Allianz

Repair or Replace

Investigating the relative GHG emissions of repairing or replacing damaged vehicle parts

A joint report by
Allianz SE, Allianz Center for Technology, Metsims Sustainability Consulting and Oakdene Hollins

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Europäische Charta
für die Straßenverkehrssicherheit

Repair or Replace – Investigating the relative GHG emissions of repairing or replacing damaged vehicle parts

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Content

Executive Summary

Typically, when processing a vehicle damage, repairing a part is also the lowest cost and therefore most preferable option for the customer. Through use of a carbon life cycle analysis (LCA), with the repair or replacement of a single part on a Volkswagen ID.3 as the functional unit for comparison, this study sought to validate the assumption that repairing a damaged vehicle part is a more climate friendly ('low-emission') option than using a replacement part. The results of this work demonstrate that repairing a vehicle part results in significantly lower greenhouse gas (GHG) emissions than replacing it.

Comparing the repair and replacement processes for nine different parts across four different countries showed that this is universally the case, even when the workshop that is carrying out the work is - relative to other workshops - operationally more efficient with regard to GHG emissions.

Figure 1 *Impact of repair and replace in a German workshop for select VW ID.3 parts (kgCO₂e)*

As governments, organisations and the general public become increasingly conscious of their own environmental impacts, these results show that there are potentially significant opportunities to create low-emission repair processes for damaged vehicles. The results for a selection of the parts studied can be seen below in Figure 2, given for an average workshop in Europe.

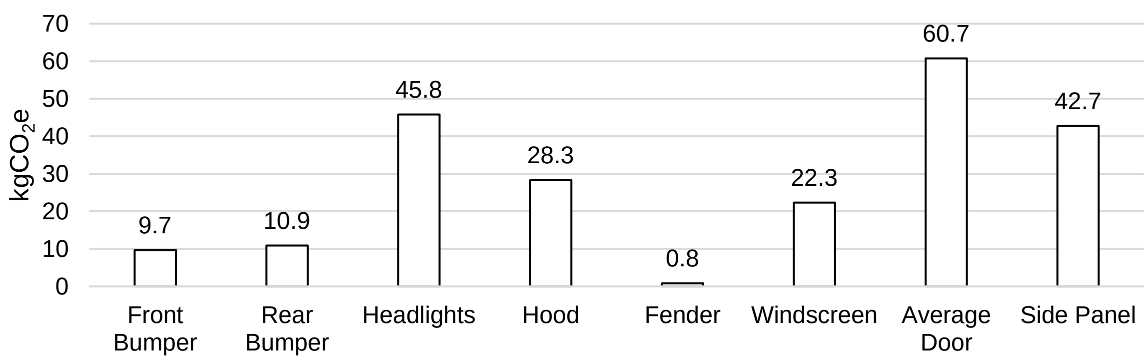

Figure 2 *EU average GHG savings from repair vs replace – VW ID.3 (kgCO₂e)*

The calculations in this study relied on a combination of data sources including published literature, information provided by commercial partners and the Ecoinvent LCI database. The method used considered the carbon impact from seven different stages of the product life cycle, from raw material production through to end-of-life disposal.

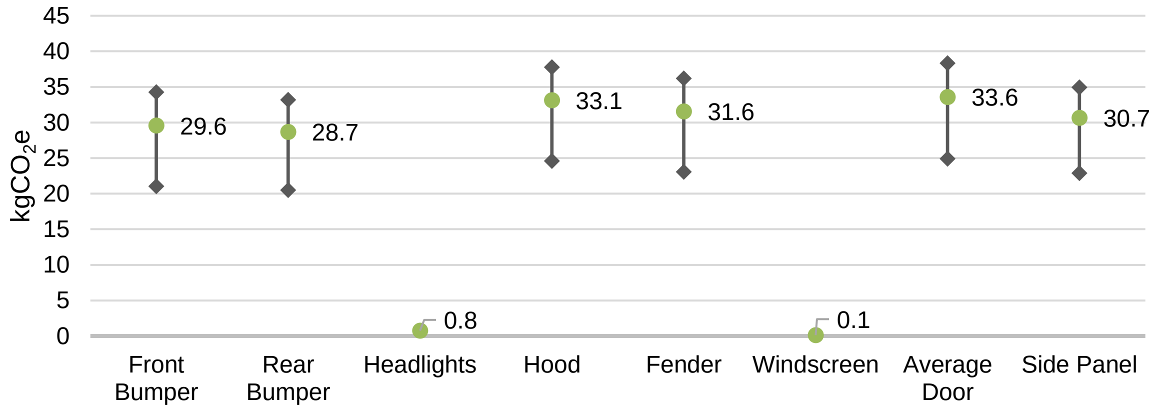

Figure 3 *Range of country-specific emissions and the EU average for the repair of parts (kgCO₂e)*

In addition to providing a robust and comprehensive dataset comparing the emissions from the repair or replace processes, the ambition of the authors is for the study to be used as a platform to kick-start new collaborations, and for the method to be refined over time. In this spirit, it is important to note that this work was an initial investigation, and in completing the work the authors encountered a number of limiting factors such as paucity of data availability for specific parts, materials and vehicles. It is intended that a future study's scope will be expanded to address these limitations and to create a stronger evidence base that will empower motor insurers and the vehicle repair industry to make smart repair decisions that effectively prioritise more climate friendly solutions.

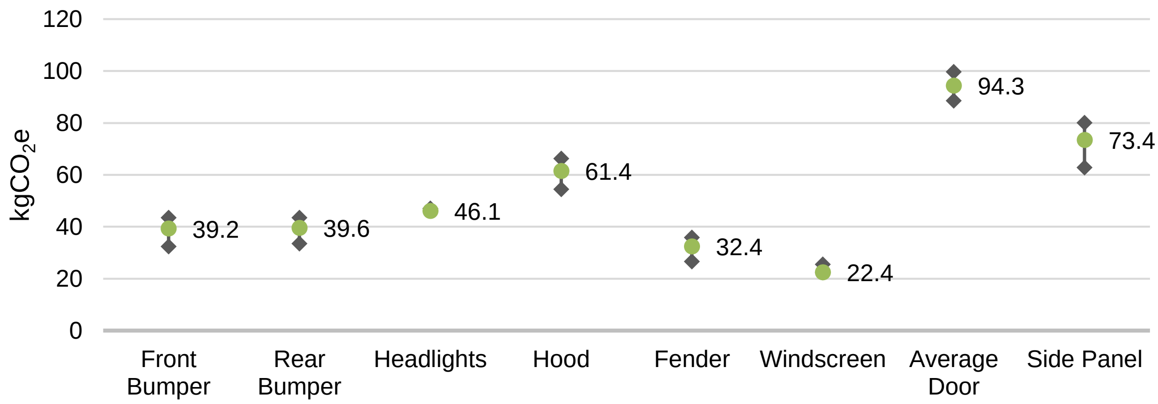

Figure 4 *Range of country-specific emissions and the EU average for replacement parts (kgCO₂e)*

Introduction

The way damage to a vehicle is rectified has an impact on the volume of greenhouse gases emitted as a result of rectifying that damage. The first step to understanding this is to be able to reliably calculate and compare the emissions resulting from different approaches to handling the same vehicle damage, such as replacing or repairing a damaged door. While previous studies of this kind have been conducted, for example by Patyk et al. (1) and Lundberg et al. (2), this study aims for full transparency on methodology and results, welcomes scrutiny, and demonstrates how the insurance industry can make advances in what is becoming known as "green repairs".

To this end, the project team has conducted a carbon life cycle analysis on nine vehicle parts of the Volkswagen ID.3, in four different countries, with a range of scenarios allowing for the particular operations of different kinds of repair workshop. The assessment used the life cycle of each vehicle part as the functional unit for comparison, and Volkwagen's ID.3 as a representative vehicle that - being an electric vehicle - should provide a level of "future-proofing" given the changing landscape of the automotive market.

The motor insurance and collision repair sectors have a long history of repairing and returning vehicles to the road, motivated by the merits of value retention - but almost entirely in the economic sense. For insurers and customers, it is typically more cost-effective to repair a component or group of components than to replace a part or vehicle after a collision. However, over time, the economic balance for many vehicle parts has shifted towards replacement, leading to what would now be considered increasingly undesirable environmental outcomes. In 2009 the Allianz Center for Technology (AZT) conducted a life cycle assessment of the environmental impacts of vehicle repair vs replacement (1). Within this work it was found that "for almost all impact categories, repair shows obvious advantages". With a view to the future on how insurance companies and vehicle repair workshops can positively influence the greenhouse gas (GHG) emissions produced in the automotive sector, the goals of this new study were as follows:

- Understand the climate impact of undertaking repair vs replace.
- Understand how repair vs replace might be affected by geographic factors.
- Drive wider change/discussion in the industry and create opportunities for collaboration.

As a result of a partnership between Allianz SE, AZT, Metsims Sustainability Consulting and Oakdene Hollins, this study involved the creation of a new series of LCAs, evaluating the environmental impacts of repairing or replacing a selection of the most commonly damaged automotive parts in workshops across Europe.

It is hoped that by sharing the methodology of this work, feedback may be collected from the wider industry on how the results can be iterated and improved upon. Ultimately, it is the goal of this work to identify opportunities for improving the sustainability of the automotive industry and to create new collaborations to this end.

Methodology

The investigation took the form of a comparative life cycle assessment (LCA) – a standardised method for modelling the environmental impact of a product or system across its entire life cycle. Undertaking an LCA involves the quantification of all relevant inflows and outflows of resources, emissions and residual products from a product/system, typically across all stages of its life cycle. By compiling this inventory of inflows and outflows (referred to as the ‘life cycle inventory’) investigators are then able to undertake a ‘life cycle impact assessment’, correlating each flow with a range of environmental impact categories (3).

LCAs are one of the key means of quantifying the potential environmental impacts of products or systems, and can help identify opportunities to improve environmental performance, inform strategic decision making, select relevant environmental performance indicators and underpin marketing claims for eco-products (3).

The LCAs conducted for this investigation considered the GHG emissions from either repairing or replacing nine commonly damaged parts in workshops within four different European nations, as well as a workshop running entirely on electricity generated by solar photovoltaic (solar PV) panels. Solar PV was chosen as the renewable energy source as it is relatively simple for workshops to use these panels as a source of renewable energy. Note that the results presented here would be different if another renewable energy source (such as wind) were selected for analysis, because different energy sources generate different emissions so the LCA data would differ.

Choosing the Worksites

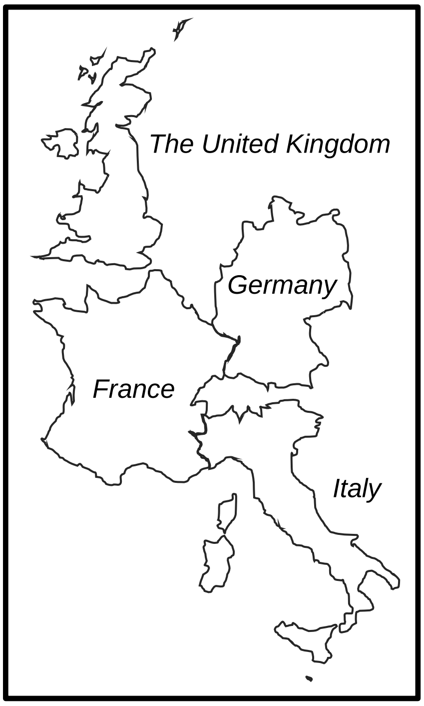

Figure 5 *Studied European nations*

A key goal of this study was to understand how the relative GHG impacts of repair or replace might vary depending on the region in which the work takes place. Based on official statistics and expert opinion from industry professionals, it was understood that the repair quotes for damaged parts in vehicle and end-of-life vehicles can differ substantially between European nations. In this initial phase of the work it was decided to investigate scenarios in Germany, France, the United Kingdom and Italy. The four nations were selected based on the availability of data, the project team’s expertise and the relative GHG intensity of each nation’s energy grid: the latter was anticipated to be a key differentiating factor in the GHG impacts.

The range of emission intensity for grid electricity in each nation can be seen below in Figure 6[1]. In addition, it was expected that this approach might scope out any regional differences and identify which factors had the largest impact on GHG emissions. Following an initial screening and validation of this assumption, the project team decided to include one further (theoretical) scenario, modelled as a worksite that had installed new solar PV generation capacity capable of supplying 100% of its electricity requirement.

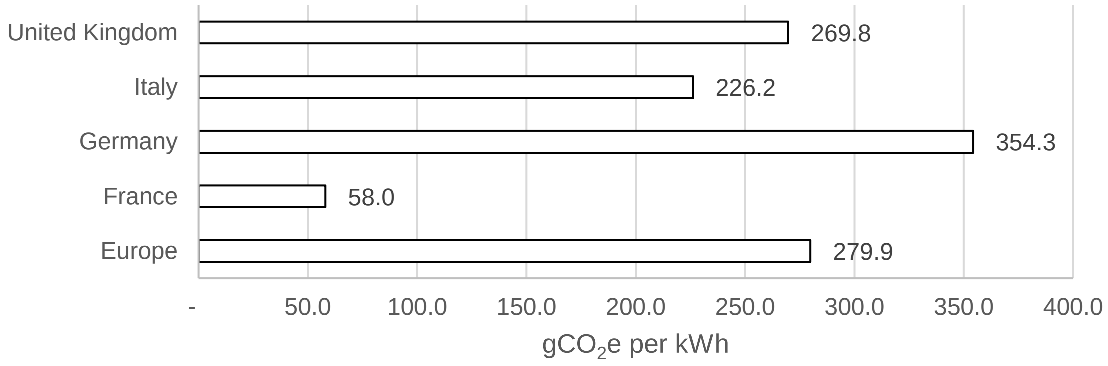

***Figure 6** Grid electricity GHG emission intensity in studied geographies (30)*

Choosing the Vehicle

The vehicle chosen for study in this investigation was a Volkswagen ID.3. In the existing literature there are a limited number of sources for the material composition of vehicles, and even fewer with detail down to the level of individual parts (4) (5).

***Figure 7** Example of the VW ID.3 investigated within this study (Image © AZT Automotive GmbH)*

To overcome this lack of data the investigation focused on a single vehicle, a Volkswagen ID.3 ('ID.3') using information provided to the AZT by commercial partners. The ID.3 is a compact-sized hatchback with a battery electric powertrain and was chosen because it was considered to be broadly representative of a wide range of passenger vehicles by the project team and had a good availability of LCI data. In addition, by choosing a battery-electric vehicle the project

[1] Of note is that these figures were not used within the project work, which relies on datasets sourced from Ecoinvent (7) that were not able to be reproduced here under Ecoinvent's terms and conditions of use.

team considered that the results would be ‘future-proofed’ against the changing composition of the automotive market as the transition to electric vehicles progresses.

Choosing the Parts

As touched on above, this study considered the repair or replacement of nine separate vehicle parts: a front door, a rear door, a side panel, headlights, a front bumper, a rear bumper, a windscreen, a bonnet/hood, and a fender. The selection of parts was based on the frequency of damage and repair claims[2]. Though not presented here, an additional investigation was also undertaken on the side panel of a Ford Fiesta, as this illustrative repair example is used by the AZT to demonstrate part repair vs replacement. Of note is that this AZT demonstration[3] highlights significant benefits for repair over replace which were not investigated in this study. An example of this is that a repair conserves the structural integrity of the vehicle, significantly reducing the risk of corrosion over the lifetime of the repaired vehicle.

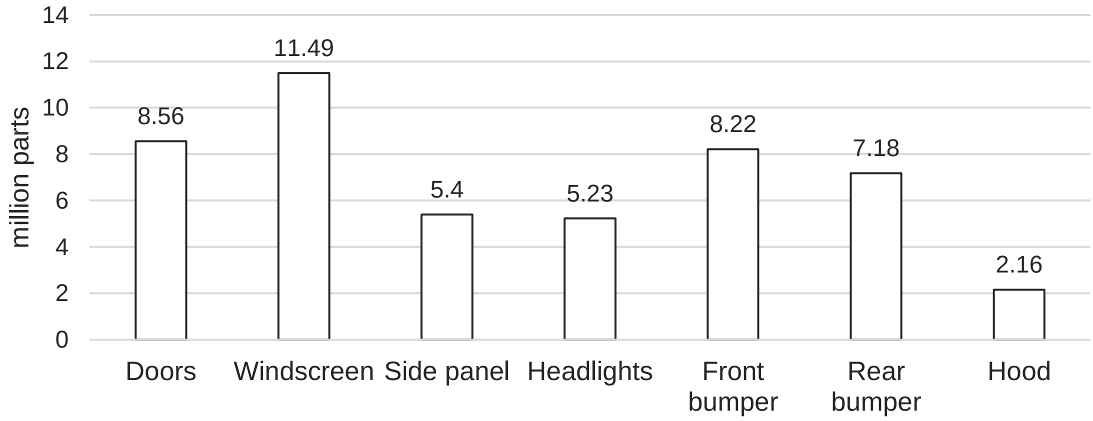

Figure 8 *Total affected car parts in Europe[2]*

Study Boundary and Approach

The functional unit of the investigation was the repair or replacement of a single part onto a damaged vehicle. The boundary of this study started at the production of the raw material for either a new replacement part or the repair materials, and ended with the vehicle being placed back on the road and the treatment of any waste generated in the process (e.g. the damaged part that has been replaced). The LCA modelling was undertaken using LCI information sourced from Ecoinvent 3.8 and a cut-off approach was taken to attributing impacts. The process stages, study boundary and functional unit considered at each worksite scenario can be seen below in Figure 9.

[2] There is no information available for the total number of vehicle repairs taking place in Europe per part. The figures presented here have been extrapolated based on a study of claims for individual parts undertaken by the AZT and the total number of collision claims for passenger cars in Germany reported by GDV (the German Insurance Association). These figures have then been scaled to the entire EU based on the number of passenger cars in Germany as reported by KBA (the German Federal Motor Transport Authority) and in the EU as reported by the European Automobile Manufacturers Association.

