Comparability of Life Cycle Assessments: Modelling and Analyzing LCA Using Different Databases

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Abstract

Life Cycle Assessment is a recognized method to assess the environmental impact of a product, of product alternatives and of deviations from different life cycle designs. Life Cycle Assessment studies usually rely on assumptions regarding certain parts of the modelled life cycle such as material extraction or processing. Life Cycle Inventory (LCI) databases support the modelling by providing the necessary inventory data. Further, software solutions such as Umberto, GaBi thinkstep, and Simapro support the modelling but may further affect the study results. Knowledge on how life cycle inventory databases may influence study results, and hence may steer a decision towards a particular database, is limited. This study aims to better understand deviations and potential inconsistencies between inventory databases causing effects on the life cycle assessment results. The production of an electric motor used in electro-mobility applications such as electric vehicles is modelled using GaBi Thinkstep software and three different life cycle inventory databases, namely Ecoinvent, GaBi professional, and the European Life Cycle Database (ELCD). Starting from the ReCiPe single score results, the analysis moves through corresponding endpoint and midpoint indicators to identify reasons for deviations. Despite some limitations, the results show both similarities and differences. Overall, it may be assumed that results deviate to a degree that can change the resulting assessment. However, the used electricity modules and the modelling of only one product (without alternatives) limit the explanatory power to some regard. Further research, in particular the modelling of product alternatives in the same setup though with different inventory databases, is necessary to better understand the effects of different databases on Life Cycle Assessment results and to assist their addressees in the interpretation of the results.

1 Introduction

Life Cycle Assessment (LCA) is a recognized method to assess the environmental impact of a product, of product alternatives and of deviations from different life cycle designs (e.g. reuse and recycling of products) [1]. LCA results can cause long-lasting impacts, especially when resulting in regulations and laws through policy decisions, although LCA results and meaning depend on a great variety of factors also outside the study, such as market dynamics and local production and processing circumstances [2]. Furthermore, policy decisions based on LCA results can cause significant shifts in financial flows, both of public funds and of private capital moving into different areas and hence into different (technical) solutions. The domain of electro mobility is one prominent example for the application of LCA results. The German government invested EUR 1.2 billion to foster electric vehicles (ELVs) through a subsidy of EUR 4000 for each e-vehicle sold since 2016. At the same time, the government supports the extension of existing e-mobility charging infrastructure with EUR 300 million [3].

However, each individual LCA study depends on a set of parameters influencing the outcome and hence the results. In addition, LCA studies usually rely on assumptions regarding certain parts of the modelled life cycle, such as energy inputs or material demand of certain production processes. The choice for a particular Life Cycle Inventory (LCI) database supporting the LCI analysis of a study has a relevant influence on the LCA results. When compiling a LCA study, one should ideally obtain primary data on material and energy inputs. However, some data are not easily available for the study owner or difficult to obtain, for example, on raw material extraction and processing. Even some data on production processes may be out of reach due to information restrictions of processing companies. Therefore, LCA models rely on LCI databases, such as ecoinvent or GaBi professional; ecoinvent being the most popular LCI database used widely across the globe [4]. Furthermore, LCA studies usually use LCA software solutions such as Umberto, GaBi thinkstep, and Simapro and the choice of LCA solution can further affect the results [5].

The different LCI databases contain data from different sources and years representing particular processes, these "average datasets" and the variety of base years and further circumstances can cause great deviations in LCA results [2]. For e-mobility, especially the electricity mix in the country of use has great impacts during the use phase. Similarly, the electricity mix influences the results of other product life phases requiring energy inputs.

Depending on the (underlying) objectives of a LCA study, the knowledge about differences between the LCI databases may steer a decision towards a particular database. For example, if the focus lies on a certain category of environmental impacts such as water use or fossil depletion, the choice for a LCI database may make an important difference. The overall results of an LCA may also differ significantly between similar models based on different databases. Therefore, this study aims to better understand deviations and potential inconsistencies between LCI databases causing effects on the LCA results. The study asks the questions (1) how much do LCA results deviate because of different LCI databases, and

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(2) would the choice of a LCI database provide a foreseeable influence on the LCA results, and if so, how could such influence be identified?
To answer the proposed questions, the following section outlines existing literature on LCA software support, on LCI databases, and on their relevance for LCA results. Section 3 explains the methodological approach chosen for this study before section 4 presents the results from the LCAs modelled with different databases. These results are discussed in section 5. This paper concludes with a brief summary of the findings and an outlook on future research opportunities.

2 State of the Art

This section outlines the discussion on inconsistencies between LCA studies that are based on different LCI databases; the resulting potential for manipulation has hardly been addressed in the past but received growing interest in recent years. Some studies investigated these differences and inconsistencies potentially resulting from using different LCA software solutions and especially different LCI databases.
Differences in LCA results depend on different factors. Besides those factors solely relying on the decisions made due to the study design (assumptions, system boundaries, etc.), other factors relate to the software or database used to model and analyse the LCA model. Speck et al. [6] analysed the impact on decision making in packaging depending on the choice of LCA software solution. They compared LCA results of SimaPro and Gabi, two widely used solutions, concluding that neither the software solution itself nor the material amounts but the characterization factors are responsible for deviation in LCA results. These characterization factors depend on the software solution and not on the database; from our experience, characterization factors may be outdated or the implementation of such factors can be inaccurate. Another study on SimaPro and Gabi examined the statistical potential of uncertainties stemming from “statistical value chains” in the biodiesel supply chain. The study concludes that differences in the result derive from errors in the LCI databases; the authors highlight that further research is necessary to verify or falsify the origin of differences [7]. However, a study comparing LCA software solutions (GaBi, SimaPro, openLCA, and Umberto) for a practitioner audience indicates that decisions on software solutions may not consider such observations on the reliability of software solutions and their impact on the LCA results [8].
Although the chosen software solution may influence the LCA results due to issues with the characterization factors, the software solution itself may only have a limited impact on the LCA results, especially when characterization models are implemented correctly. This conclusion, however, does not apply when different databases in the same LCA software are used to model the life cycle. Using only one software solution should at least eliminate deviations due to issues with the implementation of characterization models. Garrain et al. [9] compared the LCI database Ecoinvent and the European Life Cycle Database (ELCD) (amongst others) using the data quality indicators of LCA databases to evaluate selected processes of the database. They conclude that the LCA practitioner needs to carefully assess the quality of ELCD data and that their study results may vary if applied to other than the selected datasets from the LCI database. A further study built upon the latter study to develop a methodological approach for database assessment [10]. A statistical analysis of the LCI databases Ecoinvent and GaBi and the construction-specific databases IBO, CFP and Synergia analysed the deviations between LCA results and the environmental impact in terms of Greenhouse Gas (GHG) emissions of material production. The study identified the allocation rules, the system boundaries, and temporal geographical representativeness of selected modules as major causes for different LCA results [11]. Quandel [12] explicitly addressed the manipulation potential in ecological assessment and investigated how a LCA can be manipulated to favour particular product alternatives. Based on her results, she proposes solutions to overcome such disadvantages regarding the allocation of environmental impacts of co-products in particular.

