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Comparative Life Cycle Assessment Of Conventionally Manufactured And Additive Remanufactured Electric Bicycle Motors

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Abstract

In a circular economy, remanufacturing is crucial in reducing the use of primary raw materials and energy compared to new production. However, poor availability of non-standardized wear components can impede remanufacturing. Additive manufacturing is a promising alternative to conventional manufacturing or spare part purchase for those wear components required for remanufacturing. However, there is uncertainty regarding the environmental impact of using additive manufacturing for remanufacturing. This paper compares conventional and additive spare parts manufacturing to evaluate the potential environmental savings using the example of remanufacturing electric bicycle motors. Therefore, a reference motor was selected, and its manufacturing processes were modeled in SimaPro using the ecoinvent 3.8 Life Cycle Assessment database and the latest knowledge on processing and manufacturing processes. The results show that conventional production of electric bicycle motors has a climate warming potential of around 28 kg CO2-eq. Additive remanufacturing of electric bicycle motors at the end of their life cycle offers significant environmental savings potential. The extent of savings depends on the condition of the used electric bicycle motor and, accordingly, the number of components that need to be replaced. According to the IPCC method for the electric bicycle motor investigated, the study estimates that approximately 90.4 % savings potential can be achieved in terms of Global Warming Potential.

Keywords

Remanufacturing; Life Cycle Assessment; Additive Manufacturing; Electric Bicycle Motors; Circular Economy

1. Introduction

In light of the growing global awareness of the urgent challenges associated with climate change, nations have adopted proactive measures to tackle greenhouse gas (GHG) emissions and strive towards achieving carbon neutrality. For instance, Germany enacted the Federal Climate Protection Act in June 2021, intending to reduce GHG emissions by 65% by 2030, relative to the levels observed in 1990 [1].

The Circular Economy (CE) presents a viable solution that promotes sustainable practices while stimulating economic growth by minimizing GHG emissions through optimized resource utilization and waste reduction [2]. At its core, CE seeks to decouple economic growth from the consumption of resources, thereby preventing resource depletion and the disposal of waste and recyclable materials. Hence, CE aims to maintain resources within the economic system for as long as possible. Therefore, End-of-Life (EoL) strategies are

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implemented, prolonging the lifespan of products and unlocking new value by preserving the resources invested in their manufacture [3].

Within this framework, remanufacturing emerges as a crucial solution for CE, offering a highly promising EoL strategy. By enabling a new life cycle for products and components, remanufacturing reduces the consumption of natural resources and mitigates waste generation [4,5].

However, the success of remanufacturing depends upon the availability of used parts and components, as well as spare parts [6]. Since the production and sale of used products can span several years, individual parts may not be readily obtainable due to production halts, expiration of the obligation to supply spare parts, or changes in the product portfolio.

In this specific context, Additive Manufacturing (AM) presents opportunities for remanufacturing components, including producing spare parts. The combination of AM and remanufacturing, known as additive remanufacturing (AdRem), represents a forward-thinking approach to supply chain management that ensures the availability of spare parts through AM techniques [7]. AdRem leverages the advantages of AM and remanufacturing, wherein AM either substitutes or complements traditional manufacturing methods [8,9]. However, no studies have yet been conducted using life cycle methodology to assess the environmental impact of AdRem. Therefore, this paper discusses quantifying the environmental benefits of remanufacturing with additive manufacturing compared to new production.

2. State of the Art

Over the past decades, LCAs (Life Cycle Assessment) have been conducted to evaluate the environmental impact of remanufactured products [10,11]. Several studies have investigated the environmental benefits of remanufacturing compared to newly manufactured automotive components [12–20]. Lee et al. and Gao et al. compared the energy consumption and pollutant emissions of newly manufactured and remanufactured turbochargers, demonstrating that remanufacturing significantly reduces various environmental impacts [13,15]. Schau et al. conducted a sustainability assessment of alternator remanufacturing and concluded that it could reduce emissions compared to producing new parts [17]. Studies also focused on remanufacturing automotive engines, revealing significant reductions in energy consumption and various environmental impacts [16,18]. Warsen et al. compared the environmental performance of newly manufactured and remanufactured transmissions, finding that the remanufactured product outperformed the newly manufactured one in all environmental impact categories [19]. Furthermore, due to the increasing number of electric vehicles in the automotive industry, the ecological footprint of remanufactured lithium-ion batteries is increasingly being analyzed in research [12,14,20].

