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# Life cycle assessment of circular economy strategies for high-strength connection bolts in wind turbines

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## Abstract

Wind turbines are an important element of renewable energy systems, but their manufacturing requires significant amounts of materials such as steel, copper, aluminum, rare earth metals, fiberglass, and concrete, with considerable environmental impacts. One approach to reduce the environmental impacts of wind turbines and their components is the application of circular economy strategies. This study focuses on high-strength connection bolts, specifically M36 threaded steel bolts with a length of 660 mm. A comparative life cycle assessment is conducted to analyze the environmental impacts of two scenarios: recycling all bolts at the end of the wind turbine's life cycle, and reusing some bolts after inspection. The product system is modeled in openLCA, where the processes of the foreground system are linked to the Ecoinvent database in the background system. For life cycle impact assessment, the ReCiPe 2016 method is applied, focusing on climate impact. Results show that after five life cycles, reusing bolts reduces the climate impact by 48%, compared to a 42% reduction through recycling alone. Sensitivity analyses reveal that the potential for impact reduction through reuse is primarily driven by the achievable reuse rate, while factors such as production technology, electricity mix, and transportation distances play a smaller role.

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## 1. Introduction

Wind turbines play an important role in the global transition towards renewable energy systems. Driven by advancements in turbine technology, declining costs, and increasing policy support for renewable energy, the global wind turbine market has experienced rapid growth in recent years. In 2023, new wind turbines with a total power of 117 GW were installed worldwide, and the global cumulative wind power capacity surpassed the 1 TW mark [1].

During their operation, wind turbines convert wind energy into electricity without direct greenhouse gas emissions. However, the construction of wind turbines requires large amounts of materials, including steel, copper, aluminum, rare

earth metals, fiberglass, and concrete. The production of these materials and their disposal at the end of the wind turbine's service life are associated with considerable environmental impacts. Although the environmental impacts over the life cycle of a wind turbine normalized to one kilowatt-hour of electricity generated are usually much smaller than for conventional power plants based on fossil fuels, efforts are made to reduce their environmental footprint even further. One prominent approach is the application of circular economy strategies, such as recycling and reuse, to wind turbine components [2–4].

The Re-Machine project at the Fraunhofer Institute of Wind Energy Systems investigates the possibility of reusing high-strength connection bolts that are used in wind turbines instead

of recycling them. These bolts are designed to endure the high cycle loads induced by wind, waves, cyclic rotations of the hub, or alternative pitch adjustments of the rotor blades [5,6]. However, not all bolts experience these high loads and some have sufficient reserve in fatigue performance to withstand another wind turbine's life cycle. The project develops methods to test the large connection bolts after being disassembled for their ability to serve in another wind turbine's life cycle. It is expected that reusing the connection bolts not only reduces the cost of wind turbines, but also comes with environmental benefits.

The advantages of applying circular economy strategies have been explored for various products such as bottles, barrels, pallets, or textiles [7–10]. These studies usually employ life cycle assessment (LCA) to quantify the environmental impacts related to the different circular economy strategies. In most of the investigated settings, reuse strategies have led to lower impact scores than recycling strategies. Yet, to the best of the authors' knowledge, there is little evidence on the environmental benefits of reusing steel machine elements, indicating the need for a systematic assessment.

Therefore, the objective of this study is to analyze the environmental benefits of reusing high-strength connection bolts in wind turbines instead of recycling them. To this end, a comparative LCA is conducted.

After this introduction, we describe the life cycle of high-strength connection bolts and discuss potential circular economy strategies. Next, the setting of the LCA study is explained and subsequently, the assessment results are presented. The article concludes with a discussion of its contribution and an outlook.

## 2. Life cycle of high-strength connection bolts

High-strength connection bolts are commonly used in ring flanges that connect large elements of wind turbines, such as the tower segments to each other, the nacelle to the yaw bearing linked to the tower, or the rotor blades to the pitch bearing connected to the wind turbine hub [11,12]. Depending on the size of the wind turbine, it may contain more than 6,000 bolted connections. The average mass of one bolt ranges from 4 to 6 kg, with higher masses expected for future wind turbines. A typical connection bolt is depicted in Figure 1.

The life cycle of connection bolts comprises four main phases: steel production, bolt manufacturing, use in a wind turbine (including maintenance), and end-of-life. Each phase also comprises related transportation processes.

