

DEALA – A novel economic life cycle impact assessment method for differentiated economic assessments in the context of life cycle sustainability assessments

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Abstract

Legislation and market competition make it necessary to assess systems regarding their environmental, social, and economic impacts. The life cycle sustainability assessment (LCSA) approach can be used for this purpose. However, the literature shows limitations of this approach. This article focuses on the often encountered inconsistency and reduced transparency within the economic dimension due to the lack of harmonized impact assessment methods. Therefore, we propose a novel economic life cycle impact assessment (eLCIA) method called DEALA (Differentiated Economic Assessment in a Life Cycle-Oriented Analysis), which allows economic assessments at three levels of aggregation. Overall, DEALA is based on economic principles and provides a structured approach to conduct environmental life cycle costing studies, resulting in greater transparency, comparability, and flexibility, as illustrated by an initial comparison with an existing case study. DEALA also facilitates a differentiated and detailed analysis of the results so that hotspots and improvement potentials can be identified, making DEALA a suitable economic LCIA method that should be considered in future studies. These benefits are confirmed through a LCSA of a battery supply chain. The assessment provides detailed and specific insights that can be used to design more sustainable battery supply chains.

KEYWORDS

DEALA, economic life cycle impact assessment, environmental life cycle costing, industrial ecology, life cycle sustainability assessment, lithium-ion batteries

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1 | INTRODUCTION

To ensure that companies remain competitive on a global market, they must design their production systems to be economically viable. To this end, an economic assessment of production systems, considering business indicators and the entire life cycle, is essential. A common approach to assess costs or expenditures related to production systems from a life cycle perspective is life cycle costing (LCC) (Hunkeler et al., 2008). The idea of LCC was introduced as early as 1933 and has been developed over time (Leroy-Parmentier et al., 2023; Lichtenvort et al., 2008). Currently, three main types of LCC are distinguished in the literature: conventional LCC (CLCC), environmental LCC (ELCC), and societal LCC (Lichtenvort et al., 2008). CLCC is used to calculate the direct costs incurred by one stakeholder in the product life cycle. CLCC does not consider externalities or costs that are not covered by the defined stakeholder, which is usually the manufacturer or consumer of a product (Lichtenvort et al., 2008). In comparison to CLCC, ELCC usually considers more than one stakeholder. Moreover, all externalities expected to be internalized can be considered. Such externalities could be costs of CO₂-emission certificates. Furthermore, ELCC follows the structure of the standards for environmental life cycle assessment (LCA) and is therefore often conducted with an environmental assessment (Lichtenvort et al., 2008). During societal LCC, the perspective of society is considered, and further externalities are included in the assessment compared to ELCC. Furthermore, subsidies or taxes are excluded since they have no net effect (Lichtenvort et al., 2008). Although LCC and the associated types have been developed and used for many years, they have numerous limitations in their use.

1.1 | Limitations of LCC

The limitations of LCC were identified through a literature review. The detailed results are presented in [Supporting Information S1-1](#). Most importantly, the literature review reveals that the comparability across studies is hampered by the selection of different economic categories and procedures. For example, Lorenzo-Toja et al. (2016) and Resende et al. (2019) evaluated wastewater treatment systems. However, they present their results for different economic categories, so only a general comparison can be made regarding the performance of the systems. Based on the results, a detailed and differentiated comparison is not possible, which would help to select one system. Besides, the selection of economic categories and the classification of inventory data to the economic categories are often not explained, resulting in a lack of transparency, reliability, and reproducibility. This approach is not aligned with the requirements outlined in life cycle management. For instance, IEC 60300-3-3, a standard that provides a structured approach for LCC, stipulates that suitable models must be utilized for the system boundaries under consideration and that the relationships between the data and the economic categories must be clearly and unambiguously defined to ensure appropriate transparency, credibility, and reproducibility. Such requirements can also be found in business administration. For example, in the context of cost accounting, cost types must be clearly defined, an exact description of the allocations to the categories must be provided, the cost breakdown must make economic sense, and all aspects that lead to costs must be included (Haberstock, 2022). As the majority of the studies examined did not consider the relevant economic principles, there is a risk of distorted results and misleading conclusions. This applies not only to the selection and description of the economic categories but also to other aspects of business administration. For example, the timing of costs in the life cycle and the handling of overheads must be explained in more detail, as the explanation and handling of these aspects are often neglected in the studies and can have a major influence on the results.

Furthermore, the literature review indicates that only approximately half of the articles describe the basis on which LCC is carried out. In particular, reference is made to the ISO 15686-5 standard, the guidelines by Hunkeler et al. (2008), and the code of practice by Swarr et al. (2011). The ISO 15686-5 standard provides guidelines for calculating life cycle costs in the context of buildings. Hunkeler et al. (2008) and Swarr et al. (2011) refer generally to the procedure for ELCC. These documents provide a general framework for how LCC can be performed and what needs to be considered. However, these documents do not clearly define how data should be assigned to economic categories. Consequently, this must be carried out independently and described in detail by the person conducting the LCC study. This also applies to other standards, such as ISO 14045 or ISO 14051, in the context of economic assessments, which are described in more detail in [Supporting Information S1-1](#).

Indeed, the code of practice explicitly states that an impact assessment phase, comparable to LCA, is unnecessary for LCC because all inventory data are currency dependent and have only one unit of measure (Swarr et al., 2011). However, the literature review reveals that the inventory data for LCC studies were not expressed in a currency in all cases, which contradicts the statement in the code of practice. For example, in Pergola et al. (2018), working hours, electricity, and material consumption are listed, which are then multiplied by characterization factors to calculate the economic impact. Such an approach can facilitate increased flexibility in studies. For instance, in a spatially differentiated assessment, economic values for the same activities in different countries do not have to be calculated in advance; rather, the number of working hours can be specified as a uniform input, which is then multiplied by corresponding country-specific characterization factors in the life cycle impact assessment (LCIA) phase.

Since recent literature reviews (Ahmad et al., 2019; Arulnathan et al., 2022; Padilla-Rivera et al., 2023; Rodrigues & da Silva, 2024) have identified similar limitations in terms of LCC, the consideration of the LCIA phase and therefore the introduction of economic life cycle impact assessment (eLCIA) methods can resolve the described limitations, as this can facilitate various steps for the person carrying out an LCC study. For instance, the

user can select a suitable model based on the description of the associated characterization models, analogous to LCA, where objective-specific LCIA methods such as ReCiPe can be selected (Huijbregts et al., 2017). Furthermore, predefined economic impact categories can facilitate increased transparency, comparability between studies, and reproducibility, as they provide the user with guidance for implementation. In this context, standards for economic assessments can serve as valuable resource.