[3] https://www.youtube.com/watch?v=MOEz_pAfkHA

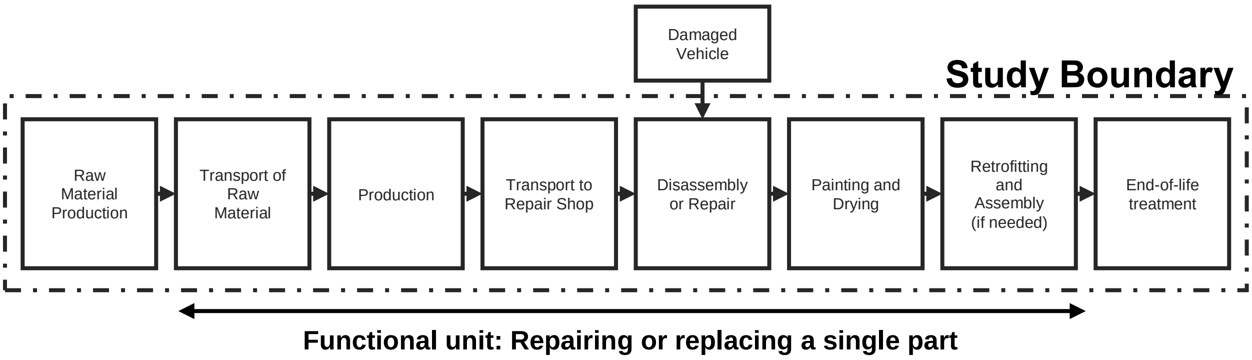

Figure 9 *Project LCA study boundary*

On the following pages a more detailed explanation is given of the modelling approach for the front door. Though this example details the processes required to repair or replace a front door, across the variety of parts we have studied the specific processes required do differ substantially. For example, for most body panels the repair process will require filling, sanding and painting, whereas for a windscreen the repair process would include only the filling of a stone chip. For the purposes of illustration we have given the example here of a front door, detailing the modelling process, assumptions, life cycle inventroy and references. Equivalent summaries for the rest of the studied parts can be found in the technical appendix at the end of this report. Alongside results for the percentage contribution of individudual LCI items to GHG emissions for an average European scenario.

If after reading the report you have any further questions about these or the details of the approach used, please contact the authors for assistance.

Modelling Repair of a Front Door

The scenario modelled for the repair of the front door of the ID.3 describes a ‘medium damage’ scenario. This means that dents and/or scratches require sheet metal repair as a significant portion of the part’s surface is deformed. The process itself requires that the existing paint finish is partially sanded down to bare metal to allow body panel repair with up-to-date tools. Finally, a tin solder replacement material is applied, dried by using an electric infrared heater, and sanded to restore the damaged area in structure and shape. Once this is complete, the door is repainted.

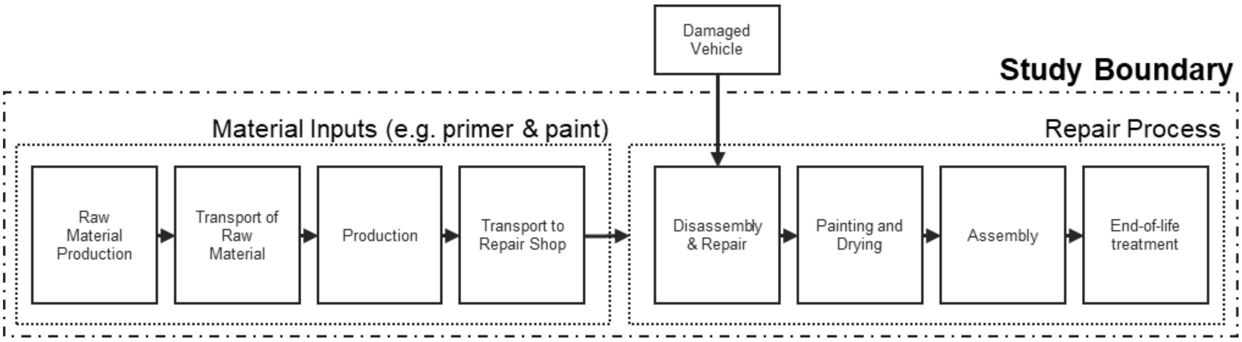

Figure 10 *Study boundary for the repair of a front door*

In contrast to the previous 2009 study by the AZT into the repair of vehicle parts, consultations with the AZT repair professionals revealed that it is now typical for entire parts to be repainted following a repair, rather than a ‘spot paint’ of just the repaired area. This is thought to be due to the difficulty workshops now experience colour-matching spot paints as a result of the development of more complex painting techniques and colour options over the last decade (6). To reflect these new developments, all repaired parts are assumed to require repainting of the complete panel or part to colour-match the adjacent parts of the receiving vehicle. The modelled painting process includes the sanding, priming, painting and curing of the front door. Once this is done the door is then placed back onto the vehicle and any waste generated in the process is sent for treatment.

Modelling assumptions

	Description
Repaired surface area	Based on assumptions by AZT (8) the damaged surface area is assumed to be a ‘medium damage’ scenario.
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differed between nations. Therefore, the generic process described here was used across all nations, with the single differentiating factor being the grid electricity mix, which was sourced from Ecoinvent (7). Similarly the eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Infrared heater operation - curing tin solder replacement material	In the repair process an infrared curing oven is used to cure the tin solder replacement material applied over the damaged surface area. The modelling of this process assumes a curing time of 30 minutes (8) and the use of a 230 volt, 10 amp (2.3 kW) infrared dryer delivering heat energy at 75% efficiency (13).
Painting process and booth operation	The modelling assumes a total painting time of 1.6 hours and a curing time of 0.75 hours for the entire panel surface based on data from AZT (8).
Curing oven operation	The energy requirement for heating and electricity is derived from technical data provided by an industry partner (12).

Life cycle inventory

Repair process	
Resource	**Reference**
Clean and strip discs	AZT (8), 3M (9), Ecoinvent (7)
Tin solder replacement material	AZT (8), Henkel Adhesives (10), Ecoinvent (7)
Sanding strips	AZT (8), 3M (11), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Electricity consumption – Workshop overheads, infrared heater and tools	Ecoinvent (7), Hedson Technologies (13)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Life cycle inventory continued

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption – Workshop overheads, tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Workshop overheads, tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of a Front Door

The scenario modelled for the replacement of the front door of the ID.3 describes a scenario in which the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, painting and placement onto the receiving vehicle. Additionally, the modelling includes the removal and end-of-life treatment of the damaged part.

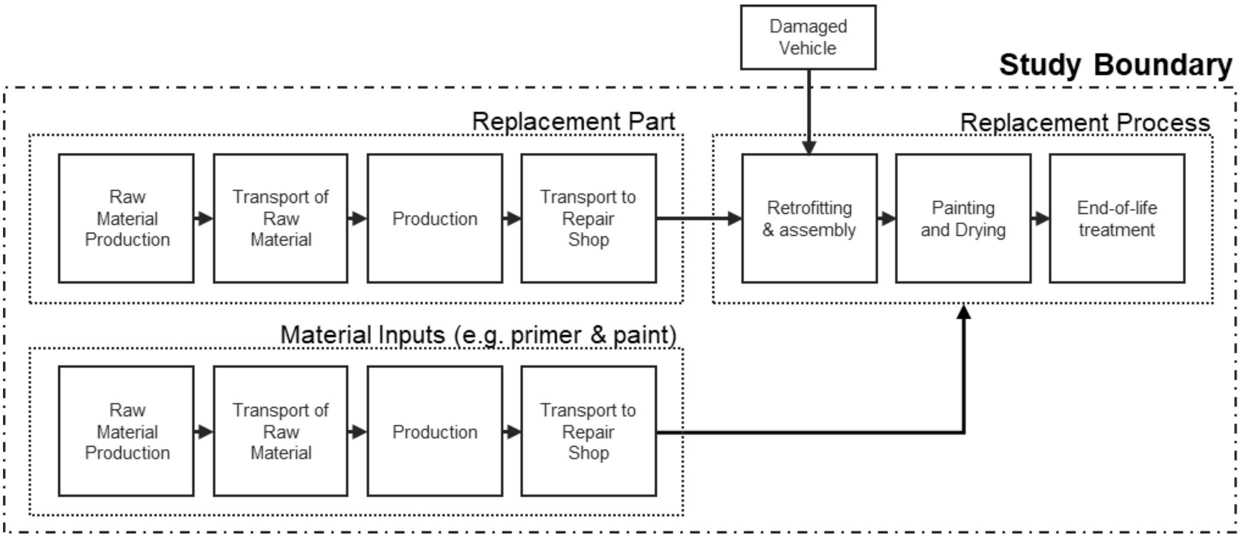

Figure 11 *Study boundary for the replacement of a front door*

The modelling assumes that the front door is originally manufactured in the European Union; the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps.

As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes priming, painting and curing, all of which take place within the repair workshop.

Modelling assumptions

	Description
Steel production	By weight, most of the replacement door is steel, so attention has been paid to ensure that the steel modelled is representative of the European Union average. 60% of the steel is modelled as being produced via a blast furnace and 40% via an electric arc furnace, equal to the average European production reported by Eurofer (17). The upstream transport of the raw steel product to the manufacturer is assumed to be 500 km by rail with an additional 300 km of road transport.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was assumed to be used across all nations, the single differentiating factor being the grid electricity mix as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.6 hours and a curing time of 0.75 hours for the entire panel surface, based on data from AZT (8). Each door is assumed to be treated individually; the energy requirement for heating and electricity is derived from technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional ‘recovery losses’ have been accounted for based on the authors’ best estimates. The assumed recycling/recovery rates for each material are: metals recycling rate 95% and recovery losses 5%; plastics recycling rate 90% and recovery losses 10%; glass (windscreens) recycling rate 75% and recovery losses 25% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Steel sheet	AZT (8), Ecoinvent (7), Industry source (12)
Adhesives	AZT (8), Ecoinvent (7), Industry source (12)
Plastic parts	AZT (8), Ecoinvent (7), Industry source (12)
Electricity consumption - Metal Shaping (Press) electricity	Ecoinvent (7)
Electricity consumption – Welding	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Seam sealing	AZT (8), Ecoinvent (7)
Cavity preservation	AZT (8), Ecoinvent (7)
Noise-absorbent mat	AZT (8), Ecoinvent (7)
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Hardener for primer	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption –Tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: Front Door

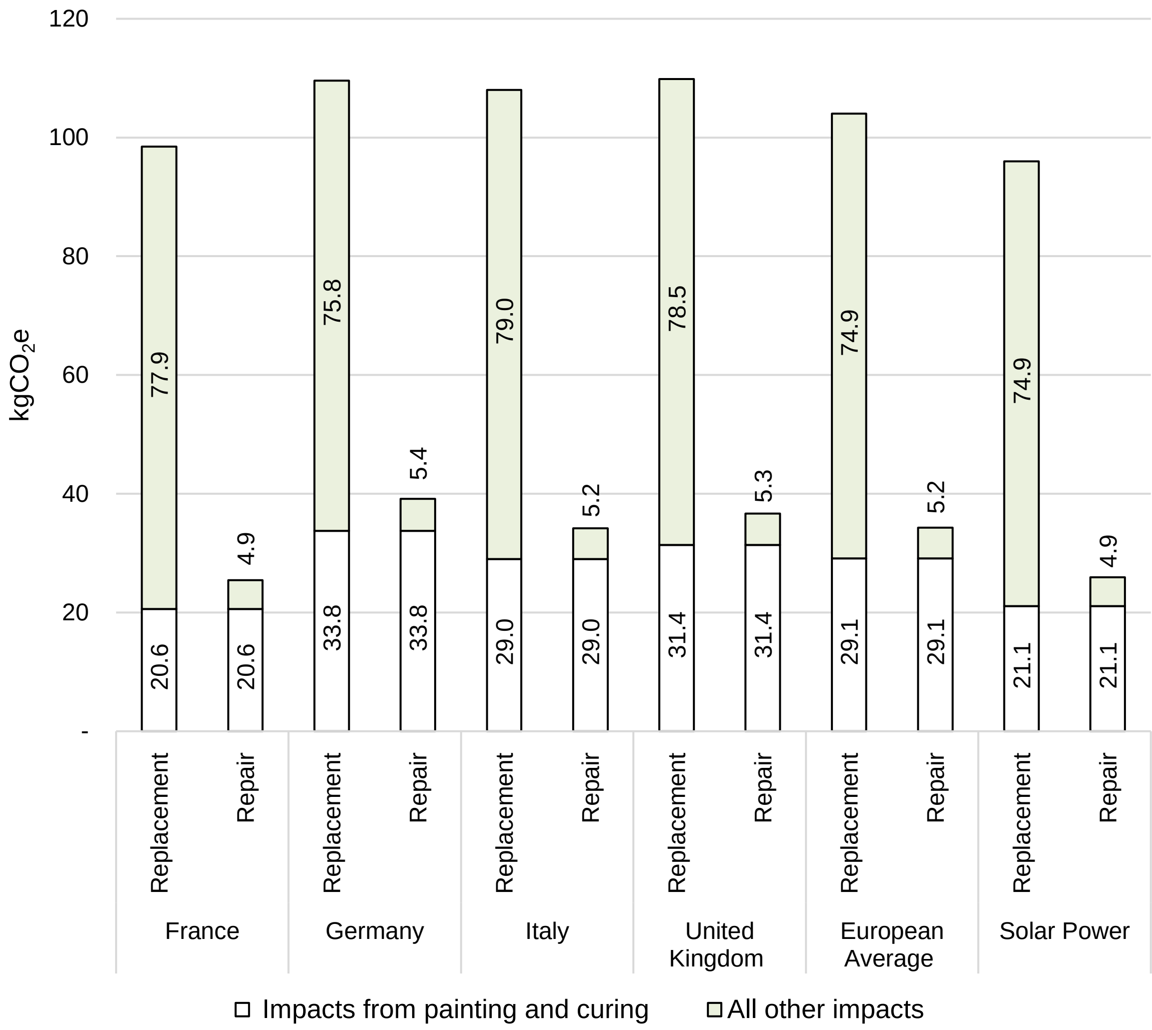

Figure 12 *Results – VW ID.3 Front door (kgCO₂e)*

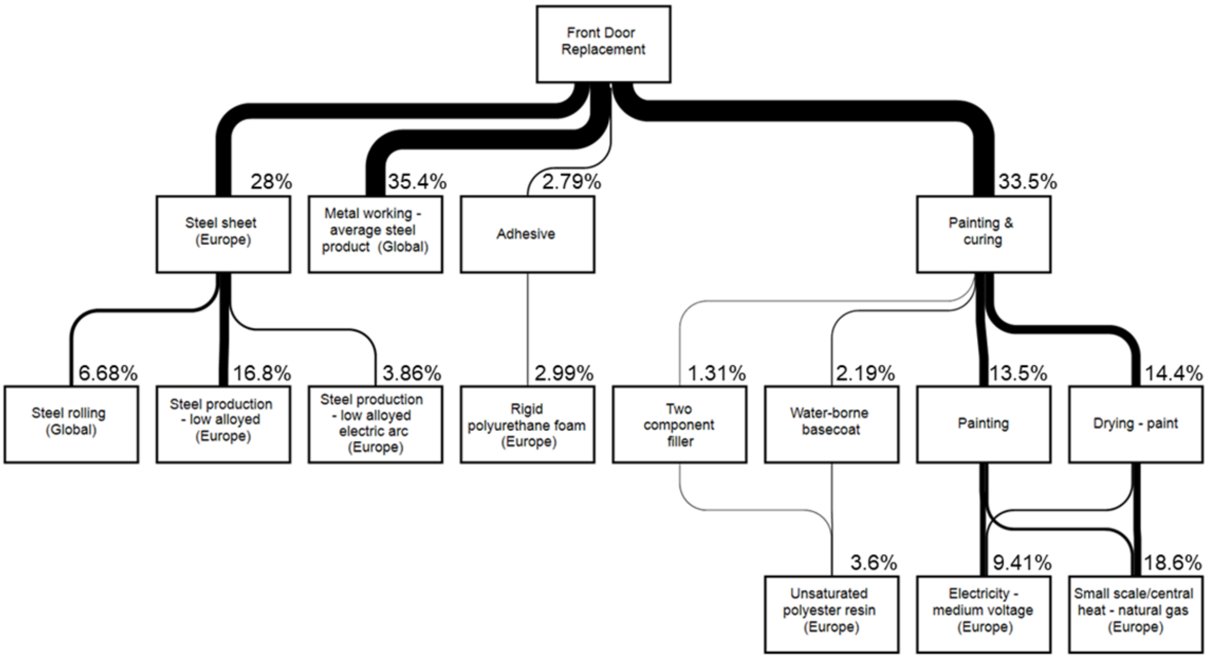

Figure 13 *Front door replacement – contribution of GHG impacts by source (1% cut off: European average scenario)*

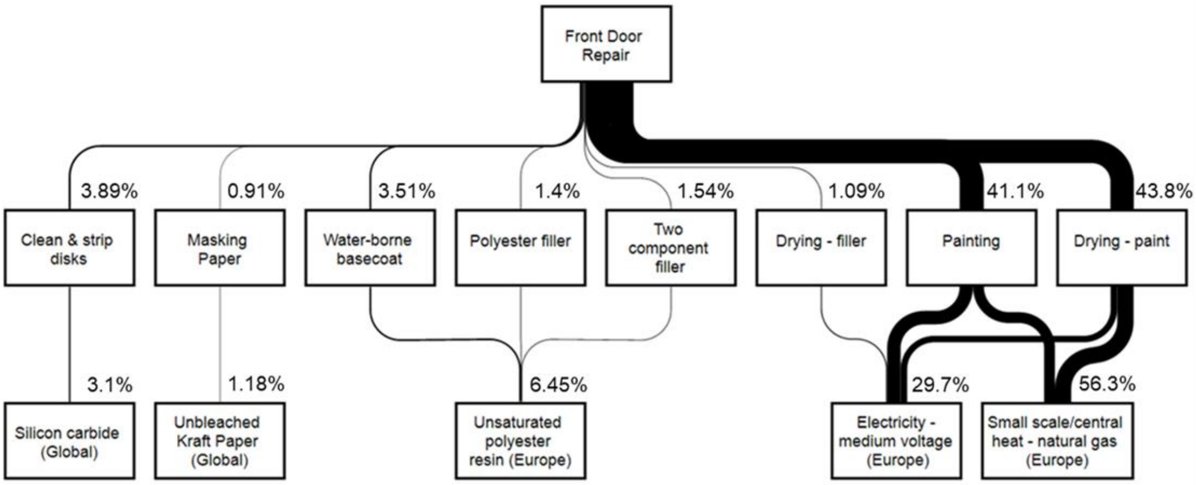

Figure 14 *Front door repair – contribution of GHG impacts by source (1% cut off: European average scenario)*

Analysis

The LCA framework established at the outset of the project was intended to allow for comparisons not just for repairing against replacing, but between countries and the different carbon impact of the production and repair process within each.

Between the countries, the emissions associated with solely the production of the replacement vehicle part (i.e. not including painting or drying) varied very little. As a percentage of the overall emissions, the standard deviations across all parts range from 1% for headlights to 4% for hoods. However, once the painting and drying time for parts is considered, the variance in emissions from the renewal process ranges from 1% for headlights to 13% for the front bumper. The only difference between these two statistics is the electricity emissions associated with the painting and drying process: this immediately shows how the emissions factor of the local electricity network affects the resulting emissions from the repair or replace process.