3 Methodological Approach

This study uses LCA as described by ISO (ISO 14040) though the objective of identifying inconsistencies between LCI databases requires some adaption of the approach. Instead of using one single LCI database to model the lifecycle, this study models the same lifecycle using three different databases. However, this requires also some flexibility in the models themselves since different LCI databases provide processes differing, for example, in their degree of aggregation (e.g. how many previous processes are considered and whether these processes are comparable).

3.1 LCA Model

This study models the life cycle of an e-motor for ELV applications using three different LCI databases, namely ecoinvent, GaBi professional, and the European Life Cycle Database (ELCD). The data on the electric motor (e-motor) for ELVs stems from a study on electro mobility [13]. Using the LCI corresponding to this e-motor, the here presented study models the production of the e-motor using the two databases Ecoinvent, Gabi and ELCD in the LCA modelling solution GaBi thinkstep. The e-motor provides 25 kW of power and weighs 58 kg; iron makes up 58% of the weight of the motor, copper and aluminium make up 20 % of the weight each. The remaining 2 % represent polyethylene [13]. These numbers regarding the material content should be treated with care as some uncertainties remain [13]. Because of the study’s objective, the issue of uncertainties in the material composition is not of greatest concern since the relative results between the models are in the focus of the analyses. This study follows a cradle-to-gate-approach modelling the production of the e-motor, considering the production of raw material, the processing of material, transport, and energy and auxiliary resources. Hence, the model does not consider the use phase of the motor nor any end-of-life consideration such as recycling. These reductions of the system boundaries to “cradle-to-gate” derive from the objective of comparing the impact LCI databases have on LCA results. Reducing the complexity helps the comparison of the models. If the objective were to compare product alternatives instead of LCI impacts, the model should ideally cover all life cycle phases of the product.

Necessary assumptions regarding the resource and energy inputs of production and processing activities stem from the approach of Dietz and Helmers (and Hartard) [13, 14]. For example, the study assumes an injection moulding process for the processing of the polyethylene. Furthermore, the production process requires heat which accounts for approx. 4.16 MJ derived from light oil and 144.54 MJ derived from natural gas [13, 15]. In contrast to Dietz and Helmers [14], the here presented model uses the original electricity mixes provided by the LCI databases, although this accounts for relevant differences (see results and discussion). In addition, transport modes and distances are either defined in the LCIs’ process modules or depend on the Ecoinvent Report No. 1 for metal transport in Europe providing standardized transport modes and distances for Europe [16]. Finally, the provision of infrastructure necessary for the production of a product causes further environmental impacts. While Ecoinvent provides datasets for such infrastructure, the other LCI databases do not provide separate datasets though supposedly consider impacts of infrastructure in their materials and production processes [17].

The modelling in GaBi using the three LCI databases requires some adjustments to the models. For example, additional modules such as for processing might be necessary in some cases. The consideration of losses during production is another difference in the modelling approaches. For example, GaBi professional usually considers these losses in its process modules while Ecoinvent requires a manual consideration of such losses. If no primary data is available, loss factors can be used to model losses [18].

3.2 LCI Databases

This section briefly outlines the three LCI databases used in this study. At the time of the study design, we were not aware of the discontinuation of the project in 2018. However, we decided to present the results in order to broaden the picture by including a freely available LCI database.

Ecoinvent

The Ecoinvent database is a commercial database from Switzerland, which has been on the market since 2003 and was one of the first comprehensive LCI databases. Today it is one of the leading inventory databases and contains both Swiss and European data [17]. Currently, Ecoinvent contains more than 13.300 datasets covering a wide range of subject areas [19]. The database contains data from the fields of transport, energy, chemicals, agriculture, building materials, metals and their processing, packaging materials, electronics and waste disposal. The database is mainly based on so-called unit processes. In contrast to accumulated process data, these are data records that do not contain several chains of unit processes. For the sake of comparability, they represent the smallest possible process step [20]. A unique feature and, at the same time, a unique selling point of the Ecoinvent database is the use of infrastructure data sets representing, for example, the construction of a factory needed to manufacture a product [17].

GaBi Professional

The Professional Version of the GaBi database contains currently more than 3778 processes. Extension can supplement the basic version. GaBi professional is currently considered one of the market-leading LCI databases [21]. The GaBi database is mainly used in the field of engineering since it provides the datasets relevant for the automotive industry including according suppliers [17]. The data sources of the GaBi datasets are heterogeneous. Preference is given to primary data from industry. However, in some cases, the database provides secondary data from publications, environmental reports from companies or public statistics [22].