Moreover, since most of the systems under investigation are also responsible for negative environmental and social impacts (Barke et al., 2022; Calvin et al., 2023; Popien et al., 2023), it is recommended to use LCC together with LCA and social life cycle assessment (SLCA) as part of a life cycle sustainability assessment (LCSA) (Ciroth et al., 2011; Padilla-Rivera et al., 2023). The literature review has shown that LCC studies are often carried out together with an environmental and in some cases a social assessment. These studies reveal further limitations that need to be considered when developing eLCIA methods. For example, the assessments are often conducted separately and under consideration of slightly different assumptions, as also shown by recent literature reviews (Costa et al., 2019; Valdivia et al., 2021). Ferrari et al. (2019) have conducted an LCSA for ceramic tiles considering different system boundaries. For the environmental and social dimension, they performed a cradle-to-grave assessment, while limiting the economic assessment to cradle-to-gate. This hampered the validity and the interpretability of the results. It would be preferable to use a consistent modeling framework such as introduced by Thies et al. (2021) to ensure the equivalence of the system boundaries and the assumptions made. In doing so, it is also important to compare the results of the three sustainability dimensions on the same aggregation level. Costs are often reported as total costs, which may be broken down into several subcategories. Simultaneously, detailed information is provided for environmental assessments for different impact categories and life cycle stages. This results in recommendations based on different levels of detail, which can be misleading. On top of this, different software tools are used to calculate the three dimensions. This can lead to a lack of clarity in the data and errors, which can result in misleading recommendations. It should therefore be ensured that LCIA methods for all three dimensions can be used uniformly in software tools.

1.2 | Objective and novelty of the study

Against this background, this article introduces a novel eLCIA method called DEALA (Differentiated Economic Assessment in a Life Cycle-Oriented Analysis), which can be generally used in LCC studies and the LCSA framework. DEALA addresses the above challenges and provides a systematic approach and guidance for future users to increase comparability and transparency between studies. Also, the method enables differentiated and aggregated assessments of production systems through a three-level structure. Additionally, DEALA can be implemented in software tools such as Brightway2 (Mutel, 2017), which allows for a straightforward and flexible application to multiple use cases.

Moreover, the applicability of DEALA is demonstrated using the example of a battery supply chain. Thus, the advantages of DEALA are highlighted even for a product with a complex supply chain, and potential challenges for future research are identified.

2 | METHODS

2.1 | Conceptual idea

DEALA is an eLCIA method that can be used in LCC to calculate economic impacts. We focus on ELCC, as this type is used in combination with LCSA, and a joint assessment is carried out in the case study. Economic impacts represent the advantages and disadvantages in terms of financial aspects that arise for stakeholders from carrying out an activity within the defined system boundaries whereby the magnitude of the advantages and disadvantages is quantified using economic impact categories. DEALA's focus is on a business administration perspective. Hence, the calculated economic impacts are intended for the analysis and improvement of cost structures or the investment decisions of stakeholders. DEALA does not aim to derive statements on economic prosperity, economic resilience, or productivity, as proposed by, for example, Arulnathan et al. (2022) and Neugebauer et al. (2016).

To calculate indicator scores, Equation (1) is used, which is similar to the calculation approach for determining environmental impacts (Goedkoop et al., 2013):

$$IS_m = \sum_i (CF_{mi} \cdot MF_i) \quad (1)$$

IS_m represents the indicator score of impact category m , while CF_{mi} represents the characterization factor of m associated with marketsphere flow i (Figure 1). Marketsphere flows are comparable to biosphere flows, such as "carbon dioxide to air" for environmental assessments and are used to represent elementary flows entering and leaving the marketsphere. The marketsphere is defined as a collection of economic resources such as labor and investments that are exchanged with the production system during its life cycle and thus represents the economic environment (Thies

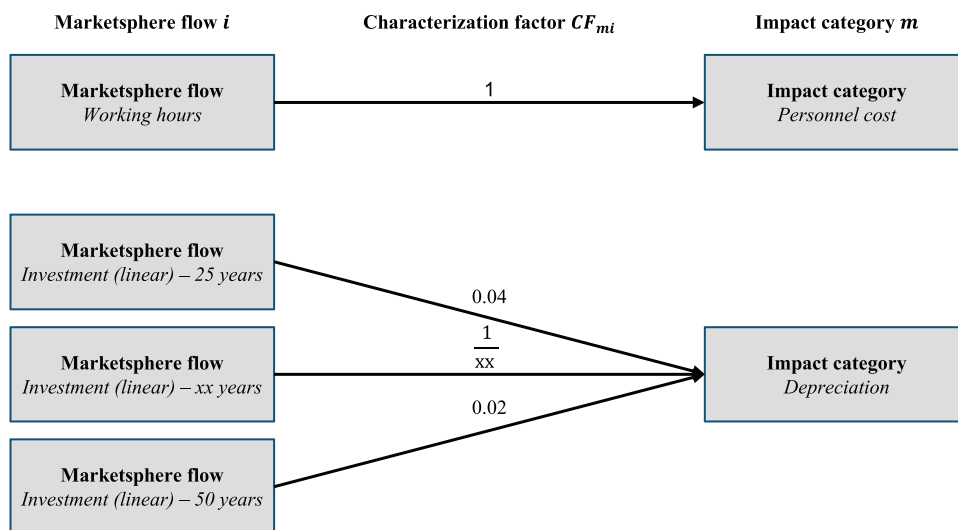


FIGURE 1 Representation of the relationship between marketsphere flows and impact categories.

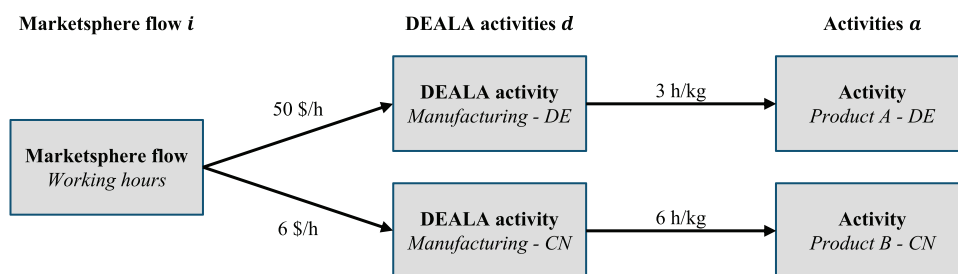


FIGURE 2 Representation of the calculation of the magnitude of a marketsphere flow.

et al., 2021). The characterization factors describe the extent to which the consumption of economic resources from the marketsphere has an impact on the stakeholder. In many instances, the consumption can be directly characterized by a value of 1, as illustrated by personnel cost in Figure 1. In contrast, if the cost of depreciation for an investment is to be determined over a specified period, the characterization must be carried out in accordance with a suitable depreciation model. Figure 1 illustrates the case of linear depreciation, in which the characterization factor can be derived as a function of the useful life. If a marketsphere flow describe revenues, a negative value is used for characterization.

Furthermore, MF_i stands for the magnitude of i in Equation (1). The magnitude is calculated based on Equation (2).

$$MF_i = \sum_d \sum_a E_{id} \cdot I_{da} \tag{2}$$

In this equation, E_{id} represents the economic value of a marketsphere flow i associated with a DEALA activity d . DEALA activities are introduced as a term to describe economic activities. The DEALA activities shown in Figure 2 can be used, for example, to describe the country-specific costs of a work hour in the manufacturing industry. For this purpose, the marketsphere flow “working hours” is assigned with an economic value to the DEALA activities. The created DEALA activities are used as inputs in activities a of the foreground system. I_{da} is used to describe the amount of DEALA activities required for a corresponding activity a . In the example, 3 h of a worker from the manufacturing sector are required to produce 1 kg of product A. Considering both activities, this leads to a magnitude of the marketsphere flow “working hours” of 186 \$/kg.

