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LCI METHODOLOGY AND DATABASES

Replacing location-based electricity consumption with market-based residual mixes in background data to avoid possible double counting: a quantitative analysis of effects and challenges

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Abstract

Purpose Most life cycle inventory (LCI) datasets include location-based electricity mixes. Using these LCI datasets in combination with market-based electricity accounting in life cycle assessments (LCAs) leads to double counting of electricity from specific sources, such as renewable energy. The goal of this paper is to analyze market-based accounting by replacing location-based electricity consumption with market-based residual mixes in all processes of the ecoinvent database. The python script for this replacement procedure is openly available.

Materials and methods We use the Brightway 2 software package to replace European location-based electricity consumption in all 21,238 processes of the ecoinvent database with residual electricity mixes on the corresponding voltage level. The ecoinvent database provides residual electricity mixes for all countries involved in European trade with market-based energy attribute certificates—Guarantees of Origin. We analyze the induced changes to the database both on an individual process level and on a database-wide level. The analysis focusses on the impact category climate change but is further extended to the impact categories terrestrial acidification, freshwater eutrophication, marine eutrophication, ozone depletion, and particulate matter formation.

Results and discussion For European processes, the implementation of the residual electricity mixes leads to average changes in the life cycle impact assessment (LCIA) results for climate change of 1%, 10%, 20%, and 50% for 2958, 733, 387, and 107 processes, respectively. Changes are especially pronounced for Norwegian and Icelandic processes due to the large differences among their location-based and residual electricity mixes. For the other analyzed impact categories, the changes in LCIA results are particularly high for freshwater eutrophication. With the push towards more primary data in LCA and GHG accounting, the impacts of using residual electricity mixes instead of location-based electricity mixes need further research on basis of quantified figures, which we present in this paper.

Conclusion This paper presents an approach towards enabling more consistent market-based accounting throughout LCAs and thereby contributes to the avoidance of double counting. Since only European residual mixes are considered, the database of this paper leads to distortion of LCA results. Further, research is needed to address double counting beyond the European electricity sector. This includes an expansion of this research to a global level and other industrial sectors. Furthermore, research is needed regarding industry-specific electricity sources in LCI datasets, which may also lead to double counting.

Keywords Life cycle assessment (LCA) · Carbon footprint · Energy attribute certificates · Double counting · Market-based method · Residual electricity mix · Brightway 2

1 Introduction

Emissions associated with direct and indirect electricity consumption make up a large proportion of most carbon footprints and are also relevant for other environmental impacts as determined by life cycle assessments (LCAs) according to ISO 14040 and 14044 (Finkbeiner et al. 2006; Ryan et al. 2016; Siddik et al. 2020). For many products, the

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main emission share and also most electricity usage originates from the supply chain, which is typically modelled using average life cycle inventory (LCI) datasets provided by databases, such as Sphera or ecoinvent (Sphera Solution GmBH 2022; Wernet et al. 2016).

To determine emissions associated with purchased grid electricity, the Greenhouse Gas (GHG) Protocol specifies two different accounting methods: the location-based and the market-based method (WRI and WBCSD 2015). The location-based method bases grid electricity emission factors on the average physical consumption mix in the region of the electricity consumer. Every grid electricity consumer in a defined region must calculate electricity-related emissions according to the same emission factor. The market-based method relies on contractual agreements, such as energy attribute certificates (EACs), to enable a unique claim for electricity from specific energy sources, such as renewable energy sources (RES). When an electricity consumer acquires such contractual agreements, the emission factor for grid electricity consumption is based on the corresponding energy sources.

Market-based accounting is particularly relevant at the product level (European Commission 2021; ISO 2019; WRI and WBCSD 2011). Further, recent primary data sharing initiatives—Pathfinder, Catena-X, and Together for Sustainability—demand or recommend market-based accounting (Catena-X 2023; TfS 2022; WBCSD 2023). However, the market-based method is critically discussed in literature. Discussion points are, e.g., missing incentives for the expansion of electricity from RES, due to low prices for market-based contractual agreements and missing additionality criteria as well as reduced incentives for energy efficiency measures (Bjørn et al. 2022; Bogensperger and Zeiselmair 2020; Brander et al. 2018; Brander and Bjørn 2023; Hulshof et al. 2019). A further and related challenge for market-based accounting is double counting of electricity from specific energy sources, such as RES (Bjørn et al. 2022; Holzapfel et al. 2023).

To avoid double counting in market-based accounting, exclusively claimed energy attributes must be excluded from the regional average electricity mix (ISO 2019; WRI and WBCSD 2015). The result is a residual electricity mix that shall be used for all grid electricity consumption, for which no market-based contractual agreements are acquired.

The residual electricity mix plays no role in location-based accounting, where all grid electricity consumers use the same emission factor, regardless of the acquisition of market-based contractual agreements. Consequently, a parallel application of market-based and location-based accounting leads to double counting of electricity from specific sources, such as RES, and thereby an under- or overestimation of electricity-related environmental impacts (Holzapfel et al. 2023). To avoid double counting, either the market-based or location-based method must be applied consistently in LCA.

For the market-based method, a consistent method application is challenging because LCAs and GHG accounts rely on average background datasets from LCI databases, such as Sphera and ecoinvent, to fill data gaps. These datasets typically use location-based averages to model environmental impacts associated with grid electricity consumption when industry-specific data are not available (Sphera Solution GmBH 2022; Wernet et al. 2016). Thus, if a reporting entity uses the market-based method to account for supplier-specific electricity sources, such as RES, for own electricity consumption and average LCI datasets for processes without primary data access, both market-based and location-based methods are applied in the same LCA.

