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Is electric retrofit beneficial from environmental, circularity, and economic perspectives? An application to off-road vehicle

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ABSTRACT

Converting an internal combustion engine vehicle (ICEV) into an electric vehicle (EV) is known as electric retrofit. This study proposes and applies a methodology for assessing the impacts of electric retrofit through an off-road vehicle case study. Circularity, environmental, and economic assessments are used to compare retrofit, ICEV, and new EV scenarios. The main contribution is a novel, more comprehensive methodology for assessing the impacts of electric retrofit that accounts for the reuse of components and vehicles, multiple environmental impact categories, the timing of the retrofit operation, and circularity. Circularity is evaluated using a newly developed longevity-variation indicator, environmental impacts are assessed through life cycle assessment, and economic performance is examined through cost analysis. The results show that the impacts of electric retrofit depend strongly on three parameters: (1) when the retrofit is performed during the ICEV lifetime, (2) the lifetime extension achieved through the retrofit operation, and (3) the reusability of vehicles and components across the scenarios. Benefits arise particularly when retrofit occurs early in the vehicle's lifetime, the retrofit components are reused, and the reuse of second-hand ICEVs is constrained. However, unless especially favorable conditions are met, electric retrofit is less attractive from circularity, environmental, and economic perspectives than purchasing a new EV and reselling the used ICEV, suggesting that retrofit is primarily suited to niche strategies. The study concludes with recommendations for improving future sustainability assessments of electric retrofit and realizing its current potential.

Abbreviations

ADEME	French Environmental and Energy Transition Agency
DWP	Difference in Willingness to Pay
EV	Electric Vehicle
GHG	Greenhouse Gas
ICEV	Internal Combustion Engine Vehicle
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
P_{new}	Price of a new EV
P_{retro}	Price of a retrofit operation
PEF	Product Environmental Footprint
RP_{comp}	Resale Price of removed ICEV components during the retrofit operation
RP_{ICEV}	Resale Price of a second-hand ICEV
S_{new}	Subsidies for purchasing a new EV
S_{retro}	Subsidies for performing an electric retrofit
x	Second-period length scaled by a new ICEV lifetime expectancy
y	Lifetime expansion caused by the retrofit operation scaled by a new ICEV lifetime expectancy

1. Introduction

Current linear economic models contribute to growing environmental damage and the transgression of planetary boundaries (Kitzmann et al., 2025). Circular economy models may help mitigate global environmental impacts. However, circular strategies do not systematically deliver environmental benefits (Slorach et al., 2020; van Loon et al., 2021); their associated environmental impacts must therefore be assessed carefully.

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Retrofit is defined as "a modification made to a product or structure to incorporate changes and developments introduced since manufacture or construction" (Oxford English Dictionary). This study focuses specifically on electric retrofit, which involves replacing selected vehicle components to convert an internal combustion engine vehicle (ICEV) into an electric vehicle (EV) (Hoeft, 2021).

Beyond the numerous examples of electric retrofit in the automotive sector (Le-Boucher; Classic Cars; Retrofleet and Mona by Retrofleet), the process can also be applied to heavy vehicles. In 2023, for example, the heavy-equipment manufacturer Manitou launched an electric retrofit project in partnership with the construction-equipment rental company Kiloutou Group (Kiloutou Group). The project involves retrofitting a construction telehandler (Fig. 1), which provides the case study examined here.

The authors previously conducted a comprehensive critical review of the circularity, environmental, and economic impacts of vehicle powertrain retrofit (Nguyen et al., 2025). Given the limited body of literature available, all relevant studies were considered, regardless of the vehicle category or propulsion technology examined, including battery-electric, hybrid, and hydrogen powertrains. Studies addressing these broader retrofit configurations were included when their methods or findings provided relevant insights into the environmental, circularity, or economic implications of retrofit. The review systematically compared the assumptions, parameters, scopes, and results of 15 studies and provided the basis for the literature analysis used throughout this article. Thirteen of the reviewed studies (Nguyen et al., 2025) found that electrification enables retrofitted vehicles to generate fewer greenhouse gas (GHG) emissions than ICEVs (Kolahchian Tabrizi et al., 2024; Allard and Castaignede, 2021; Belin and Ponsa Sala; Biswas, 2013; Dattero-Snell, 2023; El Hannach et al., 2019; Elkafas et al., 2023; Helmers et al., 2017; Innocenti et al., 2024; Napoli et al., 2022; Rizzo and Tiano, 2020; Santis and Regis, 2021; Watts et al., 2021). Compared with new EVs, the literature generally found electric retrofit to be more cost-effective (Allard and Castaignede, 2021; Dattero-Snell, 2023), except for passenger cars (Belin and Ponsa Sala; Watts et al., 2021), and to have lower environmental impacts because a large proportion of the ICEV is reused (Belin and Ponsa Sala; Helmers et al., 2017; Rizzo and Tiano, 2020). In particular, two studies that performed life cycle assessments for four vehicle types reported reductions in life-cycle GHG emissions of 28–56% (Allard and Castaignede, 2021; Belin and Ponsa Sala).

Electric retrofit is sometimes presented as a circular strategy because it can prevent a functioning ICEV from being scrapped when it is replaced by an EV (Allard and Castaignede, 2021; Dattero-Snell, 2023; Watts et al., 2021). Avoiding both this scrapping and the production of an entirely new vehicle is central to arguments that retrofit has lower environmental impacts than purchasing a new EV (Allard and Castaignede, 2021; Belin and Ponsa Sala; Dattero-Snell, 2023; Helmers et al., 2017; Rizzo and Tiano, 2020; Santis and Regis, 2021; Watts et al., 2021; Strecker et al., 2014). These arguments, however, assume that the functioning ICEV replaced by a new EV would otherwise be destroyed. If it is reused instead, no premature scrapping occurs, and its reuse can also be viewed as avoiding the production of another ICEV. Although the assumption of scrapping may hold under specific conditions, such as scrappage schemes (Transport for London), a functioning ICEV will plausibly be reused unless its owner is required or incentivized to destroy it.

Only one identified study considered the possibility that an ICEV could be reused when comparing electric retrofit with a new EV scenario (Belin and Ponsa Sala). However, it did not account for the environmental impacts avoided through this reuse. The limited consideration of ICEV reuse is therefore a major gap in the retrofit literature: excluding a realistic reuse pathway may overstate the circularity and environmental advantages attributed to electric retrofit.

The literature assessing the circularity, environmental, and economic impacts of electric retrofit presents several further gaps. First, no comprehensive circularity assessment has been identified. Second, environmental assessments are often limited to GHG emissions (Allard and Castaignede, 2021; Innocenti et al., 2024), and only one identified study considered more than two environmental impact categories (Helmers et al., 2017). Third, retrofit is assumed to occur at the beginning (Biswas, 2013), after one-third (Belin and Ponsa Sala), halfway through (Allard and Castaignede, 2021; Rizzo and Tiano, 2020), or at the end (Helmers et al., 2017; Innocenti et al., 2024) of the ICEV lifetime, yet no study has examined the influence of this timing. A sensitivity analysis of retrofit timing is therefore needed to determine when, during the vehicle lifetime, electric retrofit may be beneficial. Finally, although some studies assume that retrofit extends the vehicle lifetime (Helmers et al., 2017; Innocenti et al., 2024) and others do not (Allard and Castaignede, 2021; Rizzo and Tiano, 2020), none examines how this assumption affects the results. Understanding the influence of lifetime extension is essential for comparing the environmental impacts of retrofit with those of an ICEV and a new EV, whether the replaced ICEV is reused or scrapped.

Against this background, the study addresses the following research question:

How can the environmental, circularity, and economic impacts of electric retrofit be adequately quantified?

To address the identified gaps and answer this question, section 2 introduces a methodology whose scope encompasses circularity, environmental, and economic dimensions. The analysis compares electric retrofit with three alternatives: (1) retaining an ICEV, (2) purchasing a new EV and scrapping the replaced ICEV, and (3) purchasing a new EV while allowing the replaced ICEV to be reused. Section 2 then presents the circularity, environmental, and economic assessment methods, and sections 3.1-3.3 report the corresponding results. Section 4 discusses these findings, highlights the main gaps addressed and the most influential parameters, and formulates recommendations. Section 5 concludes with the study's implications, limitations, and directions for future research.



Fig. 1. Retrofitted construction telehandler (Manitou Courtesy ©).

2. Methods

The proposed methodology combines three complementary approaches to answer the research question. Section 2.1 first defines the goal and scope of the multicriteria assessment, covering circularity, environmental, and economic perspectives, and then presents the scenarios, key parameters, and underlying assumptions. Section 2.2 introduces the circularity assessment and a new indicator for quantifying potential extensions or reductions in product longevity. Section 2.3 describes the environmental assessment, which follows the Life Cycle Assessment (LCA) methodology specified in ISO 14040 and ISO 14044. Finally, section 2.4 presents a user-centered economic assessment for identifying the conditions under which electric retrofit may be beneficial.

2.1. Goals and scope definition

The study aims to determine when and under what conditions electric retrofit can provide environmental, circularity, and economic benefits. It therefore adopts a multicriteria assessment covering all three dimensions.

The analysis introduces three aspects that have received limited attention in previous studies:

- The most appropriate time to perform a retrofit during the ICEV lifetime
- The potential for reuse across the scenarios examined
- The influence of retrofit-induced lifetime extension on the results

The scope covers the circularity, environmental, and economic impacts of electric retrofit relative to alternative scenarios. Four product levels are considered: the complete vehicle, the ICEV powertrain, the EV powertrain, and the glider, defined as the vehicle without its powertrain. Fleet- and regional-level effects are outside the scope. A user-centered perspective is adopted to identify the conditions under which electric retrofit may be viable.