European Life Cycle Database

The European Life Cycle Database (ELCD) originated in a project of the Joint Research Center of the European Commission and was published in 2006 [23]. The data sets are limited to the most important production materials, energy sources, transport and waste treatment. The aim of the project was to freely provide a database for ISO 14040-compliant LCA data sets. The data sets came partly from commercial databases or were provided by scientists. For example, data sets from the GaBi database are represented. Data records from the Ecoinvent database are not present in the ELCD. The ELCD is the smallest database compared to Ecoinvent and GaBi. Moreover, the database project was not continued [24].

4 Results

4.1 LCIs Using the Three Different Databases

The e-motor scenario is modelled using three different LCI databases. For each model, dataset modules are used exclusively from the corresponding LCI database. However, some modules might be similar or may even have the same name, especially between GaBi and ELCD. This derives from the fact that ELCD uses some of GaBi's datasets; these datasets are usually older versions compared to the most recent version of GaBi professional. Table 1 summarizes the selected process modules of the three different LCI datasets. Modules marked (*) indicate that additional processing modules might be necessary for proper modelling.

Table 1. LCI Databases and corresponding modules for processes or materials

Material/Process	**ELCD**	**Ecoinvent**	**GaBi DB**
Iron*	Steel rebar (GLO)	Cast iron production (RER)	BF Steel billet / slab / bloom (DE) + Cast iron part (automotive) (DE)
Aluminum*	Aluminium sheet (RER)	Aluminium production, primary, ingot (UN-EUROPE)	Aluminium ingot mix (2010) (EU-27) + Aluminium die-cast part (DE)
Copper*	Copper sheet (EU-25)	Copper production, primary (RER) +	Copper sheet mix (EU-27)
Polyethylen*	Polyethylene low density granulate (PE-LD) (RER)	Polyethylene production, low density, granulate (RER)	Polyethylene low density granulate (LDPE/PE-LD) (DE) + Plastic injection moulding part (unspecific) (DE)
Electricity	Electricity grid mix 1-60kV (EU-27)	Market for electricity, medium voltage (DE)	Electricity grid mix 1kV-60kV (ENTSO)
Heat (light oil)	Heat (EU-27)	Heat production, light fuel oil, at industrial furnace 1MW (Europe without Switzerland)	Thermal energy from light fuel oil (LFO) (EU-27)
Heat (natural gas)	Heat (EU-27)	Heat production, natural gas, at industrial furnace >100kW (Europe without Switzerland)	Thermal energy from natural gas (EU-27)
Water	Process water (EU-27)	Tap water, at user (RER)	Tap water (EU-27)
Transport by truck	Articulated lorry (40t) incl. fuel (RER)	Transport, freight, lorry 16-32 metric ton, EURO3 (RER)	Truck (GLO) + Diesel mix at filling station (EU-27)
Transport by train	Rail transport incl. fuel (EU-27)	Transport, freight train, diesel (Europe without Switzerland)	Rail transport (EU-27)
Vehicle plant	-	Road vehicle factory production (RER)	-

4.2 Ecoinvent-Based LCA Model

Ecoinvent modelling is designed to consolidate processes aiming towards one final process module. Therefore, it is not possible to "pass" a product through a process. This modelling approach reduces the ability to visualise the typically sequential character of a production process (see difference between Figure 1 and Figure 2). Figure 1 shows the Ecoinvent-based model [13, 14] realized in GaBi Thinkstep. For easer orientation and for better comparability with the other scenario models, modules were clustered relating to the corresponding categories of material production, material processing, energy and auxiliary resources, and transport and infrastructure. All process modules connect to the manually created process for aggregation and manufacturing of the e-motor.