Below in Figure 15 is presented the average GHG emissions associated with all body parts. For every part analysed, repair has a lower carbon footprint associated with it than replacement does. The magnitude of this difference ranged from 99% in the case of headlights and the windscreen to 4% in the case of the fender.

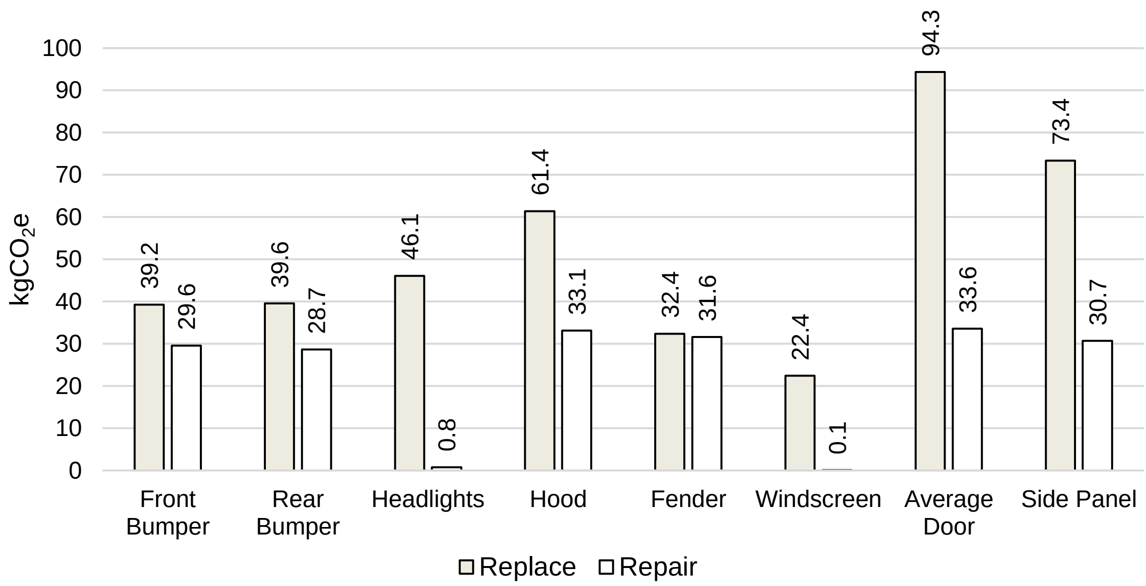

Figure 15 *Emissions from EU average repair and replacement (kgCO_2e)*

The time allowed for (and hence emissions associated with) the painting and drying process did not significantly differ between each scenario, averaging 1.56 hours for repair and 1.53 hours for replace. Hence, the major contribution to the difference in carbon emissions is largely attributed to the production of a new part rather than the repair of an existing part. This can be seen below in Figure 16. If painting and drying are excluded, these differences are even more apparent.

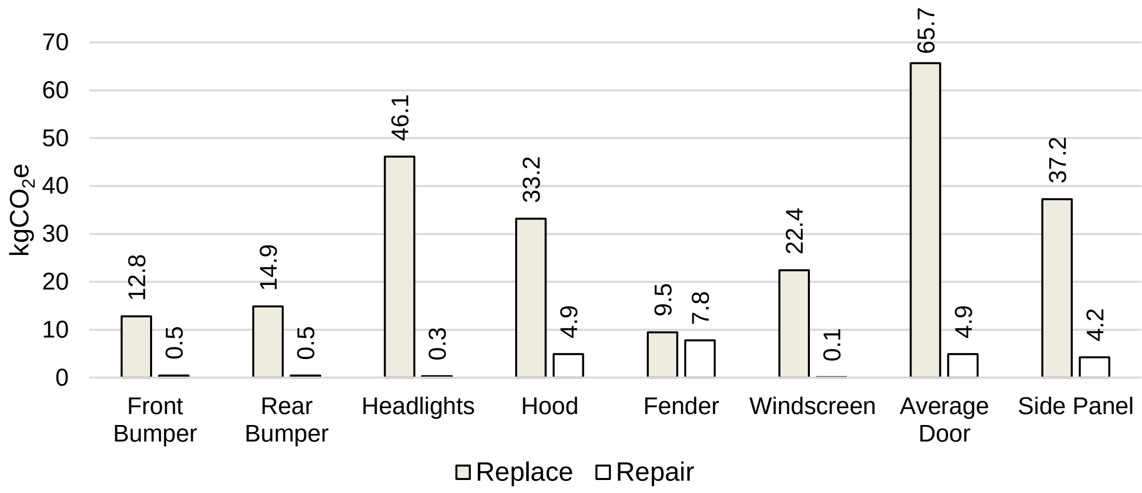

Figure 16 *Emissions from EU average repair and replacement, excluding painting and drying.*

Comparing the four countries, there is a larger carbon impact from those countries which have a higher electrical grid emissions factor. When the variance in emissions for each process is compared across the four countries assessed, the repair process - once painting and drying are included - produced the largest average difference in resulting emissions. The results (see Figure 17) show that the grid emissions associated with electricity consumption is a major contributing factor to the total emissions associated with the various repair types.

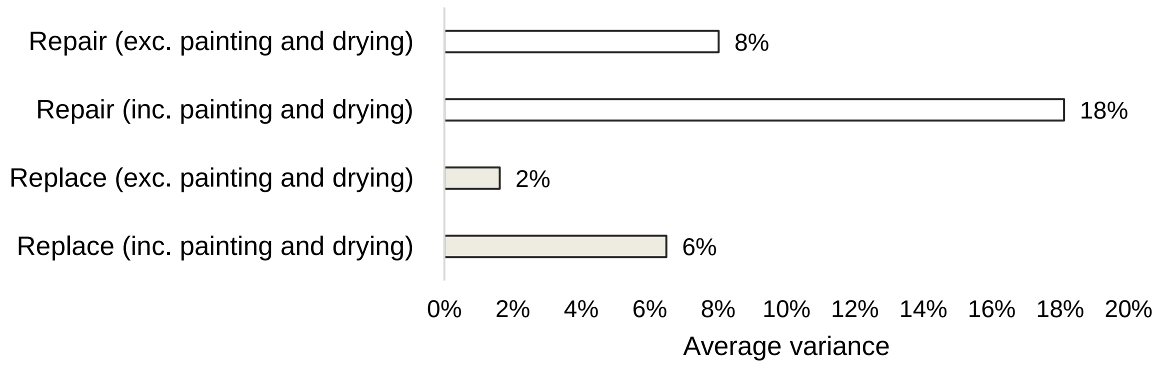

Figure 17 *Average variance between repair types*

This then raises the question of how a solar-powered "eco" workshop would affect the overall emissions from the repair or replace process. As anticipated, when considering the impact that electricity mix has on overall emissions, on average the emissions from damage rectification drop significantly, particularly for those parts that need proportionally more work done in the workshop. Headlight repair benefits the most from such an "eco" workshop, while neither windscreen replacement nor repair see a similar drop in emissions (see Figure 18).

This is due to the modelling assumption that no or negligible workshop electricity consumption takes place during either the repair or the replacement processes for windscreens.

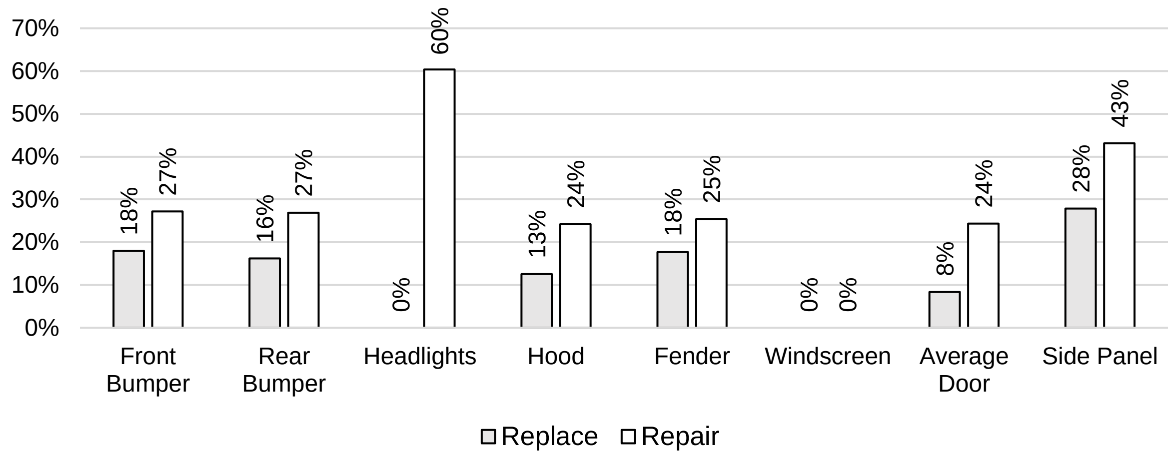

Figure 18 Emissions in the solar PV scenario as a percentage of the EU average scenario

The calculations involved using Ecoinvent factors for emissions intensity that considered the lifetime carbon of the electricity-producing assets in each country. While this an accepted and widely-used approach for undertaking an LCA, it does have limitations and can sometimes produce counter-intuitive results. The prime example for this is shown below: a workshop in France has a lower carbon intensity than that of a solar-powered workshop. As a consequence, emissions associated with the painting and drying stages of repair are shown to be lower when the workshop in question is powered by the French national grid than when powered exclusively by solar power.

The emissions factors used consider the embedded emissions associated with the manufacture of the assets used to produce the electricity. The majority of production in the French grid is from nuclear energy, which has a lower life-cycle CO_2e per kWh than solar PV (7). The life cycle emissions for the painting and drying process are correspondingly lower than those from a solar PV workshop. This has been identified as an area which will require further investigation in the future.

Table 1 Comparing the emissions in kgCO_2e of a French workshop and a solar PV workshop

	Front Bumper	Rear Bumper	Headlights	Hood	Fender	Windscreen	Average Door	Side Panel
France	21.04	20.49	0.76	24.61	23.06	0.12	24.91	22.87
Solar PV	21.53	20.97	0.76	25.10	23.56	0.12	25.41	23.32
Difference	+0.50	+0.48	0	+0.49	+0.49	0	+0.50	+0.45

The findings from this report are clear regarding how to reduce emissions following a vehicle collision. For those relatively low-cost, low-impact collisions that mainly affect bodywork and windscreens, repair should be the first choice. Demonstrating the potentially significant impacts of just a small increase in repair, a 2 percentage point increase in the repair rate in Europe is estimated to save 29,781 tonnes CO_2e - equivalent to the energy consumption of 5,148 homes[1].

Further benefits could also be gained by increasing the utilisation of low-carbon energy and grouping parts during the painting and drying processes.

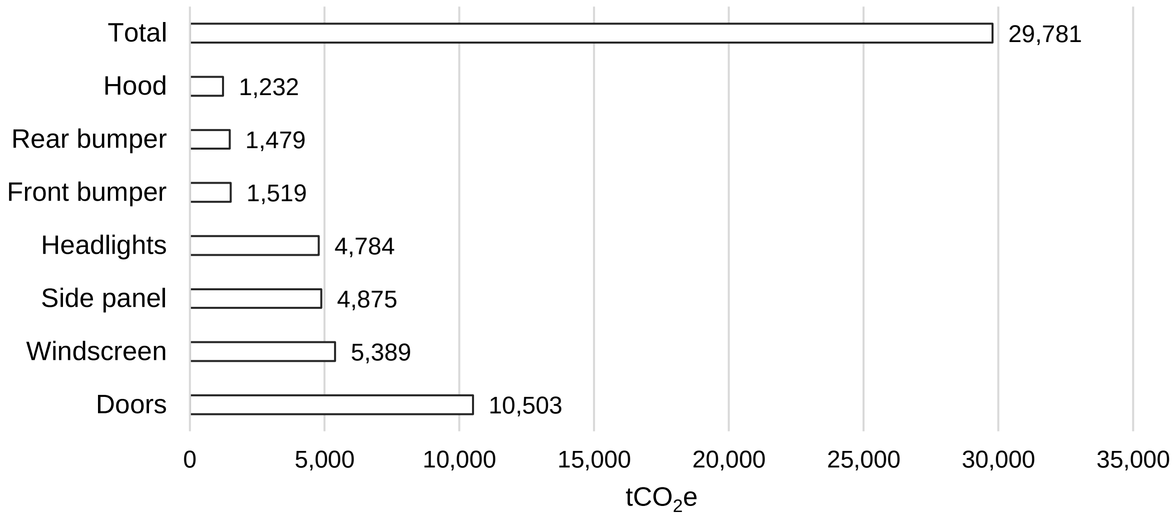

Figure 19 *Total emission savings from a 2% increase in the number of part repairs in Europe (tCO₂e)*

Conclusions

Though limited to a single vehicle across only four geographies, the results of this initial investigation of repair vs replace give strong backing to the supposition that repairing a vehicle component is the lower emitting option of the two. Furthermore, there is clear evidence that there are significant opportunities for insurers and repair shops to reduce emissions arising from vehicle damage claims across the EU.

The findings of this work provide a great basis for future investigations, and in the immediate term can be used to verify the work of insurers to promote the repair of vehicle parts and highlight opportunities for reducing the emissions from all repairs. In particular, the results of this work show clearly the high impacts of automotive painting and curing, serving to underline the importance of the ongoing work to find more environmentally-friendly alternatives for these processes. Notable examples include UV curing, quick drying formulations and ambient temperature drying solutions.

Despite these clear conclusions it is important to view this work in context as an initial scoping study. Though the difference in emissions between repair and replacement is significant, these results only consider four national contexts and rely in part on assumptions. In particular, as a result of the poor availability of data on automotive supply chains, the authors were forced to create a simplified hypothetical scenario for part manufacturing taking place within Europe.

In addition, it is not yet fully known how representative the findings are of alternative vehicles and constructions. As an example, the Volkswagen ID.3 parts studied here are primarily composed of steel, whereas many modern vehicles instead use aluminium parts. The differences between the carbon intensity of producing each material could potentially have large impacts on the outcome of these results. Furthermore, a different proportion of virgin or recycled content and the location of manufacturing may also significantly affect the relative carbon impact of repair and replacement of individual parts.

The goal of the study team is to build on this initial investigation and create a more comprehensive understanding of the relative carbon impacts of repairing and replacing vehicle parts. Future topics that might be investigated include studies of additional vehicles, variations in part compositions (e.g. aluminium vs steel, variations in recycled content) and investigating the relative impacts of reusing vehicle parts in repairs. The authors welcome challenge and future collaboration.

Works Cited

1. **Karlsruhe Institute of Technology.** *Life Cycle Assessment of Vehicle Repairs.* Munich : Allianz Deutschland AG, 2009.

2. **IVL Swedish Environmental Research Institute.** *Climate Impact of Repair.* Stockholm : IVL Swedish Environmental Research Institute, 2020.

3. **International Organization for Standards.** ISO 14040:2006(en) Environmental management - Life cycle assessment - Principles and framework. *ISO Online Browsing Platform (OBP).* [Online] 10 October 2022. https://www.iso.org/standard/37456.html.

4. **The Argonne National Laboratory.** *GREET 2 Series (Vehicle-Cycle Model).* [Spreadsheet] Lemont, Illinois : The Argonne National Laboratory, 2021.

5. **The Society of Automotive Engineers of Japan.** *Energy and CO2 Benefit Assessment of Reused Vehicle Parts through a Material Flow Approach.* Tokyo : International Journal of Automotive Engineering, 2018. 9(2):91-98.

6. **Allianz Zentrum für Technik.** Correspondance with industry stakeholders. 2022.

7. **Ecoinvent.** *Ecoinvent database version 3.8.* [Database] Zurich : Ecoinvent, 2021.

8. **Allianz Zentrum für Technik.** Internal modelling of repair process and costs. s.l. : Allianz Zentrum für Technik, 2022.

9. **3M.** Scotch-Brite™ Roloc™ Clean and Strip XT Pro Disc XO-DR, 50 mm, S XCRS, Purple - Part Number 51887, 3M ID 7100175521, UPC 00638060215388. *3M United Kingdom.* [Online] 3M, 2022. [Cited: 01 March 2022.] https://www.3m.co.uk/3M/en_GB/p/dc/v100679008/.

10. **Henkel Adhesives.** Henkel Adhesives - TEROSON EP 5020 TR . *Henkel Adhesive Technologies.* [Online] Henkel Adhesives, 2022. [Cited: 01 March 2022.] https://www.henkel-adhesives.com/uk/en/product/structural-adhesives/teroson_ep_5020_tr.html.

11. **3M.** 3M™ Hookit™ Purple Clean Sanding Abrasive Sheet Roll 334U. *3M United Kingdom.* [Online] 3M, 2022. [Cited: 01 March 2022.] https://www.3m.com/3M/en_US/p/d/b40071148/.

12. **Commercial Partner.** *Information on specific processes and technologies provided to the Allianz Zentrum für Technik by a commercial partner.* [PDF] 2022.

13. **Hedson Technologies.** *IRT IR Dryers by Hedson - IRT 1 & 2 PrepCure.* [PDF] Arlöv : Hedson Technologies, 2022.

14. **Zhang, H and Chen, M.** *Current recycling regulations and technologies for the typical plastic components of end-of-life passenger vehicles: a meaningful lesson for China.* s.l. : Springer Verlag - Journal of Material Cycles and Waste Management, 2014. 16(2).

15. **Glass for Europe.** A revised End-of-life Vehicles Directive that supports greater recycling of automotive glazing. *Glass for Europe.* [Online] Glass for Europe, June 2022. [Cited: 01 July 2022.] https://glassforeurope.com/a-revised-end-of-life-vehicles-directive-that-supports-greater-recycling-of-automotive-glazing/.

16. **Google .** Google Maps. *Google Maps.* [Online] Alphabet , 2022. [Cited: 01 March 2022.] https://www.google.co.uk/maps.

17. **The European Steel Association.** What is steel and how is steel made? *Eurofer The European Steel Association.* [Online] The European Steel Association, 17 March 2020. [Cited: 01 March 2022.] https://www.eurofer.eu/about-steel/learn-about-steel/what-is-steel-and-how-is-steel-made/.

18. **The European Commission.** *Commission Staff Working Document: Evaluation of Directive (EC) 2000/53 of 18 September 2000 on end-of-life vehicles.* Brussels : The European Commission, 2021.

19. **3M.** 3M™ Cubitron™ II Roloc™ Fiber Disc 982C. *3M Deutschland.* [Online] 3M. [Cited: 01 March 2022.] https://www.3mdeutschland.de/3M/de_DE/p/d/b40064827/.