2.1.1. Scenario definition

To investigate the environmental, circularity, and economic benefits of electric retrofit, the study builds on scenarios developed by the French Agency for Ecological Transition (ADEME) (Allard and Castaignede, 2021) and by Belin and Ponsa Sala (Belin and Ponsa Sala). Both sources assume an initial period of ICEV use that is common to all scenarios. At the end of this period, the user either retains the ICEV, retrofits it, or purchases a new EV. Purchasing a new EV creates two possible outcomes for the replaced ICEV: Allard and Castaignede (2021) assume that it is scrapped, whereas Belin and Ponsa Sala (Belin and Ponsa Sala) assume that it is reused. This study considers both outcomes, producing the four scenarios shown in Fig. 2: continued use of the ICEV by the same user ("ICEV"), conversion of the ICEV into an EV ("retrofit"), replacement of the ICEV with a new EV followed by scrapping ("new EV (ICEV scrapped)"), and replacement with a new EV followed by reuse of the ICEV by another user ("new EV (ICEV reused)").

The main originality of the scenario design lies in the fourth scenario, the new EV (ICEV reused). Although this is a realistic pathway, the literature rarely considers ICEV reuse or its associated impacts (Section 1). By omitting this pathway, previous studies tend to favor electric retrofit in three ways: they describe retrofit as more circular than purchasing a new EV because it prevents premature ICEV scrapping, as having lower environmental impacts because it avoids production of an entirely new vehicle, and as more economically attractive because they exclude the resale value of the ICEV from the new EV scenario.

2.1.2. Definition of key input parameters

The circularity, environmental, and economic analyses rely on a set of key input parameters drawn from the literature (Nguyen et al., 2025) and primary data supplied by the manufacturer. Table 1 summarizes these parameters.

A construction telehandler (Kiloutou Group) is used as the case study (Fig. 1) to address the scarcity of off-road vehicle studies and to assess the impacts of electric retrofit. Both case-study companies are French, and most of their activities are located in France or elsewhere in Europe; accordingly, the analysis assumes a mix of 65% French and 35% European activity. Based on Ecoinvent data (Ecoinvent and Ecoinvent version 3), the carbon footprint of the corresponding electricity mix is set at 194 g CO2-eq/kWh. Construction telehandlers operate in several modes, whose relative shares constitute the duty cycle. For this case study, the manufacturer specified a duty cycle of 10% driving, 20% loading, 40% lifting, and 30% idling.

No new EV is currently available for this vehicle type; assumptions are therefore required for its efficiency and battery capacity. The new EV is assumed to be as efficient as the retrofitted vehicle, although experts from the case-study company expect an optimized new-vehicle design to achieve greater efficiency. The battery capacity of the new EV is likewise

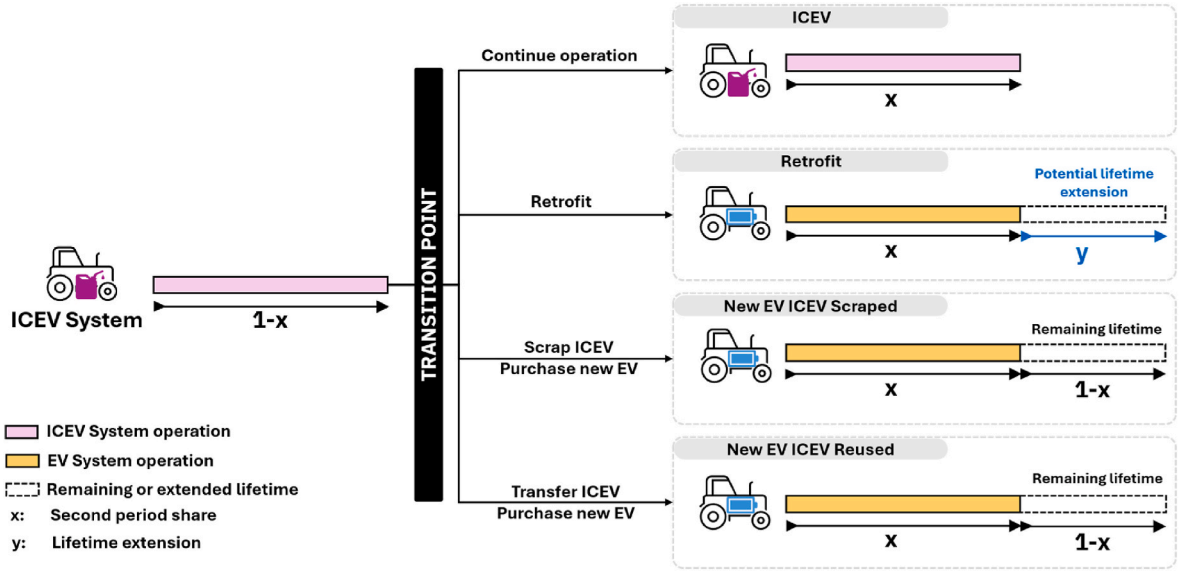


Fig. 2. Illustration of the four scenarios considered within the perimeter of the study: ICEV, Retrofit, New EV (ICEV scrapped), New EV (ICEV reused).

Table 1
Key input parameters used in the environmental, circularity, and economic analyses.

Parameter	Assumption made	Source
Type of vehicle considered	A construction telehandler	Kiloutou Group (Kiloutou Group)
Electricity mix considered	65% French and 35% European average: 194 gCO2eq/kWh	Ecoinvent v3.8 (Ecoinvent and Ecoinvent version 3)
Duty cycle	10% driving, 20% loading, 40% lifting, and 30% idling	Primary data from the manufacturer
Capacity of the retrofitted vehicle	Similar to a new EV	Primary data from the manufacturer
ICEV lifetime expectancy	10,000 work hours	Primary data from the manufacturer
Battery lifetime expectancy	10,000 work hours	Primary data from the manufacturer
Transportation distance	2005 km	Primary data from the manufacturer and PEF method (Zampori and Pant, 2019, p. 57)
Transportation mode	Truck-Europe	PEF method [Zampori and Pant, 201927, p. 57]
Energy consumption	Electricity Consumption for EV: 24,5kWh/h Fuel Consumption for ICEV: 6.70L/h	Primary data from the manufacturer
Functional unit (Environmental assessment)	1 h of machine operation following the defined duty cycle (1 h)	
Lifecycle stages (Environmental assessment)	(1) Primary resources, (2) Production, (3) Distribution, (4) Usage and maintenance, (5) End-of-life	
Point at which the retrofit is carried out	Parameter to be varied (0–10,000 h)	
Reusability of vehicles	Parameter to be varied (new EV (ICEV scrapped) and new EV (ICEV reused) scenarios)	
Reusability of retrofitted components	Parameter to be varied (0 or 100%)	
Lifespan increase caused by the retrofit operation	Parameter to be varied (0–5000 h)	

assumed to be similar to that of the retrofitted vehicle. This assumption avoids restricting the analysis to the niche case of retrofit vehicles with limited battery capacity (Nguyen et al., 2025). The EV and ICEV are also assumed to use the same glider, namely the vehicle without its powertrain (Del Duce et al., 2016).

All vehicles are assumed to have a service life of 10,000 operating hours, except the retrofitted vehicle, for which lifetime extension is treated as a variable parameter. Experts from the case-study company indicated that 10,000 h may underestimate the service life of ICEVs in this vehicle category. Because these EVs are only beginning to enter service, reliable evidence on their lifetime is not yet available. Battery-replacement needs over the vehicle lifetime are similarly uncertain. The battery is therefore assumed to have the same 10,000-h service life as the new EV, and no battery replacement is included. More robust evidence on vehicle and battery lifetimes would support more realistic assumptions in future assessments.

Transport distances combine the sales mix, distinguishing France from the rest of Europe, with the default factory-to-customer distances specified in the PEF method (Zampori and Pant, 2019, p. 57). The default PEF transport mode, road freight by truck, is applied (Zampori and Pant, 2019, p. 57). New vehicles and the retrofit kit are each assumed to be transported once, from the original equipment manufacturer to the customer.

The life-cycle stages are relevant only to the environmental assessment, which follows an LCA approach (section 2.3). The assumptions associated with each stage are therefore detailed in the environmental assessment methodology. By contrast, the circularity and economic assessments do not adopt a life-cycle approach; both are calculated at the transition between phases 1 and 2 (sections 2.2 and 2.4).

In every scenario, the combined duration of the first and second periods is assumed to equal the ICEV lifetime. All vehicles are assumed to have the same lifetime except the retrofitted vehicle, whose lifetime is treated as a variable input. The vehicle in the ICEV scenario, therefore, reaches its end of life at the end of the second period. By contrast, the vehicles in the new EV (ICEV scrapped) and new EV (ICEV reused) scenarios retain some remaining lifetime, whereas the retrofitted vehicle may or may not do so, depending on the lifetime-extension assumption. To address the literature gap concerning the optimal timing of retrofit, the transition between the first and second periods is varied in the analysis.

In the retrofit scenario, the electric powertrain may retain substantial service life when the glider reaches its end of life. Alternatively, second-hand components may be used to perform the retrofit (Watts et al., 2021). The analysis therefore treats reuse of the electric powertrain as a variable parameter.

This study addresses two gaps: the optimal timing of retrofit within the ICEV lifetime and the influence of ICEV reuse on the results. The transition between the first and second periods is therefore varied across all scenarios. ICEV reuse following the purchase of a new EV is likewise varied by comparing one scenario with reuse (new EV (ICEV reused)) and one without it (new EV (ICEV scrapped)). The economic assessment also examines intermediate conditions between complete reuse and no reuse.

