Die Bodenkultur: Journal of Land Management, Food and Environment
Volume 72, Issue 3, 113–121, 2021. DOI: 10.2478/boku-2021-0012
ISSN: 0006-5471 online, https://content.sciendo.com/view/journals/boku/boku-overview.xml

SPECIAL ISSUE
with invited papers from the 48th International Symposium "Actual tasks on Agricultural Engineering" (ATAE), March 2–4, 2021, Zagreb, Croatia, http://atae.agr.hr/, Editor: Prof. Andreas Gronauer

Comparison of a system expansion and allocation approach for the handling of multi-output processes in life cycle assessment – a case study for nano-cellulose and biogas production from elephant manure

Vergleich des Systemerweiterungs- und Allokationsansatzes für das Umgehen mit Multi-Outputs in der Ökobilanz – Fallstudie über die Produktion von Nano-Zellulose und Biogas aus Elefantendung

Theresa Krexner, Iris Kral*, Andreas Gronauer,
Francisco Javier Medel-Jiménez, Alexander Bauer

Institute of Agricultural Engineering, University of Natural Resources and Life Sciences Vienna, Peter-Jordan-Straße 82, 1190 Vienna, Austria
* Corresponding author: iris.kral@boku.ac.at

Received: 31 August 2021, received in revised form: 17 October 2021, accepted: 18 October 2021

Summary

The handling of multi-outputs in life cycle assessment (LCA) is a controversial topic in both LCA application practice and the literature. Although there is a prescribed hierarchy of how to deal with multi-outputs, which favors system expansion (including co-products and their upstream chains) as the most scientific solution over the allocation approach (dividing environmental impacts based on an allocation factor), the latter is still most common. In this study, system expansion, mass, economic, and energy-based allocation are studied within a biosystem engineering case study, which provides two marketable outputs, biogas and nano-cellulose. The global warming potential (GWP) is used as basis for comparison. There is hardly any difference between system expansion and economic allocation, but it is also shown how problematic the latter approach is for newly introduced products because the market price is still very high and not representative. Results show that the GWP with mass allocation has the lowest impact; however, this approach is inappropriate since the outputs are a solid product and biogas, which are hard to compare based on a mass basis. Overall, based on the studied approach, results can be significantly different. Hence, it is recommended to avoid comparison and interpretation of results when using different modeling approaches.

Keywords: life cycle assessment, system expansion, utilization equality, allocation

Zusammenfassung

Der Umgang mit Multi-Outputs in der Ökobilanz (LCA) ist sowohl in der Anwendungspraxis als auch in der Literatur ein kontroverses Thema. Obwohl es eine vorgegebene Hierarchie gibt wie mit Multi-Outputs umzugehen ist, die die Systemerweiterung (unter Einbeziehung der Co-Produkte und ihrer Vorketten) als wissenschaftlichste Lösung gegenüber dem Allokationsansatz (Aufteilung der Umweltauswirkungen anhand eines Allokationsfaktors) favorisiert, ist letztere immer noch am weitesten verbreitet. In dieser Studie werden Systemerweiterung, Massen- und ökonomische Allokation sowie Allokation basierend auf dem Energiegehalt auf eine biosystemtechnische Fallstudie angewendet, die zwei marktfähige Outputs, Biogas und Nano-Zellulose, liefert. Das globale Treibhausgaspotenzial (GWP) wird zum Vergleich dieser Ansätze als Basis verwendet. Es gibt kaum einen Unterschied zwischen Systemerweiterung und ökonomischer Allokation, jedoch wird gezeigt, wie problematisch der letztere Ansatz für neu eingeführte Produkte ist, da der Marktpreis noch sehr hoch und nicht repräsentativ ist. Obwohl die Ergebnisse zeigen, dass das GWP mit Massenallokation die geringste Auswirkung hat, ist die Anwendung dieses Ansatzes ungeeignet, da es sich bei den Outputs um ein festes Produkt und ein Biogas handelt, die auf einer Massenbasis schwer zu vergleichen sind. Insgesamt wird gezeigt, dass es Unterschiede in den Ergebnissen der untersuchten Ansätze gibt. Insbesondere die Interpretation und der Vergleich von Ergebnissen, die auf unterschiedlichen Ansätzen basieren, sollte vermieden werden.

Schlagwörter: Ökobilanz, Systemerweiterung, Nutzengleichheit, Allokation

Open Access. © 2021 Theresa Krexner, Iris Kral, Andreas Gronauer, Francisco Javier Medel Jimenez, Alexander Bauer, published by Sciendo. BY-NC-ND
This work is licensed under the Creative Commons Attribution-NonCommercial-NoDerivatives 3.0 License.
https://doi.org/10.2478/boku-2021-0012