Steel production typically begins with the extraction of iron ore, which is processed in a blast furnace along with coke and

limestone to produce pig iron. This pig iron is then refined in a basic oxygen furnace (BOF) or an electric arc furnace (EAF), where impurities are removed, and alloying elements may be added to achieve the desired steel properties. The molten steel is cast into billets or slabs and further shaped through forging and/or rolling processes.

For the manufacturing of high-strength connection bolts, the steel first undergoes a phosphating process to enhance its forming properties for the subsequent manufacturing steps [13]. Next, the steel is heated and pressed into a blank. In the third step, the threads are rolled using flat die rollers. While this step completes the geometry of the bolt, further enhancements to the material and surface properties are necessary to complete the final product. In the fourth stage, the phosphate levels from the steel are removed using a solution for de-phosphating the bolts. After this, the bolts undergo tempering and quenching processes to achieve the desired strength. Subsequently, the bolts are coated using a hot-dip galvanizing procedure, which involves a bath in liquid zinc heated to about 450°C. Following a final cleaning process and quality control, the bolts are packaged and loaded onto EPAL pallets. Each layer of bolts is covered with a cardboard layer and the entire shipment is wrapped in plastic to safeguard the product from rain.

The use phase starts with transporting the components from the production site to the construction site of the wind turbine. At the construction site, each bolt undergoes tightening using a hydraulic tensioner, which pulls the bolt to the precisely required preload force, ensuring accurate installation. Typically, this process is carried out in two steps: initially tensioning the bolts to 70% of the preload force, followed by the final tightening to achieve the specified force. This process necessitates a hydraulic compressor. Throughout a wind turbine's life cycle, regular maintenance is conducted to assess its condition. During these inspections, bolts are examined, and if any are found to be broken, they are replaced with new ones. During disassembly, the same process as the assembly process is reversed, requiring only one step to untighten the bolts instead of two.

After disassembly, several pathways for the end-of-life treatment of the connection bolts are possible: disposal at a scrapyard, material recycling of the bolts by smelting them to make new steel products, or reuse of the bolts in wind turbines. While disposal at the scrapyard and material recycling follow established process routes, the reuse of the bolts is a relatively new approach that is currently being investigated. It requires a thorough inspection of the bolts.

The inspection process comprises an initial cleaning step with a specialized machine. Subsequently, the bolts are tested for damages. Employing non-destructive testing methods that



Figure 1 High-strength steel connection bolt used in wind turbines

are developed within the Re-machine project, an analysis is conducted on all potential points for failure. Throughout the testing process, four different screening methods are applied: the part is subjected to ultrasound, induction thermography, eddy current testing, and photography with a camera. After the testing phase, the results are entered into a digital twin model. Following classification, the bolts are stored in a warehouse and can be used as spare parts or for the construction of new wind turbines.

### 3. Setting of the LCA study

To evaluate the environmental benefits of reusing high-strength connection bolts in wind turbines as opposed to recycling them, an LCA study is conducted. The primary objective of this LCA study is to compare the environmental impacts of the two strategies, with a specific focus on their climate change impact.

We define the functional unit for this LCA as establishing and maintaining the connection of two wind turbine parts with 100 bolts of  $d = 36$  mm in diameter and  $l = 660$  mm in length, each withstanding forces of up to  $F = 916$  kN before plastically deforming and up to  $M = 1.018$  MN before breaking, and sustaining this performance over the approximated 20-year service life of a wind-turbine. The number of 100 bolts is representative for a typical connection of a wind turbine pitch bearing.

The corresponding product system is depicted in Figure 2. The foreground system comprises the production of the bolts, their use in wind turbines, and depending on the scenario, classification and recycling processes. These activities are modeled in detail. The inputs and outputs of these activities are connected to further upstream and downstream activities in the background system. These include mining, iron production, steel production, and steel scrap disposal.

steel production, the disposal of steel scrap and transportation processes. Data for these processes were obtained from the Ecoinvent database.

In the first life cycle, it is assumed that the bolts are produced from primary steel and transported to the construction site of the wind turbine. During the use phase, regular inspections ensure that the bolts continue to fulfill their function. The maintenance rate, representing the proportion of bolts that need replacement during the wind turbine's service life, is estimated to approximately 1%. Hence, on average 101 bolts are needed in total to fulfill the functional unit. When the wind turbine is disassembled at the end of its service life, two scenarios are distinguished. In the recycling scenario, all bolts are transported to recycling facilities where 96% of the steel can be recovered and replace the respective amount of primary steel in the subsequent life cycle. In the reuse scenario, the bolts are being inspected and those classified as reusable are transported to a warehouse from where they can be used to replace new bolts. The non-reusable bolts enter recycling. At the end of the last life cycle, instead of the reuse or recycling steps, the bolts are disposed of at a scrapyard.