In addition to automotive components, the ecological impact of remanufactured products in other sectors, such as construction, medical, and electrical equipment, is already being evaluated using LCA. The research consistently demonstrated the environmental benefits of remanufacturing regarding reduced resource consumption, greenhouse gas emissions, and various environmental impacts. [21–25]

Regarding advanced technologies, Zheng et al. assessed the environmental benefits of engine remanufacturing, comparing different restoring technologies, such as brush electroplating, arc spraying, and laser cladding, to new manufacturing. The study employed an LCA to analyze resource and energy consumption and evaluate environmental impact. The results reveal that advanced restoration technologies in engine remanufacturing can restore more damaged components and minimize environmental impacts by reducing raw material consumption. [26]

While environmental studies examining the cumulative impacts of remanufactured products through LCA exist, there remains uncertainty regarding the environmental impact of utilizing AM for remanufacturing purposes. Therefore, to our knowledge, this is the first work that compares conventional and additive spare parts manufacturing to evaluate the potential environmental savings of AdRem.

3. Methodology

For the evaluation of the environmental impacts based on a life cycle approach, an LCA was carried out. According to the definition of ISO 14044, an LCA is divided into four phases: Goal and scope definition, inventory analysis, impact assessment, and interpretation of results. [27]

3.1 Goal and scope definition

The LCA is intended to investigate and compare the environmental impacts of conventional manufacturing and remanufacturing of electric bicycle motors, focusing on AdRem of planetary wheels as spare parts in a cradle-to-gate approach. As a functional unit of the study, the EBS SGI-G V2 motor was selected as a representative example of electric bicycle hub motors, see Figure 1. The motor is a central component of an electric bicycle with a rated power of 250 watts.

Figure 1: Image of the EBS SGI-G V2 motor in closed (left) and open (right) state

The system boundary of the LCA regarding conventional manufacturing considers raw material extraction, material processing, component manufacturing, motor assembly, and necessary transportation to the customer. The remanufacturing process includes the transportation of the motor to the remanufacturing facility and back to the customer. Within the remanufacturing process, the steps of disassembly, cleaning, quality control, procurement of new parts, AdRem of spare parts, and reassembly are taken into account.

Since the primary goal of the LCA is to examine and compare the manufacturing processes, the use phase and disposal of electric bicycle motors are not included. According to the definition of remanufacturing, the remanufactured product should have at least the same performance and quality as a new product [28,29]. Therefore, ideally, no differences in environmental impacts should be observed during the use phase. The cutoff approach is chosen for recycling, and the environmental impacts of these processes are attributed to the new product, thus not considered in the LCA. Figure 2 illustrates the defined system boundaries in the process flow diagram of an electric bicycle motor.