At a European level, the Association of Issuing Bodies (AIB) provides residual electricity mixes on an annual basis for each country in the European residual mix area—countries participating in the European EAC system, the Guarantee of Origin (GO) system (Association of Issuing Bodies 2023). Based on this, both ecoinvent and Sphera have recently added residual electricity mixes for the member states of the European residual mix area to their databases (ecoinvent 2022; Sphera Solution GmBH 2022). However, in both databases, these residual electricity mixes are not used as inputs for other LCI datasets.

To avoid double counting with the market-based method, Holzapfel et al. (2023) propose the replacement of location-based electricity with residual mixes in LCI datasets. To the best of our knowledge, currently no database exists that provides average LCI datasets using residual electricity mixes to model electricity related environmental impacts instead of location-based electricity mixes. The goal of this paper is to modify the ecoinvent database in order to generate such a database, analyze the corresponding effects, and critically discuss challenges for LCA implementation. To achieve this goal, we use the Python-based open-source LCA software package Brightway 2 and its Activity Browser (Mutel 2017; Steubing et al. 2020). To enable other LCA practitioners to use and further develop the created database, the developed Python script for the database modification is openly available.

In Sect. 2, we elaborate the materials and methods used to reach this goal. In Sect. 3, we compare the life cycle impact assessment (LCIA) results of the modified database to the LCIA results of the original database. In Sect. 4, we critically discuss our approach and provide directions for future research. Finally, conclusions are drawn in Sect. 5.

2 Materials and methods

Section 2.1 describes the data and geographical scope of this study. Second, the database modification procedure to replace location-based electricity mixes with residual mixes is explained in Sect. 2.2. Finally, Sect. 2.3 describes the procedure for analyzing the resulting database modification.

2.1 Data and geographical scope

The ecoinvent database provides both aggregated processes and unit processes (Wernet et al. 2016). In the Sphera database, most processes for public access are usually aggregated and would need specific agreements to be accessed on the unit process level due to intellectual property rights (Sphera Solution GmbH 2022). As the unit processes have to be changed during the database modification, the ecoinvent database is used for this study. More specifically, we use the ecoinvent database version 3.9.1 with the cutoff system model.

With the update to version 3.9, ecoinvent includes residual electricity mixes for all countries of the European residual mix area (ecoinvent 2022), which are based on data for 2021 provided by the Association of Issuing Bodies (2023). The only downstream consumers of these residual electricity mixes in ecoinvent 3.9.1 are other residual electricity mixes (e.g., electricity, high voltage, residual mix as input for electricity, medium voltage, residual mix). Thus, residual electricity mixes are not used in any other processes of the database. The electricity market mixes for all European countries except Switzerland are based on data from the International Energy Agency and reflect the situation in 2019 (ecoinvent 2022). The electricity market mixes for Switzerland are based on national statistics and reflect the situation in 2020.

Although Austria participates in the GO system, it does not have a residual electricity mix (Association of Issuing Bodies 2023), due to its mandatory full disclosure system for electricity (RIS 2013). In a full disclosure system, every unit of electricity produced and consumed must be tracked through market-based instruments. Thus, Austria's untracked electricity consumption is zero and, consequently, there is no residual electricity mix. However, even though all electricity is traced in Austria, the energy sources for electricity used in average LCI datasets are still unknown. Same as for all other countries, location-based electricity mixes are used to model electricity-related emissions in LCI datasets (ecoinvent 2022).

In order to enable a consistent application of the market-based method with average LCI datasets using Austrian grid electricity, we follow the conservative approach proposed by Holzapfel et al. (2023). As a substitute for the non-existent Austrian residual electricity mix, we calculate an average residual mix of the European residual mix area and add it to the database. This average European residual electricity mix is calculated by adding the individual country-specific residual electricity mixes to one process. The contribution of each country's residual electricity mix to the European average mix is determined by comparing the volume of the individual residual electricity mix to the total volume of all residual electricity mixes within the residual mix area (see Eq. 1). The necessary data are obtained from the Association of Issuing Bodies (2023).

$$\text{Contribution to average residual mix} = \frac{\text{volume of country's residual mix}}{\text{Total volume of all European residual mixes}} \tag{1}$$

Including the added average European residual mix as a substitute for the Austrian residual mix, the ecoinvent 3.9.1 database contains residual electricity mixes for all countries participating in the European GO system in 2021 (Association of Issuing Bodies 2023; ecoinvent 2022).

2.2 LCI database modification—replacing location-based electricity consumption with residual electricity mixes

The ecoinvent database 3.9.1 provides country-specific grid electricity consumption mixes ("market for electricity") for low-voltage, medium-voltage, and high-voltage electricity consumption (ecoinvent 2022). Based on process-specific electricity demand, electricity consumption is modelled, using the applicable voltage level as input. The low-voltage network receives electricity from the medium-voltage network and the medium-voltage grid receives electricity from the high-voltage network. Thus, all three voltage levels are interconnected. Residual electricity mixes are also provided for these three voltage levels.

