while avoiding the unnecessary proliferation of pLCI databases.	+ +
	Regional coverage	Representation of certain world regions only due to data limitations in IAMs and pLCI databases.	Country-level representation would be desirable but requires the further regionalization of underlying models or other data sources.	+ +
	Temporal coverage and representation	pLCI data is available in time series until 2100. Representation of time in scenario and LCI data is different; pLCI databases lack a real representation of time (e.g., all life cycle stages occur “at once”).	A better representation of time would be desirable, especially for long-lived products, but is a significant challenge. Temporal average datasets are an intermediate solution.	+/+ +
Accessibility	Data sharing	pLCI databases are not easily accessible, only via local generation, which requires expert knowledge, or direct sharing by pLCI database generators.	Provide easier access to pLCI databases (e.g., via LCA software/data providers).	+ +
	Data format	Integration software exports selected data formats only.	Not all data formats are supported yet (e.g., ILCD). Future formats for sharing pLCI databases may still have to be defined (e.g., to deal effectively with multiple scenarios and associated metadata).	+ +
Usability	LCA software to work with pLCI databases	Working effectively with multiple pLCI databases representing different background scenarios across time remains a challenge in most LCA software.	The superstructure approach enables working with a single background database representing different scenarios and time steps. This approach could be implemented by other LCA software.	+ + +

Table 1 (continued)

Conditions	Aspects	Current situation and challenges	Possible next steps	Priority*
Interpretability	Guidance	Limited guidance is available to guide LCA practitioners on understanding and using pLCI databases and interpreting results.	Develop high-level guidance for LCA practitioners.	++
	Documentation	Documentation could improve at all levels, including IAMs, integration software, and pLCI databases (changes compared with the original LCI database are already documented via scenario difference files). Documentation is scattered.	Additional documentation and metadata describing pLCI databases (e.g., for the included scenarios and sectors, versions of models, and integration software).	++
Continuous improvement	Coordination and stable institutions	Coordination among selected stakeholders. Update of pLCI databases and integration software depending on specific research funding.	Increased coordination among stakeholders and stable funding to improve all aspects above and streamline the generation, sharing, and use of pLCI databases.	++

*+++ = high; ++ = medium; + = low

the practical use of pLCI databases. The next steps should include the use of additional data sources to increase coverage, while ensuring, as much as possible, an acceptable level of overall model consistency. LCA software developers should think about how LCA could practically support the modeling with pLCI databases (a possible solution could be the implementation of the superstructure approach (Steubing and de Koning 2021) that enables an efficient use of pLCI databases in the Activity Browser).

Most aspects were categorized as medium priority for further development, either because of slightly lower general importance to pLCI databases, or because of ongoing progress. These aspects include guidance for LCA practitioners, coordination between relevant stakeholders and stable institutions, transparency and reproducibility, data sharing and format, documentation, coverage of scenarios and models, temporal representation, and regional coverage. Suggestions for the next steps are given in Table 1. Some aspects are already addressed very well, e.g., the use of state-of-the-art models and data or the temporal coverage, which is why these are given the lowest priority for further development. We would like to emphasize, however, that the requirements for individual aspects can very much depend on the context of a pLCA: e.g., a study that looks at climate change impacts of vehicles produced in Europe may not require a more detailed regional coverage, while a study that looks at future food products may find the existing spatial resolution of pLCI data far too limited.

Finally, while we need further excellence on the scientific level, it is very important to realize that the future of pLCI databases depends to a large degree also on technical solutions (e.g., easy access and use of pLCI databases) as well as organizational and institutional factors (e.g., can we achieve a wider consensus on how to generate and use pLCI databases for prospective LCAs?). A continuous improvement or coordination process should, therefore, be initialized that involves all stakeholders in the information chain (Fig. 1), and likely other stakeholders such as policymakers and regulators, to discuss, coordinate, and achieve a certain consensus on how pLCI databases shall be generated, shared, and used in the future.[3]

We strongly believe that making future-oriented background data available should be a priority for the LCA community to provide more meaningful environmental guidance in the ongoing and upcoming transitions of our economies, and that LCA practitioners will readily use pLCI databases once the conditions and some of the obstacles outlined in this article are addressed.