1. Introduction

Nowadays, most (industrial) processes yield more than one product. Co-production is particularly common in the chemical industry, petroleum refining, metal extraction, and agriculture (Grahl and Klöpffer, 2009). In life cycle assessment (LCA), which is a well-established method that quantifies the environmental impacts of a product or a service throughout its whole life span, this co-production of products leads to a controversial issue (Weidema and Schmidt, 2010), since a distribution of inputs and outputs has to be made between these co-products (ISO, 2006a). Although the ISO standard 14044 (ISO, 2006b) specifies a hierarchy of approaches on how to distribute such inputs and outputs, this demand can be interpreted differently by practitioners (Weidema, 2014). The ISO standard 14044 states that allocation should be avoided where possible (ISO, 2006b), which can be interpreted that this hierarchy is just a recommendation due to the use of the word "should" (Weidema, 2014). Although it is already stated in literature that the choice of the allocation parameter cannot be justified scientifically (Grahl and Klöpffer, 2009; Frischknecht, 2020), allocation is still frequently used to handle multi-output processes in attributional LCAs (Thomassen et al., 2008). Another issue why the allocation problem is such a controversial topic is that the choice of allocation factors which can be, for example, based on mass or economic values has a big impact on the results (Jolliet et al., 2016; Frischknecht, 2020). If various allocation approaches are suitable in a product system, a sensitivity analysis shall be used to demonstrate the impact of the choice (ISO, 2006b), which is often not implemented in practice. The purpose of this study is to show how the different approaches dealing with multi-output processes are to be used for a specific biosystem engineering case study and what influence these approaches have on the results. For this purpose, the global warming potential (GWP), and hence, the carbon footprint of the system are assessed. Furthermore, the methodological differences regarding, for example, system boundary or functional unit shall be examined. This study is partially based on the master thesis Krexner (2020) and the paper Krexner et al. (2022), where a comprehensive LCA about nano-cellulose and biogas production was conducted, also covering the state of the art of LCA of nano-cellulose production. In this study, the focus lies on the different multi-output approaches.

2. Materials and methods

2.1 LCA approach

LCA is a well-established method to assess the environmental impacts of a product or a service throughout its entire life span (e.g., production of raw materials, manufacturing, use, end-of-life treatment, recycling, and disposal of the product) and is based on the ISO standards 14040 (ISO, 2006a) and 14044 (ISO, 2006b). The four phases of an LCA that are defined in the ISO standard 14040 (ISO, 2006a) are: 1) the goal and scope definition that expresses the framework of the study design, like defining the functional unit, the system boundaries, and allocation rule; 2) the life cycle inventory analysis is a comprehensive compilation of inputs and outputs and their associated emissions; 3) the life cycle impact assessment aims to calculate environmental impacts based on the inventory; and 4) interpretation of the results, which are used to derive conclusions from the analyzed product system.

In this study, a multi-output process is examined. Hence, the overall environmental impacts need to be distributed between those system outputs, unless they can be assigned to one specific product. The ISO standard 14044 (ISO, 2006b) determines in a section on how to handle multi-outputs that allocation should be avoided where possible. The first alternative is dividing a process into sub-processes and collecting input and output data related to these sub-processes. This approach is only completely applicable if the sub-processes are physically separate in space and time, and thus, environmental data can be collected separately (Ekvall and Finnveden, 2001). Nevertheless, in most cases, processes will remain that are caused by more than one product. Hence, on the one hand, avoiding allocation by subdivision is rarely possible, and on the other hand, if it is theoretically possible, it needs detailed information about all sub-processes, which can be limited due to high financial costs for data collection (Ekvall and Finnveden, 2001; Frischknecht, 2020).

The second alternative stated by the ISO standard 14044 (ISO, 2006b) is the "system expansion" method to include additional functions related to the co-products. System expansion is especially used by comparative LCAs with high impacts on market shares to be expected. The system is expanded, so that every scenario meets the same system functions. Overall, there are two approaches for system expansion: 1) "utilization equality": here, the functional unit is expanded

with every additional output produced in one of the assessed systems. This leads to the fact that all studied scenarios need to be extended to include the production of all co-products to have a common system output in each scenario. Figure 1 shows, for example, product A is compared with product C, and the production of the first also produces co-product B. Hence, the comparative scenario needs to be extended to include an alternative production route, usually the most common one, for product B. If the production of product B would lead to another co-product, this would lead to the extension of system 1. Therefore, the system expansion approach can lead to big scenarios with substantially more research and data demand (Grahl and Klöpffer, 2009). 2) The second approach is called "avoided burden principle," in which the extension of the functional unit is not mandatory due to the use of credits. This is due to the fact that the environmental impacts of an alternative production process for the production of the co-product are subtracted from the multi-output process. Figure 2 shows that the simple comparison between product A and product C can remain with this approach.

Both approaches have in common that an alternative production process needs to be chosen for all co-products, which requires some arbitrariness (Grahl and Klöpffer, 2009), but the choice should still always be well explained and should favor the most common production route. Nevertheless, the use of system expansion is recommended as the most scientific solution for multi-output processes (ISO, 2006b).

If allocation cannot be avoided, an allocation of environmental burdens based on an underlying physical relationship should be used. Where physical relationships cannot be used as allocation basis, another relationship between co-products should be used (e.g., mass, economic value, or energy content) (ISO, 2006b).