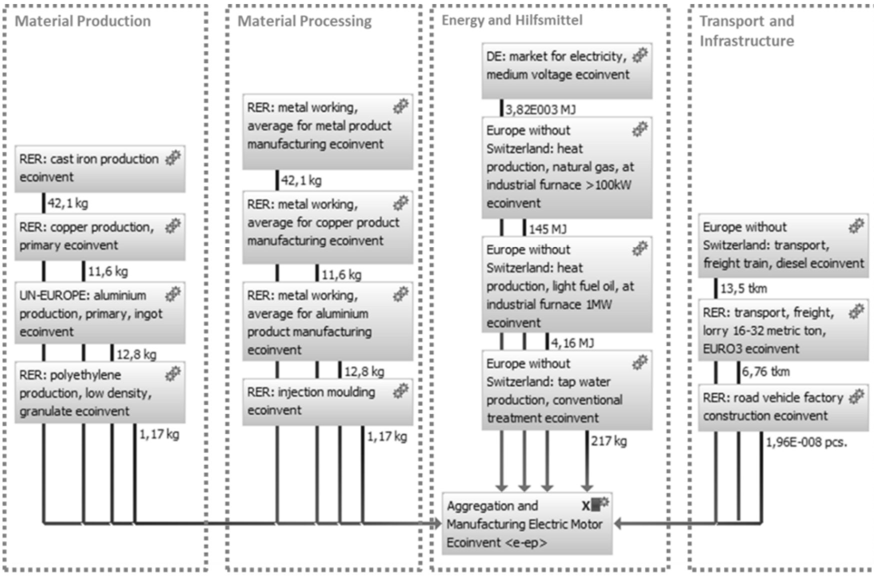

Figure 1. The system modelled in GaBi thinkstep using Ecoinvent

4.3 GaBi-Based LCA Model

The GaBi professional-based model follows a sequential design since this LCI allows for a more process-oriented modelling (see Figure 2). The model in Figure 2 uses almost the same clusters as in Figure 1 (Ecoinvent), which makes these two models easily comparable. When compared to the Ecoinvent-model (Figure 1), the identification of raw materials and corresponding material processing steps is much easier, such as the "EU-27: Aluminum ingo mix (2010) EAA" provides the input material for the "DE: Aluminum die-cast parts ts" process. In Gabi, these processes require additional inputs such as for energy or electricity. For these inputs, corresponding regions can be selected separately (e.g. electricity from different grids; not applicable in this particular case). The modelling approach of GaBi professional results in processes such as "aggregation of materials electric motor GaBi" merging all semi-finished products for rail transport. In this case, a standard distance is assumed. However, if the different semi-finished parts were to be transported over different distances and with different modes of transport, corresponding processes could be easily modelled. The transport cluster also shows that some differences occur within GaBi professional. While the truck transport module provides input connections for "goods" and requires an additional input of diesel fuel, the described aggregation process is still necessary for the rail transport. Both transport processes calculate their energy demand based on the weight of the transported goods. Noteworthy, because of this modelling approach, the transport solely considers those parts for final assembly weighing less than the semi-finished products. Since the transport has a relatively small or almost no influence on the environmental impact of this particular case, this can be neglected here.

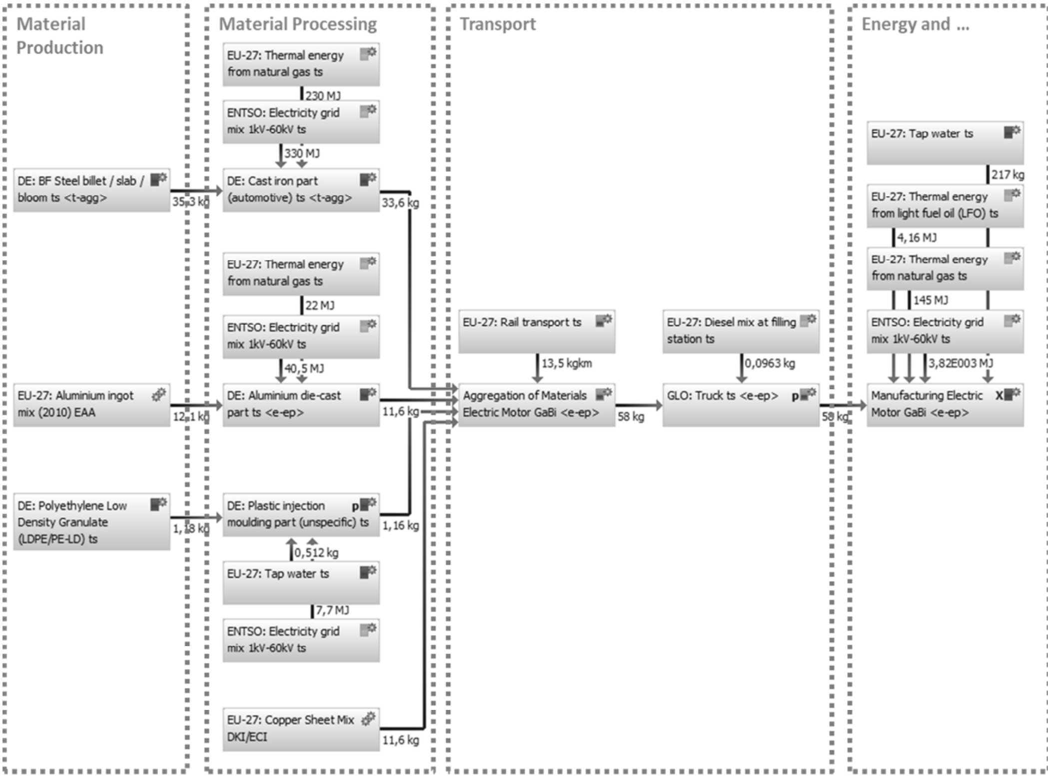

Figure 2. The system modelled in GaBi thinkstep using GaBi professional

Another difference in the modelling approaches is the consideration of losses. Since GaBi professional considers losses in its processing modules, losses are not calculated and hence not added manually to the model. For example, the "plastic injection moulding part (unspecific)" requires 1.18 kg of input material to produce 1.16 kg of output material. One limitation of this GaBi professional-based model is the "copper sheet" process because it represents a type of copper sheet that is usually too thick for applications in electrics. However, the LCI database does not provide a more suitable alternative. This is one issue of LCI databases regardless of their comparability constantly challenging LCA modelers.

4.4 ELCD-Based LCA Model

The ELCD database is the least detailed LCI in this comparison making the modelling more difficult than with GaBi professional or Evoincent. The ELCD also allows for a more process-oriented modelling approach (Figure 3). Nevertheless, the modelling rather appears like a mix of the other two databases as outlined in the following. Once again, a manually added process aggregates all materials ("Aggregation of Material Electric Motor ELCD") considering the truck transport as well. Because of limitations in the software or the ELCD, not more than one transport process with an output flow named "Transport ELCD" can be connected to the same process module. Therefore, the rail transport is connected to the "Manufacturing Electric Motor" process. In the succeeding manufacturing process, loss factors such as in the Ecoinvent-based model were considered. Therefore, the material input at this stage is higher compared to the GaBi professional-based model. Compared to the other two LCI databases, ELCD does not provide as many varieties regarding the regional specificity of processes (such as EU and US, or even country-based) resulting, for example, in the "steel rebar" process being a global ("GLO") process while "Aluminum sheet" is an EU (RER) process. Although the selected material processes seem to consider some production activity as well, losses are considered in addition since these losses refer to, for example, punching and cutting of such material sheets.