20. —. *3M United Kingdom.* [Online] 3M, 2022. [Cited: 01 March 2022.] https://www.3m.co.uk/3M/en_GB/p/d/b40068774/.

21. —. Scotch-Brite™ Roloc™ Clean and Strip XT Pro Disc XO-DR, 50 mm, S XCRS, Purple. *3M United Kingdom.* [Online] 3M, 2022. [Cited: 01 March 2022.] https://www.3m.co.uk/3M/en_GB/p/dc/v100679008/.

22. **Henkel Adhesives.** TEROSON EP 5020 - Features and Benefits. *Henkel Adhesives.* [Online] Henkel Adhesives, 2022. [Cited: 01 March 2022.] https://www.henkel-adhesives.com/uk/en/product/structural-adhesives/teroson_ep_5020_tr.html.

23. **3M.** 3M™ Hookit™ Purple Clean Sanding Abrasive Sheet 334U. *3M United Kingdom.* [Online] 3M, 2022. [Cited: 01 March 2022.] https://www.3m.co.uk/3M/en_GB/p/d/b40071158/.

24. **Henkel Adhesives.** TEROSON EP 5055 Features and Benefits. *Henkel Adhesives.* [Online] Henkel Adhesives, 2022. [Cited: 01 March 2022.] https://www.henkel-adhesives.com/de/en/product/structural-adhesives/teroson_ep_5055.html.

25. **Belron.** Patended Technology - Advanced Repair Technology (ART). *Belron.* [Online] Belron, 2022. [Cited: 01 March 2022.] https://www.belron.com/serving-customers/patented-technology/.

26. *Life cycle analysis of automotive glass: production and recycling (No. 970697).* **Balestrini, A and Levizzari, A.** s.l. : SAE International, 1997. 0148-7191.

27. **Spray Max.** 2K 2in1 Headlight Clear. *Spray Max.* [Online] Spray Max, 2022. [Cited: 01 March 2022.] https://www.spraymax.com/en/products/product/clear-coats-and-spot-blender/2k-2in1-headlight-clear/.

28. —. 1K Silicone Remover. *Spray Max.* [Online] Spray Max, 2022. [Cited: 01 March 2022.] https://www.spraymax.com/en/products/product/surface-preparation/1k-silicone-remover/.

29. **Volkswagen Group.** ID.3 Headlight Repair Kit SKU: 5H0-998-225. 2022.

30. **Our World in Data.** *Carbon Intensity of Electricity, 2021.* [Spreadsheet] Oxford : Our World in Data, 2022.

Appendix 1: Part Methodologies

Modelling Repair of an ID.3 Front Bumper

The scenario modelled for the repair of the front bumper of the ID.3 describes a 'light damage' scenario, with a crack or scratch large enough to require repair to the surface area. The process itself requires that the bumper is removed, the existing paint finish is sanded down, and the crack/scratch repaired using a plastics welding process with polypropylene reinforcing strips and the application of a two-part polyurethane repair adhesive. Once this is complete, body filler is applied to the repaired area, set using a filler hardening product, and finished. At this point the bumper is repainted, cured and placed back on the vehicle.

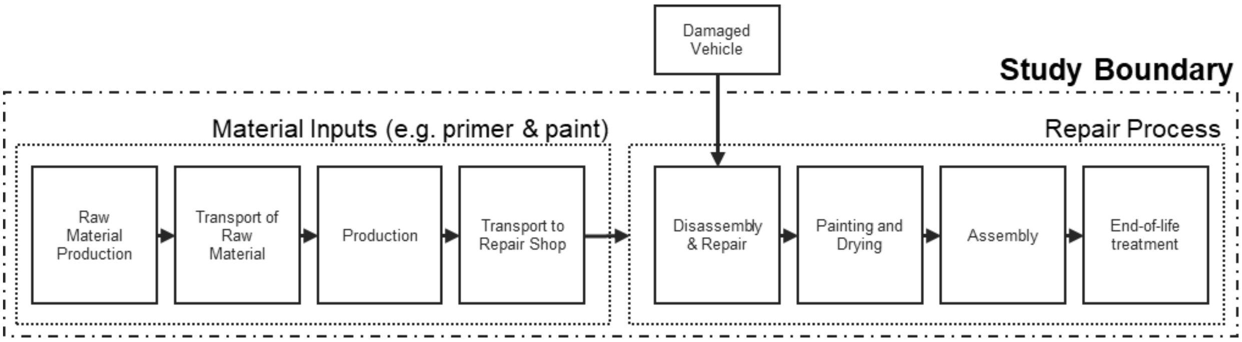

Figure 20 *Study boundary for the repair of a front bumper*

The modelled painting process includes the preparation, sanding of the part, priming (with an adhesion promoter), painting and curing. After the repair is complete any waste generated in the process is then sent on for waste treatment.

Modelling assumptions

	Description
Repaired surface area	The quantities of materials required to conduct the plastics repair are based on measurements taken by AZT of a typical damage scenario (8).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, the single differentiating factor being the grid electricity mix, as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.6 hours and a curing time of 0.75 hours for the entire panel surface, based on data from AZT (8). Each bumper is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair process	
Resource	**Reference**
Plastics repair adhesive	AZT (8), Ecoinvent (7)
Polypropylene reinforcing strips	AZT (8), Ecoinvent (7)
Fine plastic filler	AZT (8), Ecoinvent (7)
Two-component body filler	AZT (8), Ecoinvent (7)
Hardener for filler	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7), 3M (19)
Electricity consumption – Plastics welding	AZT (8), Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Cleaning thinner	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Plastic adhesion promoter	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Front Bumper

The scenario modelled for the replacement of the front bumper of the ID.3 describes a process in which the whole part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, painting, and placement onto the receiving vehicle. Additionally, the modelling includes the removal and end-of-life treatment of the damaged part.

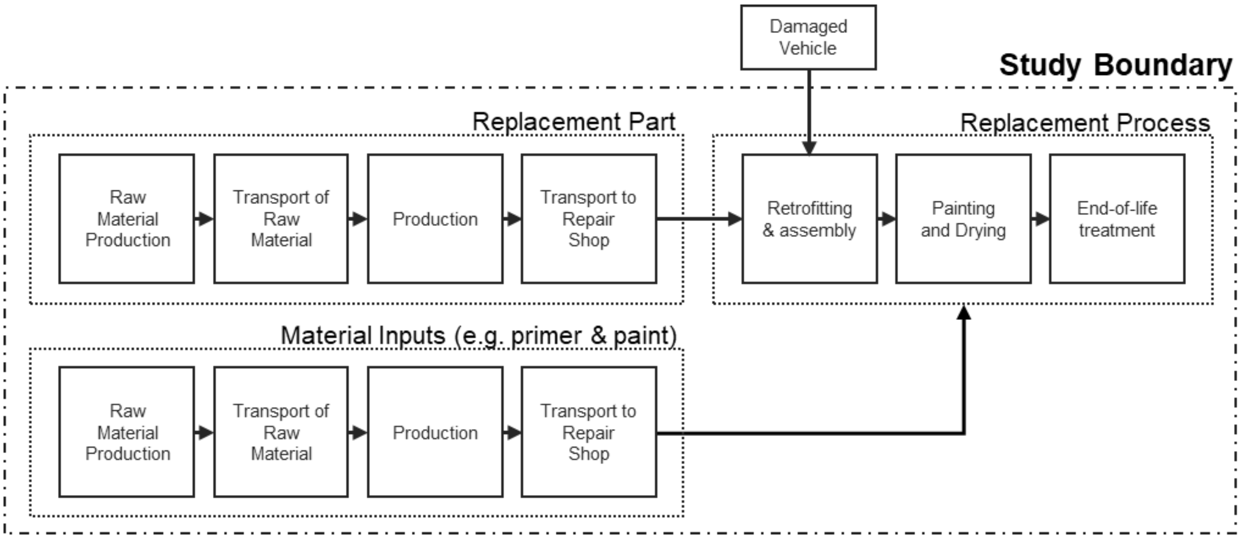

Figure 21 *Study boundary for replacing a front bumper*

The modelling assumes that the front bumper is manufactured in the EU; the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps. As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes priming (via an adhesion promoter), painting and curing, all of which take place within the repair workshop.

Modelling assumptions

	Description
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.3 hours and a curing time of 0.75 hours for the entire bumper surface, based on data from AZT (8). Each front bumper is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional ‘recovery losses’ have been accounted for based on the authors’ best estimates. The assumed recycling/recovery rates for the plastic bumper are a recycling rate of 90% and recovery losses of 10% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Rubber modified polypropylene	AZT (8), Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Cleaning thinner	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Plastic adhesion promoter	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Front Bumper

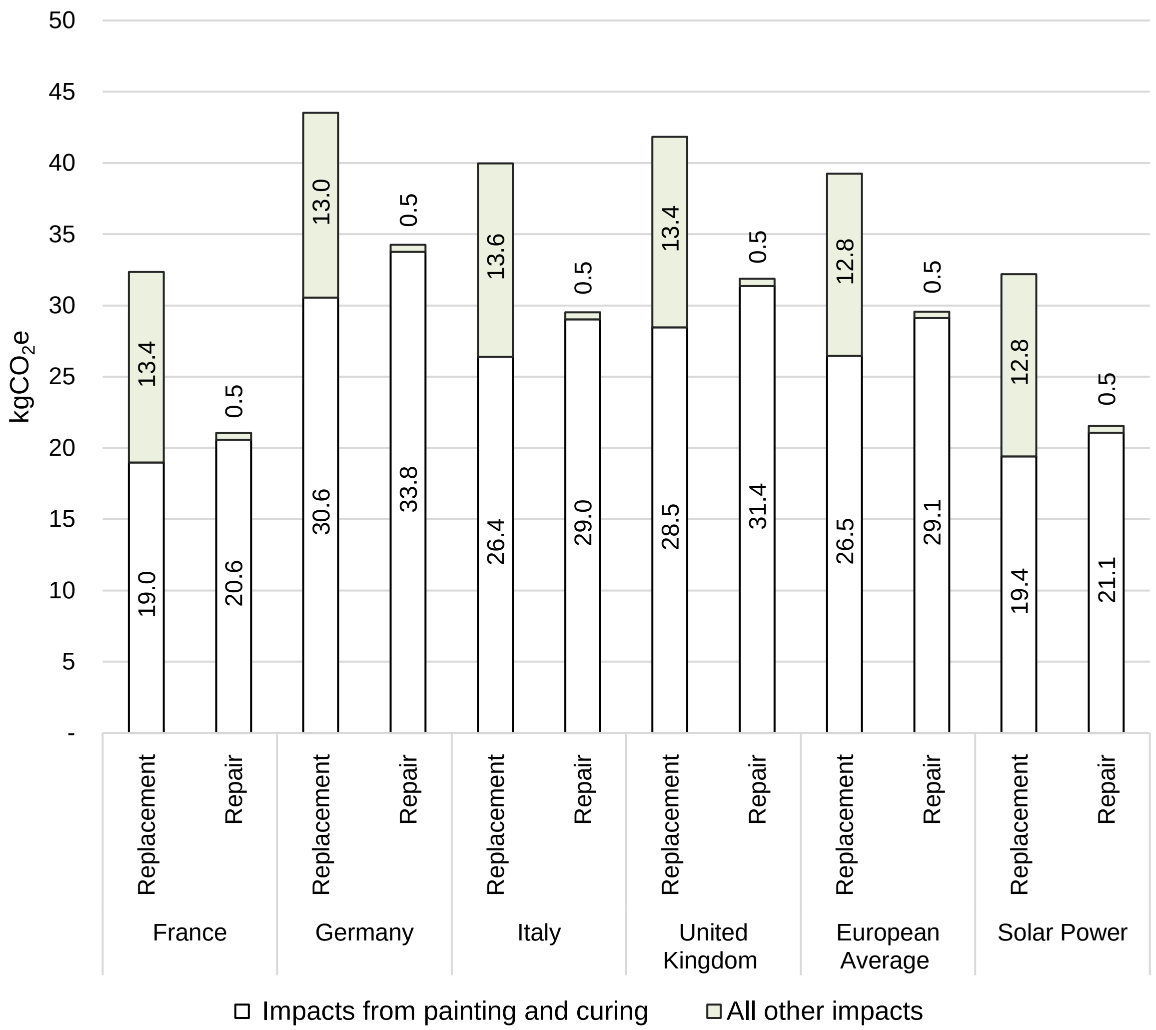

Figure 22 *Results – VW ID.3 Front Bumper (kgCO2e)*

Modelling Repair of an ID.3 Rear Bumper

The scenario modelled for the repair of the rear bumper of the ID.3 describes a 'light damage' scenario, with a crack or scratch large enough to require repair to the surface area. The process itself requires that the existing paint finish is sanded down and the crack/scratch repaired using a plastics welding process, with polypropylene reinforcing strips and the application of a two-part polyurethane repair adhesive. Once this is complete, body filler is applied to the repaired area, set using a filler hardening product, and finished. At this point the bumper is repainted, cured and placed back on the vehicle.

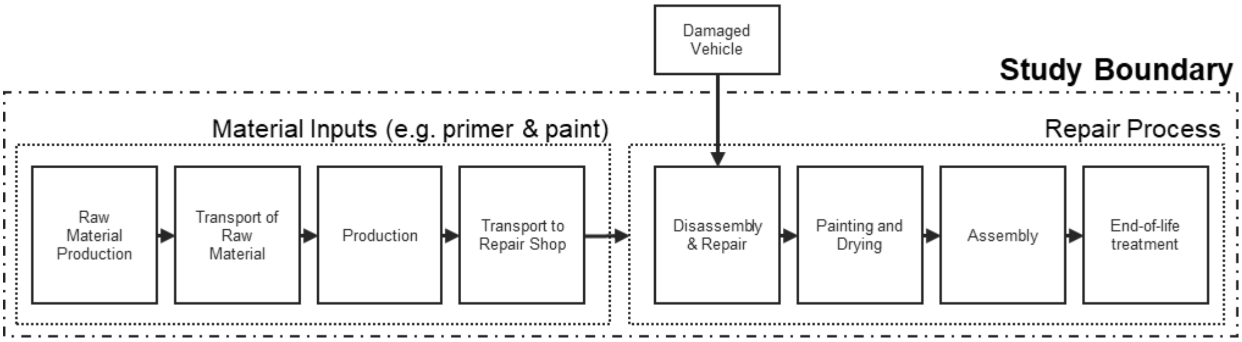

Figure 23 *Study boundary for the repair of a rear bumper*

The modelled painting process includes the sanding of the part, priming (via an adhesion promoter), painting and curing. After the repair is complete, any waste generated in the process is then sent on for waste treatment.

Modelling assumptions

	Description
Repaired surface area	The quantities of materials required to conduct the plastics repair are based on measurements taken by AZT of a typical damage scenario (8).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.5 hours and a curing time of 0.75 hours for the entire bumper surface, based on data from AZT (8). Each bumper is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair Process	
Resource	**Reference**
Plastics repair adhesive	AZT (8), Ecoinvent (7)
Polypropylene reinforcing strips	AZT (8), Ecoinvent (7)
Fine plastic filler	AZT (8), Ecoinvent (7)
Two-component body filler	AZT (8), Ecoinvent (7)
Hardener for filler	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7), 3M (19)
Electricity consumption – Plastics welding	AZT (8), Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Cleaning thinner	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Plastic adhesion promoter	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Rear Bumper

The scenario modelled for the replacement of the rear bumper of the ID.3 describes a process in which the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, painting, and placement onto the receiving vehicle. In addition, the modelling includes the removal and end-of-life treatment of the damaged part.

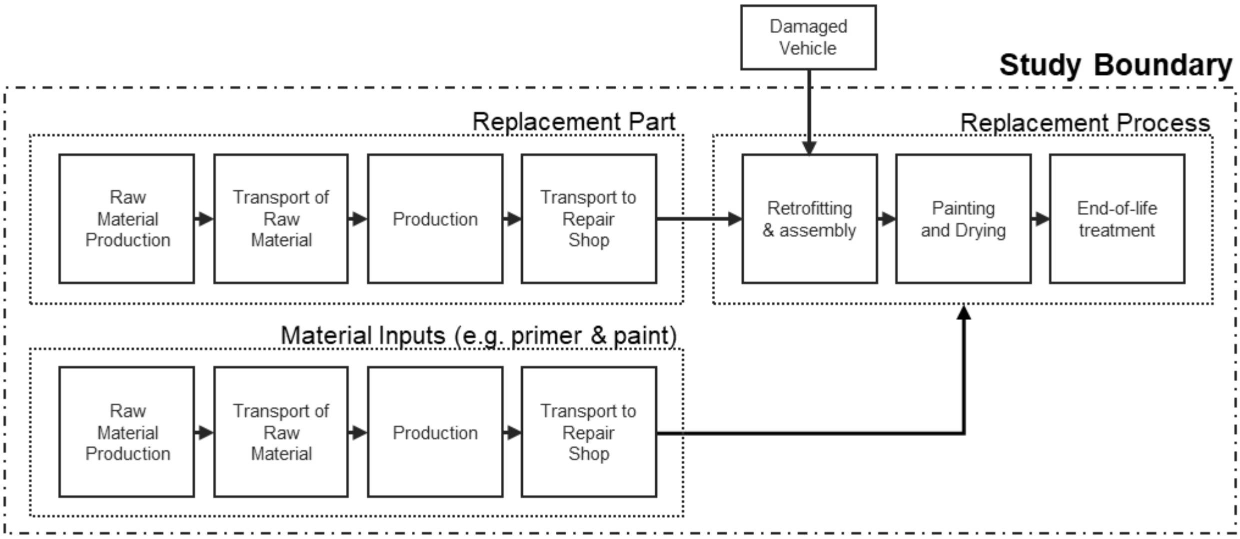

Figure 24 *Study boundary for replacing a rear bumper*

The modelling assumes that the rear bumper is manufactured in the EU; the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps. As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes priming (via an adhesion promoter), painting and curing, all of which take place within the repair workshop.