To achieve our goal of replacing European location-based electricity consumption with residual electricity mixes, we use the Python-based open-source LCA software package Brightway 2 and its Activity Browser (Mutel 2017; Steubing et al. 2020). The developed Python script analyzes all 21,238 processes in the ecoinvent database. Whenever a process has a location-based "market for electricity" process as input, the script evaluates if a residual electricity mix is available for the same location. If so, the location-based process is replaced by the corresponding residual electricity mix at the same voltage level as the original location-based "market for electricity" process. If no residual mix is available, the location-based electricity mix remains in place. This is the case if the "market for electricity" process has a location outside of the European residual mix area. The Python script to execute this replacement procedure as well as for the addition of the European average residual mix (see Sect. 2.1) is available via Zenodo at https://doi.org/10.5281/zenodo.8279972.

2.3 Life cycle impact assessment

To analyze and illustrate the impact of using European residual electricity mixes instead of location-based electricity mixes for all processes of the ecoinvent database, we compare the life cycle impact assessment (LCIA) results of the original database to the modified database. The comparison is conducted on two levels.

First, we examine the results at the single process level, illustrating the effects of the database modification for one specific process using the example of the process "silicon production, metallurgical grade." This process is chosen because it requires a large amount of electricity. Moreover, for this process, ecoinvent provides a specific process for Norway and a Rest of World (RoW) process. The difference between the average location-based electricity mix and the residual electricity mix is especially pronounced in Norway (Association of Issuing Bodies 2023; Wernet et al. 2016). We conduct two LCIAs of the processes with the impact category climate change global warming potential 100 (GWP 100)—IPCC 2021–GWP 100 (IPCC 2023). The first assessment employs the original ecoinvent database, while the second assessment uses the modified database.

Second, we assess the changes in LCIA results across the entire database. Therefore, we calculate LCIA results for all processes in both the original and the modified ecoinvent databases. For the LCIA, we use the standard amount, unit, and product of each process as a functional unit. For example, for the process "silicon production, metallurgical grade," the functional unit is 1 kg of silicon, metallurgical grade.

Since this study replaces the European "market for electricity," we investigate the changes in the European process with particular detail. Therefore, we split our analysis into processes from European locations and processes from non-European locations. The definition of European locations in this study includes all countries of the European residual mix area as well as the following regions: Europe without Austria; Europe without Switzerland; Europe without Switzerland and Austria; Europe, without Russia and Turkey; IAI Area, EU27 and EFTA; RER; RER w/o CH+DE; RER w/o RU; UCTE; and UCTE without Germany. To analyze the effects on different process types, such as mining, manufacturing, or power generation, we distinguish processes using the International Standard Industrial Classification of All Economic Activities (ISIC) as provided by ecoinvent (United Nations 2008).

As well as for the analysis of the exemplary process, the main focus of our analysis lies on the impact category climate change—IPCC 2021–GWP 100 (IPCC 2023). To demonstrate potential impacts of the database modification on impact categories other than GWP 100, we also perform an LCIA for the ReCiPe midpoint (H) impact categories: terrestrial acidification, climate change, freshwater eutrophication, marine eutrophication, ozone depletion, particulate matter formation (Huijbregts et al. 2017). These impact assessment methods and categories were chosen since they are well established and commonly used, without any specific rationale regarding the findings of the study.

In addition to the environmental impacts, we determine the total amount of electricity that is consumed within the entire supply chain of each process via a contribution analysis. We add up all process inputs that have kilowatt hour as a unit and have the terms "electricity" and/or "power" in the activity name. To gain deeper insights into the impacts of European electricity consumption, we distinguish between electricity from European and non-European locations.

3 Results

The results section is divided into three parts. The first two sections are dedicated to analyzing the effects of the database modification on the impact category GWP 100. Specifically, Sect. 3.1 focuses on the database modification's impact on the exemplary process "silicon production, metallurgical grade," while Sect. 3.2 analyzes the broader implications for the entire database. In Sect. 3.3, we explore the effects of the database modification on impact categories other than GWP 100.

3.1 Impacts on the exemplary process "silicon production, metallurgical grade"

This section explores the impacts of modifying the database on a process level by means of the exemplary process "silicon production, metallurgical grade." The ecoinvent database provides two variations of this process: one specific to Norway (NO) and another representing an average RoW process. The functional unit of both processes is 1 kg of silicon metallurgical grade. Figure 1 shows a comparison of the GWP 100 for both processes, employing both the original ecoinvent database and the modified database, which uses European residual electricity mixes instead of location-based electricity mixes.

In the case of the Norwegian process, the total GWP 100 increases by 98% when using the modified database compared to the original database. The RoW process exhibits only minor changes of around 1%. With the original database, sourcing silicon from Norway, and consequently

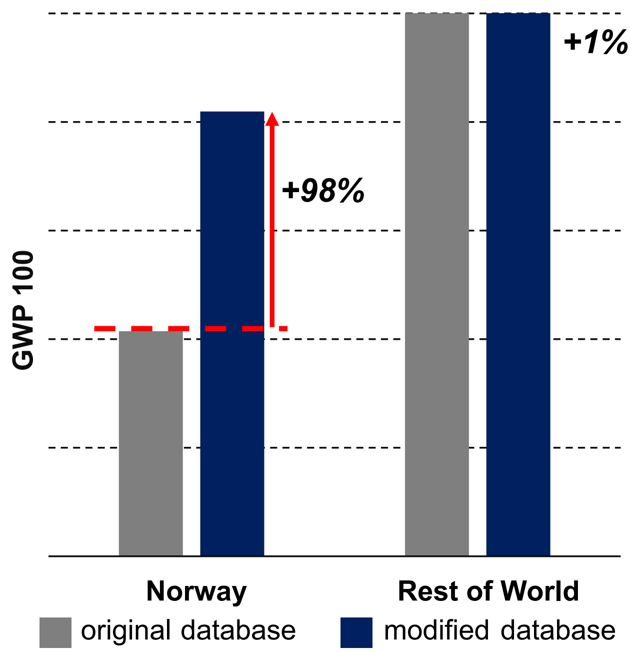


Fig. 1 Comparison of the GWP 100 results for the exemplary process "silicon production, metallurgical grade (NO and RoW)", using both the original ecoinvent database and the modified database