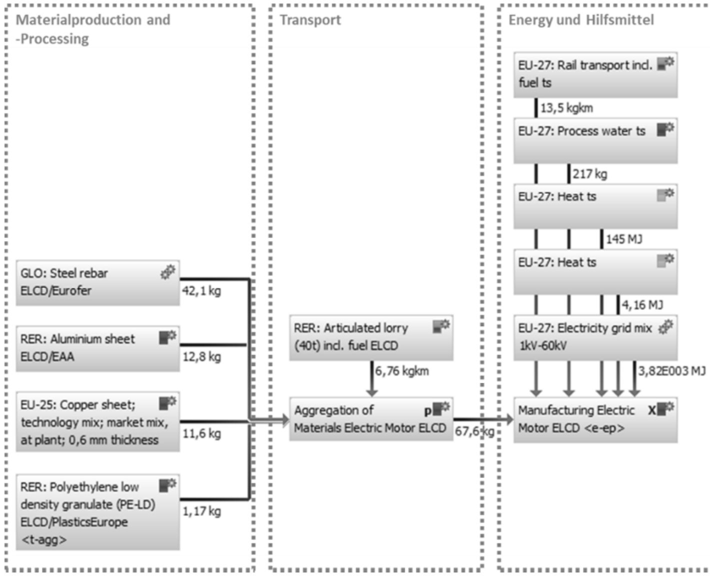

Figure 3. The system modelled in GaBi thinkstep using ELCD

4.5 Impact Assessment with ReCiPe

The impact assessment uses the ReCiPe method. Because of the great variety of midpoint indicators, only a selection will be discussed in detail. The selection is based on their relevance for the use case and the study's objective. The selection covers the ReCiPe midpoint indicators "climate change", "fossil depletion" and "metal depletion". Furthermore, the results cover all endpoint indicators and the single scores. The impact assessment makes use of the clusters that were used to organize the process modules (Material Production, Material Processing, Energy Demand and Auxiliary Resources, and Transport and Infrastructure) as far as possible depending on the corresponding LCI database. Energy required for partly aggregated processing modules (see GaBi model) will be accounted to manufacturing for comparability reasons.

Midpoint: Climate Change

The midpoint indicator Climate Change reflects the negative environmental impact of anthropogenic warming of the Earth's atmosphere [17]. Figure 4 shows the results of the corresponding ReCiPe indicator for the three LCI models. For the Ecoinvent-based model, this indicator accounts for 1114.12 kg CO2-equiv. and corresponding to the outlined process groups, the major contributors are material production (19.27 %), material processing (16.28%), energy demand and auxiliary resources (63.83%). For the ELCD-based model, this indicator accounts for 603.65 kg CO2-equiv. and corresponding to the outlined process groups, the major contributors are material production (16.02%), and energy demand and auxiliary resources (83.98%). For the GaBi professional-based model, this indicator accounts for 717.97 kg CO2-equiv. and corresponding to the outlined process groups, the major contributors are material production (26. 66%), material processing (9.13%), and energy demand and auxiliary resources (64.16%).

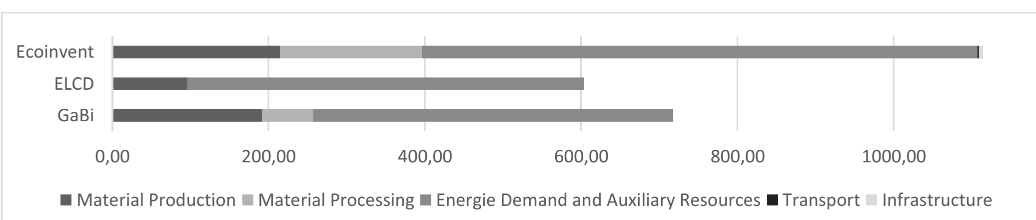

Figure 4. ReCiPe Midpoint Indicator Climate Change (kg CO_2-Equiv.) for the three models

Midpoint: Fossil Depletion

For the Ecoinvent-based model, this indicator accounts for 260.68 kg oil-equiv. and corresponding to the outlined process groups, the major contributors are material production (18.63%), material processing (15.66%), energy demand and auxiliary resources (64.92%). For the ELCD-based model, this indicator accounts for 164.12 kg oil-equiv. and corresponding to the outlined process groups, the major contributors are material production (15.65%), and energy demand and auxiliary resources (84.35%). For the GaBi professional-based model, this indicator accounts for 186.06 kg oil-equiv. and corresponding to the outlined process groups, the major contributors are material production (26.09%), material processing (9.77%), and energy demand and auxiliary resources (64.09%).

Midpoint: Metal Depletion
For the Ecoinvent-based model, this indicator accounts for 799.98 kg Fe-Equiv. and corresponding to the outlined process groups, the major contributors are material production (69.73%), material processing (28.83%), energy demand and auxiliary resources (0.94%). For the ELCD-based model, this indicator accounts for 35.21 kg Fe-Equiv. and corresponding to the outlined process groups, the major contributors are material production (94.19%), and energy demand and auxiliary resources (5.81%). For the GaBi professional-based model, this indicator accounts for 95.52 kg Fe-Equiv. and corresponding to the outlined process groups, the major contributors are material production (96.63%), material processing (0.32%), and energy demand and auxiliary resources (3.06%).

Endpoints and Single Score

Endpoint: Human Health
For the Ecoinvent-based model, the Human Health indicator (in points) accounts for 22.06 points and corresponding to the outlined process groups, the major contributors are material production (19.48%), material processing (17.84%), and energy demand and auxiliary resources (61.34%) (in process order). Transport and infrastructure account for 0.19% and 1.14% respectively. For the ELCD-based model, this indicator accounts for 10.77 points. The major contributors are material production (15.8%), and energy demand and auxiliary resources (84.2%). The remaining process groups do not contribute to this endpoint indicator. For the human health endpoint indicator of the GaBi-model accounting for 13.03 points, the major contributors are material production (26.03%), material processing (9.11%), and energy demand and auxiliary resources (64.81%). The transport (0.06%) and infrastructure (0%) have no or almost no influence.