Forty-three impact categories are defined as part of DEALA, to which marketsphere flows with corresponding characterization factors are assigned. The impact categories represent impacts along the economic impact pathway and could be interpreted as midpoint categories in analogy to LCA. DEALA distinguishes between three levels (BEIC 1–BEIC 3) of aggregation for the impact categories (Figure 3). BEIC stands for business economic impact categories, as the impact categories are used accordingly in the business administration context. BEIC 1 represents the highest aggregation level and contains two impact categories that can be used to determine total cost or total expenditures of a production system. This corresponds to categories that are most frequently used in the literature (Supporting Information S1-1) and are well suited to communicate the results. Furthermore, these impact categories can be used for detailed analysis (Section 4). The impact categories assigned to BEIC 2 can be employed to illustrate the results in greater detail. Moreover, the impact categories “investment-dependent cost,” “other cost,” “operational

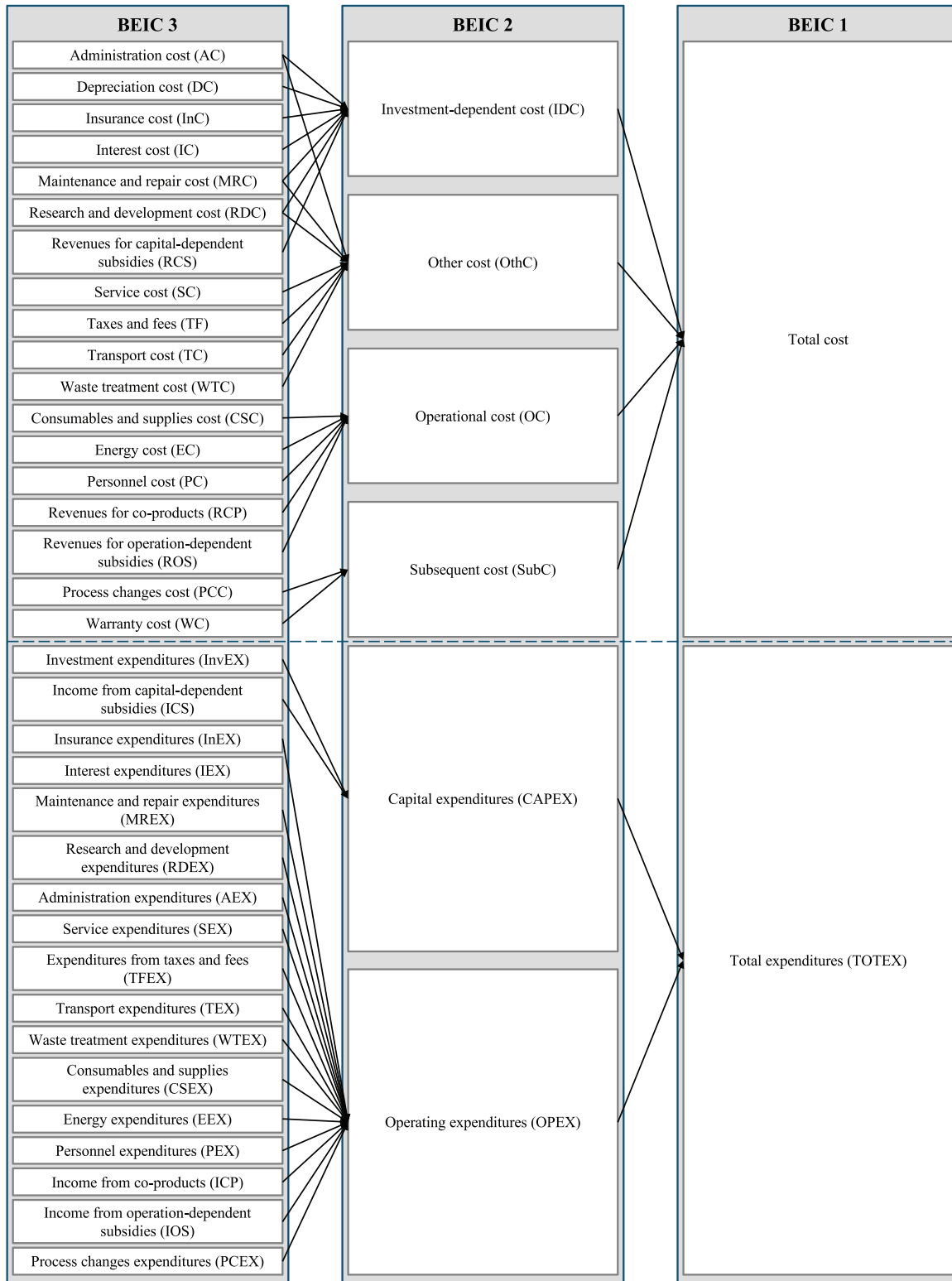


FIGURE 3 Three-level structure and business economic impact categories (BEIC) of the DEALA method.

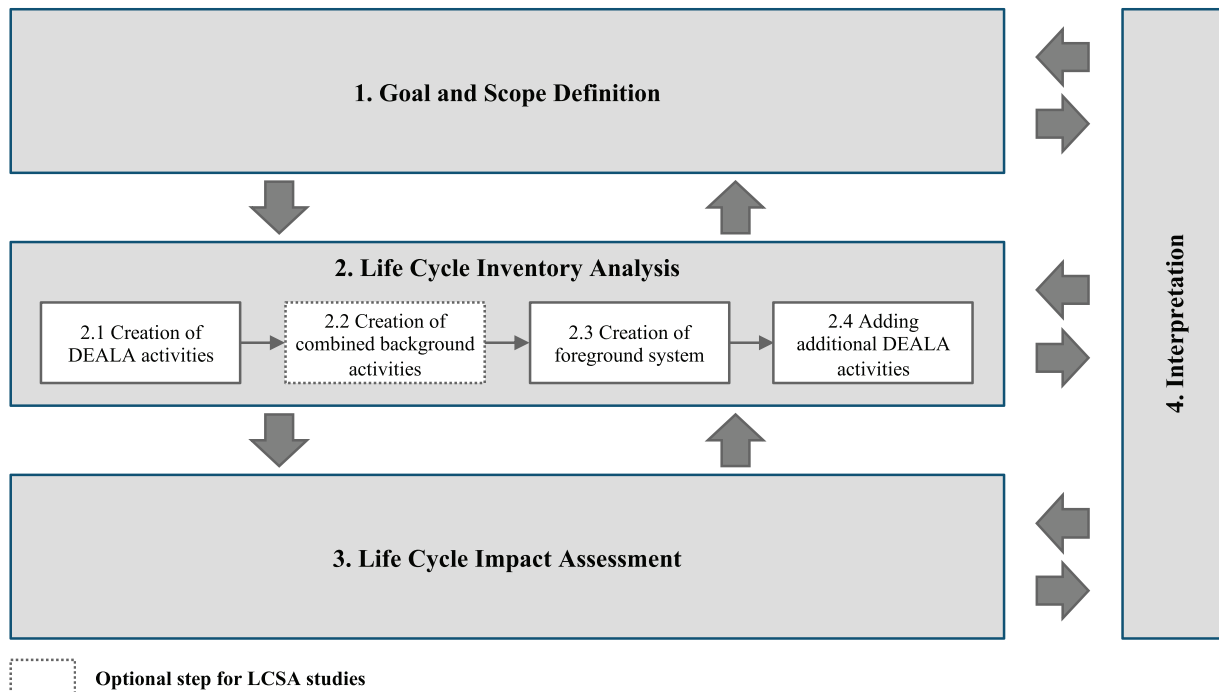


FIGURE 4 Procedure for performing an ELCC/SLCA using the DEALA method.

cost,” and “subsequent cost” correspond to categories defined in the VDI MT 3800 standard. CAPEX and OPEX also correspond to typical key performance indicators used in the industry. The lowest aggregation level is BEIC 3 and contains the impact categories that break down the costs or expenditures according to production factors. This corresponds to a typical type of classification used in business administration (Haberstock, 2022). The defined impact categories are also frequently found in the literature. Therefore, impact categories of BEIC 3 can be used to depict a detailed and differentiated picture of the economic impact of a production system. Further details on the impact categories, the impact pathways, and the analogy to LCA can be found in [Supporting Information S1-2.2](#).