selecting the specific Norwegian process, results in an almost 60% reduction in GWP 100 compared to the RoW process. However, with the modified database, the GWP 100 of the Norwegian process is only 19% lower than that of the RoW process.

The influence on the RoW process is minimal because this study only considers residual electricity mixes of the European residual mix area. Consequently, changing the default electricity mix from location-based average electricity mixes to residual electricity mixes does not significantly affect the electricity-related environmental impacts in these regions. The ecoinvent database does include residual electricity mixes for Norway. For medium voltage electricity consumption, which is used in this process, the Norwegian residual electricity mix has a GWP 100 per kilowatt hour that is more than 17 times higher than the location-based electricity consumption mix (ecoinvent 2022). Figure S1 in the supplementary material shows a comparison of location-based electricity consumption mixes and residual electricity mixes for all countries of the European residual mix area on all three voltage levels.

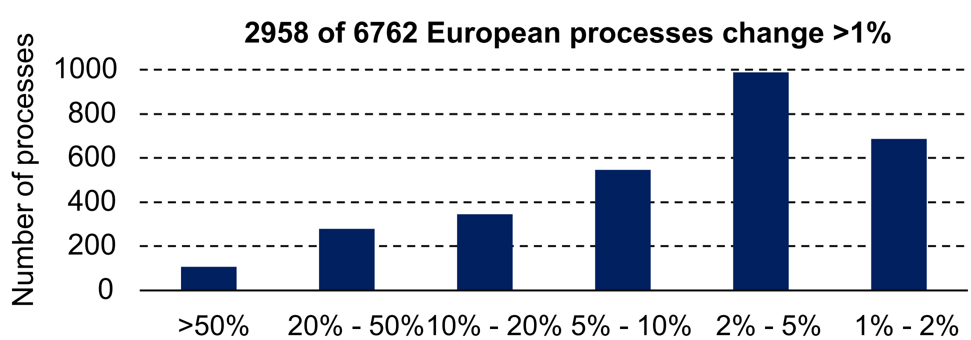
In the original process, electricity consumption accounts for less than 6% of the total GWP 100, whereas in the modified process, electricity consumption is the main contributor in Norwegian silicon production, accounting for more than 53% of the total. Consequently, the share of other emission sources in the total GWP 100 is lower in the modified database than in the original database, leading to a decrease of approximately 50% in the emission sources other than electricity consumption. For instance, the contribution of direct process emissions decreases from 69% in the original database to 34% in the modified database, and the emissions related to the input of coke decreases from 10.8 to 5.35%. Figure S2 in the supplementary material shows a contribution analysis of GWP 100 of Norwegian silicon production in the form of Sankey diagrams, both for the original database and the modified database.

3.2 Database analysis in terms of GWP 100

This section analyzes changes to all processes in the ecoinvent database caused by the electricity mix replacement procedure for the impact category GWP 100. The impact on European processes (as defined in Sect. 2.2) is significantly more pronounced than for the non-European processes. For the 6212 European processes in the ecoinvent database, the average change in GWP 100 is 7.6%, while for the other 14,476 non-European processes, it is only 0.9%. At an European level, 44% of all processes change by more than 1% as a result of the database modification. Of these processes, 733 change by more than 10%, out of which 387 change by more than 20%, and 107 processes show particularly large changes of more than 50%. Figure 2 summarizes the effects on European processes. Figure S3 in the supplementary material summarizes the effects on non-European processes.

Figure 3 (left side) lists the 30 ISIC categories for all European processes, that exhibit the highest average relative change in GWP 100, along with the number of

Fig. 2 European processes categorized by relative change in GWP 100 and the number of processes per category