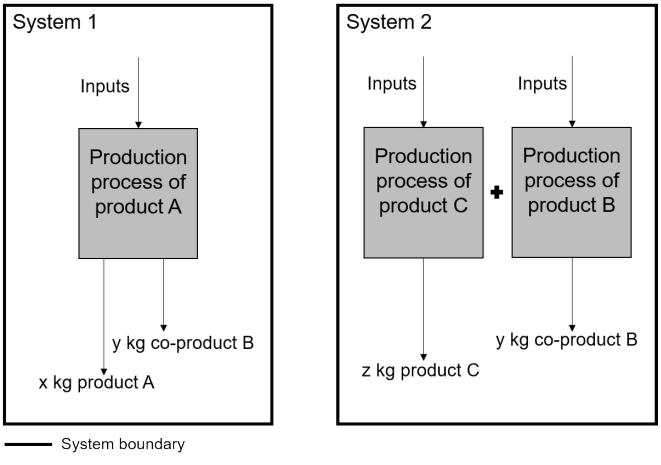


Figure 1. Overview of the "system expansion" approach based on utilization equality. Based on Grahl and Klöpffer (2009)
Abbildung 1. Überblick über den „Systemerweiterungsansatz" basierend auf „Nutzengleichheit"; basierend auf Grahl and Klöpffer (2009)

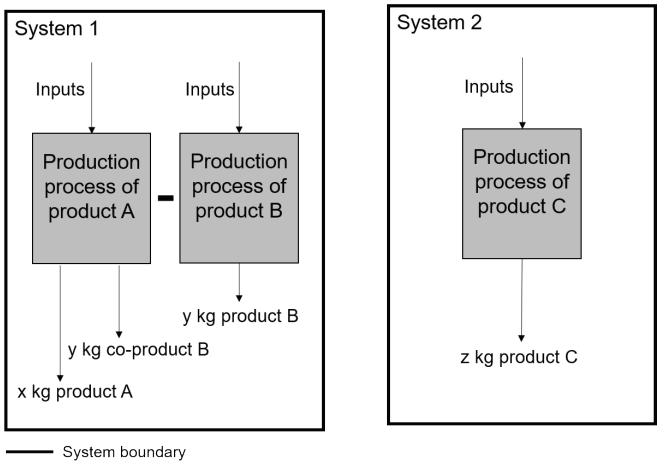


Figure 2. Overview of the "system expansion" approach based on the "avoided burden principle." Based on Grahl and Klöpffer (2009)
Abbildung 2. Überblick über den „Systemerweiterungsansatz" mit dem „avoided burden Prinzip", basierend auf Grahl and Klöpffer (2009)

2.2. Biosystem engineering case study – nano-cellulose and biogas production from elephant manure

The assessed case study is a new approach to produce nanofibrillated cellulose (NFC) from elephant manure. First, the manure is anaerobically fermented in a biogas plant, leading to biogas production as a co-product. Subsequently, the cellulose-containing fermentation residue is used to produce a pulp intermediate, which is then turned into NFC through a grinding step (Weiland et al., 2021) (see Figure 3 for the production route). The exact procedure is described in Weiland et al. (2021). In Krexner et al. (2022), a comprehensive LCA about the environmental impacts of this novel approach (labeled as manure scenario) compared to the status quo production of NFC from wood pulp (labeled as wood chips scenario) is assessed by using a system expansion approach.

As can be seen in Figure 3, the system provides two outputs, biogas and NFC. The main benefit is provided by NFC production; therefore, the functional unit, which is a reference to which all inputs, outputs, and therefore results are referring to (ISO, 2006a), is set to 1 kg of dry NFC. Process 2) biogas production provides two valuable outputs, biogas and the fermentation residue, which leads to the need to distribute inputs and outputs to the respective output. In sections 2.3 and 2.4, the different approaches of how to handle this multi-output process are explained in detail.

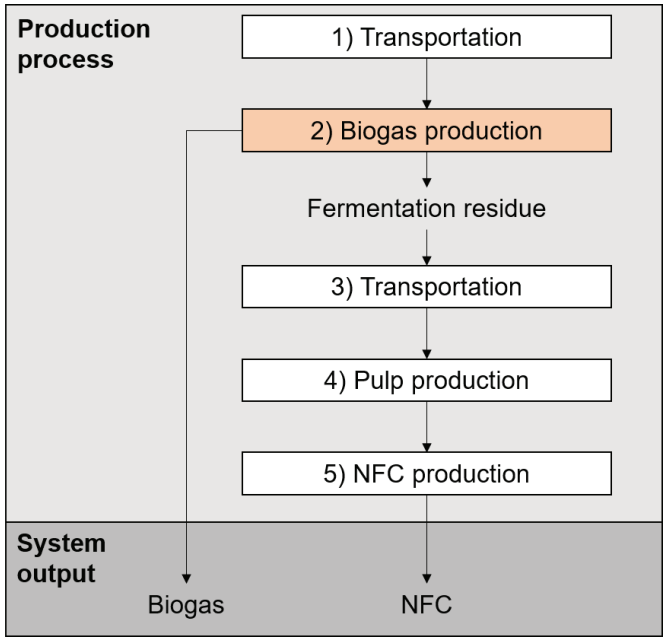


Figure 3. Overview of the new NFC production route with the valuable outputs biogas and NFC; the highlighted process 2) biogas production is the multi-output process within the production process
NFC, nanofibrillated cellulose
Abbildung 3. Überblick über den innovativen NFC Produktionsweg mit den vermarktbaren Outputs Biogas und NFC; der hervorgehobene Prozess 2) Biogas production ist der Multi-output Prozess des Produktionsprozesses

2.2.1. Software and database

OpenLCA version 1.10.3 (Green Delta GmbH, 2020) is used as modeling software with the Ecoinvent database version 3.6 (Wernet et al., 2016) and the impact assessment method ReCiPe2016 Midpoint (H) (Huijbregts et al., 2017) with the commonly used timeframe of 100 years (Goedkoop et al., 2013). The impact category climate change (GWP) is examined; hence, the carbon footprint of the case study system is assessed.