Besides the breakdown of the impact categories into the three aggregation levels, a distinction is made between the accounting variables of cost and expenditure. According to Fandel's definition, costs represent the assessed consumption of goods and services during a certain period of time for the production and sale of goods and the maintenance of the corresponding capacities (Fandel, 1991). Expenditure, on the other hand, considers payments made at a specific point in time in connection with the delivery of a good or service (Fandel, 1991). This distinction is made because the accounting variables are used for different purposes in business administration. For example, costs are used in cost accounting, but also for analyzing and deriving improvements to longer-term cost structures. Therefore, DEALA's impact categories representing costs are used for such objectives. In contrast, expenditure is used in financial and investment accounting. The results calculated based on corresponding impact categories can be used for investment decisions.

Due to different definitions of costs and expenditures, allocation and characterization of marketsphere flows to corresponding impact categories also differ. For example, imputed variables such as depreciation are not considered for expenditures, as these do not lead to payments. Accordingly, there is no allocation of marketsphere flows that are used to describe depreciation to impact categories representing expenditures. Instead, the payment for the purchase of a machine is allocated in full in the period in which it is incurred. The characterization models and thus the characterization of marketsphere flows to the impact categories are described in detail in [Supporting Information S1-2.2](#). The characterization models are provided as part of this article in a form that allows them to be integrated into standard LCA software. In this article, it is integrated into Brightway2, as this is a common tool for carrying out LCSA studies and is highly flexible due to its implementation in Python (Mutel, 2017; Popien et al., 2023).

2.2 | Application

With the described framework, DEALA can be applied in ELCC and LCSA studies. For this purpose, the steps of the DIN EN ISO 14040/44 standard with some adaptations for the ELCC are followed (Figure 4) (Ciroth et al., 2011; Rebitzer & Nakamura, 2008).

First, the *goal and scope* of the study must be defined. This includes typical steps such as the description of the system boundaries, functional unit, assumptions, and limitations. This also includes the definition of stakeholders, as this will influence the data collection for ELCC. Assuming that a component manufacturer and an original equipment manufacturer are to be included, it must be ensured that all data are available to describe the

processes of both stakeholders. Otherwise, this would lead to a biased comparison and inconsistent system boundaries. Furthermore, the selection of an impact assessment method must be specified in this step. Care must be taken to ensure that the impact categories and the method are suitable for achieving the goal of the study. For example, if only one period is investigated and the improvement of the cost structure is in focus, the DEALA impact categories representing cost are preferable, whereas expenditures should be used if the complete life cycle should be investigated and investments are in focus. Depending on the selection, all impact categories of the three BEIC levels should be considered to enable a complete mapping and all possible analyses of the results. BEIC 3 also provides good guidance for users of DEALA, as it specifies the aspects for which DEALA activities must be created. If, for example, the labor input of persons is required for an activity, corresponding DEALA activities must be created and included as input in the next step. The user should also indicate why no DEALA activities are created for certain impact categories in BEIC 3 to maintain the transparency of the study. This could be the case, for example, if no subsidies are expected for the construction of buildings.

Once the goal and scope definition has been completed, the next step is the *life cycle inventory (LCI) analysis*. In this step, all data are collected, measured, and estimated to create the inventories of the activities defined in the system boundaries. To apply DEALA, four steps must be followed.

Step 2.1 includes the creation of DEALA activities. The goal and scope definition phase serves as orientation for creating required DEALA activities. If, for instance, the lifespan and functionality of machinery or buildings are defined, corresponding DEALA activities can be created to determine the depreciation cost at a later stage. Moreover, the assumptions made can be employed to specify the regions to which the DEALA activities must be applied. Moreover, as DEALA activities represent economic activities, it is necessary to assign suitable economic values to DEALA activities, along with an appropriate marketsphere flow (Figure 2). The requisite economic values can be identified in a variety of sources, including exchanges and reports. In certain instances, they must be calculated. The references or assumptions made for an approximation of the economic value must be presented in the report of the study to maintain the study's traceability and reproducibility. Further guidance on the selection of suitable marketsphere flows can be found in [Supporting Information S1-2.2](#).

Given that the databases typically used in the background system are limited to a single sustainability dimension, a combination of the data from the background databases can be used to increase the transparency as well as the uniformity of the LCIs. Consequently, in the context of LCSA, it is recommended to create activities in optional *step 2.2* that combine inputs from environmental, social, and DEALA activity databases. For example, if the German electricity mix is based on an environmental database only environmental impacts could be assessed. This can be solved by integrating data, which contain corresponding information on the energy sector and the price of electricity in Germany. Besides, as the social assessment generally requires a much more detailed breakdown of the supply chain to reflect regional differences, this should apply analogously to the other two sustainability dimensions to maintain equivalent system boundaries and LCIs. This could be ensured with such created activities as well. However, care must be taken in this step to ensure that the value-added is used for the steps along the supply chain if only prices are known for the materials. How the value-added can be approximated on the basis of prices is described in more detail in [Supporting Information S1-2.4](#).

Afterward, the activities of the foreground system are created. In *step 2.3*, the combined activities or inputs directly from the DEALA activity database are used as inputs for the foreground activities. This depends on whether it was assumed in the goal and scope definition that a background activity has an impact on more than one sustainability dimension. For example, the use of a material usually has an impact on the environment as well as the economy. In this case, combined activities should be used for a transparent presentation. In the case of personnel deployment, on the other hand, the focus is generally on economic aspects, so that a corresponding DEALA activity is used directly as an input.

Since in practice some economic impacts are estimated depending on investments or personnel deployment, additional DEALA activities are added to the foreground activities in *step 2.4*, for which the level of input is determined using DEALA activities that have already been added. Suppose the insurance cost depend on the investment in machinery and buildings, the investment is first calculated based on the respective DEALA activities. The extent to which the insurance depends on the investment is then determined. For example, this could be 3%, which defines the DEALA activity that is added to the respective foreground activity with the calculated investment. Typical DEALA activities for which this procedure is applied are highlighted in [Supporting Information S1-2.2](#).

Once all LCIs have been created, the eLCA with the selected impact assessment method follows. The calculation follows the procedure explained in Section 2.1 and leads to indicator scores that can be presented as results of the studies. Various options are available for visualization (Section 4).

Furthermore, the calculated indicator scores and representations of the results must be used to analyze the system in detail and derive recommendations in the *interpretation phase*. This also includes validating the results and carrying out sensitivity analyses, which are highly recommended for economic assessments (e.g., due to the volatility of material prices). Moreover, the resulting indicator scores can be used in decision-support models or cost-benefit analyses for further investigations (Popien et al., 2024).