The study's geographic focus is Germany, hence relevant parameters in the foreground system, such as the electricity mix, were tailored to reflect the German context. In contrast, background activities were not localized and generally rely on global averages. The transportation of bolts in this study is modeled using lorries, diesel cars, and trains. Lorries are used for transporting bolts from production facilities to wind farms, while diesel cars are simulated for maintenance trips. Trains are employed for transporting scrap to recycling plants. Transportation distances were estimated based on the locations of a bolt manufacturer in Germany (which would also serve as the classification center), the locations of German wind farms, and steel recycling plants in Germany (Table 1).

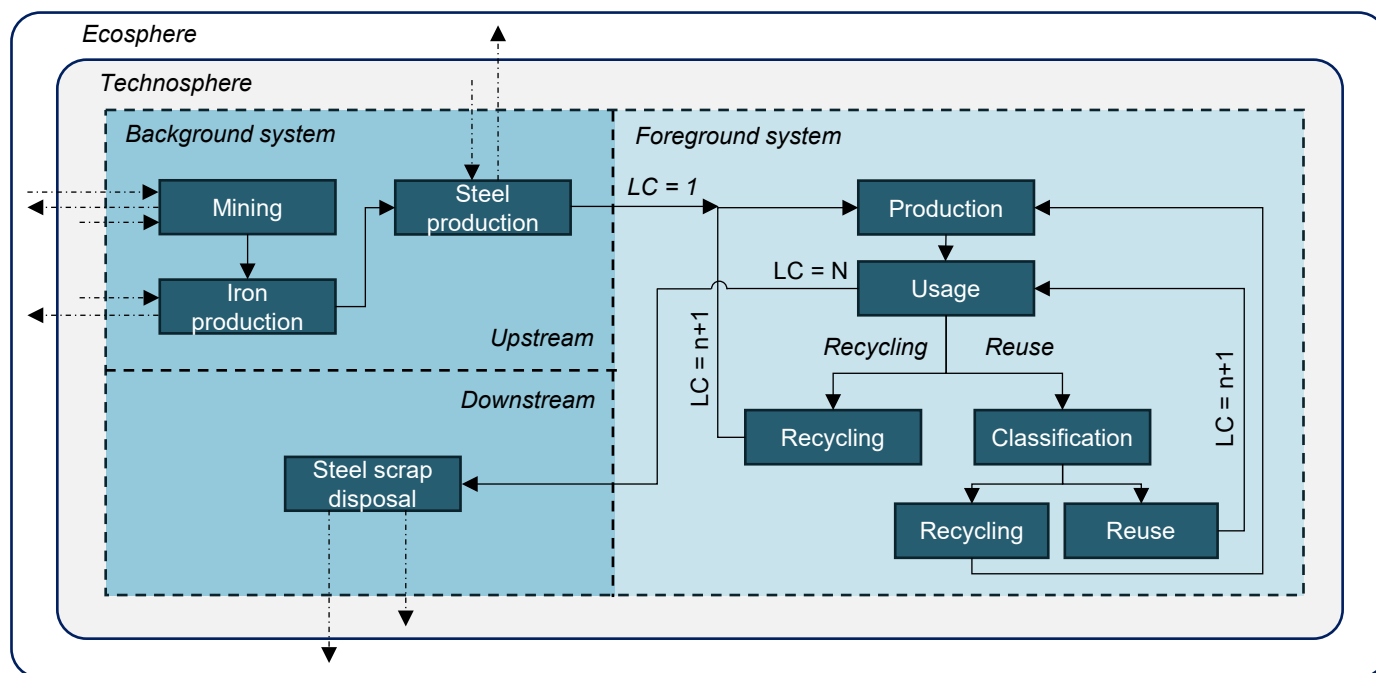


Figure 2 System boundaries for the life cycle assessment of high-strength connection bolts in wind turbines

Table 1. Transportation distances

Route	Average [km]	Std. deviation [km]
Production to wind farm	258	101
Wind farm to recycling	554	166
Wind farm to classification	258	101
Classification to recycling	415	200

The ReCiPe 2016 method [14] is used for impact assessment. While all 18 impact categories at midpoint level were calculated, this article focusses solely on the climate impact expressed as the global warming potential (GWP) due to its prominent role in the discussion of circular economy strategies and renewable energy systems

The LCA model of the connection bolts has been implemented in openLCA. After running the LCA calculations, the results were exported to MATLAB for further analyses and visualization.