Table 1. Calculation of mass allocation factors based on the produced mass of biogas and NFC in 1 year
Tabelle 1. Berechnung der Massen-Allokationsfaktoren basierend auf der produzierten Masse von Biogas und NFC in einem Jahr

Output	Unit	Amount	Mass allocation factors
Biogas	Volume (m^3/year)	1,229,177*	
	Density (t/m^3)	0.0012	
	mass (t/year)	1475	0.757
NFC	mass (t/year)	472	0.243
Total	mass (t/year)	1947	

*Measured at 1013 mbar, 0°C
NFC, nanofibrillated cellulose

Table 2. Calculation of economic allocation factors based on the feed-in tariff for electricity from biogas plants and the market value of NFC
Tabelle 2. Berechnung der ökonomischen Allokationsfaktoren basierend auf dem Einspeisetarif für Strom aus Biogas und dem Marktwert von NFC

Output	Unit	Amount	Reference	Economic allocation factors
Biogas	Supply per year (kWhel/year)	2,827,851	Own calculation, see Table 3	
	Economic value (€/kWh_{el})	0.19	BMWFW (2018)	0.00073
	Total value (€)	537,291	Own calculation	
NFC	Mass per year (t/year)	472	Own calculation	
	Economic value (€/t)	1,560,233	Own calculation, see Table 4	
	Total value (€)	737,541,227	Own calculation	0.999
Total	Value of biogas and NFC (€)	738,078,519		

NFC, nanofibrillated cellulose

2.3. System expansion approach in the case study

In the system expansion approach, the system is expanded, so that both the outputs, the product NFC and the co-product biogas, are benefits obtained from the same system (Figure 4). Hence, the utilization of the system is the provision of NFC and biogas, which also leads to an extension of the functional unit with the additional benefit of biogas production, making it a multifunctional system.
The avoided burden principle is not applied in this publication, since it sometimes goes along with negative results, which lack practical viability (Krexner et al., 2021).

2.4. Allocation approach in the case study

It is important to note that when the allocation approach is used, the allocation must be performed consistently in all upstream process modules of the process with co-products (Grahl and Klöpffer, 2009). Hence, the inputs and outputs need to be distributed between NFC and biogas in the processes 1) transportation and 2) biogas production, and further in the pre-production of energy carriers, electricity, fuels, construction, and auxiliary materials. For this approach, the functional unit remains 1 kg of NFC, which means that the system is handled as a single-output system due to the application of the allocation approach (see Figure 5). In this study, the mass, economic, and energy content allocation are analyzed for applicability to this specific case study.

Table 3. Calculation of kW hel per year based on the biogas and methane content
Tabelle 3. Berechnung der kWhel pro Jahr basierend auf dem produzierten Biogas und dessen Methangehalt

	Unit	Amount	Reference
Biogas	Volume (m^3/year)	1,229,177	Krexner (2020)
Methane	Volume (m^3/year)	746,410	Krexner (2020)
	Energy content (kWh/m^3)	9.97	Fachagentur Nachwachsende Rohstoffe e.V. (2016)
CHP	Efficiency ($\%_{el}$)	38	Fachagentur Nachwachsende Rohstoffe e.V. (2016)
	(kWh_{el}/year)	2,827,851	Own calculation

CHP, combined heat and power

2.4.1. Mass allocation

In the mass allocation approach, all inputs and outputs are allocated according to the mass ratio of the resulting product and co-products (Grahl and Klöpffer, 2009). Hence, mass allocation factors are calculated for process 2) biogas production based on the mass of the end product NFC and the resulting mass of biogas, as can be seen in Table 1. As the fermentation residue is only an intermediate product, it is not considered as a basis for the calculation of the allocation factor. The used values refer to the production of biogas and NFC in 1 year. Data of the produced biogas and NFC is based on Krexner (2020).

Calculation of the mass allocation factors shows that around 75% of the inputs and outputs must be allocated to the biogas production.

2.4.2. Economic allocation

This allocation is weighted by economic value (measured by price) (Grahl and Klöpffer, 2009). Again, economic allocation factors are calculated for process 2) biogas production, based on the economic value of the produced biogas and NFC, as can be seen in Table 2. For economic allocation, the prices of the two end products (biogas and NFC) are taken as basis for calculation. As the fermentation residue is only an intermediate product, it is not taken into account here. The system does not define the use of biogas after leaving the process, and usually, biogas is not sold but used, for example, to produce electricity in a combined heat and power (CHP) unit or it is upgraded to natural gas quality. Therefore, the feed-in tariff for electricity from biogas plants from 2018 and 2019 (BMWFW, 2018) is averaged as a representative price. Data of the produced biogas with its methane content and fermentation residue is taken from Krexner (2020). The used values refer to the production of biogas and NFC in 1 year. For the exact conversion of m^3 biogas to kWh_{el}, see Table 3. The economic value of NFC is calculated with the prices of two different shops for 0.5 and 1 kg and averaged (for calculation, see Table 4). The prices obtained for NFC are quite high, which may be due to the novelty of NFC. The prices are further just for small packages (0.5 and 1 kg), so the economic value may not be representative for large production sites, as the one-product system modeled here. Nevertheless, as no other data are available, these prices are used.