3 | CASE STUDY

3.1 | Goal and scope definition

DEALA is applied in an LCSA of a battery supply chain to illustrate its use and benefits. The goal of the study is to assess a battery life cycle in terms of its environmental, economic, and social impacts. Therefore, a battery pack with an initial energy storage capacity of 100 kWh and a calendric

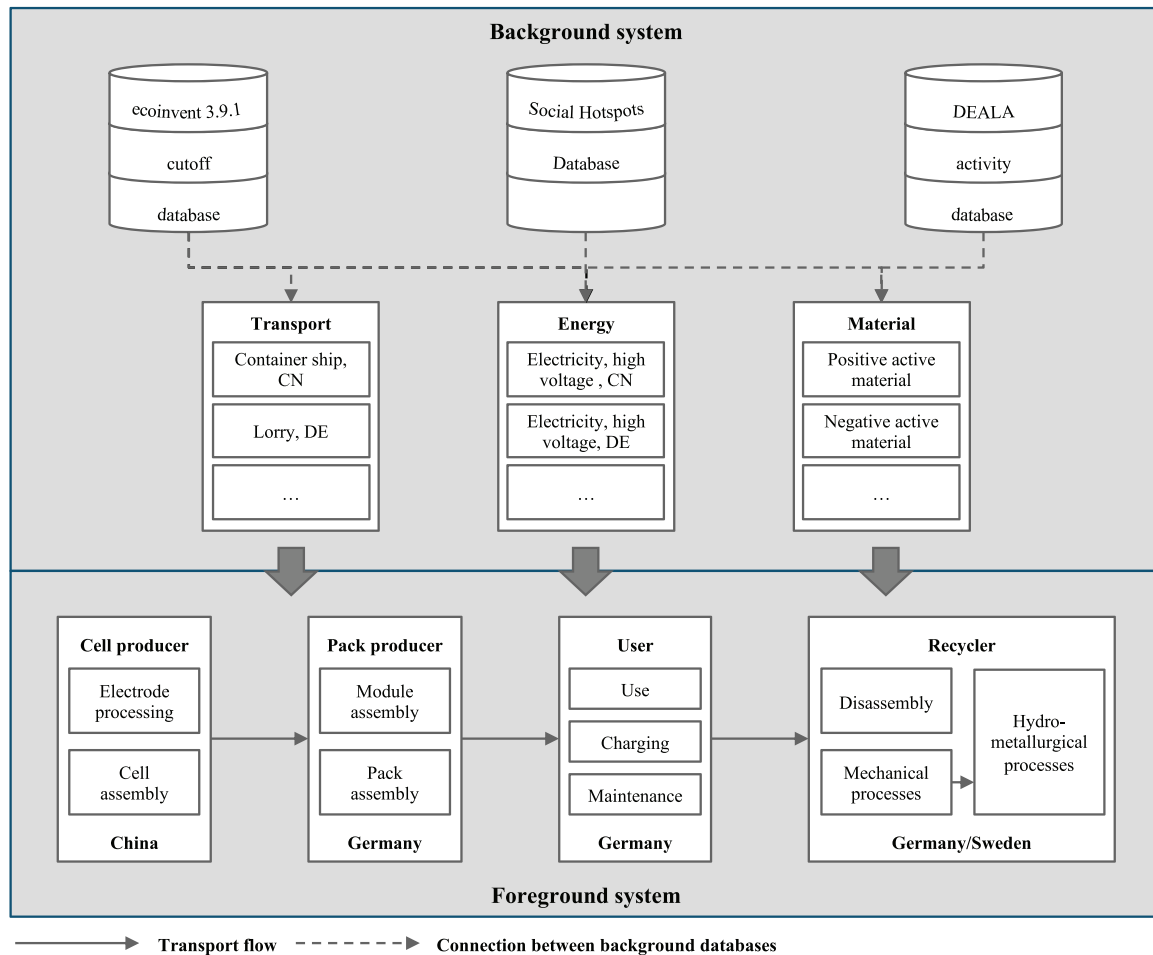


FIGURE 5 System boundaries of the life cycle sustainability assessment for the analysis of NMC811 battery.

service life of 12 years based on an average use in an electric car in Germany is defined as functional unit. The study focuses on a battery pack with a cathode composition of 80% nickel, 10% cobalt, and 10% manganese (NMC811). The definition of the functional unit leads to the investigated system illustrated in Figure 5.

The system is divided into two subsystems: foreground system and background system. The latter system consists of the external databases ecoinvent 3.9.1 cutoff (Wernet et al., 2016), the Social Hotspots Database (SHDB) (Norris & Norris, 2015), and a DEALA activity database. Furthermore, the background system contains databases for transport, energy, and materials, which represent combinations of the aforementioned databases as it is assumed that respective activities have an influence on all three sustainability dimensions.

Four stakeholders are considered in the foreground system: cell producer, pack producer, user, and recycler. For each of these stakeholders, their processes are evaluated in terms of their impacts.

The cell production is in China and includes all steps from electrode processing to cell assembly and formation. The cell production has an annual production capacity of 50 GWh. The cells produced are transported by container ship and truck to Germany, where they are assembled into battery modules and packs. The capacity in this step corresponds to the cell production capacity. It is also assumed that the battery packs will be used in Germany for 12 years, driving 13,333 km per year until 2035 (Abdelbaky et al., 2021). Furthermore, it is assumed that the user is represented by a company that bought the battery and took out a loan to cover half of the price. The recycler's processes take place at two locations. First, the batteries are discharged and dismantled in Germany and mechanically treated until the resulting black mass is transported to Sweden. In Sweden, hydrometallurgical processes are used to extract valuable secondary materials, such as lithium, nickel, and cobalt, from the black mass. The capacity of the recycling plants is designed to recycle 25,000 t per year.

To evaluate DEALA, the environmental and social impact assessments are each limited to one impact category commonly used. For the environmental impact assessment, the climate change impact category of the ReCiPe 2016 v1.03 (H) midpoint method is selected (Huijbregts et al., 2017). For the social impact assessment, the SHDB impact category risk of occupational injuries and deaths is chosen (Norris & Norris, 2015). For the eLCIA, all impact categories that represent cost are selected, as the corresponding cost structure during the life cycle phases is of interest.

3.2 | Life cycle inventory

As explained in Section 2.2, the LCI phase is divided into four steps to apply DEALA. First, data for the DEALA activities are collected. Several sources are used for this purpose. For the materials, market and/or stock exchange prices are used. The cost rates for the DEALA activities of personnel and energy, as well as the prices per square meter for construction, are based on statistical reports. As some of the data are not available for the reference year 2023, they are adjusted to the corresponding reference year. In addition, there are 12 years between production and recycling, which means that price trends must be considered. The procedure from the DIN EN ISO 14008 standard was used to approximate the price development. The price deflator of the GDP (gross domestic product) is used to approximate known values from the manufacturer's perspective. If the data is not available, the development of the GDP is used together with a price elasticity for the products to approximate future prices, for example. In this context, the GDP development of the SSP2-base scenario was used as a basis (Riahi et al., 2017). For the remaining DEALA activities, the cost rate of 1 USD per unit is defined. In the second step, combined activities for transport, energy, and material are created as defined in the goal and scope definition.