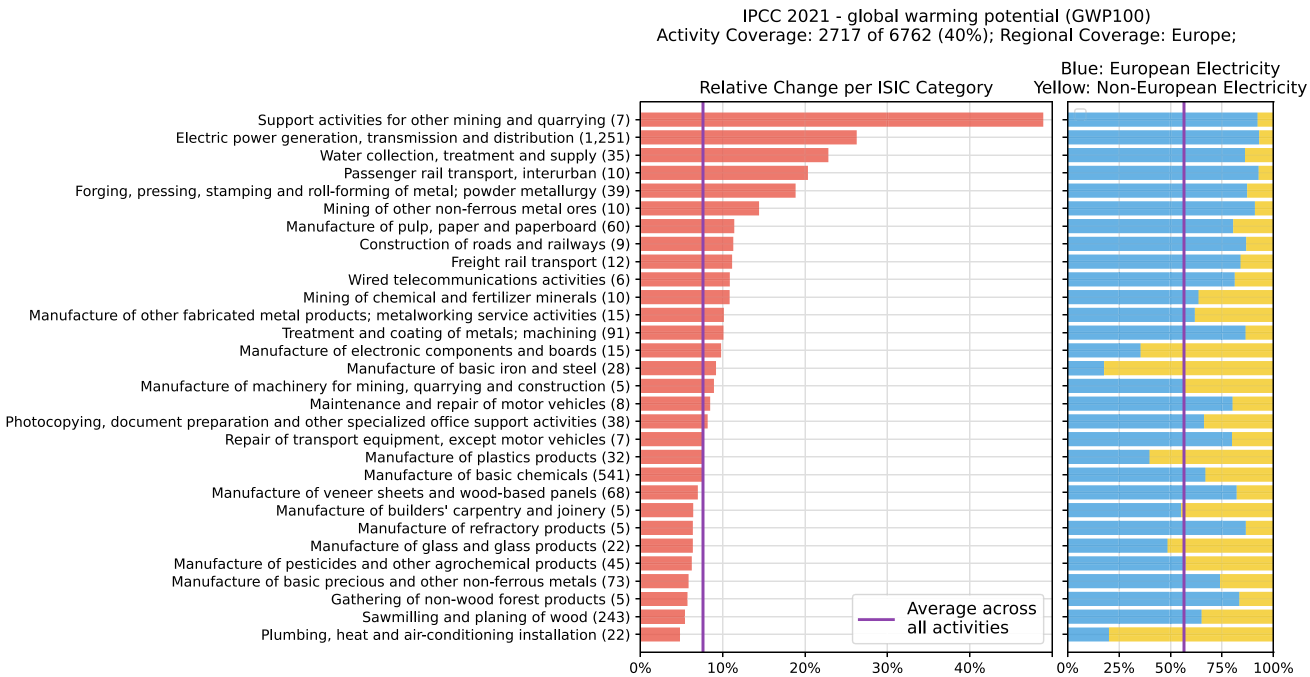


Fig. 3 Relative change in GWP 100 (left) and ratio of European electricity consumption from total electricity consumption (right), displaying the average change over all 6762 European processes (purple vertical line) and the change per ISIC category for the 30 ISIC categories with the highest average relative change in GWP 100; the number in brackets displays the number of processes per ISIC category

processes included in these categories. It also indicates the average relative change in GWP 100 across all European processes (purple vertical line). Figure 3 (right side) shows the share of European electricity consumption for each category.

In addition to the ISIC category "Electric power generation, transmission and distribution", the categories "Support activities for other mining and quarrying" and "Water collection, treatment and supply" are among the three categories most affected by the database modification. With an average change in GWP 100 of 49%, the changes in the ISIC category "Support activities for other mining and quarrying" are particularly pronounced. These are mainly drilling processes for geothermal power plants, which require a large amount of electricity.

With 160%, the database modification leads to especially great changes in the Icelandic process "deep well drilling, for deep geothermal power". Whereas the consumption of Icelandic electricity is responsible for 17.6% of the total GWP 100 in the original process, it is responsible for the majority of the GWP 100 in the residual electricity mix database, with 67.9%. This significant change can be attributed to the strong differences between the Icelandic location-based electricity mix and the residual mix. At high voltage level, the residual electricity mix has a GWP 100 eleven times higher than the location-based consumption mix.

The database modification leads to a change in 66% reduction in GWP 100 for the Swiss drilling process for "stimulation of deep well, for geothermal power," due to the lower GWP 100 (−66.2% at high voltage level) generated by the Swiss residual electricity mix compared to the location-based consumption mix.

The modified database results in a lower GWP 100 than the original one for 424 of the 1161 Swiss processes with positive GWP 100 values. As Swiss processes often consume electricity from other European countries along the supply chain, the overall GWP 100 still increases for 733 Swiss processes. For 682 Swiss processes, both the original database and the modified database result in a negative GWP 100, mainly due to energy recovery (e.g., waste treatment). For 586 of these processes the GWP 100 increases, meaning that the absolute value decreases. This is because the credit given for electricity recovery decreases as the residual electricity mix has a lower GWP 100. For 96 of these 682 processes with a negative GWP 100, the absolute value increases.

Next to Switzerland, the residual electricity mixes result in a lower GWP 100 than the location-based "market for electricity" consumption mixes for eight additional countries. For the other 25 countries in the residual mix area, the residual electricity mixes result in a higher GWP 100 than the consumption mixes, subsequently resulting in an overall increase in the GWP 100.

Figure S4 of the supporting material presents the same information as Fig. 3 for all non-European processes. Most non-European processes are only marginally affected by the database modification, as only the location-based average electricity mixes of the European residual mix area are replaced by residual electricity mixes. While on average 53% of the total electricity used in the supply chain of European processes originates from Europe, the average share of European electricity in non-European processes is only 8%. Besides the share of European electricity in overall electricity usage, also two other factors mainly determine the impact of the database modification on individual processes: the total emission share that is related to electricity consumption and the country-specific difference between location-based electricity mix and residual electricity mix.

3.3 Effects on other impact categories

In addition to the impact category climate change, other impact categories are also affected by the source of electricity consumption. Consequently, substituting location-based electricity consumption by residual electricity mixes also has an impact on the LCIA results of other impact categories. Figure 4 compares the average relative change over all European processes in the impact category climate change with the average relative changes in the impact categories terrestrial acidification, freshwater eutrophication, marine eutrophication, ozone depletion, and particulate matter formation.