Resources
For the Ecoinvent-based model, the Resources indicator (in points) accounts for 110.76 points and corresponding to the outlined process groups, the major contributors are material production (46.85%), material processing (22.93%), energy demand and auxiliary resources (29.58%). Transport and infrastructure account for 0.12% and 0.52% respectively. For the ELCD-based model, this indicator accounts for 28.83 points. The major contributors are material production (22.33%), and energy demand and auxiliary resources (77.67%). The remaining process groups do not contribute to this endpoint indicator. For the resources endpoint indicator of the GaBi-model accounting for 36.56 points, the major contributors are material production (38.93%), material processing (8.04%), and energy demand and auxiliary resources (52.98%). The transport (0.05%) and infrastructure (0%) have no or almost no influence.

Ecosystem Quality
For the Ecoinvent-based model, the Ecosystem Quality indicator (in points) accounts for 112.64 points and corresponding to the outlined process groups, the major contributors are material production (19.06%), material processing (16.43%), energy demand and auxiliary resources (64.11%). Transport and infrastructure account for 0.07% and 0.32% respectively. For the ELCD-based model, this indicator accounts for 15.21 points. The major contributors are material production (16.6%), and energy demand and auxiliary resources (83.4%). The remaining process groups do not contribute to this endpoint indicator. For the resources endpoint indicator of the GaBi-model accounting for 19.05 points, the major contributors are material production (30.45%), material processing (10.47%), and energy demand and auxiliary resources (59.04%). The transport (0.04%) and infrastructure (0%) have no or almost no influence.

Single Score
Figure 5 shows the Singe Score results (in points) corresponding to the three LCI models. The Singe Score consist of the three endpoint indicators “Human Health”, “Resources” and “Ecosystem Quality”. For Ecoinvent, the Single Score amounts to 235.46 points. With regard to the self-selected material groups, the result amounts to 30.99% for the material production modules, to 19.35% for the material processing modules, to 49.08% for the energy and auxiliary resources modules, to 0.1% for the transport modules and to 0.48% for the infrastructure modules (Ecoinvent only). The ELCD-based model amounts to 54.82 points in the single score, the lowest amongst the three models. With regard to the self-selected material groups, the result amount to 19.46% for the material production modules, and to 80.54% for the energy and auxiliary resources modules. The remaining groups do not contribute to the single score. The GaBi-based model mounts to a Single Score of 68.63 points. With regard to the self-selected material groups, the result amounts to 34.12% for the material production modules, to 8.92% for the material processing modules, to 56.91% for the energy and auxiliary resources modules, and to 0.05% for the transport modules. The infrastructure module is not Ecoinven-only hence does not contribute to the “GaBi Single Score”.

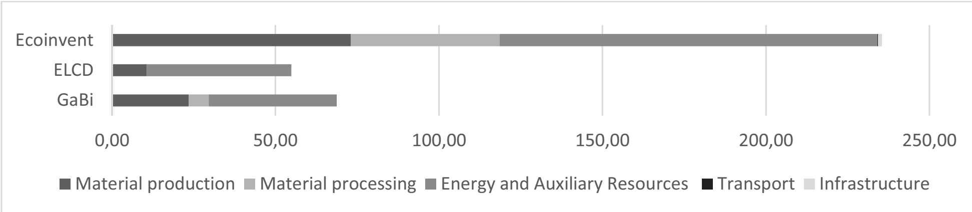

Figure 5. ReCiPe Single Score (points) for the three models

Sensitivity Analysis

For the sensitivity analysis, electricity was selected because of the overall relevance of the electricity and auxiliary resources module groups. Each model was therefore re-calculated using renewable energy modules (RE) instead of the regular energy modules (Electriciy Mix). For each model, energy modules were selected corresponding to the LCI database. For the Ecoinvent-based model, the „market for electricity, medium voltage, label certified (CH)" substitutes the „market for electricity, medium voltage (DE)" module (unfortunately, there was no DE-module for renewable energy available). For the ELCD-based model, the „Electricity from wind power (RER)" module substitutes the "Electricity grid mix 1kV-60kV (EU-27)" module. For the GaBi-based model, the „Electricity from wind power (EU-27)" process substituted the „Electricity grid mix 1kV-60kV (ENTSO)" process. The single score is used to compare the results (Figure 6). On average, the single score results are 61% below the regular results (substituted energy modules). With 77% below the reference value, the difference is highest in the case of ELCD. However, the ELCD model uses the least individual modules hence changing one single module may have a greater relative impact of the single score than in the other cases. Regardless of this limitation, the results show that the energy type used for production and processing has a significant impact on the LCA results in each of the three cases.

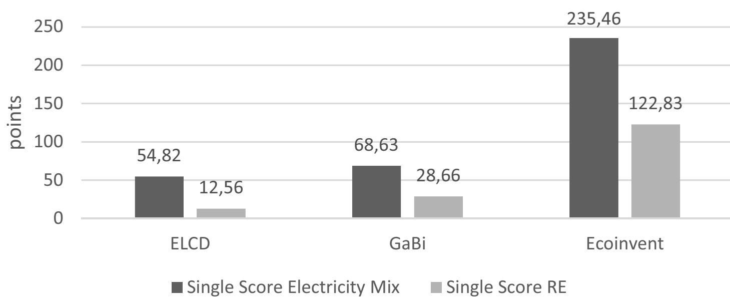

Figure 6. Single Score Results for the Sensitivity Analysis

4.6 Comparison of Overall Results

Table 2 shows the Life Cycle Impact Assessment Results based on ReCiPe for selected Midpoint indicators as well as for the Endpoint indicators and the Single Scores (both regular models and from the sensitivity analysis). It is noticeable that all impact indicators are higher in the case of the Ecoinvent database except for the impact indicator "Ionizing Radiation", which is lower compared to the results of the other two databases. In the case of the GaBi database as well as the ELCD, the electricity module "Electricity Grid Mix 1kV-60kV (ENTSO)" contributes just below 84% to the total amount of the ionizing radiation effect indicator. When modeling using the ELCD, 98% of the overall result stem from the environmental impact of the Electricity Grid Mix 1kV-60kV (EU-27) electricity module. The result of the Ecoinvent modeling is also dominated by the electricity module "market for electricity, medium voltage (DE)", but only by approximately 71%.