In the *third step*, the foreground activities are created to which inputs from the background system are linked. The material and energy flows are based on Knehr et al. (2022) and Popien et al. (2023) for the case of battery cell and pack production, while recycling data are based on Blömeke et al. (2022) and Popien et al. (2022). Transport distances between sites are calculated using the searates website (searates.com). Besides these combined inputs, three DEALA activities are directly linked to these foreground activities. The first two DEALA activities represent the depreciation of machinery and equipment as well as buildings. For the former, a usage time of 15 years, and for the latter a usage time of 33 years is assumed. Furthermore, a DEALA activity is added to the foreground activity representing the required working hours. As sector, the manufacturing sector is selected. The amounts assigned to the three DEALA activities are calculated with the BatPaC 5.1 model (Knehr et al., 2022) and the recycling assessment tool of Blömeke et al. (2022). For the foreground activity representing the use phase, only an input representing the energy demand per year is added assuming an average consumption of 18 kWh per 100 km. A separate activity is created for each year of the use phase.

In the *fourth step*, the remaining DEALA activities and social exchanges are added to the foreground activities. The DEALA activities added to the LCIs of the foreground activities are linked to maintenance and repair, insurance, interest, research and development, administration, taxes, and warranty. The first three depend on the investment and are therefore calculated in advance, which is also the case for the remaining DEALA activities that depend on the total cost, personnel cost, and profit. Furthermore, some assumptions are made. In the case of cell and pack production, DEALA activities including cost rates for waste, revenues, and subsidies are not considered. Subsidies for recycling are also excluded. Additionally, no taxes or warranties are added to the respective foreground activities of recycling. Furthermore, the added DEALA activities to the activities of the use phase are limited to depreciation, maintenance and repair as well as interest for a loan. These limitations are chosen to demonstrate the resulting transparency in the analysis phase. When all economic exchanges are added to the foreground activities, their direct economic impacts are calculated, representing the value assigned to the respective inputs from the SHDB added to the foreground activities. Detailed information on the LCIs is provided in [Supporting Information S1-3](#) and [S2](#).

4 | LCSA RESULTS

First, this section presents the economic results of the LCSA to demonstrate the possibilities of the DEALA method. Second, the economic results are presented in line with the results of the selected environmental and social impact categories to show that DEALA can be applied together with environmental and social impact assessment methods.

Figure 6 reveals the impact category with the highest impact on the indicator scores for the four defined stakeholders. It is differentiated between the three aggregation levels to illustrate the different possibilities for analyzing and reporting the DEALA results. First, Figure 6a shows the BEIC 1 level and the respective distribution of the indicator scores of total cost to the four stakeholders. It should be noted that when assigning the results to the stakeholders, the impacts are not considered twice in the case of the cell and pack producer. This means that the costs for the battery cell purchase are not assigned to the pack producer, as the corresponding costs are reflected by the cell producer's results. BEIC 1 can be used to highlight which stakeholder is responsible for the highest indicator score. In this case study, the user has the highest total cost followed by the cell producer, pack producer, and recycler. This reveals that BEIC 1 enables a good comparison between the parties involved and that easily understandable values can be reported.

If one wishes to analyze the results in more detail, the results can be presented similarly to Figure 6b. This figure represents the BEIC 2 level and shows that most cell and pack producers' costs depend on operational cost followed by other cost and subsequent cost, while the investment-dependent cost plays a minor role. For the user and recycler, the opposite is the case since investment-dependent cost has the highest share at that level. The reasons for this can be analyzed in more detail with the representation of the results of the BEIC 3 level in Figure 6c. This figure shows that most of the costs for the cell and pack producer depend on consumables and supplies cost. The user depends mainly on depreciation and energy cost, while for the recycler, the most influential impact category is personnel cost, which should lead to high indicator scores of operational cost at

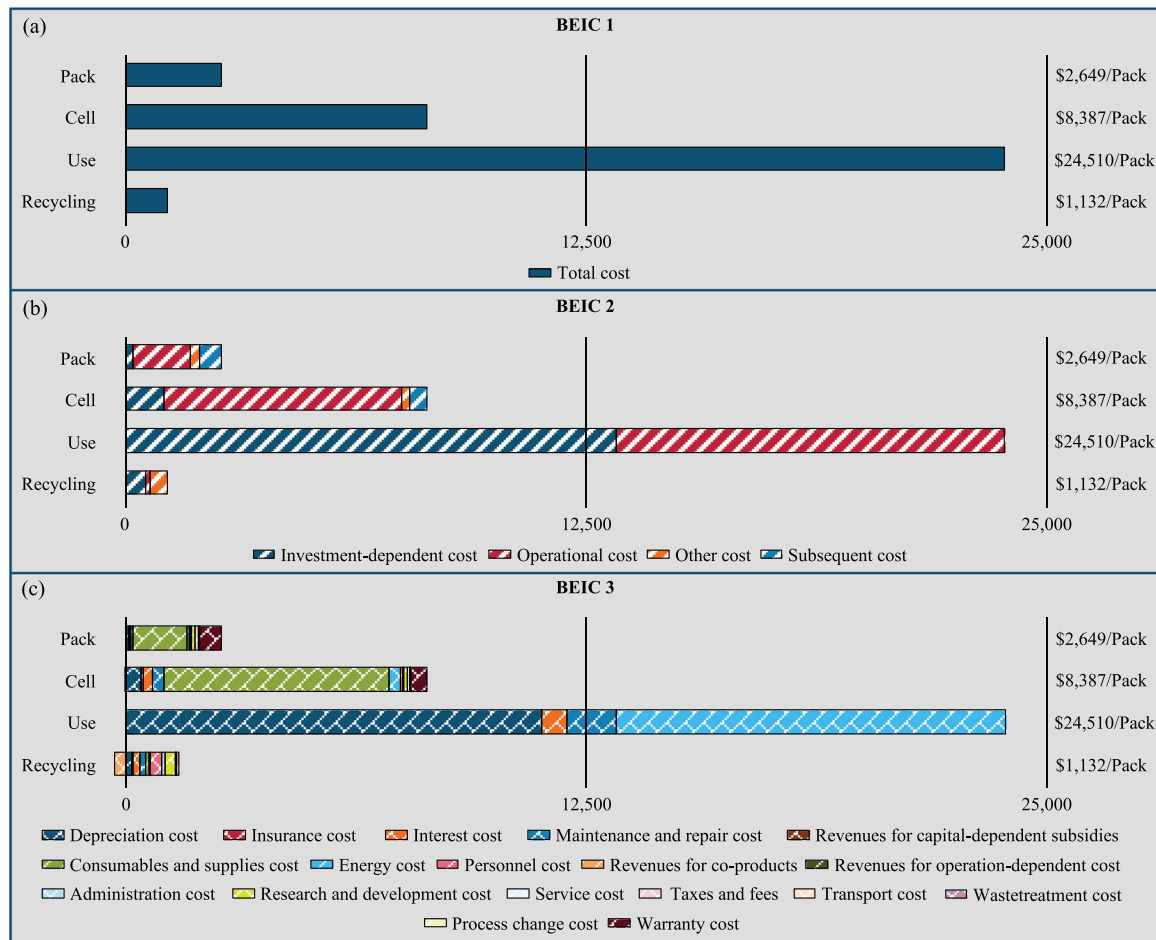


FIGURE 6 Results of the life cycle sustainability assessment at the impact category levels BEIC 1 (a), BEIC 2 (b), and BEIC 3 (c). The underlying data for this figure are available in the sheet “impact categories article” of Supporting Information SI 3.

BEIC 2. However, Figure 6c shows a negative indicator score for revenues for co-products, which explains the small indicator scores for operational cost. This underlines that the results can be analyzed in more detail at BEIC 3 level.