Modelling assumptions

	Description
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used across all nations, with the single differentiating factor being the grid electricity mix, as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.1 hours and a curing time of 0.75 hours for the entire bumper surface, based on data from AZT (8). Each rear bumper is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional ‘recovery losses’ have been accounted for based on the authors’ best estimates. The assumed recycling/recovery rates for the plastic bumper are a recycling rate of 90% and recovery losses of 10% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Rubber modified polypropylene	AZT (8), Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Cleaning thinner	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Plastic adhesion promoter	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Rear Bumper

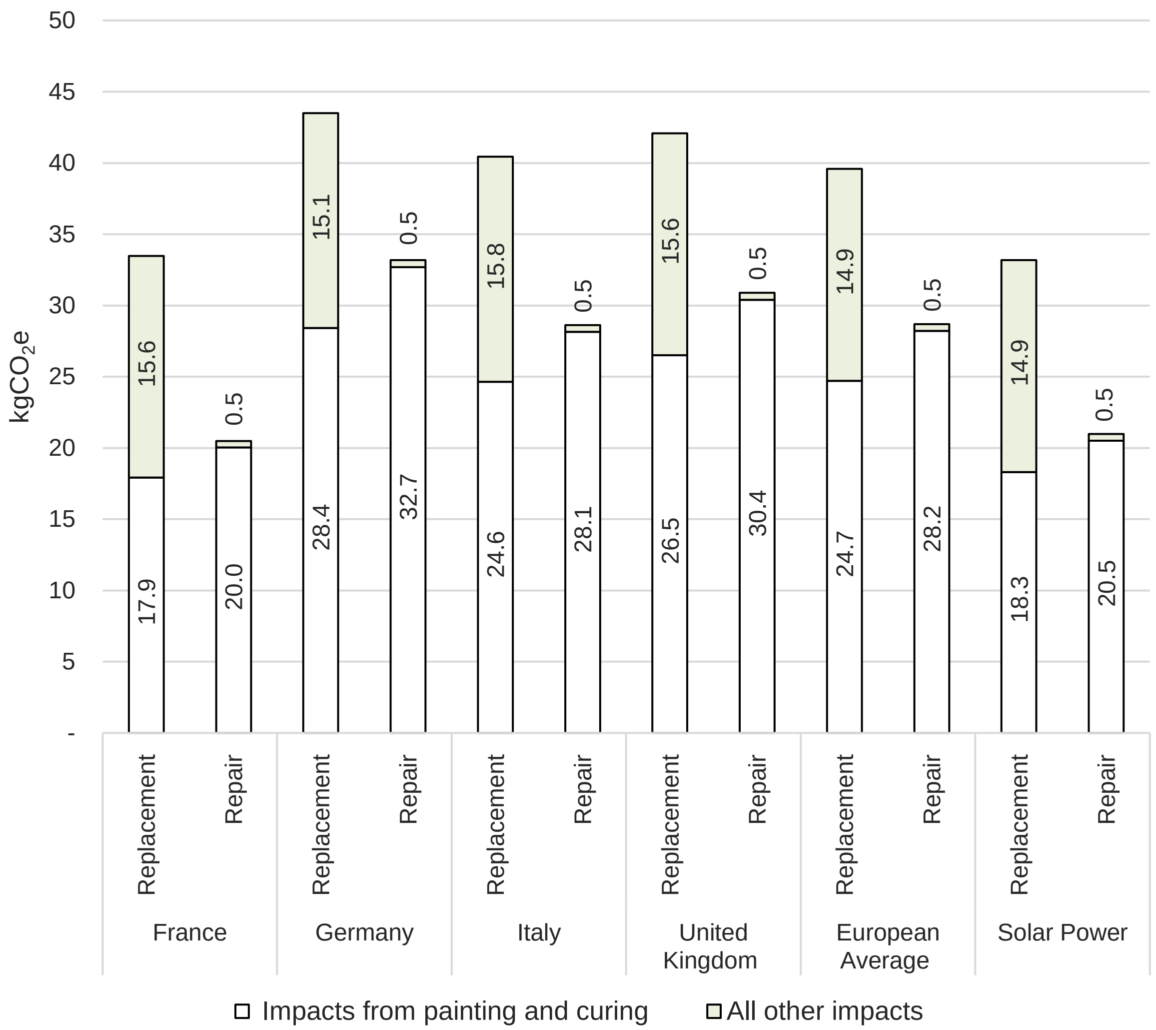

Figure 25 Results – VW ID.3 Rear Bumper (kgCO₂e)

Modelling Repair of an ID.3 Rear Door

The scenario modelled for the repair of the rear door of the ID.3 describes a ‘light damage’ scenario, with a dent or scratch large enough to require that 6.5% of the surface area is repaired. The process itself requires that the existing paint finish is sanded down to bare metal and a tin solder replacement material is applied to restore the damaged area. Once this is complete, the filler is dried using an electric infrared heater and finished, at which point the door is repainted. The modelled painting process includes the sanding, priming, painting and curing of the front door. Once this is complete the door is then placed back onto the vehicle and any waste generated in the process is sent for treatment.

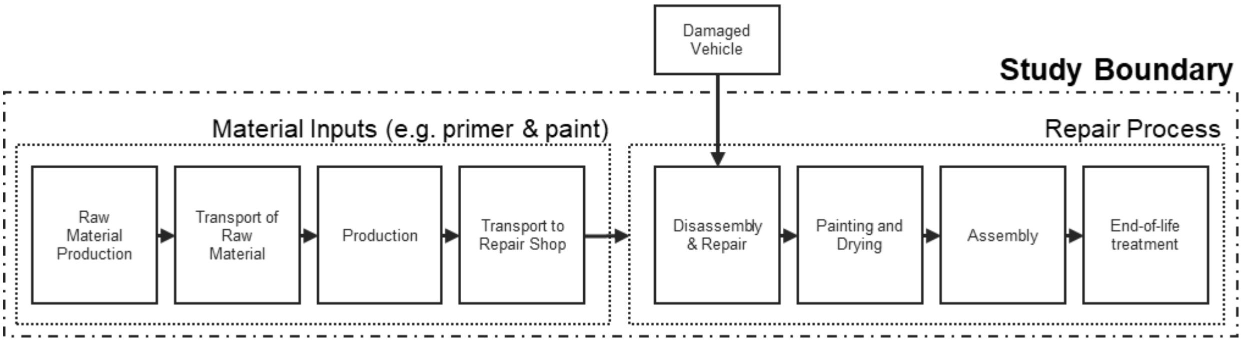

Figure 26 *Study boundary for the repair of a rear door*

Modelling assumptions

	Description
Repaired surface area	Based on data from AZT (8) the repaired surface area is assumed to be 6.5% of the entire surface area. This denotes a 'light damage' scenario.
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Infrared heater operation - curing body filler	In the repair process an infrared curing oven is used to cure the body filler applied over the damaged surface area. The modelling of this process assumes a curing time of 30 minutes (8) and the use of a 230 volt, 10 amp (2.3kW) infrared dryer delivering heat energy at 75% efficiency (13).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.5 hours and a curing time of 0.75 hours for the entire panel surface, based on data from AZT (8). Each rear door is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair Process	
Resource	**Reference**
Clean and strip discs	AZT (8), 3M (9), Ecoinvent (7)
Tin solder replacement material	AZT (8), Henkel Adhesives (10), Ecoinvent (7)
Sanding strips	AZT (8), 3M (11), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Electricity consumption –Infrared heater & tools	Ecoinvent (7), Hedson Technologies (13)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Rear Door

The scenario modelled for the replacement of the rear door of the ID.3 describes a process whereby the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, painting, and placement onto the receiving vehicle. In addition, the modelling includes the removal and end-of-life treatment of the damaged part.

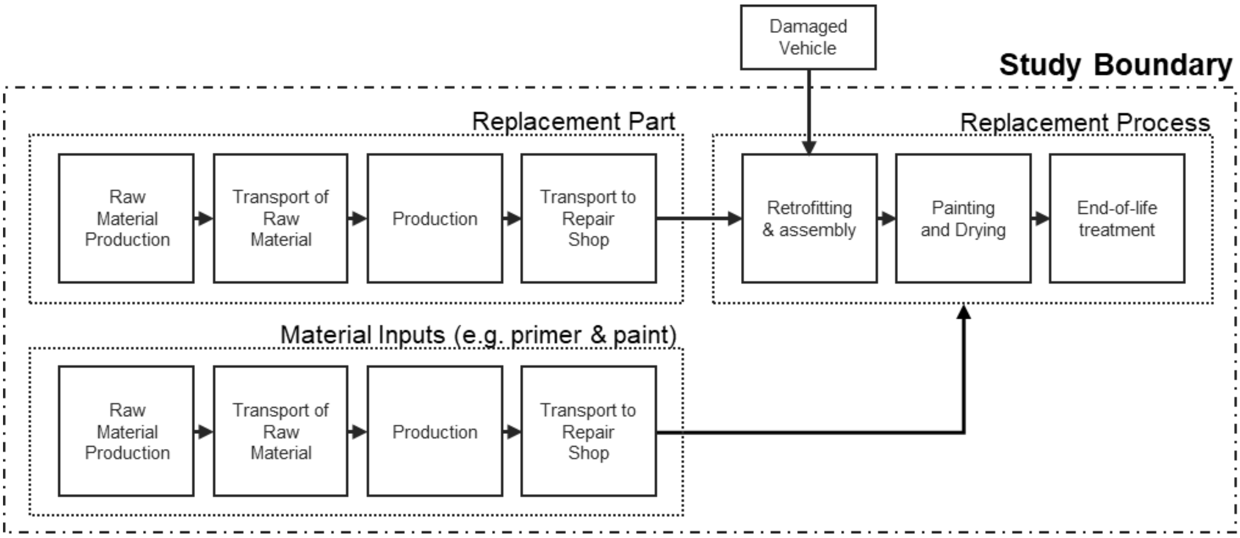

Figure 27 *Study boundary for the replacement of a rear door*

The modelling assumes that the front door is originally manufactured in the European Union; the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps.

As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes priming, painting and curing, all of which take place within the repair workshop.

Modelling assumptions

	Description
Steel production	By weight, most of the replacement door is steel, so attention has been paid to ensure that the steel modelled is representative of the European Union average. 60% of the steel is modelled as being produced via a blast furnace and 40% via an electric arc furnace, equal to the average European production reported by Eurofer (17). The upstream transport of the raw steel product to the manufacturer is assumed to be 500 km by rail with an additional 300 km of road transport.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.5 hours and a curing time of 0.75 hours for the entire door surface, based on data from AZT (8). Each door is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional ‘recovery losses’ have been accounted for, based on the authors’ best estimates. The assumed recycling/recovery rates for each material are: metals recycling rate 95% and recovery losses 5%; plastics recycling rate 90% and recovery losses 10%; glass (windscreens) recycling rate 75% and recovery losses 25% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Steel sheet	AZT (8), Ecoinvent (7), Industry source (12)
Adhesives	AZT (8), Ecoinvent (7), Industry source (12)
Plastic parts	AZT (8), Ecoinvent (7), Industry source (12)
Electricity consumption – Metal Shaping (Press) electricity	Ecoinvent (7)
Electricity consumption – Welding	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Seam sealing	AZT (8), Ecoinvent (7)
Cavity preservation	AZT (8), Ecoinvent (7)
Noise-absorbent mat	AZT (8), Ecoinvent (7)
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Hardener for primer	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption –Tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Rear Door

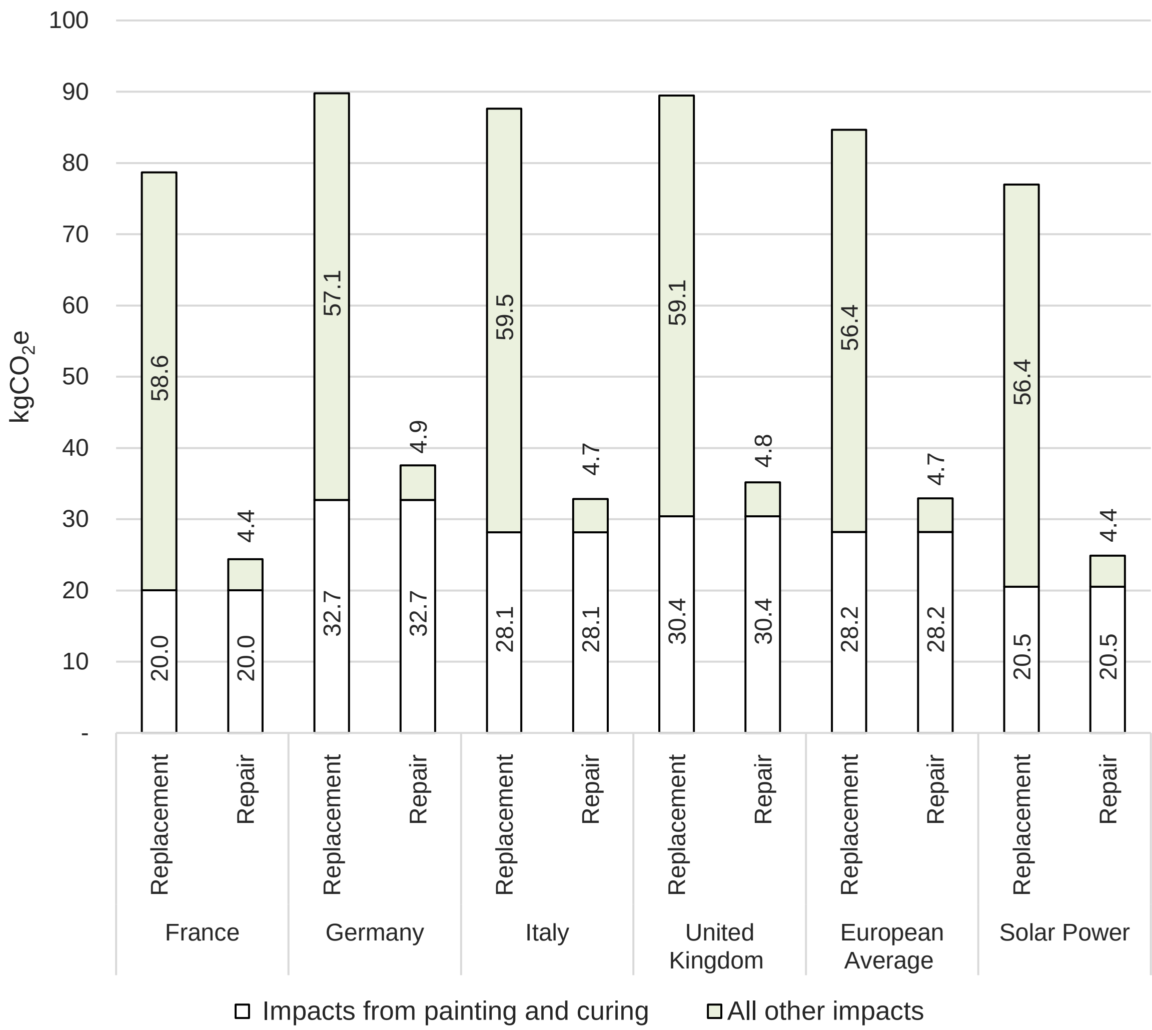

Figure 28 *Results – VW ID.3 Rear Door (kgCO₂e)*

Modelling Repair of an ID.3 Hood

The scenario modelled for the repair of the hood of the ID.3 describes a 'light damage' scenario, with a dent or scratch large enough to require that 6.6% of the surface area is repaired. The process itself requires that the existing paint finish is sanded down to bare metal and a body filler putty is applied to restore the damaged area. Once this is complete, the filler is dried using an electric infrared heater and finished, at which point the door is repainted.

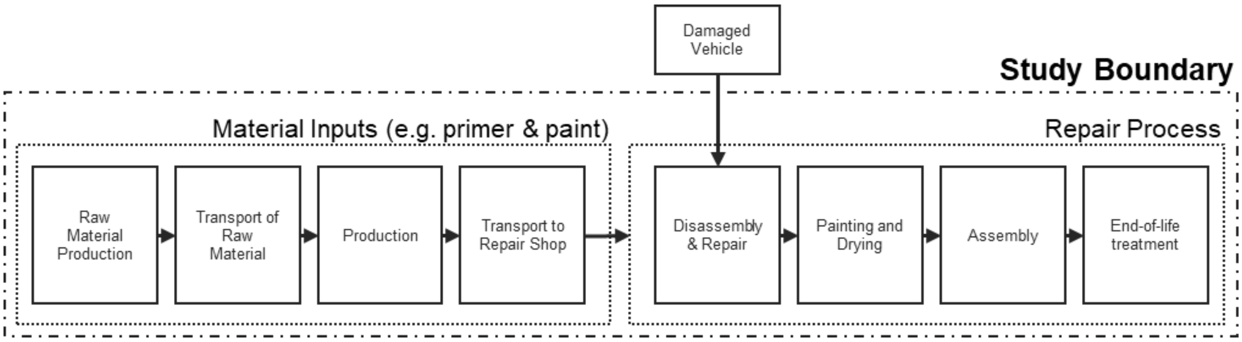

***Figure 29** Study boundary for the repair of a hood*

The modelled painting process includes the sanding, priming, painting and curing of the hood. Once this is complete the hood is then placed back onto the vehicle and any waste generated in the process is sent for treatment.

Modelling assumptions

	Description
Repaired surface area	Based on data from AZT (8) the repaired surface area is assumed to be 6.6% of the entire surface area. This denotes a 'light damage' scenario.
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used for the model across all nations, with the single differentiating factor being the grid electricity mix, as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Infrared heater operation - curing body filler	In the repair process an infrared curing oven is used to cure the body filler applied over the damaged surface area. The modelling of this process assumes a curing time of 30 minutes (8) and the use of a 230 volt, 10 amp (2.3kW) infrared dryer delivering heat energy at 75% efficiency (13).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.5 hours and a curing time of 0.75 hours for the entire surface of the hood, based on data from AZT (8). Each hood is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair process	
Resource	**Reference**
Clean and strip discs	AZT (8), 3M (9), Ecoinvent (7)
Body filler	AZT (8), Henkel Adhesives (10), Ecoinvent (7)
Sanding strips	AZT (8), 3M (11), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Electricity consumption – Infrared heater & tools	Ecoinvent (7), Hedson Technologies (13)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption –Tools, paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas –Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Hood

The scenario modelled for the replacement of the hood of the ID.3 describes a process whereby the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part (primarily of stamped steel), transport to the workshop, painting, and placement onto the receiving vehicle. In addition, the modelling includes the removal and end-of-life treatment of the damaged part.