Table 2. Life Cycle Impact Assessment (ReCiPe) Results for selected Midpoints, Endpoints, the Single Score and the Single Score of the Sensitivity Analysis

	Ecoinvent	ELCD	GaBi
Human Toxicity (kg 1.4-DB Equiv.)	2012.48	18.71	74.94
Climate Change (kg CO2-Equiv.)	1114.12	603.65	717.97
Photochemical Oxidation (kg NMVOC)	2.97	1.51	1.69
Fossil Depletion (in kg oil-Eqiv.)	280.68	164.12	186.06
Metal Depletion (in kg Fe-Equiv.)	799.98	35.21	95.52
Human Health (points)	22.06	10.77	13.03
Resources (points)	100.76	28.83	36.56
Ecosystem Quality (points)	112.64	15.21	19.05
Single Score (points)	235.46	54.82	68.63
Single Score (Sensitivity Analysis) (points)	122.83	12.56	28.66

Similar to Takano et al [11], the standard deviation is used to identify which ReCiPe indicator has the largest differences between the different databases. With a relative standard deviation of 162%, the values of the human toxicity midpoint indicator are most different between the three LCAs. Terrestrial ecotoxicity follows with 142% and the consumption of metals with 137%. The ecosystem quality endpoint indicator shows a standard deviation of 113%, the single score of 84% and the endpoint indicator resources of 71%. The human health and photochemical oxidation indicators (39%), the climate change indicator (33%) and the fossil depletion indicator (29%) show the lowest deviations.

4.7 Deviations of Selected Processes between the Three Models

The single score results summarizing the endpoint results serve as basis to identify and analyse selected process modules that may have a significant impact on the deviation of the LCA results. The single score results of individual modules (not of the entire LCA) show similarities and differences as well. Comparing material modules from the three databases, the polyethylene modules (without processing modules) result in very similar single scores (Ecoinvent and GaBi 0.4, ELCD 0.41 [points]). Similarly, the Ecoinvent and the GaBi professional database modules for iron result in single scores of 11.3 (GaBi) and 11.73 (Ecoinvent) (points). Greater deviations occur for aluminium and copper. For aluminium, Ecoinvent scores 1.5 times higher than GaBi professional does while ELCD scores less than 0.5 times of GaBi professional. Especially copper shows very great deviations with a single score of 45.12 points for Ecoinvent, this score is 29 times higher than the corresponding GaBi professional score and still 20 times higher than the ELCD score.

On average, the single scores of the ELCD material modules are only half the corresponding GaBi single scores and less than 15% of the corresponding Ecoinvent scores. The single scores of the GaBi professional material modules are on average 1/3 of the ecoinvent scores. This observation of single scores does not include the processing modules (such as injection moulding). This is important because the Gabi professional processing modules account for much less additional points regarding the single scores than its counterparts in the Ecoinvent-based model. The aluminium processing in the Ecoinvent model is an extreme case but illustrates the impact: The Ecoinvent module causes an almost 600 times higher score than the corresponding GaBi module (ELCD does not provide separate processing modules).

When looking at the energy and auxiliary resources, the natural gas modules of all databases provide similar results. However, the electricity modules show differing results. While the electricity modules of GaBi professional and ELCD cause similar single scores, the score of the corresponding ecoinvent module is significantly higher and at the same time the highest single score value of all modules. The Ecoinvent transport modules score more than 10 times then the other two databases whose single scores are 0.1 or lower.

In summary, in all three models the electricity modules cause the highest impact to the single score. In case of GaBi professional and ELCD, the material module for iron causes the next highest contribution to the single score, followed by aluminium. In case of Evoinvent, the material module for copper is second highest regarding its contribution to the single score, followed by iron. The latter would be different if processing modules were considered as well. In that case, aluminium would be second highest contributor. These processing modules are an important contributor to the LCA results in case of Ecoinvent. As a result, the high environmental impact of the processing modules in case of Ecovinent contributes significantly to the different database-specific singe scores.

5 Discussion

Based on the LCI database choice, significant differences in LCA results may occur. Reasons for deviations are different modelling approaches underlying the design of the respective LCI database. In this study, we focused on the LCI databases used with one particular software solution, namely GaBi. The GaBi software is designed for a more process-oriented modelling approach as is the LCI database GaBi professional. However, different LCI databases can be used with the GaBi software, such as ecoinvent and ELCD. Due to the discontinuation of ELCD, corresponding results are not discussed in detail. In addition to the LCI database, the selection of a LCA software solution (such as GaBi) may have an influence on the study results. For example, GaBi thinkstep advises the user that datasets from Ecoinvent used in GaBi may cause unrealistically high results for water consumption [25]; the here presented study did not show any such issue. However, errors and deviations due to compatibility issues between software and databases may not be eliminated and hence may provide some margin for manipulation.

One prominent example for differences in LCA results due to different LCI database relating to e-mobility can be found in the energy mix provided by LCI databases. As the latest available energy mix for EU/Germany, the LCI Ecoinvent V 3.1 energy mix is based on the year 2008 while the LCI GaBi professional energy mix is based on the year 2012. Since the energy mix has changed over the years 2008-2012, the results of a LCA using this energy mix, for example as energy input during the use phase of an ELV, depend significantly on the available energy mix. In addition, the results depend on the chosen model for the data interpretation such as ReCiPe or Ecoindicator 99. Due to this significant variation between LCI databases regarding the electricity mix, the sensitivity analysis performed had only limited explanatory power. Nevertheless, it shows that LCA requires specialized knowledge also on the LCI database. Users of LCI databases may not always be aware of particular details causing great impacts on the LCA results. This is both a limitation of the here presented study as it is a result, namely the disadvantages when almost entirely relying on data from LCI database for the life cycle inventory assessment (LCIA). The study showed that not only the electricity mix, although having a significant impact on the results, but also material production and processing causes important deviations. This may in fact be more worrying than the electricity mix. While the electricity mix can be individually designed using electricity production modules for different energy sources, these production modules are much harder to replace with primary data by LCA practitioners.