The database modification leads to changes in all five analyzed impact categories. The changes in the impact categories terrestrial acidification, ozone depletion, and particulate matter formation are lower than for climate change, meaning the replacement with residual mix leads to fewer changes in these impact categories. Whereas the changes are larger for freshwater eutrophication and marine eutrophication, meaning that the replacement with residual electricity mixes leads to higher changes compared to GWP 100. The impact on freshwater eutrophication is especially pronounced with a change of 14.1%.

A main reason for these high changes in freshwater eutrophication is the high freshwater eutrophication value for electricity production from hard coal. For Germany, electricity from hard coal has a 23 times higher freshwater eutrophication value than the average of all other electricity production processes included in ecoinvent 3.9.1 (ecoinvent 2022). Electricity from hard coal makes up the main share of the German residual electricity mix (>41% on high voltage level). Further, the German residual electricity has a high contribution to the European attribute mix. For the process “electricity, high voltage, European attribute mix” German electricity from hard coal has the second highest share of all 155 electricity processes with almost 15%.

Figures S4 to S14 in the supplementary material provide a more detailed analysis of the induced changes in terms of each impact category. Similar to Fig. 3, these Figures display the relative change for each impact category alongside the share of European electricity consumption, categorized in terms of the ISIC categories.

4 Discussion

Section 4.1 provides a discussion regarding the use of electricity from specific energy sources in industry-specific LCI datasets and Sect. 4.2 provides a general discussion.

4.1 Electricity from specific sources in industry-specific LCI datasets

By substituting location-based electricity “market for electricity” mixes with residual electricity mixes throughout the ecoinvent database, this study presents an approach to drive the analysis towards more consistent market-based life cycle accounting with quantified results, while avoiding double counting. However, some ecoinvent processes include electricity consumption other than location-based “market for electricity” processes, such as industry-specific electricity mixes. One example is related to the aluminum industry. Ecoinvent 3.9.1 provides specific “market for electricity” processes for aluminum production in different regions, defined by the International Aluminium Institute (IAI) (ecoinvent 2022; International Aluminium Institut 2022). These processes are based on the available electricity consumption mix on the corresponding voltage level of aluminum-producing regions. The mixes can differ from the average country mix since aluminum is often produced in areas with a high availability of electricity. For the European process—IAI Area, EU27 and EFTA—the high-voltage electricity mix for the aluminum industry consists of ca.

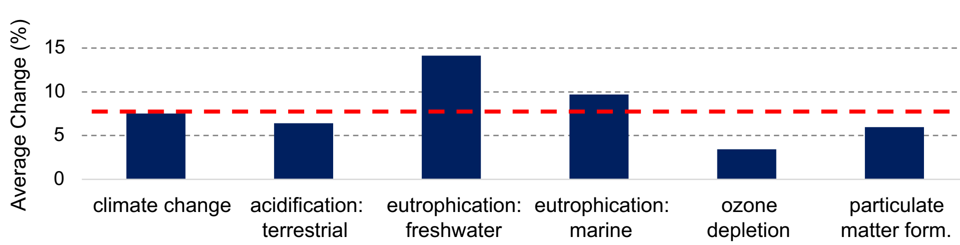


Fig. 4 Average relative change per impact category over all European processes

70% electricity production from hydropower, ca. 50% from Norway, and ca. 35% from Iceland. These electricity mixes are built with “electricity production” processes, instead of country-specific “market for electricity” processes. Thus, the replacement with residual electricity mixes does not take place in the main Python script of this study. Nevertheless, the process description of the aluminum industry-specific “market for electricity” processes corresponds to the location-based method. Thus, aluminum industry-specific processes can lead to double counting when applied in combination with market-based electricity accounting.

To illustrate the potential impacts of using residual electricity mixes in industry-specific LCI datasets, we provide an extension to the main Python script of this study. This script replaces the specific electricity production mixes contained in aluminum industry-specific electricity mixes with residual electricity mixes.

The “transmission network” processes are included on an aggregated level in the “market for electricity, high voltage, aluminum industry.” Thus, the first step is the calculation of residual electricity mixes “without transmission network”. A copy of each residual electricity mix is added to the database and the transmission network activities are deleted. Next, the script examines each specific electricity production process for the aluminum industry, such as “electricity production, hydro, aluminum industry.” For each electricity production input of this process, the script evaluates if a residual electricity mix is available for the process location. If yes, the specific electricity production process, e.g., “electricity production, hydro, reservoir, alpine region” (location: NO), is replaced with the country-specific residual electricity mix without transmission network (location: NO). If no residual electricity mix is available in the database, the original electricity production process remains in place. The Python script is available via Zenodo at https://doi.org/10.5281/zenodo.8279972.

Figure 5 shows the resulting differences in GWP 100 for the original database, the modified database and the modified database with extension for the processes “market for electricity, high voltage, aluminum industry” (functional unit: 1 kWh of electricity) and “aluminum production, primary, ingot” (1 kg of aluminum primary, ingot), both for the location IAI Area, EU27 and EFTA.

For the analyzed aluminum processes, the GWP 100 results of the original database and the modified database only differ by 2% and 1%, respectively, since the general replacement procedure of this study does not directly affect the aluminum-specific electricity mixes. However, the extended replacement process significantly influences GWP 100. For the process “market for electricity, high voltage, aluminum industry,” the GWP 100 increases by 180%. For the process “aluminum production, primary, ingot,” the GWP 100 rises by 64%.