[3] An international professional network, where pLCI databases are already being discussed, is the prospective LCA network: https://prospectivelcanetw.wixsite.com/prospectivelcanet

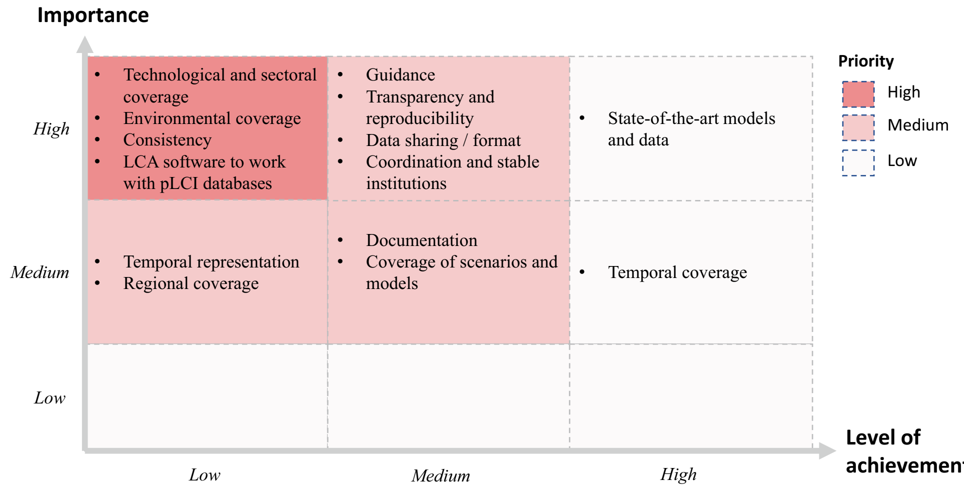

Fig. 2 Importance versus level of achievement for all aspects and resulting priorities

5 Conclusions and outlook

Developing pLCI databases is crucial for the LCA community to provide meaningful environmental decision support for future technologies. This article provided an overview of the information chain related to the generation, sharing, and use of pLCI databases. Based on that, we structured and discussed the conditions for the broad application of pLCI databases and highlighted future priorities. While the paper aimed to describe the information chain and conditions in general, by far not all challenges were addressed. For example, specific solutions may be needed to generate pLCI databases from certain LCI databases and scenario data sources and many practical aspects may require solutions, e.g., how different stakeholders, such as industry associations, could contribute to future-oriented LCI data, or how pLCI databases could be generated that fit specific needs (e.g., compliance with LCA guidelines and standards). With this article, we hope to provide valuable input to deepen the discussion on this important topic and stimulate efforts in bringing pLCI databases and their surrounding ecosystem to the next level.

Appendix

A non-exhaustive list of recent publications that use prospective LCI databases (in addition to those listed in the references section).

Cox B, Mutel CL, Bauer C, Mendoza Beltran A, van Vuuren DP (2018) Uncertain Environmental Footprint of Current and Future Battery Electric Vehicles Environ Sci Technol 52:4989–4995 https://doi.org/10.1021/acs.est.8b00261.

Li C, Mogollón JM, Tukker A, Dong J, von Terzi D, Zhang C, Steubing B (2022) Future material requirements for global sustainable offshore wind energy development Renewable Sustainable Energy Rev 164:112,603 • https://doi.org/10.1016/j.rser.2022.112603.

Xu C, Steubing B, Hu M, Harpprecht C, van der Meide M, Tukker A (2022) Future greenhouse gas emissions of automotive lithium-ion battery cell production Resources, Conservation and Recycling 187:106,606 https://doi.org/10.1016/j.resconrec.2022.106606.

Zhong X, Hu M, Deetman S, Steubing B, Lin HX, Hernandez GA, Harpprecht C, Zhang C, Tukker A, Behrens P (2021) Global greenhouse gas emissions from residential and commercial building materials and mitigation strategies to 2060 Nature Communications 12:6126 https://doi.org/10.1038/s41467-021-26212-z.

Yang X, Hu M, Tukker A, Zhang C, Huo T, Steubing B (2022) A bottom-up dynamic building stock model for residential energy transition: A case study for the Netherlands Applied Energy 306:118,060 https://doi.org/10.1016/j.apenergy.2021.118060.

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Gibon, T., Menacho, À. & Guiton, M. Carbon Neutrality in the UNECE Region: Integrated Life-cycle Assessment of Electricity Sources UNITED NATIONS ECONOMIC COMMISSION FOR EUROPE. March 2022.pdf (2021).

Cavalett, O., Watanabe, M. D. B., Fleiger, K., Hoenig, V. & Cherubini, F. LCA and negative emission potential of retrofitted cement plants under oxyfuel conditions at high biogenic fuel shares. Sci. Reports 2022 121 12, 1–14 (2022).

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Lamers, P., Ghosh, T., Upasani, S., Sacchi, R. & Daioglou, V. Linking life cycle and integrated assessment modeling to evaluate technologies in an evolving system context: a Power-to-Hydrogen case study for the United States. Environ. Sci. Technol.

Strathoff, P. et al. On the Design and Sustainability of Commuter Aircraft with Electrified Propulsion Systems. AIAA Aviat. 2022 Forum (2022) https://doi.org/10.2514/6.2022-3738.

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Declarations

Competing interests The authors declare no competing interests.

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