Table 4. Calculation of average market price of NFC
Tabelle 4. Berechnung des durchschnittlichen Marktpreises von NFC

	Mass (kg)	Price (€)	Price (€/kg NFC)	Reference
NFC	1	794	794	Nanografi Nano Technology (2021)
	0.5	466	932	Nanografi Nano Technology (2021)
	0.5	1477	2954	Cellulose Lab (2019)
Mean			1560	

NFC, nanofibrillated cellulose

2.4.3. Allocation by energy content

The calculation of allocation factors in this approach is based on the calorific value of the products and is normally used for special applications (Grahl and Klöpffer, 2009). While this approach would be applicable for the co-product biogas, which has a high energy content, it is not applicable for NFC, since the main reason for NFC use is to take advantage of its special physical and chemical properties and not to exploit its low energy content. Hence, this allocation approach is not applied in this study.

3. Results and Discussion

The relative GWP of the overall system with the three different approaches of multi-output handling are shown in Figure 6. The absolute GWPs for the approaches are compared and the highest value is set to 100%. The lower values are shown as percentage share.

The overall system modeled with the system expansion approach has the highest GWP impact. While the difference in GWP calculated with the system expansion and the economic allocation approach (GWP 0.02% lower) is negligible, and hence is not visible in the diagram, the mass

Table 5. Comparison of GWPs of the overall system, the biogas and NFC production with the system expansion, mass allocation, and economic allocation approaches
Tabelle 5. Vergleich des Treibhausgaspotenzials (GWP) des Gesamtsystems, der Biogas- und NFC-Produktion mit dem „Systemerweiterungs"-, Massenallokations- und ökonomischen Allokationsansatzes

	System expansion	Mass allocation	Economic allocation
	(kg CO_2 eq./kg NFC)		
Overall system	4.30	3.62	4.30
5%–95% Interpercentile range	3.92–5.09	3.25–4.29	3.96–5.08
Biogas production	0.90	0.22	0.90
NFC production	3.40	3.40	3.40

NFC, nanofibrillated cellulose

allocation approach shows a reduction of 15.9%. Overall, the difference between mass allocation and the other approaches is solely due to the mass allocation factors which assign only 24.3% of the environmental impact of the biogas production to the overall production of NFC.

The absolute values of the GWP of the overall system, but also the contributions of the biogas and NFC production parts for a more detailed comparison of results with the different approaches are shown in Table 5. The values shown in Table 5 for the mass and economic allocation refer to the GWPs that arise solely for the production of 1 kg of NFC (environmental impacts referring to the biogas production are allocated based on the calculated allocation factors, see Tables 1 and 2), while the values for the system expansion approach show the environmental impacts of the production of 1 kg NFC and the additional biogas.

The GWP of the NFC production part is the same in all three approaches, since the processes are solely used to produce NFC, making it a single-output process. The contribution of the biogas production to the overall GWP is 21% for the system expansion and economic allocation approaches, respectively, and only 5.09% in the mass allocation scenario. On the one hand, the large difference occurs because the system expansion approach considers the environmental impact of the production of two products, the NFC and the co-product biogas. On the other hand, in the economic allocation approach, the allocation factor is calculated based on the current market price. This is particularly difficult in this case because there are hardly any prices for pure biogas, but only for the products made from it (e.g., biogas with natural gas quality or electricity). Furthermore, NFC is a rather new