The environmental and circularity assessments assume perfect substitution (Plevin et al., 2014): (1) use of a second-hand ICEV replaces rather than supplements use of a new ICEV, and (2) use of a retrofitted EV replaces rather than supplements use of a new EV. Plevin et al. (2014) question this assumption because of indirect and scale effects. Such effects are difficult both to estimate (Sanchez et al., 2012) and to incorporate into an assessment (Sanchez et al., 2012; Pohl et al., 2019); they are therefore excluded here, although they offer promising directions for improving the environmental assessment of electric retrofit. Section 4.2.4 discusses the substitution assumption and presents a sensitivity analysis.

2.2. *Circularity assessment method*

The literature generally portrays electric retrofit as more circular than replacing an ICEV with a new EV (Allard and Castaignede, 2021; Dattero-Snell, 2023; Watts et al., 2021). Although this claim strongly affects environmental and economic assessment results, it has received little direct investigation (section 1). The relevant question is therefore whether electric retrofit is indeed more circular than either retaining the ICEV or purchasing a new EV while reusing the replaced ICEV.

Circularity assessments can address many dimensions of the circular economy. ISO 59020 (ISO, 2024), for example, proposes 13 core indicators, ranging from "Average reused content of an inflow" and "Per cent actual recycled material derived from outflow" to "Ratio (on-site or internal) water reuse or recirculation." For electric retrofit, however, claims of greater circularity rest specifically on the presumed greater longevity of the retrofit scenario relative to new EV scenarios, because much of the vehicle avoids premature scrapping (section 1). In addition, the retrofitted and new EVs in this case study are assumed to share the same architecture and therefore to have comparable end-of-life recyclability and energy-recovery potential, as well as similar recycled-material content in their inflows.

The circularity assessment consequently adopts a "slowing-the-loop" perspective, emphasizing the extended use and reuse of products (Bocken et al., 2016) rather than loop closure. A new longevity-variation

indicator is introduced to compare the scenarios. It measures the potential lifetime gained or lost through a process. In this study, "product" encompasses complete products, subassemblies, and components. The baseline is the scenario in which the relevant lever is not activated; where applicable, it represents use of the product until the end of its service life without a specific intervention. The indicator requires three parameters:

(1) **Remaining lifetime before transition.** This is the potential remaining lifetime of products if no extension or reduction occurs, as in the baseline scenario. It is measured at the end of the first phase.
(2) **Theoretical lifetime associated with production.** This is the theoretical lifetime of products that are absent during the first phase but must be introduced for the transition to the second phase. It is measured at the phase transition.
(3) **Remaining lifetime after transition.** This is the potential remaining lifetime of products following the transition. It is measured at the beginning of the second phase.

Product lifetime increases when expected remaining life is greater after the transition than before it; conversely, it decreases when remaining life is greater before the transition. Premature scrapping is a particular case in which a product has remaining life before the transition but none afterward. Potential lifetime is also lost when a new product is used for less than its theoretical lifetime, that is, when its remaining lifetime after transition is shorter than its theoretical lifetime associated with production. Equation (1) defines the indicator:

$$\text{Longevity} - \text{variation indicator} = \text{Remaining lifetime (after transition)} - \text{Remaining lifetime (before transition)} - \text{Theoretical lifetime (production} - \text{related)} \quad (1)$$

A positive indicator value denotes lifetime extension, whereas a negative value denotes lifetime reduction. If the extension affects the entire product uniformly, a longevity variation of 0.2 means that its lifetime has increased by 20% of one complete product lifetime. Similarly, a value of −0.5 represents a reduction equal to 50% of one complete product lifetime.

The scenarios in the case study are compared using this indicator. To keep the analysis tractable, component replacement, use behavior, and maintenance are assumed to be identical across scenarios.

The circularity assessment includes a second ICEV user in each scenario so that the effects of second-hand ICEV reuse are represented more realistically. Each scenario is therefore evaluated against the following problem:

> "*An ICEV owner wishes either to replace the vehicle with an EV or to retain it until the end of its service life. At the same time, at least one other user requires an ICEV with similar characteristics. Under a perfect-substitution assumption, what is the longevity variation in each scenario?*"

Fig. 2 illustrates how each scenario addresses this problem. The ICEV, new EV (ICEV reused), and new EV (ICEV scrapped) scenarios are straightforward to represent and measure with the indicator. The retrofit scenario is more complex and requires additional detail. Using the representation in Fig. 2, it is therefore divided into three subscenarios:

- **Retrofit (ICEV components scrapped)**, in which the ICEV components removed during retrofit are scrapped.
- **Retrofit (ICEV components reused)**, in which the removed ICEV components are reused until the end of their service life.
- **Retrofit (kit reused)**, which resembles Retrofit (ICEV components reused) but uses second-hand rather than new EV components for the retrofit. These second-hand components are used until the end of their service life. Alternatively, new components may be installed during retrofit and subsequently reused after the glider reaches its end of life.

In the Retrofit (ICEV components reused) and Retrofit (kit reused) scenarios, components are obtained from or transferred to users outside the represented system. Their expected remaining lifetime is therefore subtracted from or added to the production-related parameter, depending on whether the component is sourced from or reused by another user. Section 3.1 reports the indicator for each scenario as a function of these parameters and draws conclusions about retrofit circularity.

2.3. Environmental assessment method

The environmental assessment is based on an LCA of the electric retrofit of a construction telehandler (Kiloutou Group) and follows the general methodology defined by ISO 14040 and ISO 14044 (ISO, 2006a; ISO, 2006b). Its primary objective is to compare the environmental impacts of the retrofit scenario with those of retaining an ICEV and purchasing a new EV, whether the replaced ICEV is reused or scrapped. This comparison assesses whether electric retrofit constitutes a viable environmental strategy. A second objective is to identify influential parameters through sensitivity analyses of retrofit timing and lifetime extension.

The system boundary covers primary-resource extraction, production, distribution, use and maintenance, and end of life. The function delivered by the system is the performance of material-handling activities by a construction telehandler, including driving, loading, lifting, and idling. A substantial share of its energy consumption and environmental impacts therefore occurs while the machine is stationary or performing handling operations rather than traveling. For this reason, the most appropriate functional unit is operating hours rather than travelled distance. Accordingly, the functional unit is defined as 1 h of machine operation following the duty cycle specified in Table 1. The four scenarios are compared using a functional unit of 1 h of machine operation and an assumed total service life of 10,000 h. The reference scenario consists entirely of ICEV operation over this lifetime. In the retrofit, new EV (ICEV reused), and new EV (ICEV scrapped) scenarios, the operating share varies: $1 - x$ is the fraction of the lifetime operated with the ICEV, and x is the fraction operated with the EV. Electricity used during operation is modeled using a mix of 65% French and 35% European electricity. The reference year is 2023.

The LCA is conducted using Ecodesign Studio (Altermaker), Ecoinvent database version 3.8 (Ecoinvent and Ecoinvent version 3), and the Environmental Footprint 3.0 method (European Commission). Primary data are obtained from the telehandler manufacturer, including bills of materials and duty cycles; the retrofit practitioner, including the energy used for the retrofit operation; and the rental company, including the sales mix. Requests to access these data should be addressed directly to Manitou.

Whereas most existing studies focus on GHG emissions, this study evaluates all 16 environmental impact indicators included in the Product Environmental Footprint (PEF) method (European Commission, 2021).

Operation impacts are calculated from the hourly energy or fuel consumption corresponding to the defined duty cycle and the associated life-cycle inventory datasets. The impacts associated with the production, retrofit, and end-of-life stages are allocated over the considered operating lifetime and expressed on the same hourly basis. With the exception of the ICEV engine, which is assumed to be reused in the retrofit scenario, components are modeled as recycled, energy-recovered, or landfilled according to their material composition and the Ecoinvent database. A cut-off approach is applied to end-of-life modeling: collection, sorting, incineration, and landfilling are included, whereas recycling processes, impacts avoided through secondary-material production, and energy recovery are excluded. Vehicles that have not reached end of life by the end of the second phase, or that are reused by another user, are allocated a share of their life-cycle environmental impacts proportional to the time spent within the scenarios. For example, if the ICEV is transferred to another user after 3000 h in the new EV (ICEV reused) scenario, 30% of its cradle-to-grave impacts are assigned to the scenario.

In the retrofit scenario, the ICEV components removed during the retrofit operation are assumed to be reused for their remaining useful lifetime. Under the perfect substitution assumption adopted in this study, their reuse is assumed to avoid the production of equivalent replacement components. An environmental credit is therefore attributed to the retrofit scenario by subtracting the share of the production impacts corresponding to the remaining lifetime of the removed components. This share is represented by x, i.e., the proportion of the initial ICEV lifetime remaining at the time of the retrofit operation. If these components were not reused, this credit would not be applied, and the corresponding impacts would be added to the retrofit scenario. Retrofit kits are assembled in France, transported to the customer, and installed locally. In the baseline scenario, the kits contain new components, are not reused after the glider reaches end of life, and produce no extension of vehicle lifetime. These assumptions are varied for the four impacts that contribute most to the PEF single score in this case study: fossil resource use, climate change, mineral resource depletion, and particulate matter. In the new EV (ICEV reused) scenario, the ICEV is assumed to be reused locally. Section 3.2 presents and discusses the results, comparing the environmental impacts of the scenarios and identifying the key parameters.