Another reason for deviations in LCA results between software solutions (GaBi thinkstep, Umberto, Simapro, etc.) may be difficulties in adapting the available LCI databases to these software solutions. This aspect has not been addressed by the analysis of the results. Since the modelling approaches of LCA software solutions differ and since the adaption of impact assessment models to software solutions provides some room for human error, this aspect of LCA should be of concern for every LCA practitioner and the research community.

The results of the different models showed significant deviations and accordingly address the first research question asking how much LCA results deviate because of different LCI databases. Although this study only discusses one case using three different LCI databases, and hence results are limited to this case, other studies have come to similar results. Therefore, and since no other findings are known, it may be assumed that results deviate to a degree that can change the resulting assessment. However, it has not been assessed in this case whether the assessment of product alternatives (e-motor vs combustion engine) would result in contradicting product-alternative suggestions when using different databases. Such assessment would provide additional insight on the manipulation potential through LCI database choices. The latter leads to the second research question that asked if the choice for a LCI database would provide foreseeable influence on the LCA results, and if so, how to identify such influence? The results of this study do not provide sufficient evidence for foreseeable influence on LCA results depending on the applied LCI database. Nevertheless, the result for this case indicate that the relative contributions of particular product life phases (production, processing) may differ and that the different databases assess the impact of certain modules differently. Specific knowledge on these differences may provide some margin for manipulation, for example when setting system boundaries or when selecting particular modules such as aggregated modules for products instead of separate production and processing models. Such choice may even be argued satisfyingly hence not raising immediate concern when analyzing the LCA results. It should be noted that the intention of this study is not to motivate for such manipulation but rather to raise awareness for such issues beyond the LCA professionals who most likely are aware of such challenges.

6 Conclusion and Outlook

The results showed that the decision for a LCI database can have a significant impact on the LCA result hence on potential decisions made based on such results. Different LCA stakeholders may have different objectives and intentions when conducting LCA studies or when using study results. Therefore, addressees of LCA results have to take great care when provided with LCA study results, for example as decision support. This is, however, a challenge especially for stakeholders not being experts on conducting LCA studies.

The electricity modules proved to cause significant impact on the overall results and at the same time showed significant deviations between the three databases. In all three models, the chosen electricity modules provide 1 kWh of electricity in a medium voltage grid to the end consumer. All modules consider losses of the electricity transmission and voltage transformation. An analysis of these electricity modules would be promising to generate a better understanding for deviations in the results. For example, the (output) mass flows of each individual module could be compared. Although even such analysis has its limitation since databases may have their unique flows, it would contribute to the knowledge on LCIA and the challenges when using LCI databases in general.

This research paved the way towards a forthcoming study on LCI database comparison using a life cycle model including the use phase and a more detailed analysis of the LCA results.

7 Zusammenfassung

Die Ökobilanzierung ist eine anerkannte Methode zur Bewertung von Umweltauswirkungen eines Produkts, von Produktalternativen und von Abweichungen bei unterschiedlichen Lebenszyklusdesigns. Life-Cycle-Assessment-Studien basieren in der Regel auf Annahmen in Bezug auf bestimmte Teile des modellierten Lebenszyklus wie Materialgewinnung oder -verarbeitung. Life Cycle Inventory (LCI) -Datenbanken unterstützen die Modellierung, indem sie die erforderlichen Inventardaten bereitstellen. Darüber hinaus unterstützen Softwarelösungen wie Umberto, GaBi thinkstep und Simapro die Modellierung, können aber die Studienergebnisse weiter beeinflussen. Das Wissen darüber, wie Daten aus Life Cycle Inventory-Datenbanken die Studienergebnisse beeinflussen können, könnten somit auch eine Entscheidung für eine bestimmte Datenbank steuern. Diese Studie zielt darauf ab, Abweichungen und mögliche Inkonsistenzen zwischen Inventardatenbanken, die Auswirkungen auf die Ökobilanz-Ergebnisse haben, bessere zu verstehen. Die Produktion eines Elektromotors, der in Elektromobilitätsanwendungen wie Elektrofahrzeugen verwendet wird, wird mit der Software GaBi Thinkstep und drei verschiedenen Bestandsdatenbanken (Ecoinvent, GaBi professional und der European Life Cycle Database (ELCD)) modelliert. Ausgehend von den ReCiPe-Einzelergebnis-Ergebnissen bewegt sich die Analyse von den entsprechenden Endpoint- zu den Midpoint-Indikatoren, um Gründe für Abweichungen zu identifizieren. Trotz einiger Einschränkungen zeigen die Ergebnisse sowohl Ähnlichkeiten als auch Unterschiede. Insgesamt kann davon ausgegangen werden, dass die Ergebnisse zu einem Grad abweichen, der die Beurteilung beeinflussen kann. Die verwendeten Strommodule und die Modellerstellung nur eines Produkts (ohne Alternativen) schränken jedoch die Aussagekraft einigermaßen ein. Weitere Untersuchungen, insbesondere die Modellierung von Produktalternativen im selben Setup, jedoch mit unterschiedlichen Inventardatenbanken, sind notwendig, um die Auswirkungen unterschiedlicher Datenbanken besser zu verstehen und um Empfänger von Ökobilanzen bei der Interpretation zu unterstützen.

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