If one wants to analyze which activity contributes the most, hotspot analyses can be conducted. Figure 7 shows up to five DEALA activities that contribute the most to the indicator score of total cost for each considered stakeholder. This level of analysis allows for a differentiated and detailed analysis of the processes so that suggestions for improvement can be developed accordingly. For the pack manufacturer, warranty leads to the highest indicator score, while for the user depreciation for the battery has the highest share. In contrast, for the cell manufacturer and the recycler, lithium carbonate and working hours lead to the highest impacts. In the latter case, this depends on the assumption that disassembly and dismantling are done manually. Therefore, one possible alternative that should be investigated is the automation of these processes.

Figure 8 compares the economic impact category total cost with the impact categories climate change and risk of occupational injuries and deaths at process level. In particular, the processes of the foreground system and their respective impacts are presented. Regarding total cost, the results for the cell producer show that the mixing process of the positive electrode paste accounts for the highest share at 56%. The cell production process has the second largest share with 27%. The total cost of the pack producer is split into 62% for pack assembly and 38% for module assembly. The processes with the highest costs for the user are use (50%) and charging (44%) over the entire life cycle. Regarding recycling, the disassembly process (60%) is responsible for the highest total cost, followed by the hydrometallurgical processes (30%). A similar picture can be drawn for the impact category climate change. The user emits the most kilograms of CO₂e followed by the cell producer, pack producer, and recycler. However, the allocation of impacts differs from the total cost. Due to the assumption that only for the charging process environmental aspects are included, 100% of the environmental impacts are allocated to that process of the user.

For pack manufacturers, the module assembly process has a slightly higher share (54%) than pack assembly (46%). The cell manufacturers cause the highest CO₂e emissions through the mixing processes of the positive electrode paste (51%) and cell assembly (30%). For the recycler, the results show that the disassembly processes play a minor role in the environmental impact categories (8%). Instead, the hydrometallurgical processes influence the indicator score the most (54%). This is also the case for the social impact category (61%). In the social impact category, the user's

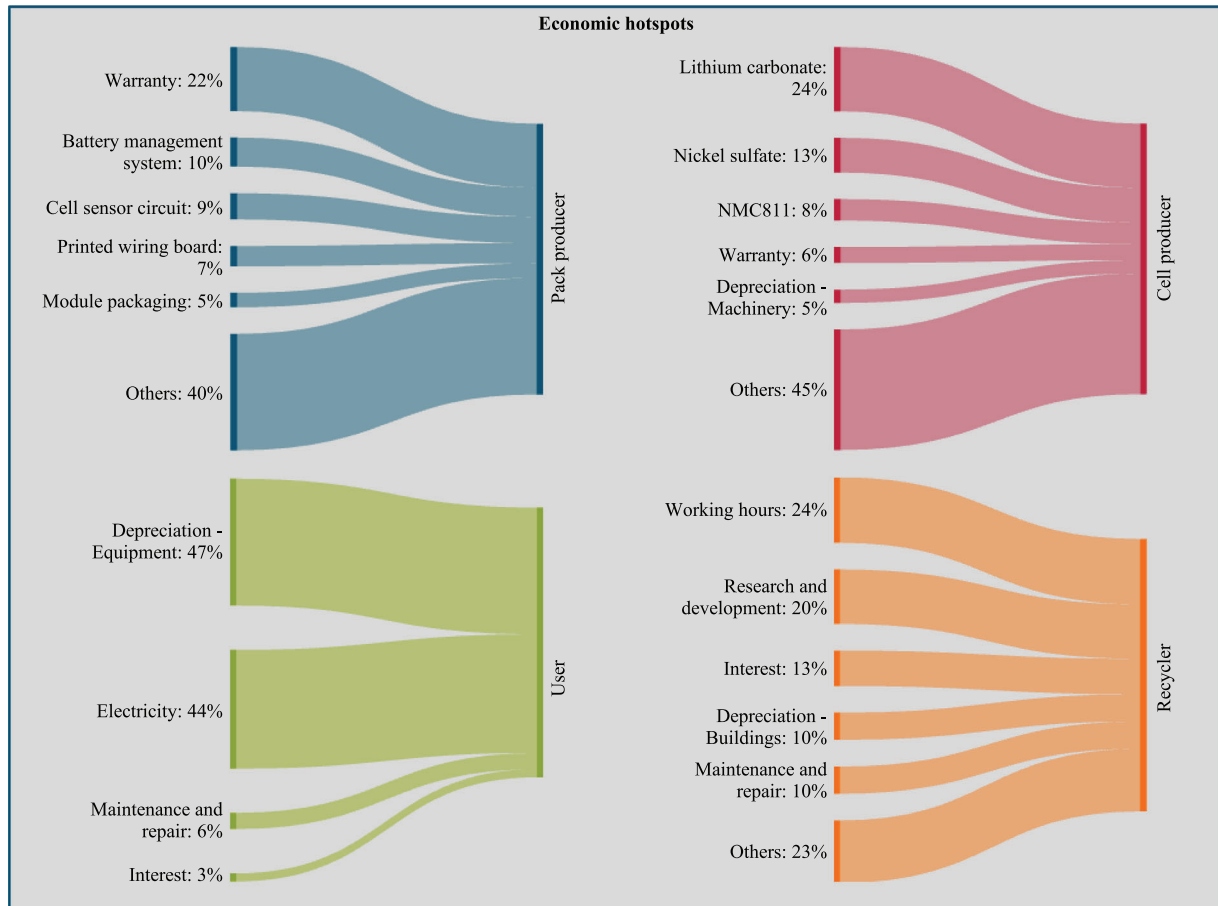


FIGURE 7 Economic hotspots of the pack producer, cell producer, user, and recycler. The underlying data for this figure are available in the sheet “activities total cost” of Supporting Information SI 3.

processes have less influence than the cell and pack manufacturer’s processes. This is particularly true when one considers that these risks are considered for a lifespan of 12 years, while for the other stakeholders it relates to the significantly shorter production period associated with the battery.

5 | DISCUSSION

The application of DEALA in the presented case study and the corresponding results prove that DEALA can be appropriately used as an eLCIA method in the context of ELCC and LCSA studies. Equivalent system boundaries are applied, and common LCIs are generated for the activities. The equivalent system boundaries and the joint LCIs can improve comparability between the sustainability dimensions and reduce the risk of misleading recommendations derived from the results. Moreover, the potential for utilizing the DEALA method within the LCSA framework enables its integration with additional decision-support approaches, including optimization models (Popien et al., 2024) or simulation models (Ginster et al., 2024). Furthermore, DEALA is based on economic standards and provides impact categories on a three-level structure. This leads to several advantages of DEALA. First, the different aggregation levels allow users to present and analyze the economic impacts differently. The impact categories of BEIC 1 and 2 are important for companies that use the results as performance indicators to report on economic impacts and are, therefore, appropriate for such use cases. Furthermore, DEALA offers BEIC 3, which can provide information that can be used to analyze product systems in detail and to derive recommendations. Second, DEALA provides a predefined structure of impact categories. As DEALA is intended to explain which impact categories have been selected and why, this results in greater transparency as shown in the case of subsidies.