2.4. Economic assessment method

The economic assessment primarily seeks to determine the highest retrofit price that remains competitive with the purchase of a new EV. This threshold can help manufacturers and prospective retrofit providers assess whether they can offer retrofit operations at a sufficiently low cost to enter the market, and it can help ICEV owners judge whether retrofit is economically attractive. Because retrofit timing is varied, the analysis also investigates when retrofit is most advantageous, allowing interested owners to assess whether postponing the operation would be beneficial. The assessment compares retrofit only with purchasing a new EV, rather than with retaining an ICEV, for the following reasons:

- The literature compares electric retrofit economically with new EVs less often than with ICEVs: respectively, 4 and 7 of the 15 studies included in the critical review (Nguyen et al., 2025).
- New EVs can be regarded as the principal alternative to electric retrofit: if they were both available and less expensive, users would have little economic incentive to select retrofit.
- Excluding the ICEV alternative simplifies the analysis by avoiding operating-cost differences, such as fuel costs, which are assumed here to be identical for retrofitted and new EVs.
- The literature rarely considers reuse of the replaced ICEV in new EV scenarios (section 1), even though including this pathway could substantially alter conclusions about the cost-effectiveness of electric retrofit.

At a minimum, the economic comparison must account for the retrofit price and the price of a new EV. Subsidies may support either vehicle retrofit or new EV purchases (Watts et al., 2021; Transport for London; Directorate for Legal and Administrative Information) and may consequently influence user preferences. The resale value of the ICEV following a new EV purchase can also materially affect the results (Belin and Ponsa Sala) and is therefore included. Moreover, retrofit removes major ICEV components (Hoeft, 2021) that may retain a significant resale value (eBay), which is likewise incorporated into equation. A retrofitted vehicle and a new EV are not equivalent products: the former already exhibits wear and some degree of obsolescence. Actual or perceived differences in sustainability (Biswas, 2016), circularity (Boyer et al., 2021), obsolescence (Guillard et al., 2023), reliability (Hensher et al., 2014), and quality (Whitehead, 2006) may therefore shape user choice. Rather than assigning a separate assumption to each attribute, the model captures their combined effect through the difference in willingness to pay between a retrofitted and a new EV. Willingness to pay is defined as "[…] the maximum price a customer is willing to pay for a product or service" (Stobierski). Equation (2) accordingly compares the purchase of a new EV with electric retrofit:

$$P_{retro} - S_{retro} - RP_{comp} + DWP \leq P_{new} - S_{new} - RP_{ICEV} \quad (2)$$

P_{retro} and P_{new} are the customer prices of the retrofit operation and new EV, respectively. S_{retro} and S_{new} are the corresponding subsidies for retrofit and new EV purchase. RP_{comp} is the resale price of the ICEV components removed during retrofit. RP_{ICEV} is the resale price of the ICEV. DWP is the difference in willingness to pay between a new and a retrofitted EV. When the inequality holds, retrofit is more cost-effective than purchasing a new EV.

Because both the availability and amount of subsidies vary across regions and over time, subsidies are set to zero to simplify the analysis. The results are therefore reported without subsidies, although their potential influence and associated issues are discussed in section 4.2.2.

The analysis considers multiple market values for the ICEV and its components, as well as a scenario involving ICEV engine failure. Equation (2) is parameterized from two sources: (1) case-company databases, covering new EV and ICEV prices, second-hand ICEV prices, weights, and steel market values; and (2) expert estimates from managers responsible for second-hand equipment and the retrofit project when observed data are unavailable, covering older second-hand ICEV prices, engine repair or replacement costs, willingness to pay, and revenue from dismantled ICEVs. Because these data may be commercially sensitive, access requests should be addressed directly to Manitou. Where relevant, each input is specified using both pessimistic and optimistic values. For example, the market value of recycled steel is set at €100/t and €300/t. Inputs that depend on retrofit timing are recorded from 0 to 10,000 h at 1000-h intervals. A spreadsheet calculator then solves the equation with the retrofit price as the unknown. For each scenario, the equation is solved twice, first using inputs least favorable to retrofit and then using those most favorable to it. The resulting threshold is the maximum retrofit price that remains more cost-effective than purchasing a new EV. Section 3.3 reports this threshold as a function of retrofit timing because several terms depend on this variable (RP_{comp}, DWP, and RP_{ICEV}).

3. Results

3.1. Circularity assessment results

Table 2 presents the parameters and longevity-variation indicator for each scenario. As illustrated in Fig. 2, x denotes the length of the second period normalized by the lifetime of a new ICEV, while y denotes the lifetime extension produced by retrofit, normalized in the same way. The unit of analysis is therefore one new-ICEV lifetime.

Consider the Retrofit (ICEV components scrapped) scenario. Before

Table 2
Circularity parameters and longevity-variation indicator for each scenario.

Key parameters	ICEV	Retrofit (ICEV's components scrapped)	Retrofit (ICEV's components reused)	Retrofit (kit reused)	New EV (ICEV scrapped)	New EV (ICEV reused)
Remaining lifetime (before transition): gliders	x	x	x	x	x	x
Remaining lifetime (before transition): ICEV powertrains	x	x	x	x	x	x
Theoretical lifetime (production-related): gliders	1	1	1	1	$1+1$	1
Theoretical lifetime (production-related): ICEV powertrains	1	1	$1-x$	$1-x$	1	0
Theoretical lifetime (production-related): EV powertrains	0	1	1	x	1	1
Remaining lifetime (after transition): gliders	$1+x$	$1+x+y$	$1+x+y$	$1+x+y$	$1+1$	$1+x$
Remaining lifetime (after transition): ICEV powertrains	$1+x$	1	1	1	1	x
Remaining lifetime (after transition): EV powertrains	0	$x+y$	$x+y$	$x+y$	1	1
Longevity-variation: gliders	0	y	y	y	$-x$	0
Longevity-variation: ICEV powertrains	0	$-x$	0	0	$-x$	0
Longevity-variation: EV powertrains	0	$x+y-1$	$x+y-1$	y	0	0

the transition, the first user owns an ICEV with a remaining lifetime x, whereas the second user does not yet own a vehicle. The total remaining lifetime before transition is therefore x for one complete ICEV. The transition requires production of an electric powertrain for the first user's retrofit and, simultaneously, production of a new ICEV for the second user. The theoretical lifetime associated with production thus comprises one new EV powertrain and one new ICEV, each with a normalized lifetime of 1. At the start of the second phase, the first user owns a retrofitted vehicle that will be used for $x+y$ before reaching end of life, while the second user owns an ICEV with its full lifetime remaining (1). The remaining lifetime after transition is consequently $1+x+y$ for the gliders, 1 for the ICEV powertrain, and $x+y$ for the EV powertrain installed in the retrofitted vehicle. Applying Eq. (1), the longevity variation is -x for the ICEV powertrain because it has a remaining lifetime x before transition but is destroyed during retrofit. Similarly, the value for the EV powertrain is $x+y-1$ because a new powertrain with a theoretical lifetime of 1 is produced but used only for $x+y$, until the retrofitted vehicle reaches end of life.

The new EV (ICEV scrapped) scenario is less circular than the ICEV and new EV (ICEV reused) scenarios because an entire ICEV is scrapped prematurely. In the longevity-variation indicator, this loss appears as $-x$ for both the ICEV powertrain and the glider, representing destruction of a complete ICEV with a potential remaining lifetime x. Thus, the earlier the transition between the two phases, the larger x becomes and the less circular the new EV (ICEV scrapped) scenario is.

The ICEV and new EV (ICEV reused) scenarios have the same longevity-variation value because neither extends nor reduces vehicle lifetime. They differ, however, in the required powertrain: the ICEV scenario uses an ICEV powertrain, whereas the new EV (ICEV reused) scenario introduces an EV powertrain.

The circularity of the retrofit scenarios depends strongly on four parameters:

(1) **Reuse of the removed ICEV components.** This parameter distinguishes Retrofit (ICEV components scrapped) from Retrofit (ICEV components reused). Comparison of their longevity-variation values shows that reusing the removed components prevents the premature loss of an ICEV powertrain with a potential remaining lifetime x and therefore increases circularity.
(2) **Timing of the retrofit operation.** The variable x is linked to retrofit timing. As Table 2 shows, when the EV powertrain is not reused, a larger x yields a higher longevity-variation value for the retrofit scenario. A new EV powertrain is required but is used for only x rather than for a full normalized lifetime of 1, thereby causing premature loss. Performing the retrofit earlier therefore reduces the potential lifetime lost from the EV powertrain.
(3) **Reuse of the EV powertrain.** In Retrofit (kit reused), powertrain reuse avoids the premature loss described above. The longevity-variation value for this scenario therefore no longer depends on retrofit timing. Because it causes no lifetime reduction, Retrofit (kit reused) is then at least as circular, according to the indicator, as the ICEV and new EV (ICEV reused) scenarios.
(4) **Lifetime extension achieved through retrofit.** This parameter is represented by y. For the glider, extending lifetime increases the longevity-variation value by the duration of the extension, y. For the EV powertrain, lifetime extension can reduce premature loss in the Retrofit (ICEV components scrapped) and Retrofit (ICEV components reused) scenarios. However, a post-retrofit remaining lifetime longer than the lifetime of a new EV appears unrealistic; $x+y$ must therefore remain below 1. In Retrofit (kit reused), the EV powertrain is also assumed to benefit from lifetime extension. This entails reconditioning either during retrofit, if sourced from another user, or at the vehicle's end of life, if subsequently transferred to another user, and produces a longevity variation of $+y$.

The retrofit scenarios can consequently be either the most or the least circular, depending on the lifetime extension achieved, reuse of the EV powertrain, and timing of the operation. This finding challenges the general claim that retrofit is more circular than new EV scenarios. Because its presumed environmental advantages are partly grounded in this circularity claim, those advantages must also be examined. The following section therefore compares the environmental impacts of the scenarios.