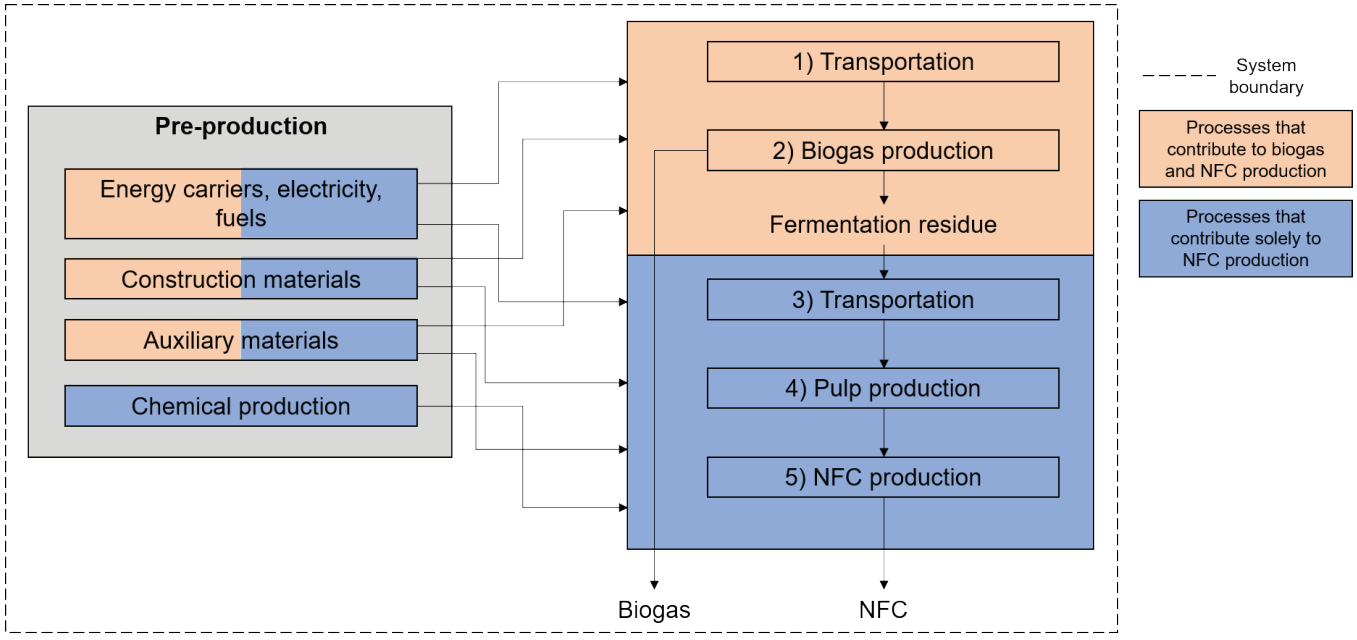


Figure 4. System diagram with the "system expansion" approach with "utilization equality." Both the outputs, the product NFC and the co-product biogas, are handled as outputs from the same system, making it a multi-output system. The dashed line illustrates the system boundary; orange processes contribute to biogas and NFC production and blue processes solely to NFC production
NFC, nanofibrillated cellulose
Abbildung 4. Systemdiagramm mit dem „Systemerweiterungsansatz" mit „Nutzengleichheit": Das System wird gesamtheitlich betrachtet und beinhaltet beide Outputs, NFC und das Koppelprodukt Biogas, was es zu einem Multi-output System macht; die gestrichelte Linie markiert die Systemgrenzen; orange Prozesse tragen zur Produktion von Biogas und NFC bei, blaue Prozesse nur zur NFC Produktion

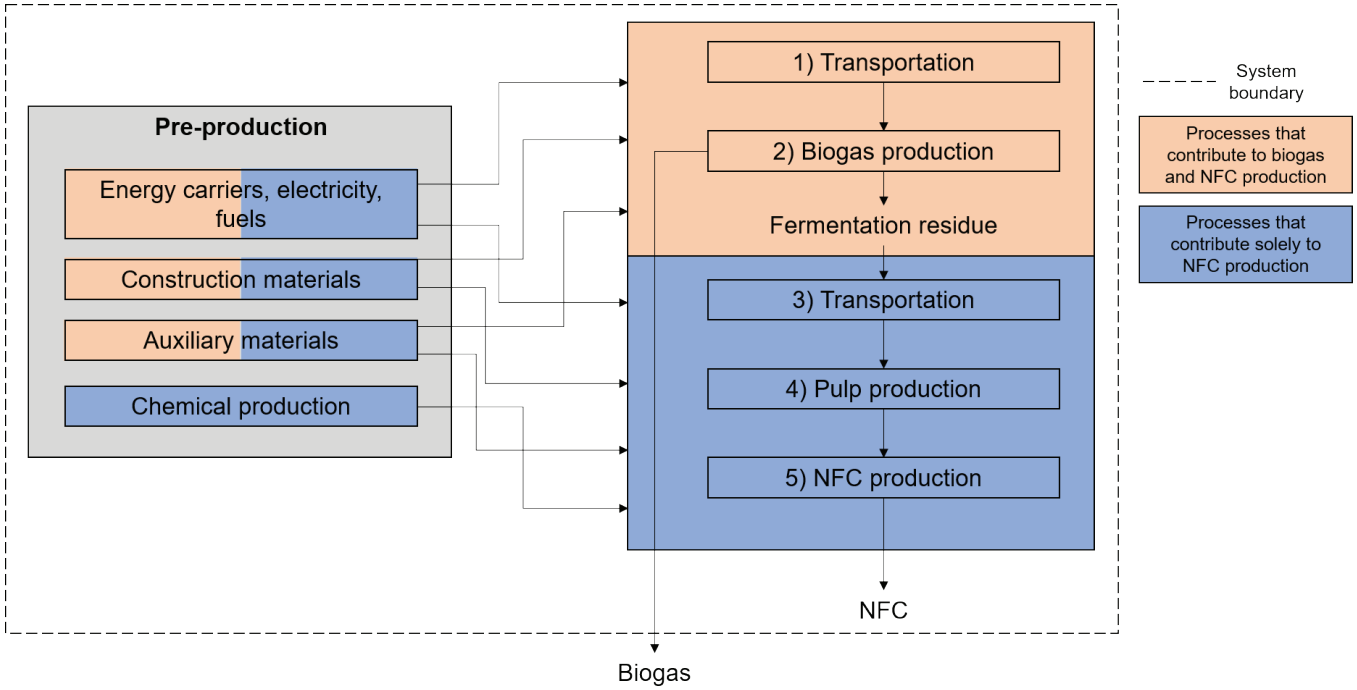


Figure 5. System diagram with the allocation approach. The system is handled like a single-output system due to the allocation approach with the product NFC. The dashed line illustrates the system boundaries; orange processes contribute to biogas and NFC production and blue processes solely to NFC production

NFC, nanofibrillated cellulose

Abbildung 5. Systemdiagramm mit dem Allokationsansatz: nur das Hauptprodukt NFC wird als Output betrachtet, die Umweltwirkungen des Biogases werden alloziert; orange Prozesse tragen zur Produktion von Biogas und NFC bei, blaue Prozesse nur zur NFC Produktion

product, which is hardly produced on a large scale yet, and therefore cannot benefit from the "economy of scale" so far, which makes the current price very high. LCA is often used to assess the environmental impacts of new products or technologies. If economic allocation is used, it refers to current market prices, which are often significantly higher for new products that have just been introduced to the market than for well-established products. Thus, a price is used that is not representative, shifting the environmental impacts often to novel technologies or products. Another argument that can be found in the literature against economic allocation is the fact that prices fluctuate over time and often differ in various locations (Ayer et al., 2007; Wardenaar et al., 2012).