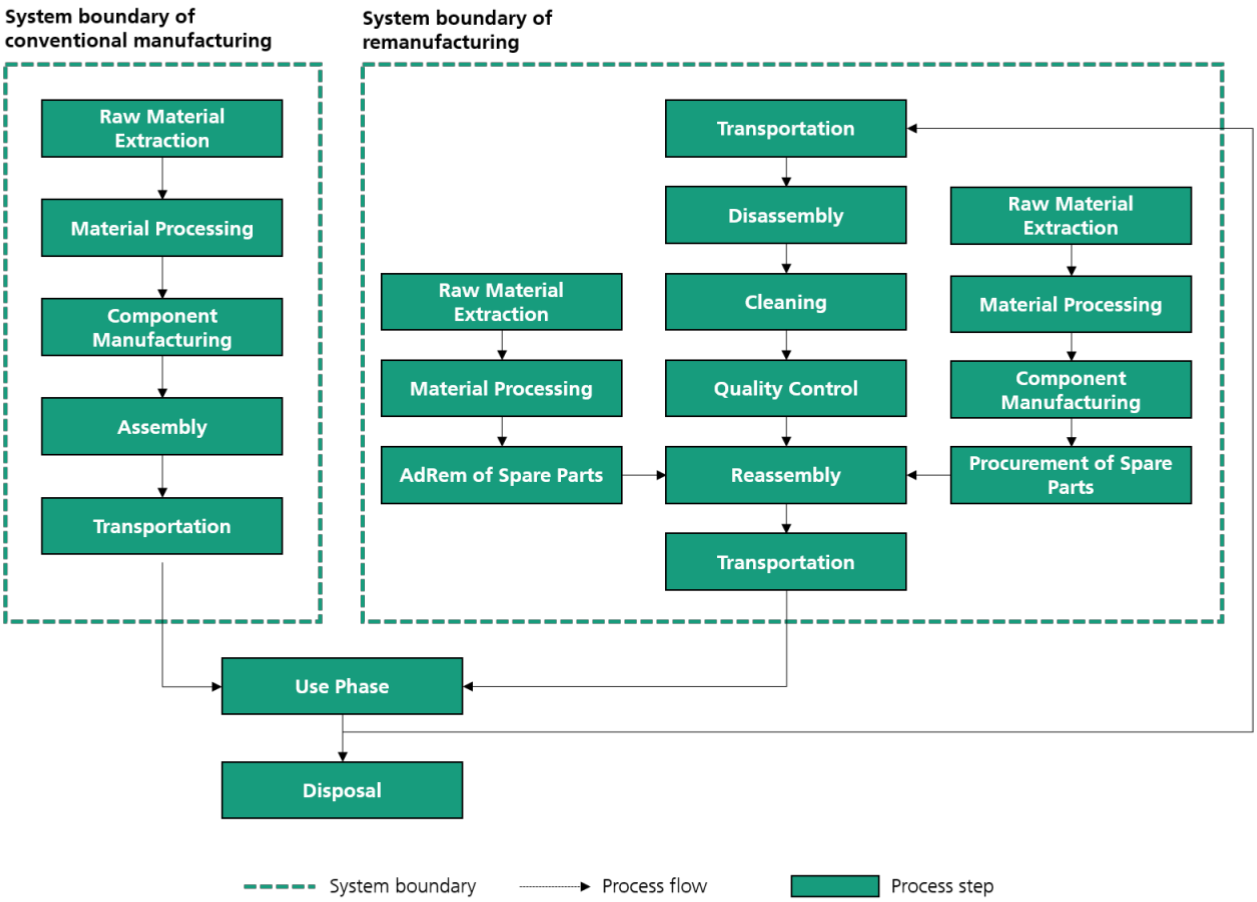

Figure 2: System boundary of conventionally manufactured and remanufactured electric bicycle motor

The LCA was modeled in SimaPro using the ecoinvent 3.8 Life Cycle Assessment database and the latest processing and manufacturing processes knowledge. The data for the LCA were obtained from experts, technical literature and journal entries, manufacturer information on machines, and analysis of electric bicycle motors.

3.2 Inventory analysis

During the disassembly process, the electric bicycle motor was separated into 28 components, and some parts were further destructed to enable a detailed weight analysis of the individual materials. Table 1 presents the components' names, quantities, weights, materials, and scrap rates. According to expert knowledge, the scrap rate column represents the estimated likelihood that the component will not be reused and will require replacement at the end of its lifespan.

Components with negligible environmental impacts due to their size, energy consumption, or weight can be cut off and excluded from consideration [27]. Hence, all components and materials weighing one gram or less were excluded. The bearings used in both motors partially contain a small proportion of plastic covers. The LCA does not consider this proportion, and the weight is assigned to the material steel.