3.2. Environmental assessment results

Fig. 3 compares the environmental impacts of the retrofit scenario with those of the ICEV, new EV (ICEV reused), and new EV (ICEV scrapped) scenarios. The underlying data are provided in SI 1. The heatmaps in Fig. 3 show changes across the 16 PEF impact categories for the three comparisons, assuming no lifetime extension and no reuse of the EV powertrain. Under these assumptions, earlier retrofit consistently improves environmental performance because it avoids producing an EV powertrain that would be used for only a short period. Retrofit can have lower impacts than the new EV (ICEV scrapped) scenario for every indicator considered. When performed sufficiently early in the ICEV lifetime, it can also substantially outperform the ICEV scenario for

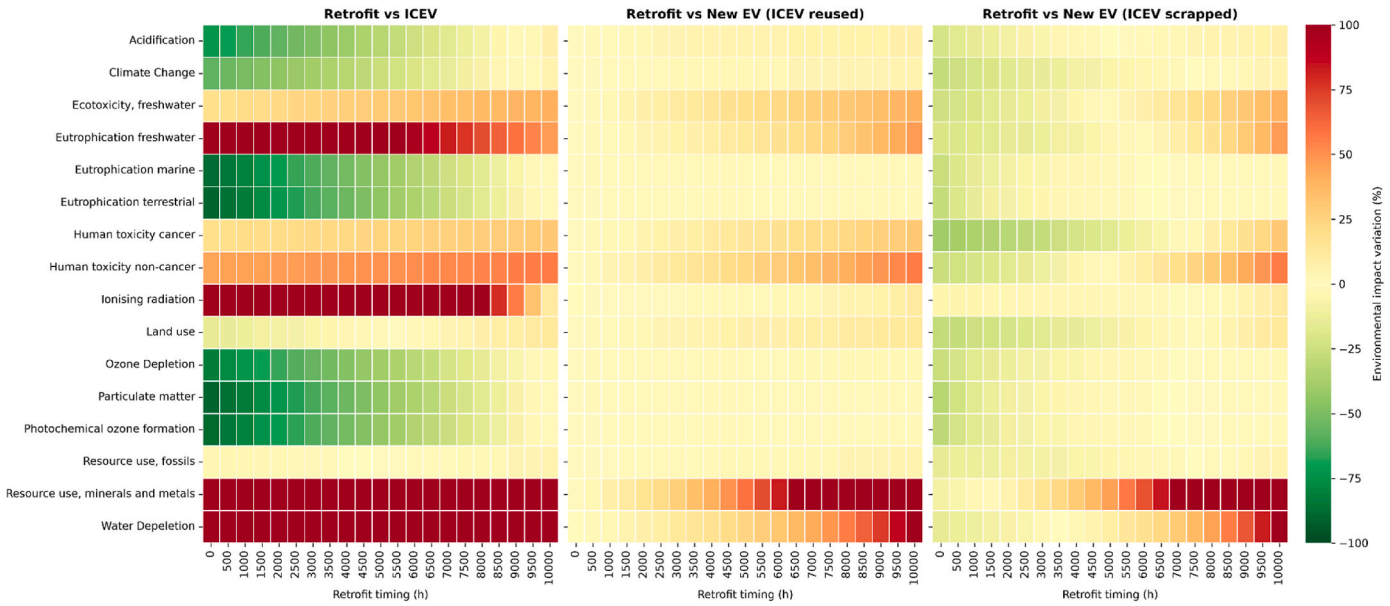


Fig. 3. Environmental benefit of retrofit according to retrofit timing.

acidification, ozone depletion, marine and terrestrial eutrophication, photochemical ozone formation, fossil resource use, climate change, particulate matter, and land use. The threshold for "sufficiently early" differs across indicators. Conversely, retrofit has the highest impacts when performed at the end of the ICEV lifetime.

Relative to the ICEV scenario, retrofit requires production of an additional EV powertrain but replaces thermal operation with electric operation during the second period. Although its production-related impacts are therefore higher, electric use generates lower impacts than thermal use for several indicators, including acidification, ozone depletion, marine and terrestrial eutrophication, photochemical ozone formation, fossil resource use, climate change, particulate matter, and land use. Retrofit can consequently have lower impacts than the ICEV scenario for these categories, particularly when performed early. The comparison also identifies four categories in which retrofit impacts may be up to 100% higher: mineral resource depletion, freshwater eutrophication, ionizing radiation, and water depletion. For these indicators, either EV operation has substantially higher impacts than ICEV operation or production of the retrofit kit, namely the EV powertrain, has a particularly high impact.

For every indicator considered, retrofit has greater environmental impacts than the new EV (ICEV reused) scenario. It nevertheless

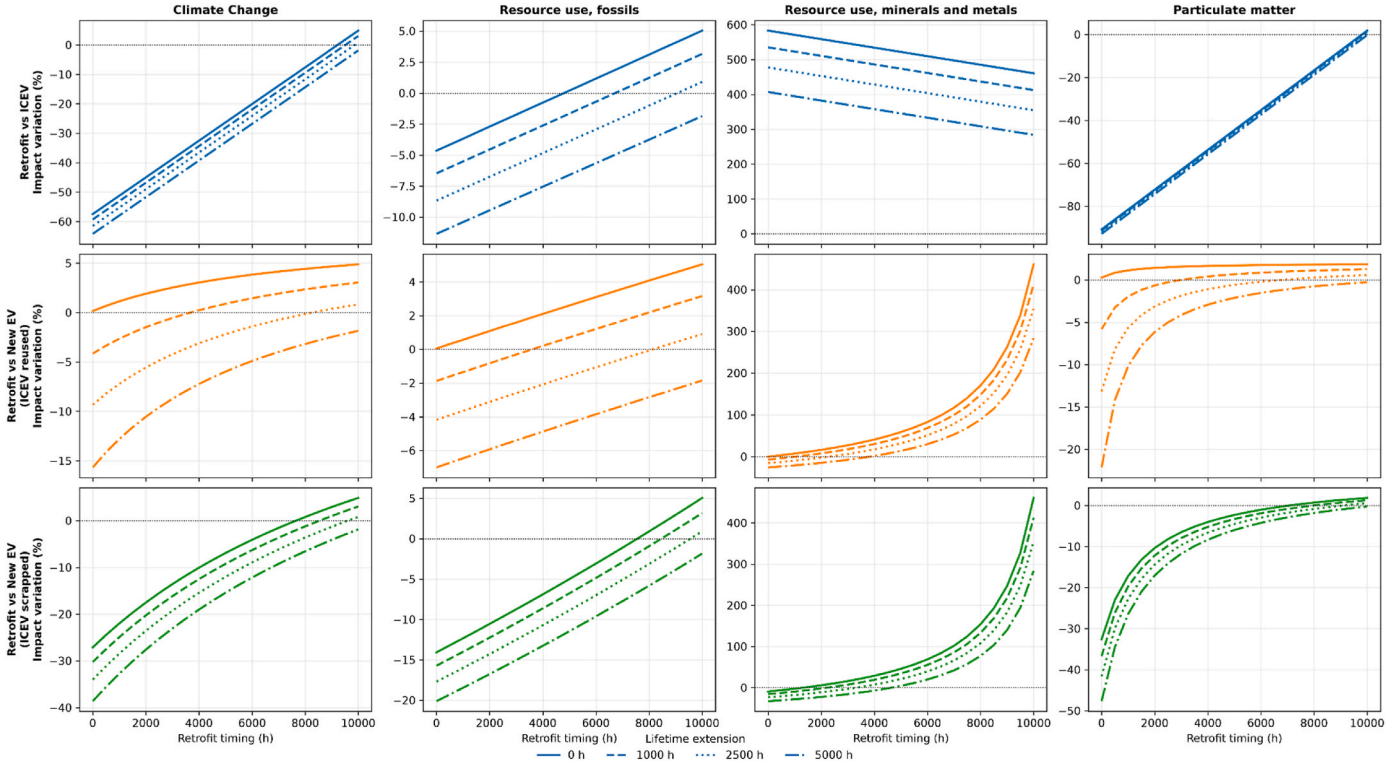


Fig. 4. Effect of lifetime extension on retrofit impact variation.

performs better across all categories when the ICEV is scrapped rather than reused in the new EV scenario. Because the use phase is identical across the EV scenarios, their differences arise primarily during production. Premature scrapping and the production of vehicles and components are therefore major drivers of impact. These environmental findings are consistent with the circularity assessment: the new EV (ICEV reused) scenario, which maximizes longevity, has the lowest impacts, whereas the relative performance of retrofit and new EV (ICEV scrapped) depends on the lifetime lost, retrofit timing, and the contribution of EV-powertrain or ICEV production to each impact category.

If the electric powertrain is reused in the retrofit scenario, the production and use-phase impacts of retrofit become identical to those of the new EV (ICEV reused) scenario, leaving distribution as the source of difference. As shown for the four "kit reused" indicators in SI 2 - fossil resource use, climate change, mineral resource depletion, and particulate matter - the impacts of the two scenarios are then almost identical, with a maximum difference of 0.37%.

Lifetime extension increases the service life of both the glider and EV powertrain in the retrofit scenario, reducing production-related impacts per hour of use. Fig. 4, with tabulated data provided in SI 3, shows substantial reductions for fossil resource use, climate change, mineral resource depletion, and particulate matter. Retrofit must extend vehicle lifetime to have lower impacts than the new EV (ICEV reused) scenario. The conclusion regarding timing remains unchanged: for all indicators except those for which EV operation has higher impacts than ICEV operation, such as mineral and metal resource depletion, earlier retrofit produces better environmental performance.

The credit associated with the reuse of the removed ICEV components represents only 0.8%–1.9% maximum of the GWP impact and approximately 0.5% of the ADPE impacts of the retrofit scenario. If these components were not reused, the corresponding avoided impacts would simply be added to the retrofit scenario. Consequently, this assumption has only a limited influence on the environmental results and does not change the main conclusions of the study.