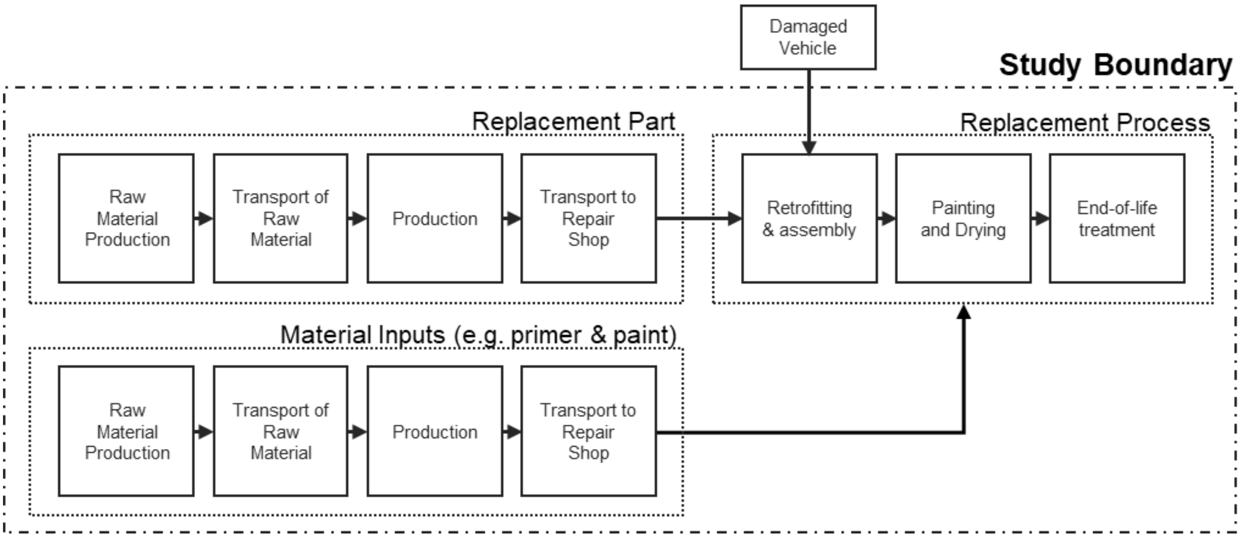

__Figure 30__ Study boundary for the replacement of a hood

The modelling assumes that the hood is originally manufactured in the European Union; the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps.

As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes priming, painting and curing, all of which take place within the repair workshop.

Modelling assumptions

	Description
Steel production	By weight, most of the replacement hood is steel, so attention has been paid to ensure that the steel modelled is representative of the EU average. 60% of the steel is modelled as being produced via a blast furnace and 40% via an electric arc furnace, equal to the average European production reported by Eurofer (17). The upstream transport of the raw steel product to the manufacturer is assumed to be 500 km by rail with an additional 300 km of road transport.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used in the model across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.5 hours and a curing time of 0.75 hours for the entire hood surface, based on data from AZT (8). Each hood is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional 'recovery losses' have been accounted for based on the authors' best estimates. The assumed recycling/recovery rates for materials in the ID. 3 hood are a metals recycling rate of 95% and recovery losses of 5%, with a plastics recycling rate of 90% and recovery losses of 10% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Steel sheet	AZT (8), Ecoinvent (7), Industry source (12)
Adhesives	AZT (8), Ecoinvent (7), Industry source (12)
Plastic parts	AZT (8), Ecoinvent (7), Industry source (12)
Electricity consumption - Metal Shaping (Press) electricity	Ecoinvent (7)
Electricity consumption – Welding	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Seam sealing	AZT (8), Ecoinvent (7)
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Hardener for primer	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Hood

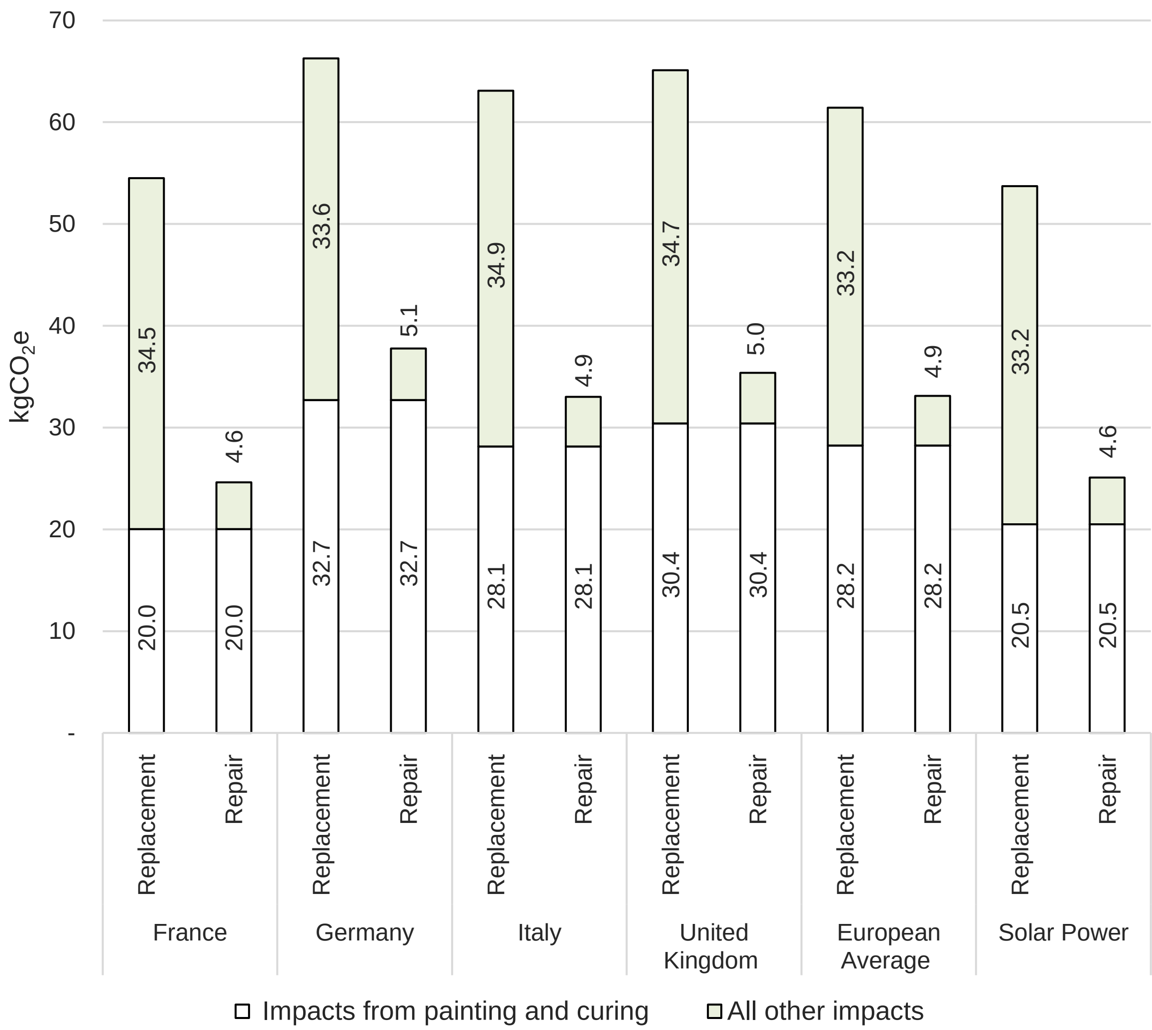

Figure 31 *Results – VW ID.3 Hood ($kgCO_2e$)*

Modelling Repair of an ID.3 Side Panel

The scenario modelled for the repair of the side panel of the ID.3 describes a ‘light damage’ scenario, with a dent or scratch large enough to require that 3.6% of the surface area is repaired. The process itself requires that the existing paint finish is sanded down to bare metal and a body filler putty applied to restore the damaged area. Once this is complete, the filler is dried using an electric infrared heater, and finished; at this point the side panel is repainted. Unlike most other studied parts, the side panel remains on the vehicle throughout this entire repair process.

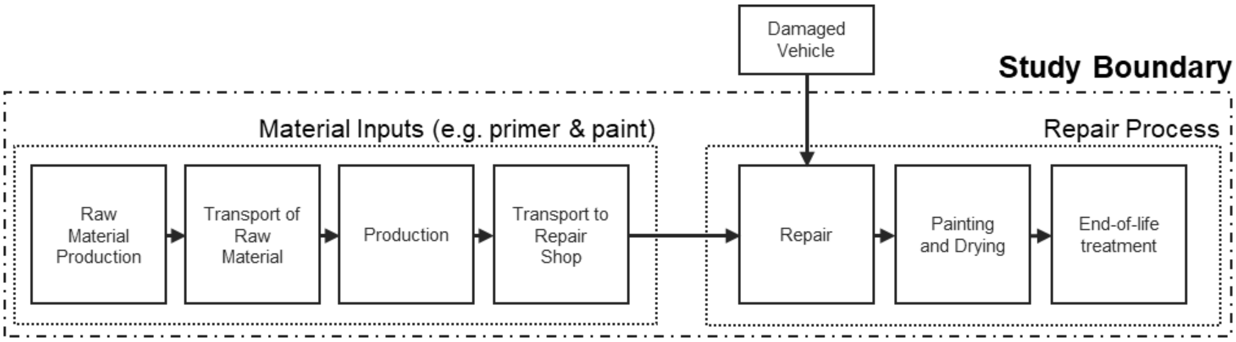

Figure 32 *Study boundary for the repair of a side panel*

The modelled painting process includes the preparation/masking of the vehicle, sanding of the part, priming, painting and curing. After the repair is complete any waste generated in the process is then sent on for waste treatment.

Modelling assumptions

	Description
Repaired surface area	Based on data from AZT (8) the repaired surface area is assumed to be 3.6% of the entire surface area. This denotes a 'light damage' scenario.
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, which was sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Infrared heater operation - curing body filler	In the repair process an infrared curing oven is used to cure the body filler applied over the damaged surface area. The modelling of this process assumes a curing time of 30 minutes (8) and the use of a 230 volt, 10 amp (2.3kW) infrared dryer delivering heat energy at 75% efficiency (13).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.3 hours and a curing time of 0.75 hours for the entire panel surface, based on data from AZT (8). Each side panel is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair process	
Resource	**Reference**
Clean and strip discs	AZT (8), 3M (9), Ecoinvent (7)
Body filler	AZT (8), Henkel Adhesives (10), Ecoinvent (7)
Sanding strips	AZT (8), 3M (11), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7), 3M (19)
Electricity consumption – Infrared heater & tools	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Side Panel

The scenario modelled for the replacement of the side panel of the ID.3 describes a process in which the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and includes the manufacture of the replacement part, transport to the workshop, painting, and placement onto the receiving vehicle. The modelling also includes the removal and end-of-life treatment of the damaged part.

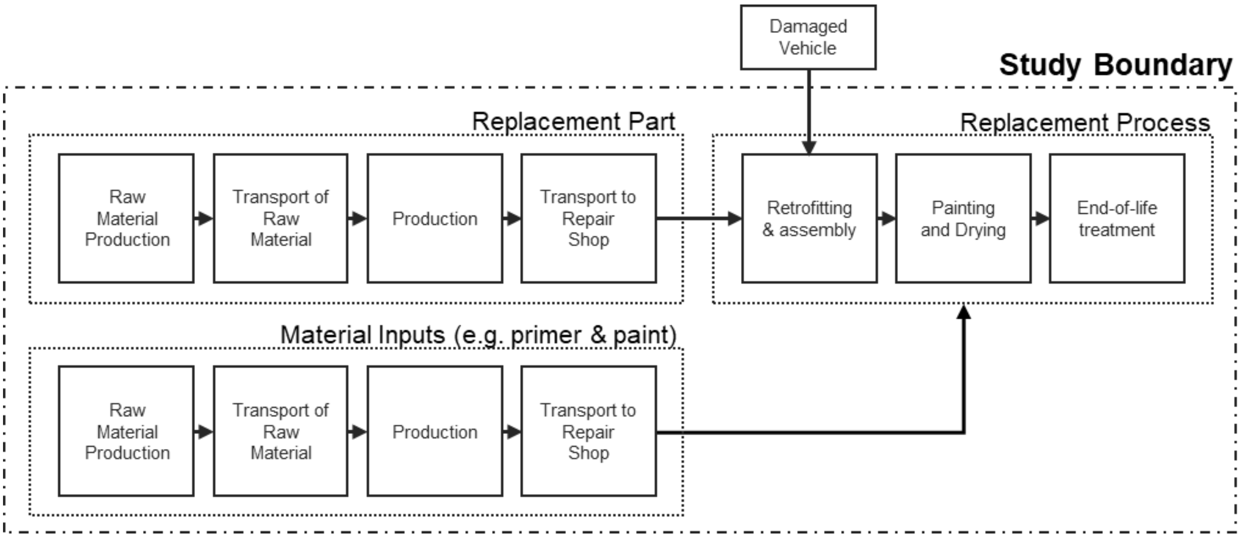

__Figure 33__ Study boundary for replacing a side panel

The modelling assumes that the side panel is manufactured in the European Union, and the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps. As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes masking, priming, painting and curing, all of which take place within the workshop.

Modelling assumptions

	Description
Steel production	By weight, most of the replacement panel is steel, so attention has been paid to ensure that the steel modelled is representative of the EU average. 60% of the steel is modelled as being produced via a blast furnace and 40% via an electric arc furnace, equal to the average European production reported by Eurofer (17). The upstream transport of the raw steel product to the manufacturer is assumed to be 500 km by rail with an additional 300 km of road transport.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1.3 hours and a curing time of 0.75 hours for the entire panel surface, based on data from AZT (8). Each side panel is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional 'recovery losses' have been accounted for based on the authors' best estimates. For the metal panel, a recycling rate of 95% and recovery losses of 5% are assumed (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Steel sheet	AZT (8), Ecoinvent (7), Industry source (12)
Electricity consumption - Metal Shaping (Press) electricity	Ecoinvent (7)

Life cycle inventory continued

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Clean and strip discs	AZT (8), Ecoinvent (7), 3M (21)
Sanding discs	AZT (8), Ecoinvent (7), 3M (19)
Body filler	AZT (8), Ecoinvent (7), Henkel Adhesives (22)
Sanding strips	AZT (8), Ecoinvent (7), 3M (23)
Finger grinder strips	AZT (8), Ecoinvent (7), 3M (20)
Keyhole saw blade	AZT (8), Ecoinvent (7)
Epoxy adhesive (2-component)	AZT (8), Ecoinvent (7), Henkel Adhesives (24)
Seam sealing	AZT (8), Ecoinvent (7)
Cavity preservation	AZT (8), Ecoinvent (7)
Noise-absorbent mat	AZT (8), Ecoinvent (7)
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Hardener for primer	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Gas-shielded welding	AZT (8), Ecoinvent (7)
Resistance spot welding	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Side Panel

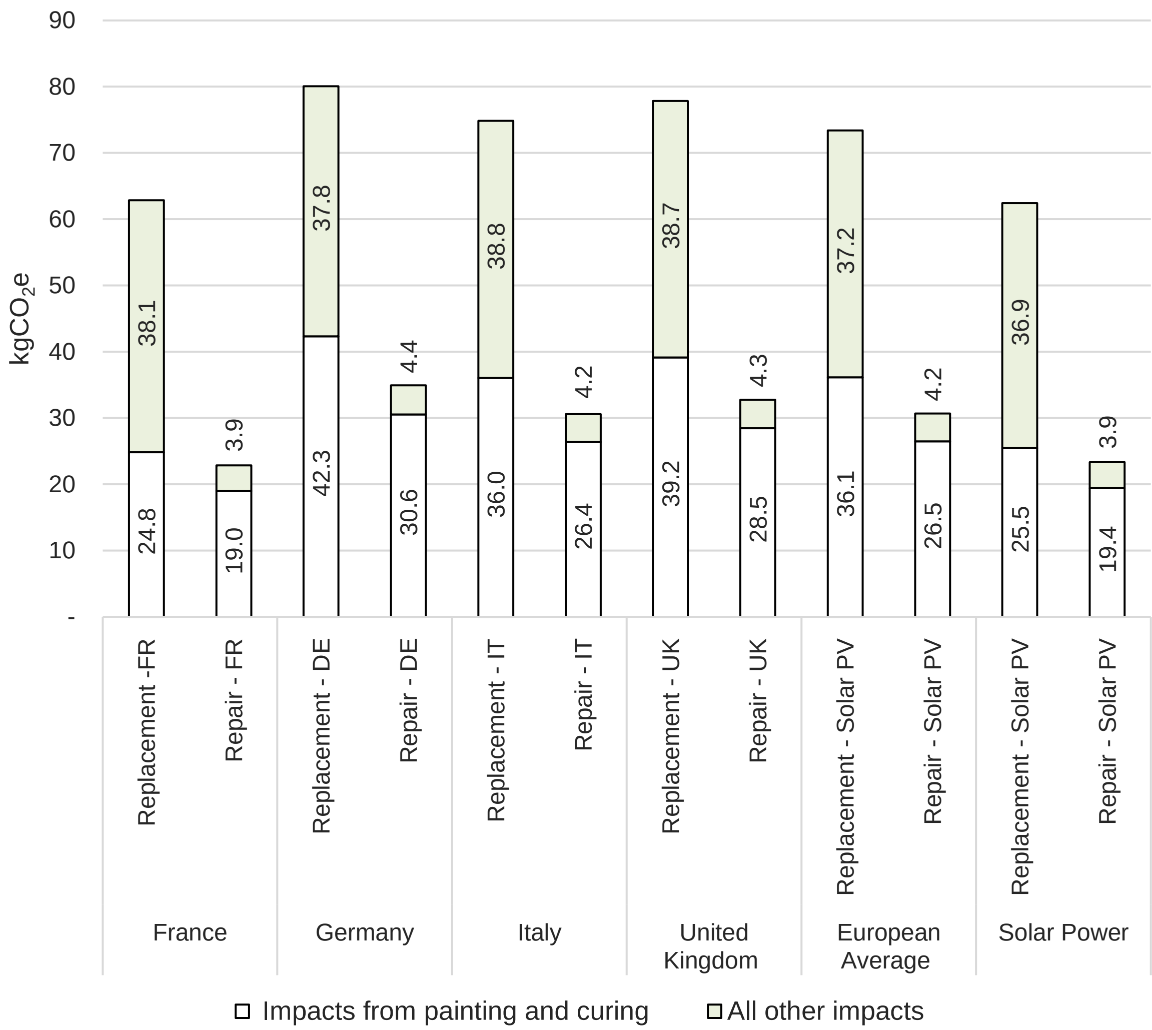

Figure 34 *Results – VW ID.3 Side Panel (kgCO$_2$e)*

Modelling Repair of an ID.3 Fender

The scenario modelled for the repair of the fender of the ID.3 describes a 'light damage' scenario, with a dent or scratch large enough to require that 9% of the surface area is repaired. The process itself requires that the existing paint finish is sanded down to bare metal and a body filler putty applied to restore the damaged area. Once this is complete, the filler is dried using an electric infrared heater and finished, after which the side panel is repainted. Unlike most other studied parts but like the side panels, the fender remains on the vehicle throughout this entire repair process.