Table 1: Component overview of the EBS SGI-G V2 motor

No.	Component	Quantity	Weight [grams]	Materials	Scrap rate
1	Shaft nut	2	8	Steel	5 %
2	Washer	2	8	Steel	100 %
3	Motor housing with ring gear	1	579	Aluminum (463 g) / Steel (116 g)	5 %

4	Bearing 6001RS	1	19	Steel	100 %
5	Washer	1	1	Steel	100 %
6	Circlip for planetary wheels	3	1	Steel	100 %
7	Planetary carrier	1	420	Steel	30 %
8	Bearing 6903RS	1	17	Steel	100 %
9	Bearing 6901RS	1	11	Steel	100 %
10	Cassette with freewheel	1	235	Steel	10 %
11	Case cover	1	101	Aluminum	5 %
12	Plastic cover winding package	1	10	PVC	< 5 %
13	Cover of circuit board	1	2	PVC	< 5 %
14	Sun gear	1	50	Steel	< 5 %
15	Circlip	1	< 1	Steel	100 %
16	Slot nut	1	1	Steel	0 %
17	Bearing 6902RS	2	18	Steels	100 %
18	Rotor (with magnets)	1	517	Steel (368 g) / Neodymium (149 g)	< 5 %
19	Plastic cover	1	1	PVC	< 5 %
20	Shaft seal	3	< 1	Rubber	100 %
21	Screw	30	28	Steel	100 %
22	Cover for nut	6	20	PVC	< 5 %
23	Nut	6	33	Steel	100 %
A	Planetary wheel*	3	70	Steel (37 g) / PVC (33 g)	10 %
B	Shaft with motor cable	1	210	Steel (176 g) /Copper (13 g) / PVC (21 g)	20 %
C	Stator with circuit board	1	796	Electrical Sheet (446 g) / Copper (186 g) / Aluminum (149 g) / Nylon (16 g)	< 5 %

* Process of AdRem used for manufacturing spare parts

The total weight of the components amounts to 3186 grams. The control unit required for the electric bicycle motor's operation is not integrated into the motor but exists as a separate module and is, therefore, not considered in the analysis.

3.3 Impact assessment

This LCA focuses on the Global Warming Potential (GWP), generally considered the most relevant impact category in the transportation sector [30]. The calculation method used is the IPCC 2021 GWP100 (including CO2 uptake), which quantifies the Global Temperature Potential (GTP) climate change factors of IPCC with a timeframe of 100 years, where carbon dioxide uptake and biogenic carbon dioxide emissions are explicitly included [31]. The life cycle inventory is based on the weight and material analysis of the components. Based on the material data, technical literature, company inquiries, and project data, conventional manufacturing, transportation, and remanufacturing processes were modeled in the LCA software SimaPro.

Conventional manufacturing includes producing all the components of the electric bicycle motor following the modeled processes of the electrical sheet, copper, steel, aluminum, magnets, and plastics (PVC and Nylon). In addition to these processes, transportation of the finished electric bicycle motor from China to Germany and the transport within Germany was also considered. Both transport activities are modeled with the ecoinvent processes “transport, freight, lorry >32 metric tons, EURO6 and transport, freight, sea, container ship based”.