## 4. Results and discussion

### 4.1. Comparison of recycling and reuse strategies

The results of the impact assessment for climate change, along with the contributions from each life cycle stage, are shown in Figure 3 for both the recycling and reuse strategies. As expected, the environmental impact is influenced by the number of life cycles considered.

In the single life cycle scenario, which reflects a linear economy where bolts are produced, used, and disposed of, the climate change impact amounts to 2,240 kg CO<sub>2</sub>-eq per functional unit. This value is slightly higher than that for basic steel products because it includes the manufacturing and transportation processes of the bolts. Most of this impact stems from the initial production of the bolts, while the contribution of the use phase and the disposal phase are much smaller.

When a recycling strategy is applied, assuming a 96% recycling efficiency, the climate change impact decreases to an average of 1,301 kg CO<sub>2</sub>-eq per life cycle after five cycles, representing a 42% reduction compared to the linear economy scenario. This reduction highlights the significant environmental benefits of replacing primary steel with recycled steel, which more than compensates for the additional burdens of the recycling process.

The reuse strategy offers even greater climate benefits. Assuming that 50% of the bolts can be reused for one additional life cycle, with the same 96% recycling rate for bolts that cannot be reused, the average climate impact per life cycle drops to 1,167 kg CO<sub>2</sub>-eq after five cycles. This corresponds to a 48% reduction in climate impact compared to the linear economy scenario, demonstrating the additional environmental value of bolt reuse alongside recycling.

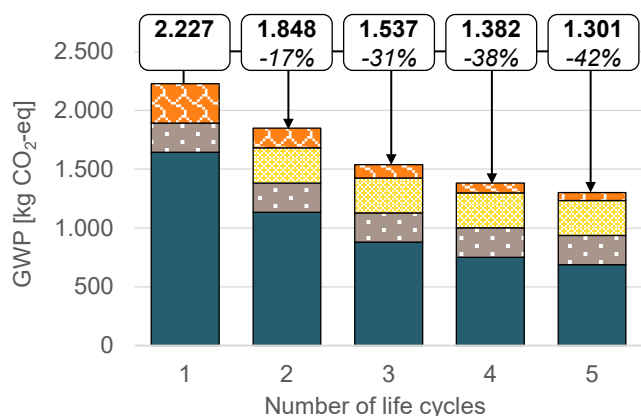
### 4.2. Sensitivity analysis

To check the robustness of our results, a sensitivity analysis is conducted in which the key parameters of the LCA setting are varied. The following parameters are analyzed:

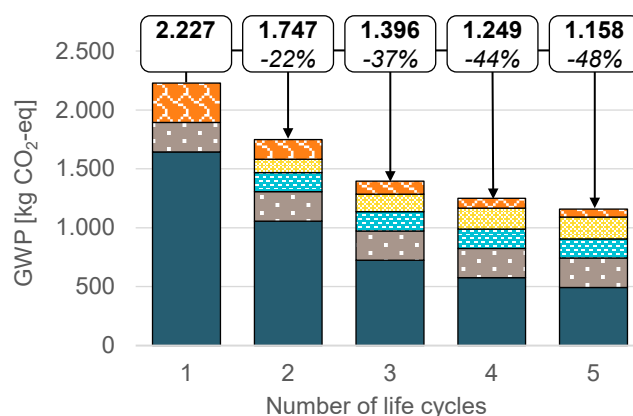
- Reuse rate
- Transportation distances
- Steel production technology
- Electricity mix

In the initial assessment up, an estimated reuse rate of 50% was assumed. Here, an optimistic case with a reuse rate of 80% and a pessimistic case with a reuse rate of 5% are investigated. Regarding transportation, the cases of reduced distances by 100 km between production plant and wind farm, between maintenance company and the wind farm, and reduced between wind farm and recycling plants are analyzed. As the steel for making the connection bolts is not necessarily sourced from a European steelmaker (as assumed in the initial setting), the effect of switching to the average global steel production technology (BOF) is analyzed. Finally, we consider the use of