The challenge of calculating mass allocation factors in this particular case study was that the co-products must be converted to the same unit. Here, biogas, which is actually expressed in liters or cubic meters, was converted to kilograms. The conversion into a mass unit and the comparison in this unit makes little sense for a gas compared to a solid product, especially since the value of the biogas lies within its energy content. The conversion of the NFC to energy content also serves little purpose since NFC is used as the basis material for further material exploitation and has a low energy content.

There are several studies reporting differences in results by handling multi-outputs in various ways (e.g., Flysjö et al., 2011; Wardenaar et al., 2012; Dalgaard et al., 2014). Cherubini et al. (2018) even found that the GWP representing the climate change impact category is the one affected the most by using different allocation approaches. Wardenaar et al. (2012) found in their bio-electricity case study that even in small systems, the choice of allocation approach has a substantial impact on results. Depending on the choice of allocation, a GWP reduction compared to a reference production chain from 16% to 60% was found. They further stated that if LCA as a method is used for policy-related purposes, the need for comparable results is high and results need to be highly robust and consistent, which is not the case while using different allocation approaches as they can produce very different results.

A solution to overcome both the price and unit problem is to apply the system expansion approach by including co-products in the functional unit. This approach could be especially useful for LCAs of new products or technologies, to be independent

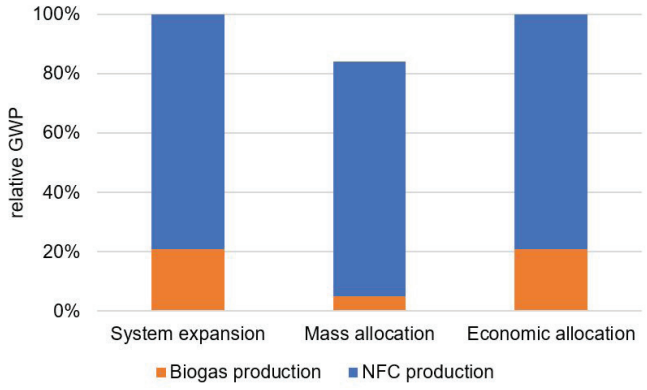


Figure 6. Relative GWP of the overall system with the different approaches of multi-output handling
GWP, global warming potential
Abbildung 6. Relatives Treibhausgaspotenzial (GWP) des Gesamtsystems für die verschiedenen Ansätze mit multi-outputs umzugehen

of market prices and their fluctuations. Further, only with the system expansion approach, the mass, energy, or elementary balances will remain intact, since only fully intact processes are taken into account (Weidema and Schmidt, 2010). Nevertheless, this approach can lead to big scenarios with substantially more research and data demand (Grahl and Klöpffer, 2009).
Overall, the choice of how to handle multi-outputs is still a very controversial topic. On the one hand, attention should be paid to providing a model of a system that is as holistic as possible, which also includes co-products. However, this is often associated with a considerable amount of additional research and data, and systems quickly become large and complex. To avoid such complicated systems, allocation can be applied. However, it should always be considered that any allocation factor has a large impact on the result. This is especially important not only for policy-related LCAs, but also for the economic allocation of newly introduced products, which do not yet have a representative market value. In the interpretation of results, that is, in the last step of any LCA, this should be considered. If several allocation approaches are possible, the influence of these approaches must be examined more closely in a sensitivity analysis, according to ISO 14044 (ISO, 2006b). Furthermore, when comparing LCAs, the approach of dealing with multi-outputs has to be taken into account. This is because even when the same allocation method is applied, still different results can be obtained (Wardenaar et al., 2012), highlighting the need for transparent and comprehensive descriptions of LCA studies.

4. Conclusion

The aim of the present study was to assess the GWP impacts of different methods to handle multi-outputs for an LCA case study with nano-cellulose and biogas as system outputs. Similar results were obtained for GWP when comparing a system expansion approach to economic allocation, but a 15.9% lower GWP was obtained when applying mass allocation. The latter is due to the fact that the allocation factor was calculated based on mass, in which the gaseous output biogas and the solid product NFC are difficult to compare. Therefore, 75% of the environmental burdens are allocated to biogas production. Problems of applying economic allocation occurred because for a rather new product with no representative market price, allocation factors cannot be calculated properly and/or change extensively over time and in different regions. This makes it hard to compare LCA results of different studies, even if all are using economic allocation. A third approach using energy content had to be discarded immediately as it is unfair to compare biogas (high energy content) against nanocellulose (very low energy content). Overall, it was shown that LCA results based on applying different methodological approaches of dealing with multi-outputs should not be compared with each other, since each approach has its own underlying purpose and advantages and disadvantages. Nevertheless, it was shown that the system expansion approach avoids problems related to allocation, including fluctuating market prices, subjective choice of allocation parameter with no scientific base, or using factors that do not reflect the purpose of the studied outputs properly. System expansion, however, needs higher data and research effort, and therefore resources. In the end, it is up to LCA experts to choose an approach that best suits a problem and justify the decision transparently.

Reference

Ayer, N. W., Tyedmers, P. H., Pelletier, N. L., Sonesson, U. and A. Scholz (2007): Co-product allocation in life cycle assessments of seafood production systems: Review of problems and strategies. The International Journal of Life Cycle Assessment 12, 480–487.