For the remanufacturing process, the steps of disassembly, cleaning, quality control, procurement of new parts, AdRem of spare parts, and reassembly were considered. Disassembly and reassembly are performed manually by trained personnel. These processes were divided into 22 steps for the EBS SGI-G V2. Since the process involves purely manual operations and, according to Klöpffer, the manufacture of the production machines can be ignored, disassembly and reassembly are not considered in the LCA [32]. Also, the quality control process is not considered as no data was available, and no significant environmental impacts are expected. The cleaning process was modeled with the Pero R1 cleaning system. [33] The average energy consumption, solvent replacement, and batch size per electric bicycle motor were considered for modeling. The assumptions result in an energy consumption of 0.95 kWh and 6.2 ml of solvent per cleaned electric bicycle motor. Since ecoinvent does not offer a large variance of solvents, ethanol is used for modeling. For the production of AdRem spare parts, using the example of planetary gears, the UltiMaker 5S printer was used. [34] Due to the high requirements for production costs, elongation at break, and noise emissions of the planetary gears, nylon was selected as the printing material. In addition to the environmental impacts during the raw material extraction and material processing, energy consumption during printing was taken into account. The scrap rates of the individual components are used to model the average procurement of new parts and the associated average environmental impact. As with conventional manufacturing, transportation of the components from China to Germany and the transport within Germany was considered. In addition, for the transportation of the used and remanufactured electric bicycle motor, an average transport route of 400 km within Germany to the remanufacturing site and back to the customer is assumed. The transport activity was modeled with the ecoinvent process “transport, freight, lorry >32 metric tons, EURO6”.

Table 2 shows the LCA results of the EBS SGI-G V2 electric bicycle motor according to the IPCC 2021 GWP100 (incl. CO2 uptake) method. The environmental impact is given as the CO2-equivalent value for each component.

Table 2: IPCC results of the EBS SGI-G V2

		Conventional Manufacturing		**Remanufacturing**		
No.	**Component**	**kg CO2-eq**	**Percentage**	**Scrap rate**	**kg CO2-eq**	**Percentage**
1	Shaft nut	0.060	0.1 %	5 %	0.004	0.1 %
2	Washer	0.064	0.1 %	100 %	0.064	2.4 %
3	Motor housing with ring gear	5.841	20.8 %	5 %	0.292	10.9 %
4	Bearing 6001RS	0.077	0.3 %	100 %	0.077	2.9 %
5	Washer	-	-	-	-	-
6	Circlip for planetary wheels	-	-	-	-	-
7	Planetary carrier	1.693	6.0 %	30 %	0.508	18.9 %
8	Bearing 6903RS	0.069	0.2 %	100 %	0.069	2.6 %
9	Bearing 6901RS	0.044	0.2 %	100 %	0.044	1.6 %
10	Cassette with freewheel	0.947	3.4 %	10 %	0.095	3.5 %
11	Case cover	1.172	4.2 %	5 %	0.059	2.2 %
12	Plastic cover winding package	0.038	0.1 %	0 %	0.000	0.0 %
13	Cover of circuit board	0.008	0.0 %	0 %	0.000	0.0 %

14	Sun gear	0.202	0.7 %	0 %	0.000	0.0 %
15	Circlip	-	-	-	-	-
16	Slot nut	-	-	-	-	-
17	Bearing 6902RS	0.145	0.5 %	100 %	0.145	5.4 %
18	Rotor (with magnets)	9.386	33.5 %	0 %	0.000	0.0 %
19	Plastic cover	-	-	-	-	-
20	Shaft seal	0.030	0.1 %	0 %	0.000	0.0 %
21	Screw	0.113	0.4 %	100 %	0.113	4.2 %
22	Cover for nut	0.212	0.8 %	0 %	0.000	0.0 %
23	Nut	0.133	0.5 %	100 %	0.113	4.2 %
A	Planetary wheel*	0.498	1.8 %	10 %	0.069	2.6 %
B	Shaft with motor cable	0.857	3.1 %	20 %	0.171	6.4 %
C	Stator with circuit board	5.733	20.5 %	0 %	0.000	0.0 %
	Transport, truck	0.111	0.4 %	-	0.221	8.2 %
	Transport, ship	0.628	2.2 %	-	0.062	2.3 %
	Remanufacturing process	-	0.0 %	-	0.577	21.5 %
	Total	**28.030**	**100 %**		**2.683**	**100 %**

* Process of AdRem used for manufacturing spare parts

3.4 Interpretation of results

Compared to conventional manufacturing, assuming the given assumptions, remanufacturing the EBS SGI-G V2 electric bicycle motor can save 90.4 % on average of the GWP according to the IPCC 2021 GWP100 (incl. CO2 uptake) method. Depending on the material, e.g., magnets or electrical sheet, up to 100 % of the materials can be reused. The material savings from remanufacturing the electric bicycle motor is shown in Figure 3. The component, weight, and scrap rate significantly influence this scenario's impacts. In the remanufacturing scenario, producing new parts accounts for 63.7 % of the total environmental impact. However, only cleaning and AdRem were considered within the manufacturing process, as the remaining work was carried out manually.