### A) Recycling



### B) Reuse



■ Production ■ Use ■ Classification ■ Recycling ■ EOL

Figure 3 Comparison of impact scores for climate change of connection bolts over several life cycles for (A) recycling strategy and (B) reuse strategy

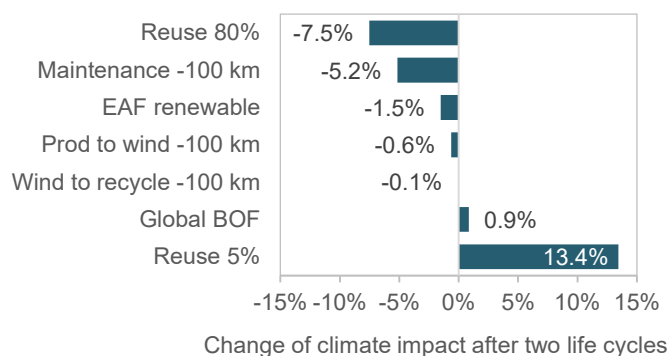


Figure 4 Sensitivity analysis of climate impact scores in the reuse scenario

renewable energy for the operation of the EAF in the recycling phase instead of Germany's average electricity grid mix.

Figure 4 shows the sensitivity of the climate impact scores in the reuse scenario after two life cycles. The most notable changes are due to variations in the reuse rate. A high reuse rate of 80% leads to a reduction in climate impact by 7.5%, whereas a low reuse rate of 5% would increase the climate impact by 13.4%. The effect of reduced distance from maintenance company to the wind farm (-5.2%) is larger than the effect of reduced distances between wind farms and production plants (0.6%) and recycling plants (-0.1%). This is because the impacts of the latter two were already low in the initial setup due to the use of truck and train transportation. The use of renewable energy in the steel recycling process leads to a small reduction of climate impact (-1.5%), whereas the switch to global steel production technology results in a small increase (+0.9%)

### 4.3. Discussion

In summary, our results demonstrate that reusing high-strength connection bolts in wind turbines offers clear environmental advantages in terms of reducing climate impact. While recycling bolts over multiple life cycles already achieves a significant reduction in climate impact (reduction of 42% after five cycles), the additional benefit of bolt reuse is relatively modest (reduction of 48% after five cycles).

The sensitivity analysis highlights that the overall effectiveness of reuse strategies is influenced considerably by the reuse rate. However, technical limitations restrict the potential for further improvement. While advances in non-destructive testing methods can improve the accuracy of detecting reusable bolts, some bolts may have experienced excessive loads, making them unsuitable for reuse from a safety perspective.

There are several limitations that should be considered when referring to the results of this study. First, the analysis over multiple life cycles implies a time horizon of several decades. There is considerable uncertainty how the production system of wind turbine components as well as upstream material and energy supply chains will evolve during this time frame. Secondly, the study was conducted with a focus on wind turbines in Germany. Finally, the assumptions on recycling and reuse rates and energy consumption of non-destructive testing

were based on lab experiments. The results should be updated when better empirical data becomes available.

## 5. Conclusion

This article presents a comparative life cycle assessment to evaluate the environmental impacts of circular economy strategies for high-strength connection bolts in wind turbines. Drawing on recent advancements in non-destructive testing and refurbishing methods, we developed a life cycle model to quantify the environmental benefits of reusing bolts, providing new insights into this emerging approach.

Our study contributes to the circular economy literature by offering a detailed case study within the wind energy sector, comparing the environmental impacts of two alternative strategies: recycling and reuse. Additionally, it offers a comprehensive overview of the life cycle of high-strength connection bolts, provides insights into their environmental impacts and identifies key influencing factors.

Future research should address several areas. First, expanding the analysis to include different types of bolts with varying dimensions and materials would provide a broader understanding of potential impacts. Second, exploring other wind turbine components and their interactions as part of a complex technical system would yield more holistic insights. Finally, complementary studies on the economic potential and social benefits of reusing bolts could enhance the overall perspective on sustainability.

## Declaration of Generative AI and AI-assisted technologies in the writing process

After preparing the initial draft of the manuscript, the authors used generative artificial intelligence, specifically ChatGPT-4o, to improve readability and language of the text. The author reviewed and edited the final manuscript as needed and take full responsibility for the content.

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