BMWFW (2018): Verordnung der Bundesministerin für Wissenschaft, Forschung und Wirtschaft über die Festsetzung der Einspeisetarife für die Abnahme elektrischer

Energie aus Ökostromanlagen für die Jahre 2018 und 2019 (Ökostrom-Einspeisetarifverordnung 2018 – ÖSET-VO 2018). StF: BGBl. II Nr. 408/2017.

Cellulose Lab (2019): 2019 Cellulose Lab Nanocellulose Products Price. https://www.celluloselab.com/wp-content/uploads/2019/05/CelluloseLab_Product_Price_List_2019.htm. Accessed on 05.07.2021.

Cherubini, E., Franco, D., Zanghelini, G. M. and S. R. Soares (2018): Uncertainty in LCA case study due to allocation approaches and life cycle impact assessment methods. The International Journal of Life Cycle Assessment 23, 2055–2070.

Dalgaard, R., Schmidt, J. and A. Flysjö (2014): Generic model for calculating carbon footprint of milk using four different life cycle assessment modelling approaches. Journal of Cleaner Production 73, 146–153.

Ekvall, T. and G. Finnveden (2001): Allocation in ISO 14041 – a critical review. Journal of Cleaner Production 9, 197–208.

Fachagentur Nachwachsende Rohstoffe e.V. (2016): Faustzahlen. https://biogas.fnr.de/daten-und-fakten/faustzahlen. Accessed on 28.06.2021.

Flysjö, A., Cederberg, C., Henriksson, M. and S. Ledgard (2011): How does co-product handling affect the carbon footprint of milk? Case study of milk production in New Zealand and Sweden. The International Journal of Life Cycle Assessment 16, 420–430.

Frischknecht, R. (2020): Sachbilanz. In: Lehrbuch der Ökobilanzierung. Springer Berlin, Heidelberg, pp. 43–100.

Goedkoop, M., Heijungs, R., Huijbregts, M., De Schryver, A., Struijs, J. and R. Van Zelm (2013): ReCiPe 2008: A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level. RVIM. https://www.rivm.nl/documenten/a-lcia-method-which-comprises-harmonised-category-indicators-at-midpoint-and-endpoint. Accessed on 21.01.2020.

Grahl, B. and W. Klöpffer (2009): Sachbilanz. In: Ökobilanz (LCA) – Ein Leitfaden für Ausbildung und Beruf. Wiley-VCH Verlag GmbH & Co. KGaA Weinheim, Germany, pp. 63-194.

Green Delta GmbH (2020): openLCA (Version 1.10.3). www.openlca.org.

Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., Hollander, A. and R. Van Zelm (2017): ReCiPe2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Bilthoven, The Netherlands. https://www.pre-sustainability.com/download/Report_ReCiPe_2017.pdf. Accessed on 21.01.2020.

ISO (2006a): Life cycle assessment – Principles and framework, EN ISO 14040:2006. Brussels: European Committee for Standardization.

ISO (2006b): Life cycle assessment – Requirements and guidelines, EN ISO 14044:2006. Brussels: European Committee for Standardization.

Jolliet, O., Saade-Sbeih, M., Shaked, S., Jolliet, A. and P. Crettaz (2016): Inventory Analysis of Emissions and Extractions. In: Environmental Life Cycle Assessment. CRC Press Boca Raton, pp. 47–104.

Krexner, T. (2020): Life cycle assessment of biogas and nano-cellulose production from elephant manure. Master thesis, University of Natural Resources and Life Sciences, Vienna.

Krexner, T., Bauer, A., Zollitsch, W., Weiland, K., Bismarck, A., Mautner, A., Medel-Jiménez, F., Gronauer, A. and I. Kral (2022): Environmental life cycle assessment of nano-cellulose and biogas production from elephant manure. Journal of Environmental Management 34, 115093.

Nanografi Nano Technology (2021): Cellulose Nanofiber (Cellulose Nanofibril, Nanofibrillated Cellulose, CNFs). https://nanografi.com/popular-products/cellulose-nanofiber-cellulose-nanofibril-nanofibrillated-cellulose-cnfs/. Accessed on 05.07.2021.

Thomassen, M. A., Dalgaard, R., Heijungs, R. and I. De Boer (2008): Attributional and consequential LCA of milk production. The International Journal of Life Cycle Assessment 13, 339–349.

Wardenaar, T., van Ruijven, T. W. J., Mendoza, A., Vad, K., Heijungs, R. and J. Guinée (2012): Differences between LCA for analysis and LCA for policy: A case study on the consequences of allocation choices in bio-energy policies. The International Journal of Life Cycle Assessment 17, 1059–1067.

Weidema, B. P. (2014): Has ISO 14040/44 Failed Its Role as a Standard for Life Cycle Assessment?. Journal of Industrial Ecology 18, 324–326.

Weidema, B. P. and J. H. Schmidt (2010): Avoiding Allocation in Life Cycle Assessment Revisited. Journal of Industrial Ecology 14, 192–195.

Weiland, K., Wlcek, B., Krexner, T., Kral, I., Kontturi, E., Mautner, A., Bauer, A. and A. Bismarck (2021): Excellence in excrements: Upcycling of herbivore manure into nanocellulose and biogas. ACS Sustainable Chemistry & Engineering 9, 15506–15513.

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E. and B. Weidema (2016): Ecoinvent database version 3.6. https://www.ecoinvent.org/.