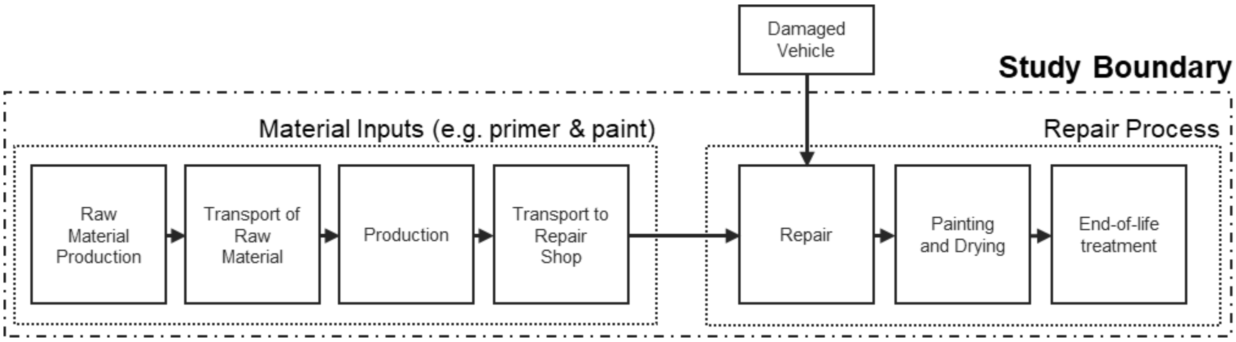

Figure 35 *Study boundary for the repair of a fender*

The modelled painting process includes the preparation/masking of the vehicle, sanding of the part, priming, painting and curing. After the repair is complete any waste generated in the process is then sent on for waste treatment.

Modelling assumptions

	Description
Repaired surface area	Based on data from AZT (8) the repaired surface area is assumed to be 9% of the entire surface area. This denotes a 'light damage' scenario.
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used in the modelling across all nations, with the single differentiating factor being the grid electricity mix, as sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Infrared heater operation - curing body filler	In the repair process, an infrared curing oven is used to cure the body filler applied over the damaged surface area. The modelling of this process assumes a curing time of 30 minutes (8) and the use of a 230 volt, 10 amp (2.3kW) infrared dryer delivering heat energy at 75% efficiency (13).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1 hour and a curing time of 0.75 hours for the entire fender surface, based on data from AZT (8). Each fender is assumed to be treated individually; the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12).

Life cycle inventory

Repair process	
Resource	**Reference**
Clean and strip discs	AZT (8), 3M (9), Ecoinvent (7)
Body filler	AZT (8), Henkel Adhesives (10), Ecoinvent (7)
Sanding strips	AZT (8), 3M (11), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7), 3M (19)
Electricity consumption – Infrared heater & tools	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Sanding discs	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Modelling Replacement of an ID.3 Fender

The scenario modelled for the replacement of the fender of the ID.3 describes a process whereby the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, painting, and placement onto the receiving vehicle. The modelling also includes the removal and end-of-life treatment of the damaged part.

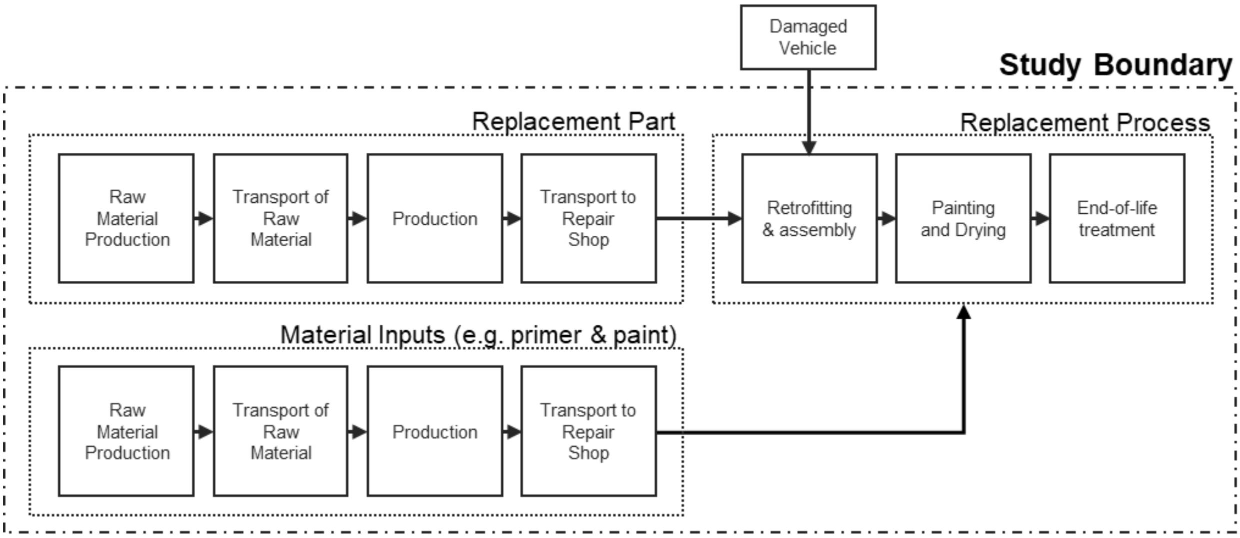

Figure 36 *Study boundary for the replacement of a fender*

The modelling assumes that the fender is manufactured in the European Union, and the average transport distances from the point of manufacture to the workshops in each nation studied have been estimated using Google Maps.

As with the repair scenario, it is assumed that the replacement part is painted to colour-match the receiving vehicle. The modelled painting process includes masking, priming, painting and curing, all of which take place within the workshop.

Modelling assumptions

	Description
Steel production	Steel accounts for the majority of the replacement fender by weight. Therefore, attention has been paid to ensure that the steel used in the model is representative of the European Union average. 60% of the steel is modelled as being produced via a blast furnace and 40% via an electric arc furnace, equal to the average European production reported by Eurofer (17). The upstream transport of the raw steel product to the manufacturer is assumed to be 500 km by rail with an additional 300 km of road transport.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used for modelling across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Painting process and booth operation Curing oven operation	The modelling assumes a total painting time of 1 hour and a curing time of 0.75 hours for the entire fender surface, based on data from AZT (8). Each fender is assumed to be treated individually, and the energy requirement for heating and electricity is derived from confidential technical data provided by an industry partner (12)
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional 'recovery losses' have been accounted for based on the authors' best estimates. For the metal panel, a recycling rate of 95% and recovery losses of 5% are assumed (14) (15) (18).

Life cycle inventory

Repair process	
Resource	**Reference**
Steel sheet	AZT (8), Ecoinvent (7), Industry source (12)
Electricity consumption - Metal Shaping (Press) electricity	Ecoinvent (7)

Protective equipment	
Resource	**Reference**
Disposable rubber gloves	AZT (8), Ecoinvent (7)
Fine dust filter mask	AZT (8), Ecoinvent (7)

Painting and Curing	
Resource	**Reference**
Base coat (water-borne)	AZT (8), Ecoinvent (7)
Clear coat (2-component)	AZT (8), Ecoinvent (7)
Hardener for clear coat	AZT (8), Ecoinvent (7)
Paint cups (plastics)	AZT (8), Ecoinvent (7)
Polyester filler	AZT (8), Ecoinvent (7)
Grounding / primer	AZT (8), Ecoinvent (7)
Filler (2-component)	AZT (8), Ecoinvent (7)
Hardener for primer	AZT (8), Ecoinvent (7)
Spray thinner (2-component)	AZT (8), Ecoinvent (7)
Stone chip protection	AZT (8), Ecoinvent (7)
Silicone remover	AZT (8), Ecoinvent (7)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)
Gas-shielded welding	AZT (8), Ecoinvent (7)
Resistance spot welding	AZT (8), Ecoinvent (7)
Electricity consumption – Tools, paint booth, and curing process	AZT (8), Ecoinvent (7), Industry source (12)
Heat, Natural gas – Paint booth and curing process	AZT (8), Ecoinvent (7), Industry source (12)

Results: ID.3 Fender

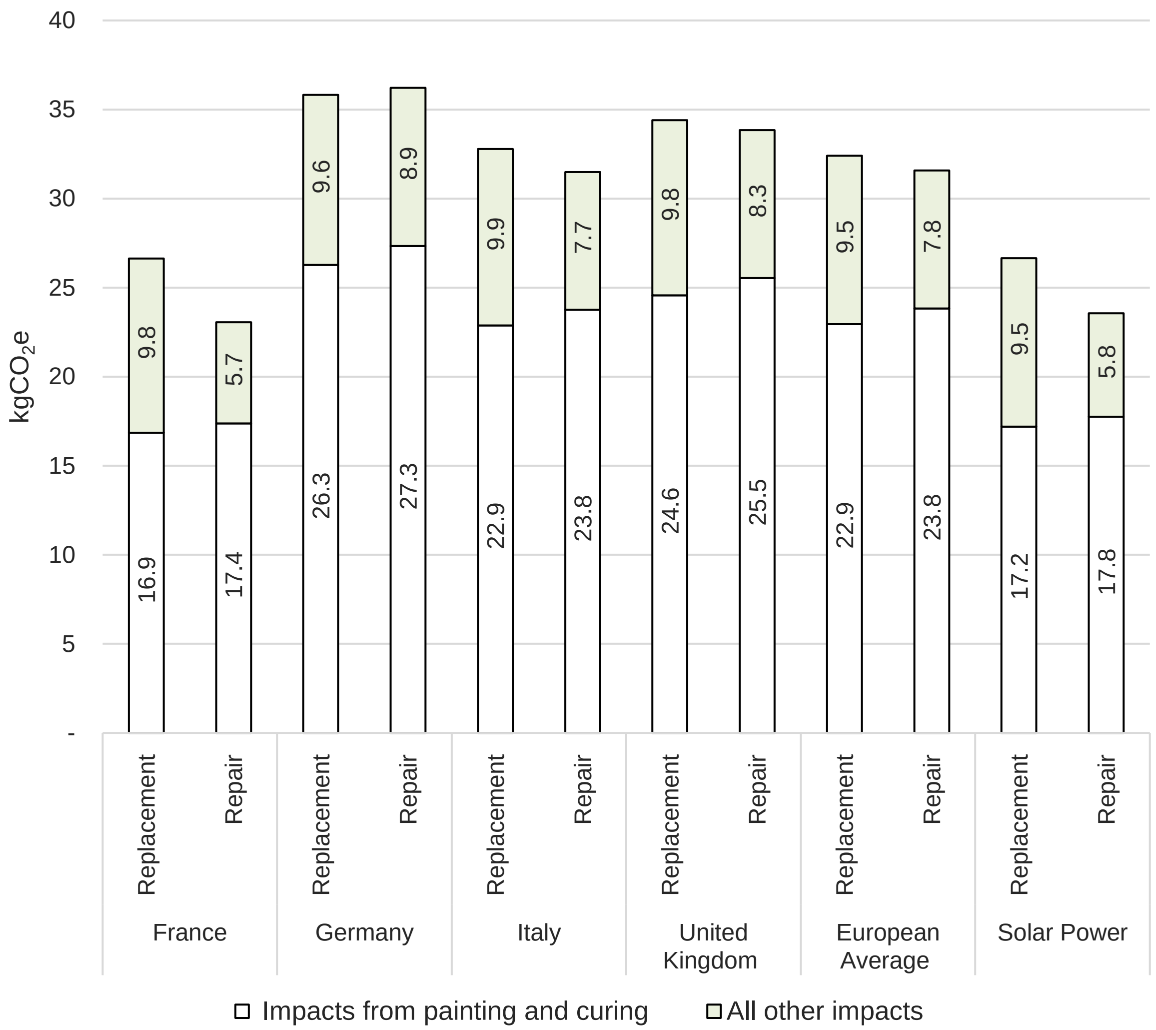

Figure 37 *Results – VW ID.3 Fender (kgCO$_2$e)*

Modelling Repair of an ID.3 Windscreen

The scenario modelled for the repair of the windscreen of the ID.3 assumes that the windscreen has been chipped, requiring a repair using a single capsule of acrylic acid.

The repair process itself includes the in-situ cleaning of the repair area with glass cleaner and then injection and air drying of a single acrylic resin repair capsule. Once this is complete any waste generated in the process is sent for treatment. It is assumed that throughout this process no or negligible energy is consumed.

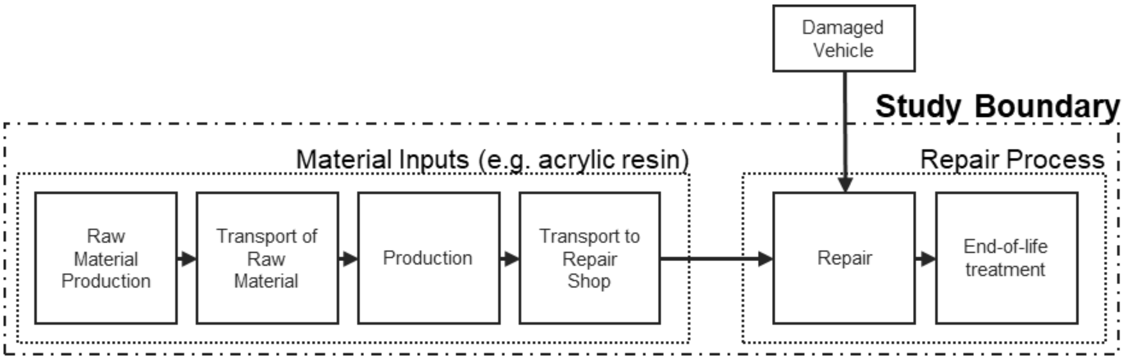

Figure 38 *Study boundary for the repair of a windscreen*

Modelling assumptions & Life cycle inventory

Description	
Repaired surface area	Based on data from AZT (8) the repaired surface area requires a single acrylic repair capsule, such as those supplied by Belron for its Advanced Repair Technology (ART) (25).
Glass cleaning solution	Based on data from AZT (8) it is assumed that 50ml of alcohol-based glass cleaning solution is required in the repair process.

Repair Process	
Resource	**Reference**
Acrylic-based resin	AZT (8), Ecoinvent (7), Belron (25)
Alcohol-based glass cleaning solution	AZT (8), Ecoinvent (7)

Modelling Replacement of an ID.3 Windscreen

The scenario modelled for the replacement of the windscreen of the ID.3 assumes that the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, and placement onto the receiving vehicle. The modelling also includes the removal and end-of-life treatment of the damaged part.

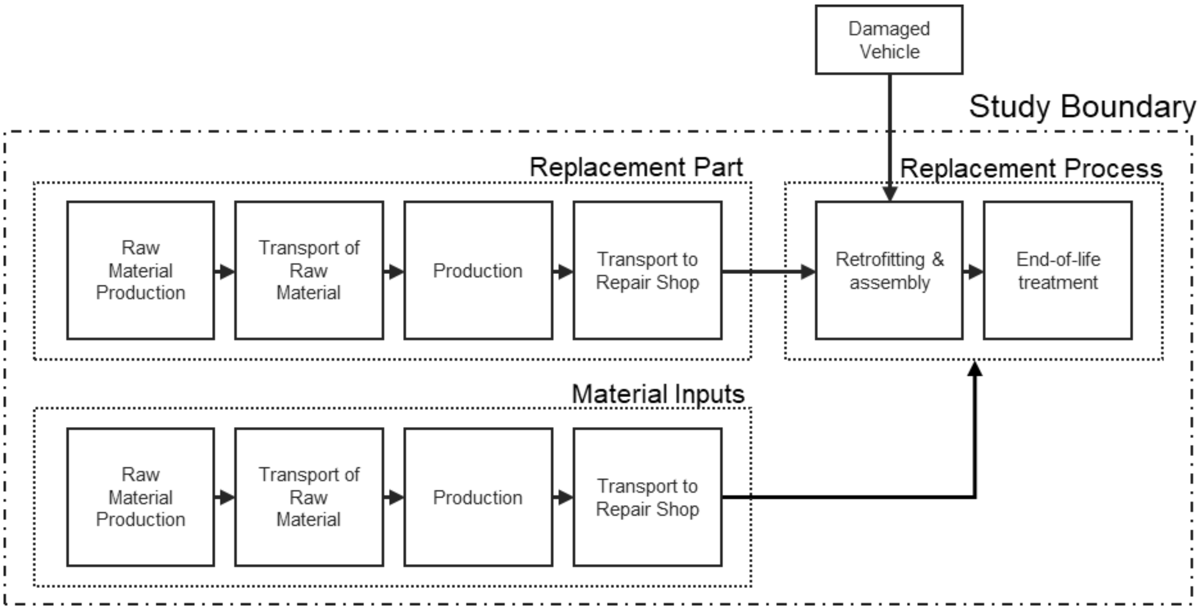

Figure 39 *Study boundary for the replacement of a windscreen*

The modelling assumes that the windscreen is originally manufactured in Herzogenrath, Germany, with the average transport distances from the point of manufacture to the workshops in each nation studied estimated using Google Maps. As for repair, it is also assumed that the removal and replacement of the windscreen on the vehicle requires no or negligible energy.

Modelling assumptions

	Description
Windscreen glass production	The production of the replacement windscreen is modelled based on the inputs and processes published by Balestrini & Levizzari 1997 (26). These figures have been verified against a recent but unpublished LCA of windscreen production conducted by Metsims Sustainability Consulting.
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional 'recovery losses' have been accounted for based on the best estimate of the authors. The assumed recycling/recovery rates for windscreen glass are: recycling 75%, recovery losses 25% (14) (15) (18).