Furthermore, a comparison with a previous study demonstrates the advantages of DEALA. Popien et al. (2023) conducted a cradle-to-gate LCSA for various battery supply chains. The authors utilized the value-added approach (Heijungs et al., 2013; Moreau & Weidema, 2015) and presented the results as total cost. This approach makes it considerably more challenging to comprehend the composition of the total cost, as cumulated values comprising personnel and energy cost are already utilized as input in the LCIs. Furthermore, this aggregation makes it more difficult to analyze

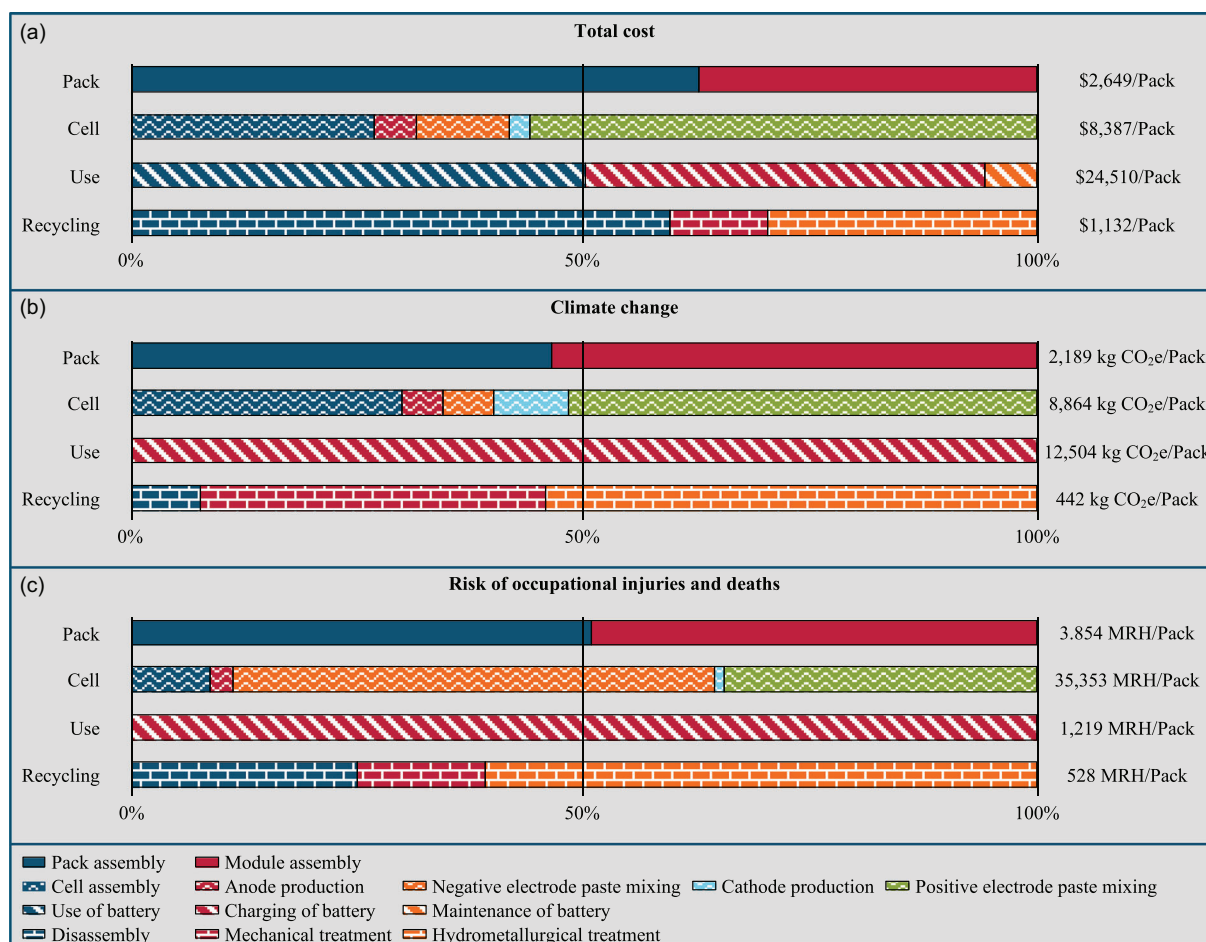


FIGURE 8 Results of the impact categories total cost (a), climate change (b), and risk of occupational injuries and deaths (c) at process level. The underlying data for this figure are available in the sheet “processes” of Supporting Information SI 3.

and compare the results to this study. Moreover, the flexibility of the comparison in the study was significantly constrained. As input data for the value-added must be calculated in advance, the costs of activities in different countries must be calculated with significantly greater effort than is required by the structure of the DEALA method. To examine these benefits of DEALA in more detail, further studies should be carried out that consider existing approaches to economic assessment from the literature.

Besides, applying the case study reveals some limitations of the DEALA method. First, DEALA requires a large amount of data to be collected, calculated, and estimated to determine indicator scores. This can be particularly challenging when assessing global supply chains, as region-specific data is required. Furthermore, appropriate models are required to estimate, for example, the production space and the number of working hours if this data is not available. At this point, however, it is possible to simplify the assessment from the stakeholder’s perspective. For example, upstream and downstream processes not considered can be modeled as a black box. This means, for example, that only the material price for a purchased component is considered instead of the associated process steps and detailed DEALA activities. These aspects highlight that sensitivity and uncertainty analyses are required when conducting ELCC or LCSA studies. Therefore, the represented case study in this article must be extended in terms of such aspects to derive reliable recommendations.

The current status of DEALA offers three levels for conducting the eLCA divided into two perspectives. However, it may be necessary to consider additional or other impact categories to meet the objective of a study, for example, to calculate the profitability of the stakeholder. Consequently, the DEALA method should be extended for such cases, which is possible due to its flexible structure. Moreover, DEALA is limited to cost and expenditures, which are important indicators to assess the economic dimension of production systems. However, as shown in the studies by Neugebauer et al. (2016) or Arulnathan et al. (2022), further indicators such as productivity or resilience are important for the assessment from a general economic perspective. The structure of DEALA and the cost and expenditure variables can be used as a basis for integrating corresponding approaches in the future.

6 | CONCLUSION

This article emphasizes the need for an eLCIA method for LCC and LCSA studies. This need is a direct consequence of the identified research gaps, such as comparability, transparency, and flexibility of current approaches for economic assessments in this context. To address these gaps, this paper presents a novel eLCIA method called DEALA. It allows for a flexible, differentiated, and detailed analysis of processes, products, and supply chains regarding their economic impacts. This new method is validated through a case study that examines an illustrative battery supply chain. The validation has shown that the structure of DEALA allows assessments at different aggregation levels so that the economic impacts can be reported in terms of industry standards. Moreover, they can be presented in much more detail, which helps to identify hotspots in the system under study. Recommendations for improvements can be derived from the identified hotspots. Additionally, the predefined impact categories and the guidelines provided can increase the transparency of the process for calculating the indicator scores. This guideline can also lead to a better comparability of studies using DEALA.

Furthermore, creating joint LCIs for all three sustainability dimensions reduces the risk of assessing the environmental, economic, and social impacts based on different system boundaries. It thus ensures better comparability of the respective impacts. Moreover, the structure and procedure of DEALA can lead to high flexibility of the method so that changes can be easily added, and different types of assessments are possible.

Consequently, DEALA should be used in future studies for different production systems to assess the economic impact in a structured way. By conducting such studies, the knowledge gained can be used to further develop DEALA, for example, to include further economic standards with their respective impact categories. Furthermore, the benefits of DEALA should be considered in more detail, for example, in studies that use the DEALA results in decision support models or cost–benefits analyses compared to existing approaches.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in the Supporting Information.

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SUPPORTING INFORMATION

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