Fig. 5 presents the contribution of the main components and processes to the GWP and ADPE impacts of the four scenarios. The transition is assumed to occur at 5000 operating hours, with no lifetime extension or retrofit-kit reuse. The results distinguish the impacts associated with ICEV manufacture, EV manufacture, retrofit-kit manufacture, ICEV use and maintenance, EV use and maintenance, and end-of-life. Data used to perform the contribution analysis is provided in SI 4.

In the New EV (ICEV reused) scenario, the allocated ICEV-manufacturing impacts are halved compared with the other scenarios. This difference results from the reuse of the ICEV and the perfect substitution assumption: when the transition occurs at 5000 h, the reused ICEV has 50% of its expected lifetime remaining and is assumed to substitute the production of an equivalent new ICEV. Consequently, 50% of the ICEV-manufacturing impacts are considered avoided.

The comparison between the manufacture of the retrofit kit and that of a new EV differs substantially between the two impact categories. For ADPE, retrofit-kit manufacture is more impactful than the allocated manufacture of the new EV in the two New EV scenarios. The new EV is operated for only 50% of its expected lifetime within the considered period and retains 50% of its lifetime after this period. Its manufacturing impacts are therefore allocated proportionally to the share of its lifetime included in the scenario. In contrast, under the examined scenarios, the retrofitted machine reaches its end-of-life at the end of the second period, and the retrofit kit is not subsequently reused. The retrofit scenario, therefore, bears the complete manufacturing impacts of the retrofit kit.

The opposite result is observed for GWP, where retrofit-kit manufacturing is less impactful than the allocated manufacturing of the new EV. This difference can be explained by the respective contributions of the glider and the electric powertrain. GWP impacts associated with new-EV manufacture are strongly influenced by glider manufacture, which is avoided in the retrofit scenario because the existing glider is retained. Conversely, ADPE impacts are mainly driven by the manufacture of the electric powertrain included in both the retrofit kit and the new EV. Consequently, whether retrofit-kit manufacture or new EV manufacture is the most impactful depends on the relative contribution of the glider and electric-powertrain manufacturing processes to the impact category considered.

Overall, the results show that the environmental impacts from the end-of-life are negligible compared to the manufacturing and use phases. The use and maintenance phase is the main contributor to GWP, particularly because of ICEV operation, whereas the manufacturing phase dominates ADPE due to the production of the electric powertrain and retrofit kit.

Finally, the use-phase contributions are identical across the three electrified scenarios because they follow the same operating profile: 5000 h of ICEV operation during the first period and 5000 h of EV operation during the second period. The use phase, therefore, differentiates continued ICEV operation from the electrified scenarios but does not explain the differences among the Retrofit, New EV (ICEV scrapped), and New EV (ICEV reused) scenarios. At a fixed transition point, changing the electricity-mix carbon footprint would affect the use-phase impacts of these three scenarios equally and would therefore not modify their relative ranking. Their comparison is instead driven by differences in manufacture, reuse, allocation, and remaining lifetime.

3.3. Economic assessment results

Fig. 6 presents the main economic results, while SI 5 provides the tabulated results and intermediate market-degradation scenarios.

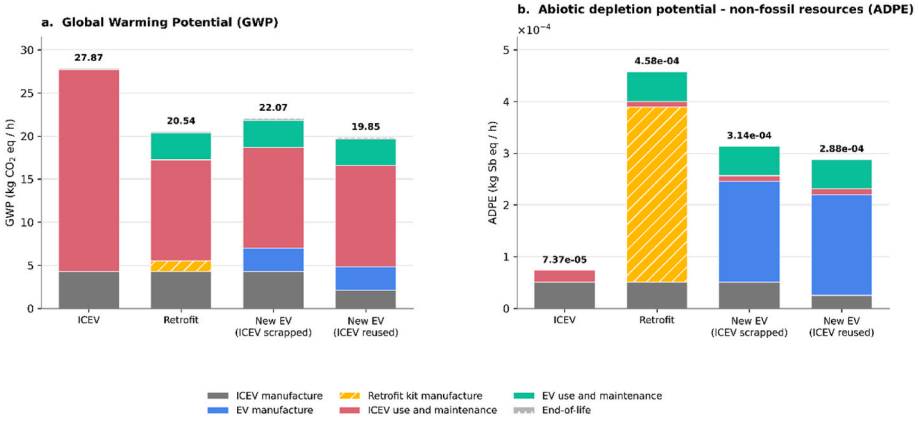


Fig. 5. The contribution of the main components and processes to the environmental impacts of (a) Global Warming potential (GWP) and (b) abiotic depletion potential – non fossil resources, at 5000h operating time, in the four scenarios considered (i.e., ICEV, Retrofit, New EV (ICEV scrapped) and New EV (ICEV reused)).

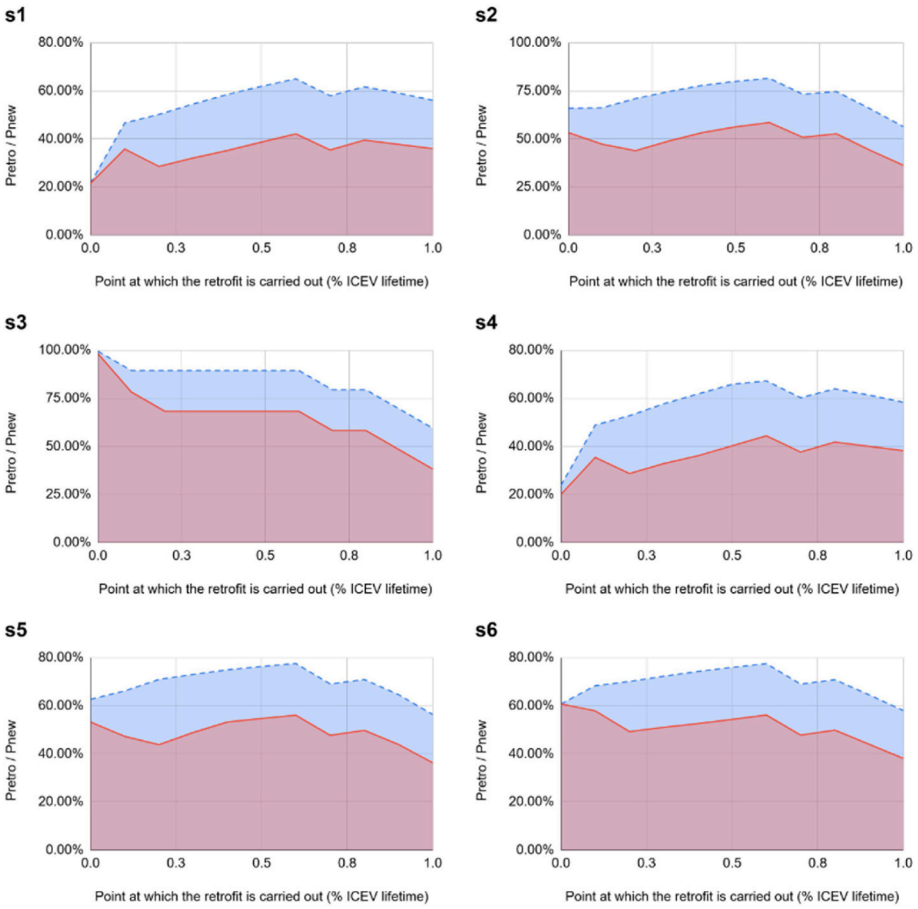


Fig. 6. Cost-effectiveness of the electric retrofit (P_{retro}/P_{new}) depending on the point at which the retrofit is carried out (% ICEV lifetime). P_{retro} Retrofit operation maximum price, $\mathbf{P_{new}}$ Price for purchasing a new EV. Dashed lines = optimistic data; solid lines = pessimistic data. s1: ICEV market is not downgraded; s2: no second-hand ICEV market but second-hand ICEV's components market is not downgraded; s3: no second-hand ICEV and no ICEV's components markets; s4: ICEV market is not downgraded but ICEV's engine broken; s5: ICEV market is 50% downgraded but second-hand ICEV's components market is not downgraded; s6: second-hand ICEV and ICEV's components markets are 50% downgraded.

Scenario s1 illustrates how to interpret the graphs. If retrofit occurs after 30% of the potential ICEV lifetime, or 3000 h on the abscissa, the maximum retrofit price that remains more cost-effective than purchasing a new EV is 32% of the new EV price under pessimistic assumptions (solid line) and 54% under optimistic assumptions (dashed line). If retrofit occurs at 8000 h, the corresponding threshold is 39% or 62% of the new EV price, depending on whether the assumptions are pessimistic or optimistic.

In the baseline scenario (s1), where the second-hand ICEV market is not degraded, the retrofit price must remain below 60% of the new EV price even under optimistic assumptions, and below 40% under pessimistic assumptions. Available information is insufficient to determine whether these thresholds are achievable for the case-study vehicle type, although they may already be attainable for other vehicles, such as buses (Allard and Castaignede, 2021; Watts et al., 2021). The thresholds vary only slightly with retrofit timing because two effects partly offset one another: ICEV resale value and the difference in willingness to pay. As the ICEV ages, its resale value declines, reducing the amount recovered when a new EV is purchased later in its life. At the same time, postponing retrofit reduces the condition and remaining lifetime of the retrofitted vehicle, thereby increasing the difference in willingness to pay between retrofitted and new EVs.

The value of the second-hand ICEV market and its component market is an important determinant of retrofit cost-effectiveness. If the ICEV cannot be resold (s2), or can be sold for only half its current price (s5), while component values remain unchanged, retrofit becomes substantially more cost-effective than in the baseline scenario but may still be too expensive. Under pessimistic assumptions, its price must remain at approximately 50% or less of the new EV price; under optimistic assumptions, it may exceed 75%. Beyond a certain degree of market degradation, however, a further decline in second-hand ICEV prices has little effect because dismantling the vehicle yields greater value than reselling it intact.