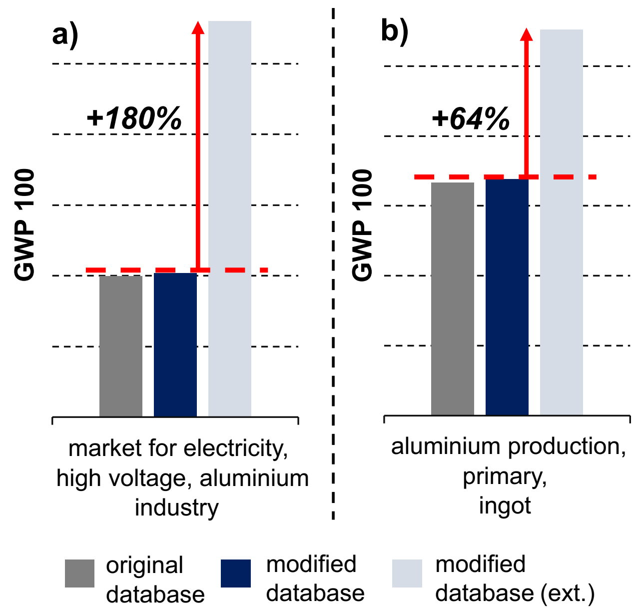


Fig. 5 Comparison of the GWP 100 results of the processes "market for electricity, high voltage, aluminum industry (**a**) and aluminum production, primary, ingot (**b**), location IAI Area, EU27 and EFTA", using the original database, the residual mix database, and the extended residual mix database

As demonstrated for the aluminum industry, the avoidance of double counting regarding industry-specific electricity mixes which are based on specific location-based consumption regions is challenging for market-based accounting. Moreover, even in the context of location-based accounting, the use of electricity mixes with different spatial granularity, as done in the case of the “market for electricity, high voltage, aluminum industry,” can lead to double counting. This stems from the fact that the specific electricity mix of the production region (e.g., the northern part of Norway for aluminum) is also accounted for in the average country electricity consumption mix, as elaborated by Holzapfel et al. (2023).

Industry-specific market-based electricity consumption mixes can play an important role in avoiding double counting and improving database consistency. For example, if it is known that all paper in a specific region is produced using electricity from RES with valid market-based certificates, there would be no risk of double counting if this industry-specific mix (100% electricity from RES) is used to model paper production from this region in the database. However, if electricity from RES is only acquired for 50% of the paper production in this region, there would still be a risk of double counting when using the industry-specific electricity mix (50% electricity from RES and 50% residual electricity mix) for modelling the average LCI datasets for paper from this region. Contractual agreements for electricity from RES could be counted once on a specific supplier level and once in the industry-specific mix. If paper consumers know that their supplier uses 100% electricity from RES, they might want to account for the specifically supplied paper using 100% electricity from RES. If paper consumers know that their supplier does not consume electricity from RES, they might be inclined to use an average LCI dataset which calculates environmental impacts using the industry-specific electricity mix (50% electricity from RES and 50% residual electricity mix).

Further research is necessary to avoid double counting while at the same time avoiding putting datasets of regions with a market-based electricity tracking system at a systematic disadvantage. Research regarding the question if and how industry-specific electricity sources should be included in industry-specific average LCI datasets is especially relevant.

4.2 General discussion

The results of this study show that, for many processes, changing from location-based electricity consumption to residual electricity mixes has a significant effect on the LCIA results. Residual electricity mixes mostly correspond to a higher GWP 100—and other environmental impacts—than location-based electricity consumption mixes of the same country. Consequently, this study's database modification generally results in higher environmental impacts and thus represents a variation of the database to support a remedy of open aspects "European vs. Non-European situation" and enables further quantitative validation on the impacts of industry- and region-specific data.

Replacing European location-based electricity consumption mixes with residual electricity mixes while leaving electricity consumption in other regions unchanged leads to a distortion of the database. Average environmental impacts of European processes in comparison to non-European processes are higher in the modified database of this study than in the original database. Placing generic LCI data sets from Europe at a disadvantage from an environmental optimization point of view.

However, not only Europe but also other regions are using or are starting to implement EAC systems. For major electricity markets, the USA and India both have a Renewable Energy Certificate (REC) system (Center for Resource Solutions 2023; Shrimali and Tirumalachetty 2013) and China has implemented a Green Electricity Certificate system (Hong et al. 2017). Additionally, there is a global REC system, known as the international REC (iREC) system. Especially the North American RECs system is frequently used to claim grid electricity from specific sources on an individual level.

To achieve a consistent database, residual electricity mixes need to be available and consistently used for all regions in which market-based contractual agreements allow the exclusive claiming of electricity from specific energy sources. Considering residual electricity mixes beyond Europe would especially impact the results of non-European processes, for specific regions with EAC systems. Further, the results of global processes, such as RoW, would be impacted. Consequently, also the RoW results for the exemplary process "silicon production, metallurgical grade" would be different (see Sect. 3.1).

Future research is needed to reliably calculate residual electricity mixes for all regions in which market-based contractual agreements are used and consistently use them in GHG accounting and LCA. As long as only European residual electricity mixes are available, practitioners need to be aware of the distortion coursed by using different types of electricity mixes for different geographical regions and address this transparently in corresponding studies.