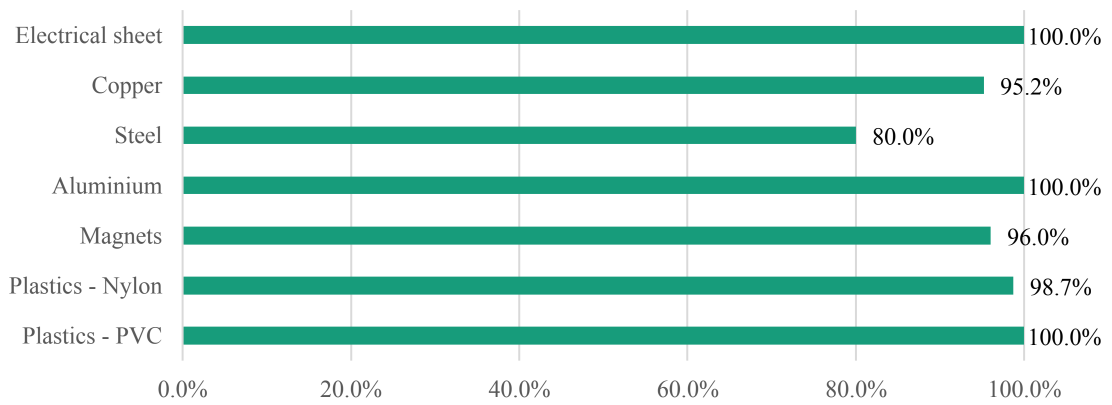

Figure 3: Material savings of the EBS SGI-G V2 through remanufacturing

The distinction between the magnet and other materials is evident when considering its significant environmental impact per gram. Figure 4 compares the proportion of materials in electric bicycle motors' weight and their corresponding contribution to GWP, as determined by the IPCC 2021 GWP100 (incl. CO2 uptake) method.

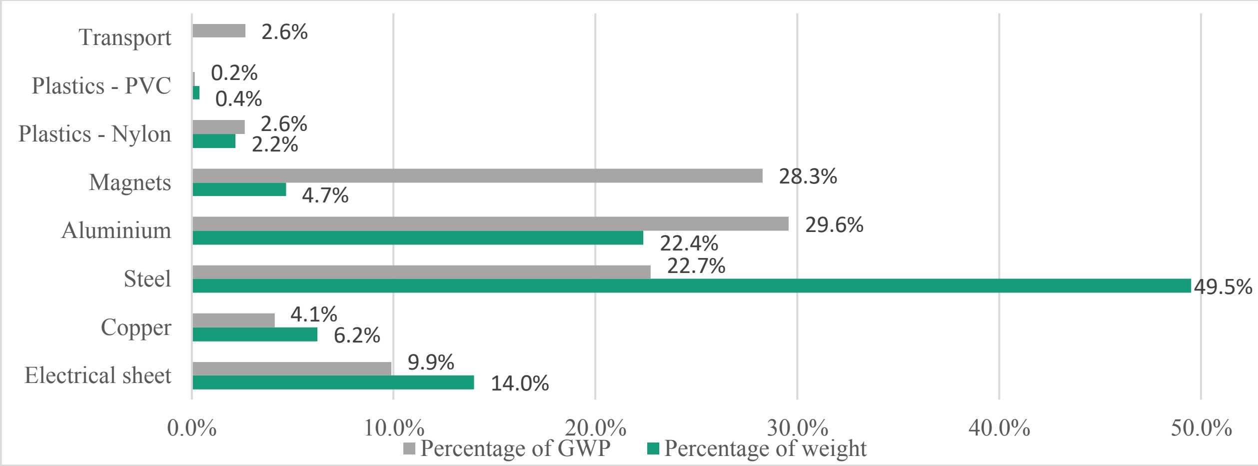

Figure 4: Comparison of the share of weight and GWP of the materials for new component manufacturing