Life cycle inventory

Manufacturing	
Resource	**Reference**
Silicon sand	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Solvay soda ash	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Sodium sulphate	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Dolomite	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Limestone	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Vegetable coal	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
‘Internal scrap‘	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Nitrogen	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Hydrogen	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Tin	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Natural gas	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Air - Combustion	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)
Electricity – Production	AZT (8), Ecoinvent (7), Balestrini & Levizarri (26)

Results: ID.3 Windscreen

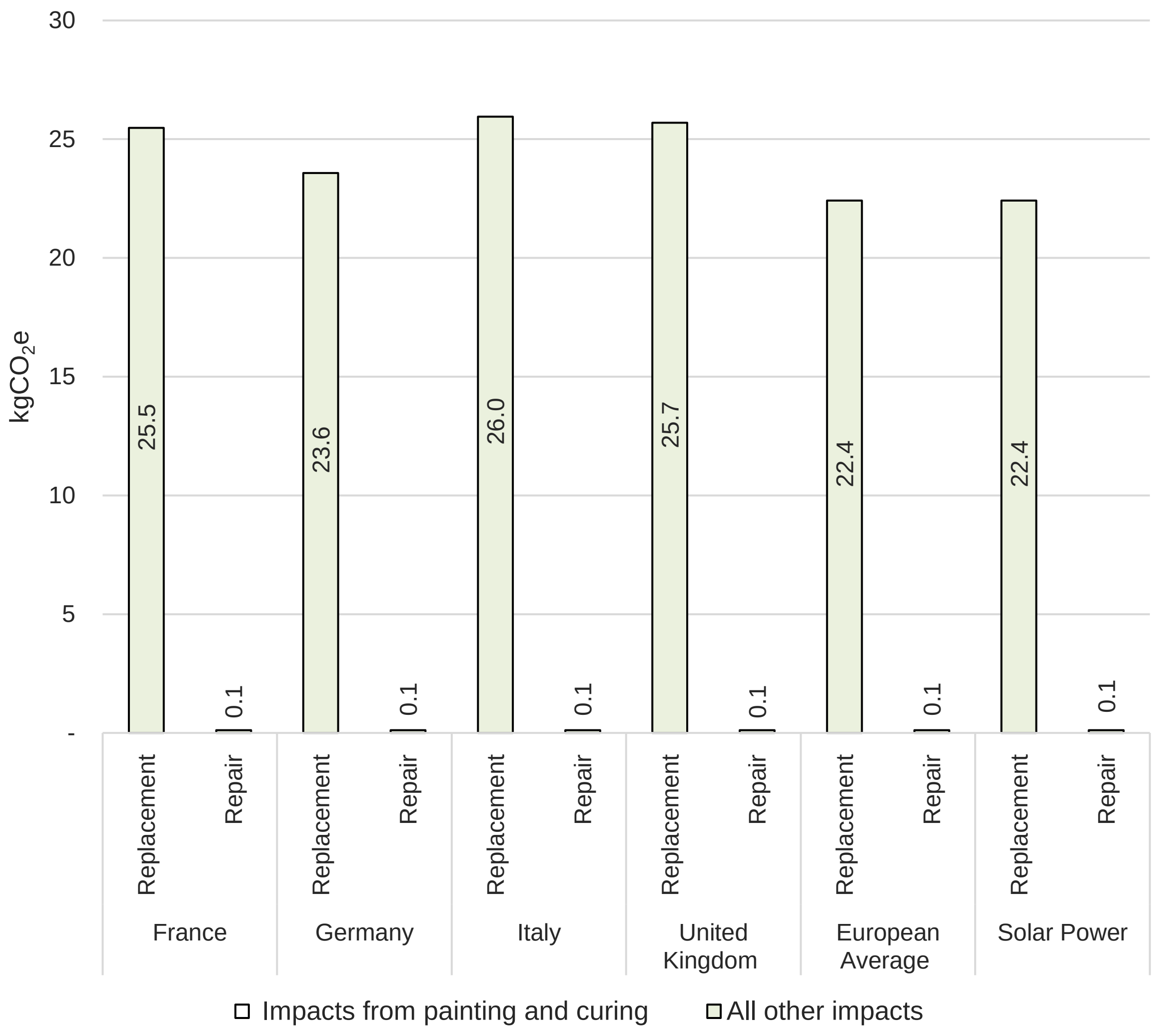

Figure 40 *Results – VW ID.3 Windscreen (kgCO₂e)*

Modelling Repair of an ID.3 Headlight

Two different scenarios were investigated for the repair of the ID.3 headlight. The first scenario is one in which the mounting bracket at the rear of the part is damaged, and the second describes scratches on the front lens of the headlight. The repair process modelled for each are as follows:

Scenario 1 – The damaged brackets are removed and replaced with OEM spares made from polypropylene. Only the brackets are replaced in this process, assuming that the screws are retained from the original part.

Scenario 2 – The area around the headlight is protected using masking paper and masking tape before the polycarbonate front lens is sanded, cleaned and painted with a clear coat. The clear coat is then air dried, the masking removed and any waste generated in the process is sent for final treatment.

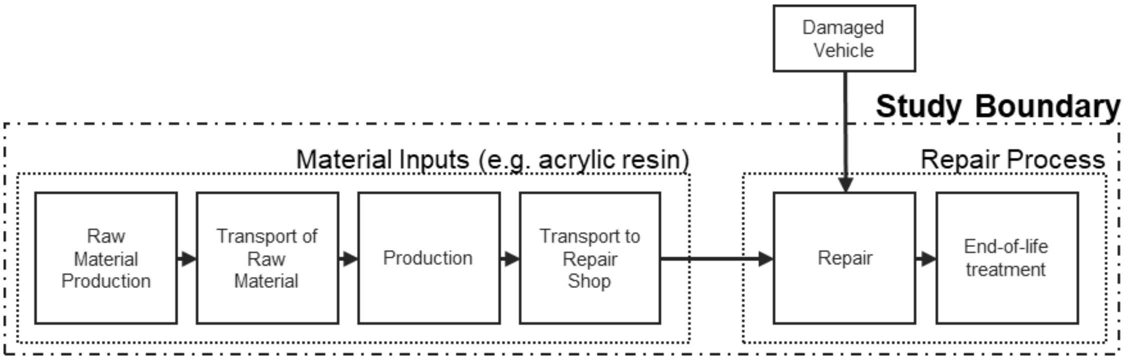

Figure 41 *Study boundary for the repair of a headlight*

Modelling assumptions

	Description
Scenario 1 – Replacement brackets	The replacement brackets have been characterised by AZT (8) based on a mounting bracket repair kit supplied by the OEM Volkswagen.
Scenario 2 - Repaired surface area	Based on data from AZT (8) the repaired surface area requires 125 ml of acrylic-based clear coat – modelled on the formulation of Spray Max's 2K 2in1 Headlight Clear product (27).
Scenario 2 - Cleaning solution	Based on data from AZT (8) it is assumed that 200 ml of silicon remover is required to clean the lens surface area. This product has been modelled based on Spray Max's 1K Silicone remover product (28).

Life cycle inventory

Repair Process	
Resource	**Reference**
Replacement brackets	AZT (8), Ecoinvent (7), Volkswagen Group (29)
Clear coat	AZT (8), Ecoinvent (7), Spray Max (27)
Cleaning solution	AZT (8), Spray Max (28)
Masking paper	AZT (8), Ecoinvent (7)
Masking tape	AZT (8), Ecoinvent (7)

Modelling Replacement of an ID.3 Headlight

The scenario modelled for the replacement of the headlight the ID.3 assumes that the entire part is replaced. The cradle-to-gate life cycle impacts of the production of the new part are modelled using a cut-off approach. The modelled processes start with the production of the raw materials and include the manufacture of the replacement part, transport to the workshop, and placement onto the receiving vehicle. In addition, the modelling includes the removal and end-of-life treatment of the damaged part.

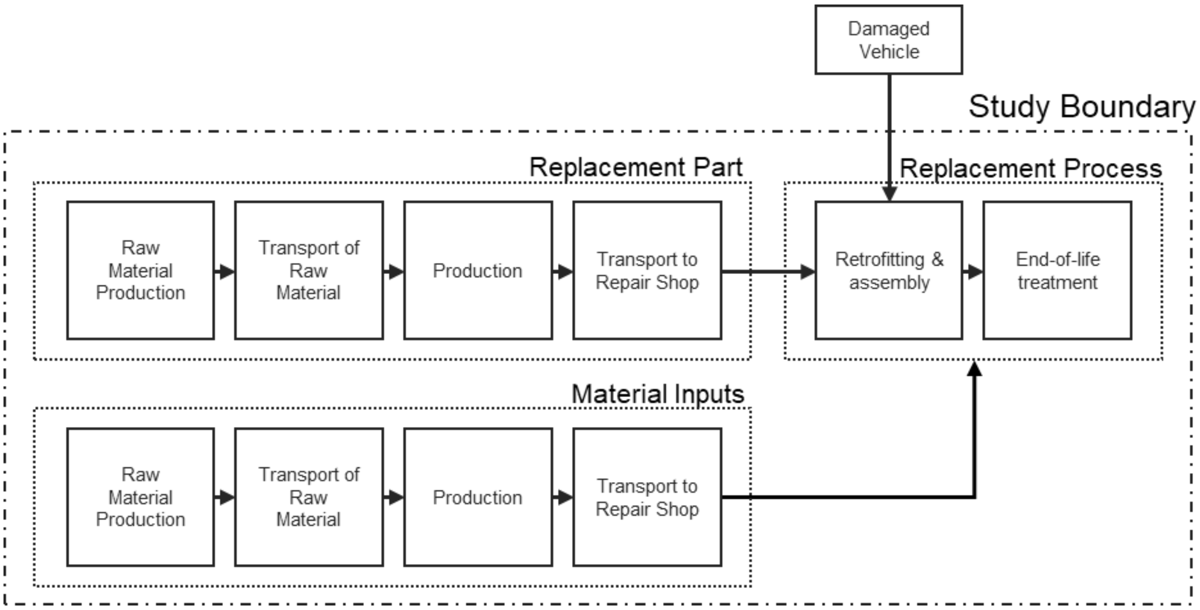

Figure 42 *Study boundary for the replacement of a headlight*

The modelling assumes that the headlight is originally manufactured in the Czech Republic, with the average transport distances from the point of manufacture to the workshops in each nation studied estimated using Google Maps.

Modelling assumptions & Life cycle inventory

	Description
Workshop differentiation	Through a literature review and consultation with industry experts, it was found that there was little evidence that treatment processes differ between nations. Therefore, the generic process described here was used to model across all nations, with the single differentiating factor being the grid electricity mix, sourced from Ecoinvent (7). The eco-workshop scenario assumed an 100% electricity supply from solar PV, as characterised in Ecoinvent (7).
Upstream logistics	All logistics are assumed to take place using European average HGV road transport as described in Ecoinvent (7). The distances from the point of manufacture to the workshops in each nation are: Germany 300 km, Italy 1,377 km, France 1,030 km and the UK 1,004 km – sourced from Google Maps (16).
End-of-life treatment	It is assumed that all the damaged end-of-life parts are routed to recycling facilities through workshops. To account for losses of materials from damaged parts between the crash site and each workshop, some additional 'recovery losses' have been accounted for based on the authors' best estimates. The assumed recycling/recovery rates for each material are: metals recycling rate 95% and recovery losses 5%; plastics recycling rate 90% and recovery losses 10%; glass (headlight) recycling rate 85% and recovery losses 15% (14) (15) (18).

Manufacturing

Resource	Reference
Non-ferrous metal	AZT (8), Ecoinvent (7)
Ferrous metal	AZT (8), Ecoinvent (7)
Polycarbonate	AZT (8), Ecoinvent (7)
Thermoplastics	AZT (8), Ecoinvent (7)
Thermoset plastic	AZT (8), Ecoinvent (7)

Results: ID.3 Headlight

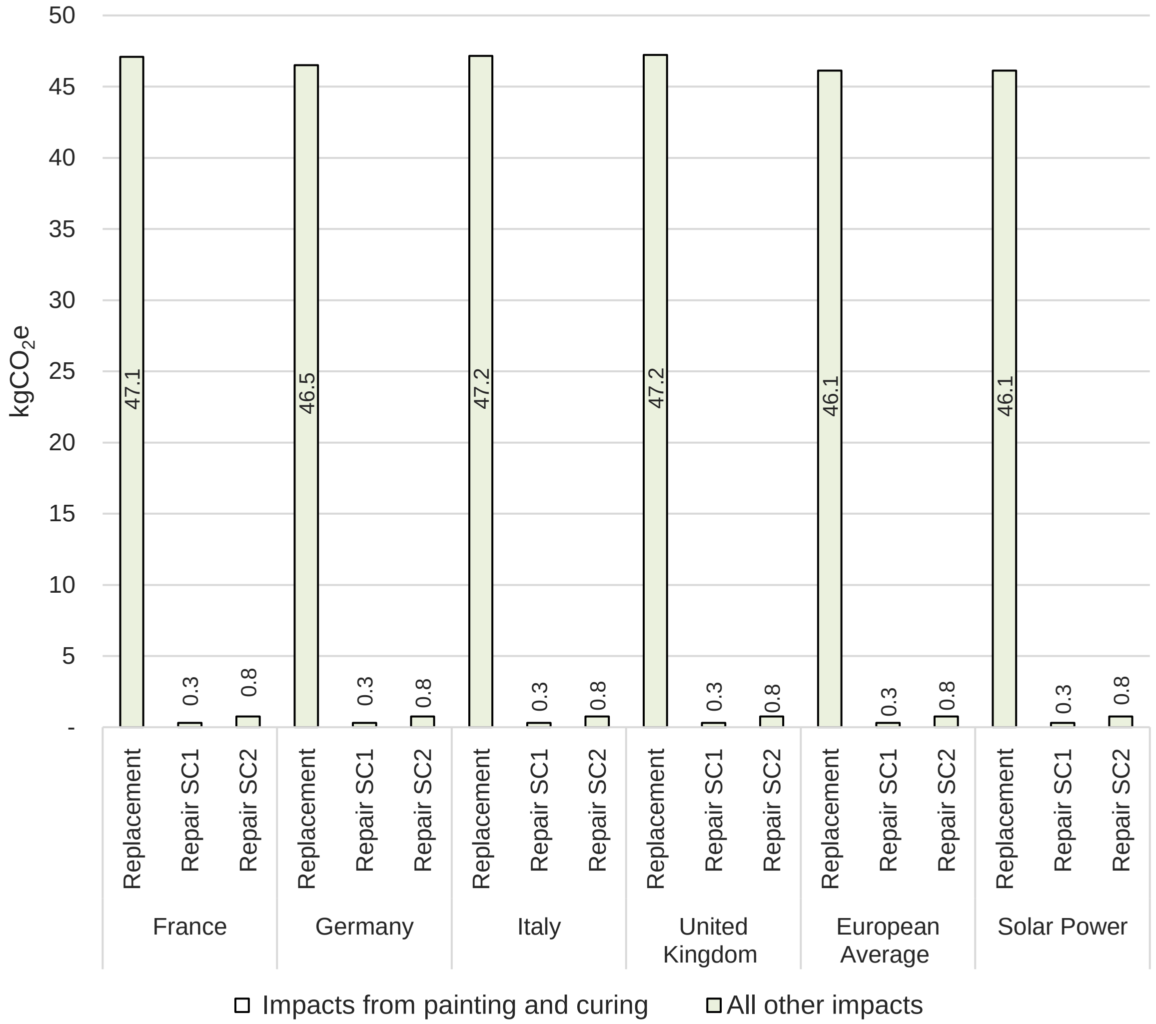

Figure 43 *Results – VW ID.3 Headlight (kgCO₂e)*

Appendix 2: GHG contribution per inventory item – European average scenarios (1% cut off)

Table 2 *Percentage contribution to European average repair scenarios per inventory item (1% cut off)*

	Front Bumper	Rear Bumper	Front Door	Rear Door	Hood	Side Panel	Fender	Wind-screen	Headlight Scenario 1	Headlight Scenario 2
Acrylic binder – 34% solution w/o water (Europe)										23.1%
Electricity – medium voltage (Europe)	33.1%	32.8%	29.7%	29.7%	29.5%	29.2%	30.9%			
Ethoxylated alcohol (Europe)								99.6%		
Kraft paper – bleached (Europe)										2.8%
Kraft paper – unbleached (Europe)			1.2%	1.1%	1.1%					27.7%
Metal working – average aluminium product									51.6%	
Methyl ethyl ketone (Europe)										45.7%
Polyester resin – unsaturated (Europe)			6.5%	5.7%	6.1%	5.1%	2.9%			
Polypropylene granulate (Global)									18.1%	
Silicon Carbide (Global)			3.1%	3.2%	3.2%	3.5%	3.4%			
Small scale or central heat – natural gas (Europe)	65.3%	65.7%	56.3%	57.2%	56.9%	58.2%	59.6%			
Steel – low alloyed (Europe)									30.2%	

Table 3 *Percentage contribution to European average replacement scenarios (sheet metal parts) per inventory item (1% cut off)*

	Front Door	Rear Door	Hood	Side Panel	Fender
Electricity - medium voltage (Europe)	9.4%	11.1%	15.3%	18.2%	21.6%
Electricity - medium voltage (Poland)					
Electronic components (Global)					
Epoxy resin - liquid (Europe)				1.3%	
Freight lorry - >32 t Euro 6 (Rest of the world)					
Injection moulding process (Global)					
Metal working - average steel product (Global)	35.4%	31.8%	25.4%	19.6%	12.7%
Non-ferrous metals					
Polycarbonate (Europe)					
Polyester resin - unsaturated (Europe)	3.6%	3.7%	5.1%	4.2%	4.2%
Polyethylene granulate (Global)				1.1%	
Polypropylene granulate (Global)					
Polyurethane flexible foam (Europe)					
Polyurethane rigid foam (Europe)	3%	3.7%	1.04%		
Sheet rolling - steel (Global)	6.7%	6.0%	4.8%	3.7%	2.4%
Silicon Carbide (Global)				2.9%	
Silicone Products (Europe)					
Small scale or central heat - natural gas (Europe)	18.6%	22.2%	30.7%	31.5%	49.2%
Soda Ash - dense (Global)					
Steel - chromium steel (Global)					
Steel - low alloyed (Europe)	16.8%	15.1%	12.0%	9.3%	6.0%
Steel - Low alloyed electric arc (Europe)	3.9%	3.5%	2.8%	2.1%	1.4%
Steel - reinforcing (Europe)				1.4%	
Synthetic rubber (Global)				1.1%	

Table 4 Percentage contribution to European average replacement scenarios (non-sheet metal parts) per inventory item (1% cut off)

	Front Bumper	Rear Bumper	Fender	Wind-screen	Headlight
Electricity - medium voltage (Europe)	21.9%	19.7%	21.6%		
Electricity - medium voltage (Poland)				3.2%	
Electronic components (Global)					46.8%
Epoxy resin - liquid (Europe)					
Freight lorry - >32 t Euro 6 (Rest of the world)				3.8%	
Injection moulding process (Global)	12.4%	14.3%			
Metal working - average steel product (Global)			12.7%		2.4%
Non-ferrous metals					1.5%
Polycarbonate (Europe)					35.0%
Polyester resin - unsaturated (Europe)			4.2%		
Polyethylene granulate (Global)					
Polypropylene granulate (Global)	19.8%	22.9%			5.1%
Polyurethane flexible foam (Europe)					2.1%
Polyurethane rigid foam (Europe)					2.3%
Sheet rolling - steel (Global)			2.4%		
Silicon Carbide (Global)					
Silicone Products (Europe)					1.5%
Small scale or central heat - natural gas (Europe)	45.5%	42.7%	49.2%	43.2%	
Soda Ash - dense (Global)				12.0%	
Steel - chromium steel (Global)					2.3%
Steel - low alloyed (Europe)			6.0%		
Steel - Low alloyed electric arc (Europe)			1.4%		
Steel - reinforcing (Europe)					
Synthetic rubber (Global)					

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