As described in Sect. 2.1, Austria as a full disclosure country does not have a residual electricity mix, even though it is part of the European residual mix area. By taking the European average residual mix as a proxy in this study, we follow the conservative intermediate solution proposed by Holzapfel et al. (2023). However, this approach leads to potential inconsistencies since it bases Austrian electricity consumption in LCI datasets completely on non-Austrian electricity sources. Other options, which could be implemented on a short-term basis, would also be possible. For example, Austria's total supplier mix or a former residual mix could be used instead. Another option would be to leave the Austrian location-based market for electricity mix in place. Holzapfel et al. (2023) also address a mid- to long-term option of adopting the GO system to only account for electricity from RES. In this case, Austria would have a residual electricity mix which could be used for this study. Further research is needed to clarify if EACs should only be used for electricity from RES and which electricity mix should be used to model average LCI datasets in countries with a full tracking system in place.

It needs to be noted as a limitation of this study that European residual electricity mixes are based on data from 2021 and thus more recent data than the location-based electricity consumption in the ecoinvent database 3.9.1 (ecoinvent 2022). The European electricity market mixes represent the situation in 2019 and 2020 for Switzerland, respectively. The share of renewable energy in European electricity mixes is generally rising over time (Eurostat 2024). Thus, the differences between the original database and the database developed in this study would most likely be more pronounced if both market for electricity mixes and residual electricity mix were based on the same year.

Whereas electricity consumption mixes are technology-based and follow a relatively stable development, residual electricity mixes are market-based and can have larger variations from one year to another. Making the database dependent on residual electricity mixes from a specific year could hence lead to higher fluctuations in the LCI dataset and increase overall database uncertainty. This potential uncertainty should be addressed in future research.

Especially considering the recent push towards increasing the primary data share (PDS) in product carbon footprints, the use of conservative secondary data that avoids double counting is relevant. On an overarching level, the World Business Council for Sustainable Development (WBCSD) drives primary data sharing along the supply chain with the Pathfinder framework (WBCSD 2023). For the automotive industry and chemical industry, the initiatives Catena-X and Together for Sustainability (TfS), respectively, are pushing towards increasing the PDS and develop corresponding guidance documents (Catena-X 2023; TfS 2022). These initiatives demand or recommend market-based electricity accounting. It is likely that suppliers, aiming to reduce the carbon footprint of their products, will use EACs such as GOs to do so. Thus, the discrepancy between average location-based electricity mixes and residual electricity mixes is likely to further increase. Nevertheless, it needs to be addressed that primary data sharing for GHG accounting and LCA is still at an early stage. Especially small- and medium-sized companies often do not have access to primary data, whereas larger companies have more possibilities to acquire primary data from their suppliers.

It is important to generally differentiate if GHG accountings and LCAs follow the location-based or the market-based method and communicate transparently which method is used. However, GHG accounting and LCA are currently in a phase of mixing location-based average and market-based supplier-specific data. Market-based data is used if it is available (and often when it is beneficial for reducing environmental impacts). Otherwise, location-based data is used. The modified database of this study provides one step towards improving the consistency of market-based accounting, since it omits electricity which is claimed on an individual level from average database processes. However, the database of this study potentially puts European processes and products at a disadvantage if the approach is not globally applied. Until a global solution exists, one possibility could be to publish both the results using the original (location-based) database and the database with residual electricity mixes as default if the market-based method is generally applied in an LCA or GHG accounting. Purely location-based studies do not allow the claiming of grid electricity from specific sources. Thus, the modified database would distort results and should consequently not be used.

The approach of this study provides a potential solution towards avoiding double counting with market-based electricity accounting. However, double counting is not only an issue in the electricity sector. The GHG protocol also allows the use of contractual agreements to claim the use of energy from specific sources for steam, heat, and cooling energy systems (WRI and WBCSD 2015). The rising relevance of green hydrogen and biogases is likely to increase the use of contractual agreements in gas networks (Velazquez Abad and Dodds 2020). With the push towards primary data sharing in the supply chain, industrial averages for materials, parts, or products, which are used as secondary data, are also at risk of double counting. If materials, parts, or products are claimed as primary data by individual companies, their inclusion in average mixes that are used by all companies that did not acquire primary data leads to double counting challenges. Future research needs to be conducted on how to address these issues in LCA and GHG accounting.

5 Conclusion

We use the Python-based LCA software package Brightway 2 to replace European location-based electricity consumption with residual electricity mixes for all processes of the ecoinvent database. Thereby, this study provides an approach towards enabling more consistent market-based electricity accounting throughout an LCA. Thereby, it contributes to the avoidance of double counting of electricity from specific sources. The Python script is available via Zenodo at https://doi.org/10.5281/zenodo.8279972.

The changes, induced by the database modification, are most pronounced for processes located in countries with high differences between the location-based electricity mix and the residual electricity mix, such as Norway or Iceland. Besides GWP 100, other impact categories are also affected by the database modification. The changes are particularly pronounced for the impact category freshwater eutrophication. To improve the consistency of electricity accounting in LCI datasets, research is needed regarding the question if and how industry-specific electricity sources can be included in average LCI datasets is necessary. Furthermore, research is needed to address double counting beyond the European electricity sector. This includes an expansion of this research to other global regions and other industrial sectors.

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Data availability The authors declare that all data supporting the findings of this study are available as stated within this published article (and its supplementary material). The developed Python code for the database modification is available via Zenodo at https://doi.org/10.5281/zenodo.8279972.

Declarations

Conflict of interest The authors declare no competing interests.

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