If the second-hand ICEV market collapses, the component market will plausibly decline as well. This is the most favorable case for retrofit because the ICEV resale value falls sharply. In this situation, however, the difference in willingness to pay is no longer offset by ICEV resale value, and retrofit cost-effectiveness declines rapidly with time (s3). Thus, without subsidies, the economically optimal retrofit timing relative to purchasing a new EV depends on whether the ICEV can be resold. If it cannot, earlier retrofit is preferable. If it can, timing has little influence, although approximately 6000 h is the most favorable point in this case study.

Finally, failure of the ICEV engine (s4) has little effect on retrofit cost-effectiveness because repairing or replacing the component costs relatively little compared with the price of a complete vehicle. Engine failure also affects both alternatives in comparable ways: under retrofit, it either prevents resale of some removed ICEV components or creates repair costs; under new EV purchase, it requires repair or replacement of the engine before the second-hand ICEV can be resold.

4. Discussion

This section compares the circularity, environmental, and economic

results with those reported in the literature. It then identifies the principal gaps addressed by the study and uses the findings to formulate recommendations.

To the authors' knowledge, this is the first study to propose an integrated method for assessing the circularity, environmental, and economic dimensions of electric retrofit. The results reveal no major trade-offs among these dimensions, although they depend strongly on the parameters identified and discussed in section 4.2.

4.1. Circularity assessment results

The proposed indicator is related to the longevity indicator developed by Franklin-Johnson et al. (2016), which measures how long a material remains within a product system, but differs from it in four important respects. First, whereas their indicator assesses material longevity (Franklin-Johnson et al., 2016), the present indicator assesses product longevity, as proposed by Moraga et al. (2019). Second, recycling lies outside the present scope. Third, the indicator captures not only activities that extend product lifetime but also those that reduce it, such as scrapping functional subassemblies. Fourth, unlike the Franklin-Johnson et al. indicator (Franklin-Johnson et al., 2016), which is expressed as an absolute duration, the proposed indicator is relative and measures gains or losses in expected lifetime against a baseline scenario.

Several studies claim that electric retrofit is more circular than purchasing a new EV because it enables much of the existing vehicle to be reused (Allard and Castaignede, 2021; Dattero-Snell, 2023; Watts et al., 2021). However, a comprehensive circularity assessment of retrofit has previously been lacking. This study addresses that gap by introducing a method for measuring longevity variation across the scenarios. The results show that retrofit may be either the most or the least circular option, depending on the parameters discussed in section 4.2. In particular, reuse assumptions strongly influence both circularity and, consequently, the environmental impacts of the scenarios. Future work should incorporate the probability and quality of reuse to produce more accurate circularity estimates and could further extend the assessment to include recycling.

The authors therefore recommend using longevity-based indicators to assess the impacts of electric retrofit, whether the indicator proposed by Franklin-Johnson et al. (2016) or the one developed here. This recommendation rests on two findings. First, component reuse and longevity underpin the circularity and environmental benefits attributed to retrofit in the literature because they reduce production-related impacts (Allard and Castaignede, 2021; Belin and Ponsa Sala; Dattero-Snell, 2023; Helmers et al., 2017; Rizzo and Tiano, 2020; Santis and Regis, 2021; Watts et al., 2021; Strecker et al., 2014). Second, the longevity of the retrofit EV powertrain depends on when the operation occurs. If the powertrain is not subsequently reused, retrofit may require production of a new powertrain for a shortened service life, leading to premature scrapping and strongly affecting environmental performance, as shown in section 3.2.

4.2. Environmental assessment results

With the exception of Helmers et al. (2017), previous studies evaluate electric retrofit using only one or two environmental indicators. The present LCA provides a broader assessment across multiple indicators and examines the key parameters identified in section 4.2. Because few LCA studies of electric retrofit are available, opportunities for direct comparison remain limited. Existing studies compare retrofit either with an ICEV or with a new EV; both comparisons are necessary. The following paragraphs compare the results under three assumptions: the EV powertrain is not reused, retrofit does not extend vehicle lifetime, and the operation occurs during the first half of the ICEV lifetime.

- **Comparison of electric retrofit with an ICEV scenario**: Overall, the results are consistent with the literature: retrofit has lower impacts for climate change (Belin and Ponsa Sala; Innocenti et al., 2024; Napoli et al., 2022; Santis and Regis, 2021) and air pollution (El Hannach et al., 2019; Rizzo and Tiano, 2020), but higher impacts for mineral resource use (Belin and Ponsa Sala; Helmers et al., 2017). They also broadly agree with Helmers et al. (2017), except for particulate matter, fossil resource use, land use, and marine eutrophication. These differences can be partly attributed to the electricity mix used in the model. As noted in section 3.2, the mix is predominantly French and therefore relies heavily on uranium, which affects the fossil-resource-use indicator.
- **Comparison of electric retrofit with a new EV scenario**: The results agree with the literature (Belin and Ponsa Sala; Helmers et al., 2017; Rizzo and Tiano, 2020) in showing lower impacts for retrofit across all indicators, but only when the ICEV replaced by the new EV is assumed to be scrapped prematurely (new EV (ICEV scrapped)). If the ICEV is instead reused (new EV (ICEV reused)), the result is reversed: retrofit has higher impacts for every indicator. This finding demonstrates the importance of the ICEV-reuse assumption in new EV scenarios. Among the reviewed studies, only Carbone 4 (Belin and Ponsa Sala) included ICEV reuse in a new EV scenario, but it did not credit that reuse with avoiding the production impacts of another ICEV.

4.3. Economic assessment results

The economic analysis does not compare retrofit with continued use of the ICEV and therefore cannot determine which of these two alternatives is more cost-effective. Relative to purchasing a new EV, the results indicate that retrofit must be comparatively inexpensive and/or that the second-hand ICEV market must be degraded for retrofit to become preferable. The findings therefore provide less support for the economic superiority of retrofit than some previous studies (Allard and Castaignede, 2021; Dattero-Snell, 2023). Belin and Ponsa Sala (Belin and Ponsa Sala) and Watts et al. (2021) show that its economic relevance depends on vehicle type, but neither examines off-road vehicles; future research should address this gap. The present approach is also less favorable to retrofit than studies based on total cost of ownership without ICEV resale following a new EV purchase (Allard and Castaignede, 2021; Dattero-Snell, 2023), simple price differences (Watts et al., 2021), or total cost of ownership including ICEV resale (Belin and Ponsa Sala).

Differences from TCO-based findings can be partly explained by how depreciation is treated. Studies using TCO (Allard and Castaignede, 2021; Belin and Ponsa Sala) assume that the residual value of a new EV declines faster than that of a retrofitted EV, which affects the resulting TCO. The present method does not model this difference in depreciation. More generally, TCO was deliberately excluded for the following reasons:

- Reliable data on use, maintenance, and externalities are difficult to obtain because electric retrofit remains a niche and relatively recent activity.
- Electric retrofit is sometimes presented as a low-cost electrification strategy (Kozłowski and Czerepicki, 2023) that can serve financially constrained customers, who may be unable to adopt a TCO perspective.
- Comparing a new EV with a retrofitted EV resembles comparing products that serve the same purpose but differ in quality. A lower-cost option may have a better TCO without necessarily being preferred, because users may value the comfort, functions, and durability of the higher-quality alternative. For new and retrofitted EVs, relevant differences may include battery capacity, availability of recent functions, perceived environmental impacts, expected residual value, and maintenance costs. Because the available data and

study duration did not allow these attributes to be distinguished, the analysis uses an aggregate difference in willingness to pay, estimated by the retrofit project manager and the manager responsible for second-hand equipment and subsidies, rather than depreciation alone.

Methodological differences between the present approach and the literature - specifically, between an economic calculation at the time of the operation and a life-cycle approach - limit direct comparison of the results. The observed differences may therefore reflect both perspective and method. Life cycle costing, particularly TCO, was excluded because of limited data, the user-centered scope, including financially constrained users, and differences in product quality. As a result, maintenance costs, residual-value depreciation, and financing costs are not modeled directly: they either overlap with willingness to pay or do not arise at the time of the retrofit decision.

4.4. Main parameters and recommendations

The results identify three parameters that strongly shape the circularity, environmental, and economic impacts of electric retrofit (section 3), yet have received little attention in the literature: (1) retrofit timing, (2) reuse of vehicles and components, and (3) lifetime extension achieved through retrofit.

4.4.1. Moment of retrofit

This study examines in detail the most appropriate time to perform retrofit during the ICEV lifetime. All three assessments confirm the importance of timing. Counterintuitively, performing retrofit as early as possible maximizes circularity (section 3.1) and minimizes most environmental impacts (section 3.2). Depending on timing, retrofit may have either higher or lower environmental impacts than purchasing a new EV and scrapping the replaced ICEV; the same applies to most indicators when retrofit is compared with continued ICEV use. Timing has less influence on economic performance because it affects both the resale value of the ICEV following a new EV purchase and the difference in willingness to pay between new and retrofitted EVs. However, when the second-hand ICEV market is degraded, retrofit timing becomes economically decisive. Two qualifications must nevertheless be considered:

(1) **The importance of timing depends on whether components and the ICEV are reused (section 4.2.2).** When premature scrapping occurs - for example, for the ICEV in the new EV (ICEV scrapped) scenario or for the EV powertrain in Retrofit (kit not reused) - timing affects circularity and environmental performance by changing the magnitude of the lifetime lost (sections 3.1 and 3.2). When reuse occurs - for example, for the ICEV in the new EV (ICEV reused) scenario or the EV powertrain in Retrofit (kit reused) - timing no longer affects these results.