Considering the LCA of AdRem of the planetary wheels, it is noticeable that the process with 0.694 kg CO2-eq. has a higher impact than conventional manufacturing with 0.498 kg CO2-eq. However, since only 10 % of the planetary wheels are scrapped, their CO2 impact, with 2.6 % of the total emissions of the electric bicycle motor, only plays a subordinate role in the overall process.

4. Conclusion

The paper aims to assess the environmental impacts associated with the conventional manufacturing of the EBS SGI-G V2 electric bicycle motor, estimating it to be around 29 kg CO2-eq. The findings of the manufacturing comparison validate the earlier assumptions that remanufacturing not only offers potential material savings but also reduces environmental impacts. However, quantifying these savings is challenging due to various factors, e.g., variation of quality of used products and materials, company-specific manufacturing and remanufacturing processes, and reverse logistics activities that come into play. In this context, the proportion of procuring new parts due to different quality levels of used products, for example, influences the overall result and leads to possible deviations even with identical remanufacturing processes. Hence, further analyses could focus on considering the influences mentioned above. Based on the assumptions made in this study, the potential reduction in GWP, according to the IPCC 2021 GWP100 (incl. CO2 uptake) method, is approximately 90.4 %.

Although AdRem of the planetary wheels has a higher carbon footprint than conventional manufacturing, remanufacturing used products with AdRem components has a significantly lower impact than new production. Therefore, despite the poorer environmental performance at the component level, AdRem can be reasonable if it allows delivery times to be met or spare parts to be made available to enable remanufacturing. The impact of the AdRem process on the overall process must be assessed on a case-by-case basis, depending on the product. Thereby, the proposed procedure can be applied to other products or components.

Similar to previous LCAs, this study faces challenges due to limited data availability, especially primary data, and the need to establish clear system boundaries for a comprehensive and realistic evaluation. To enhance the robustness of the results, additional (primary) data on the environmental impacts and energy consumption of the production facilities, along with a detailed examination of the electronic components used, could be incorporated alongside the findings of this study.

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Biography

Julian Große Erdmann (*1994) has been a research associate at Fraunhofer IPA since 2020, focusing on the Circular Economy and resource-efficient optimization in production. He focuses on business field development in remanufacturing, optimizing business and production processes, strategy development, and business case creation.

Alexander Mahr (*1991) studied mechanical engineering at the Friedrich-Alexander University Erlangen-Nuremberg in 2017. Since then, he has worked as a research associate at the Chair Manufacturing and Remanufacturing Technology of the University of Bayreuth and, since 2021, as a project manager at the Fraunhofer IPA on industrialization and resource efficiency of additive manufacturing processes.

Patrick Derr (*1998) studied engineering management at the University of Bayreuth in 2022. His bachelor thesis at the Chair Manufacturing and Remanufacturing Technology focused on the LCA of electric bicycle motors. Besides his master's studies, he works as a research assistant at Fraunhofer FIT.

Philipp Walczak (*1982) studied chemistry in Heidelberg. He co-founded the Heidelberg-based company Electric Bike Solutions GmbH (EBS) in 2009 and acts as managing director. EBS sells and develops components and drives systems for small electric mobility used in e-bikes and similar vehicles.

Jan Koller (*1992) is a group manager at the Fraunhofer IPA Project Group Sustainable Manufacturing in Bayreuth. His work focuses on Circular Economy with particular emphasis on remanufacturing. In national and international research and industrial projects, he addresses the challenges of remanufacturing and develops efficient, innovative, and sustainable solutions.