(2) **Retrofit timing and lifetime extension (section 4.2.3) are treated as independent rather than interdependent parameters.** No study currently establishes how retrofit affects vehicle life expectancy. In the absence of better evidence on the relationship between timing and extension, this study therefore applies a uniform distribution to lifetime extension. It is nevertheless plausible that later retrofit produces a longer extension relative to the remaining ICEV lifetime. If such interdependence were demonstrated, and if the extension were sufficiently large, conclusions about the influence of retrofit timing could change substantially.

4.4.2. Reuse of components and ICEVs

The analysis varies three reuse parameters: reuse of the ICEV following a new EV purchase, reuse of ICEV components removed during retrofit, and reuse of the EV powertrain in the retrofit scenario. Of these, ICEV reuse following a new EV purchase most strongly determines whether retrofit or a new EV is preferable. Across sections 3.1-3.3, the new EV (ICEV reused) scenario consistently outperforms the new EV (ICEV scrapped) scenario. If use of a second-hand ICEV substitutes for use of a new one, scrapping a functioning and reusable ICEV offers neither circularity nor environmental benefits; from the consumer perspective, it offers no economic benefit either. Scrappage schemes (Transport for London; Phillips) that condition new EV subsidies on destroying a functioning ICEV may therefore be detrimental. From circularity and environmental perspectives, the authors recommend enabling reuse of these vehicles while controlling new ICEV production so that the system approaches perfect substitution.

Electric retrofit requires an EV powertrain but may use it for substantially less time than a new EV would. If the retrofit uses new components that are not reused when the retrofitted vehicle reaches end of life, those components are scrapped prematurely. As sections 3.1 and 3.2 show, using second-hand retrofit components or reusing the EV powertrain afterward can substantially improve circularity and reduce environmental impacts. Economically, second-hand components can lower the retrofit price (Watts et al., 2021), while resale of the EV powertrain can further improve cost-effectiveness. However, the evidence gap remains: the practical reusability of vehicles and components requires further investigation before the impacts of electric retrofit can be assessed more accurately.

4.4.3. Lifetime extension

Lifetime extension is a major driver of the circularity and environmental results. Without it, retrofit cannot be more circular or have lower environmental impacts than purchasing a new EV and reselling the second-hand ICEV. Its economic influence remains unresolved and should be examined in future research. If retrofit includes reconditioning, comparisons must also include reconditioned new EV and ICEV scenarios; otherwise, any observed benefit cannot be attributed clearly to retrofit rather than to reconditioning.

4.4.4. Perfect substitution assumption

The study assumes perfect substitution (section 2.1.2), but this assumption affects the three assessments differently:

- **Economic.** The economic assessment is independent of the substitution assumption.
- **Circularity.** The substitution assumption changes how the scenarios are represented (section 2.2) but not the indicator results. Producing a new product does not affect longevity if that product is expected to complete its full service life. For example, under a 0% rather than 100% substitution rate, a complete ICEV may be added to the new EV (ICEV reused) scenario because reusing the original ICEV no longer avoids production of a new one. This added ICEV nevertheless has a remaining lifetime after transition of 1, a remaining lifetime before transition of 0 because it did not previously exist, and a theoretical lifetime associated with production of 1. Its contribution to Eq. (1) is therefore zero, as shown in Eq. (3):

$$Longevity_variation\ indicator = 1 - 0 - 1 = 0 \quad (3)$$

- **Environmental.** The substitution assumption fundamentally changes the environmental results. Without substitution, the reused ICEV supplements rather than replaces production of a new ICEV, creating a rebound effect through additional production and use. If this effect is included within the scope, a 0% substitution assumption requires both (1) removing the impacts avoided through ICEV reuse and (2) adding the impacts of the reused ICEV's remaining use, relative to the 100% substitution assumption applied in the main analysis. This is equivalent to adding the ICEV-scenario impacts to the new EV (ICEV reused) scenario in proportion to the reused ICEV's remaining lifetime, x. To illustrate the influence of substitution, a

Table 3
Sensitivity of climate change and mineral and metal resource use to the substitution assumption. Retrofit is performed at 5000 h without lifetime extension or reuse of the retrofit kit.

Impact category	Substitution rate	Retrofit scenario	New EV (ICEV scrapped) scenario	New EV (ICEV Reused) scenario
Climate Change (kg CO2 eq/h)	0%	20.54	22.07	33.79
	25%	20.54	22.07	30.31
	50%	20.54	22.07	26.82
	75%	20.54	22.07	23.34
	100%	20.54	22.07	19.85
Resource use, minerals and metals (kg Sb eq/h)	0%	4.58E-04	3.14E-04	3.25E-04
	25%	4.58E-04	3.14E-04	3.16E-04
	50%	4.58E-04	3.14E-04	3.07E-04
	75%	4.58E-04	3.14E-04	2.98E-04
	100%	4.58E-04	3.14E-04	2.88E-04

sensitivity analysis is performed for climate change and mineral resource depletion across the three EV scenarios, using substitution rates of 0%, 25%, 50%, 75%, and 100% and assuming retrofit at 5000 h (Table 3).

The sensitivity analysis shows that substitution can be a major driver, particularly when ICEV impacts are large relative to EV impacts. A 25-percentage-point change in the substitution rate is sufficient for retrofit to generate lower GHG emissions than the new EV (ICEV reused) scenario. For mineral resource depletion, changing the assumption increases the impacts of new EV (ICEV reused), although this scenario retains substantially lower impacts than retrofit at every substitution rate examined.

In all cases, a lower substitution rate increases the environmental impacts attributable to the reused ICEV. Varying this assumption essentially demonstrates that producing and operating more machines causes greater impacts than avoiding their production and use. The best outcome is consequently to reuse the ICEV under conditions approaching perfect substitution. Rather than incentivizing ICEV destruction, the authors recommend limiting new ICEV production so that reuse increasingly substitutes for new production.

4.4.5. Generalizability

The multicriteria method is applied to a construction-telehandler case study. This vehicle type is particularly relevant to electric retrofit because of its high residual value, long service life, and the industry's need to decarbonize. The direction of influence of the identified parameters can be generalized across vehicle categories, but the magnitude of the results remains case-specific. Differences in total lifetime and retrofit-kit size between a heavy-duty off-road vehicle and a passenger car, for example, will change the magnitude of the impacts, whereas ICEV reuse, lifetime extension, and retrofit-kit reuse will affect both categories through the same mechanisms.

4.4.6. Recommendations

A combination of at least some of the following conditions is therefore required for electric retrofit to outperform purchasing a new EV across the three dimensions considered:

1. Retrofit performed early in the vehicle lifetime
2. Reuse of the retrofit EV powertrain
3. Substantial lifetime extension resulting from retrofit
4. Limited potential to reuse the ICEV following a new EV purchase

In addition, the electric retrofit industry is likely to be temporary because it depends on the gradual withdrawal of ICEVs (Allard and Castaignede, 2021). Retrofit is therefore unlikely to replace new EVs in the general market and is better understood as a niche solution. Several potential niches emerge from the analysis. If regulations or market conditions prevent reuse of the ICEV, the new EV (ICEV reused) pathway is unavailable, and retrofit competes instead with new EV (ICEV scrapped) or degraded-market scenarios. Low-cost retrofit using second-hand components (Watts et al., 2021) represents another possible niche. Finally, some users may perceive little or no difference in willingness to pay between a retrofitted vehicle and a new EV.

5. Implications

This study develops and applies a methodology for assessing the impacts of electric retrofit through an off-road vehicle case study. Circularity, environmental, and economic assessments compare retrofit with ICEV and new EV scenarios. The principal contribution is a more comprehensive assessment method that accounts for vehicle and component reuse, multiple environmental impact categories, retrofit timing, and circularity. The results show that three parameters strongly determine retrofit performance: (1) the point in the ICEV lifetime at which retrofit occurs, (2) the lifetime extension produced by the operation, and (3) the reusability of vehicles and components across scenarios. Future studies should include these parameters to improve generalizability, identify the conditions under which retrofit is beneficial, and compare it with more realistic alternatives. Some environmental trade-offs arise when retrofit is compared with continued ICEV use, but no other major trade-offs are identified. By addressing gaps that call current knowledge of retrofit impacts into question, the study shows that, unless particularly favorable conditions are met, retrofit is less circular, has higher environmental impacts, and is less economically attractive than purchasing a new EV and reselling the second-hand ICEV.

The study has several limitations. Evidence on the lifetime extension realistically achieved through retrofit is currently scarce, as is evidence on the relationship between retrofit timing and vehicle life expectancy. Examining this interdependence and its effects on circularity and environmental impacts is therefore a promising direction for future research. The analysis also does not propagate uncertainty, despite the insight that such an analysis could provide. The economic assessment is constrained by limited real-world data, particularly on willingness to pay, which is a major driver of economic preference but is estimated here from expert judgment rather than potential-customer surveys. Vehicle downtime during retrofit and the associated opportunity costs are also excluded. Furthermore, the perfect-substitution assumption is probably only partly valid and tends to favor the new EV (ICEV reused) scenario. Further improvements should address the influence of vehicle category, the lifetime extension produced by retrofit, potential synergies with reconditioning, the lack of consensus on whether retrofit or continued ICEV use is more cost-effective, inclusion of a second-hand EV scenario, and comparison with other energy-transition retrofits. Differences between retrofitted and new EVs, including efficiency and use behavior, also warrant investigation. Finally, the circularity assessment could incorporate recycling and the probability of reuse, given the strong influence of vehicle and component reuse on the results.

More broadly, holistic assessments that integrate circularity, environmental, economic, and social dimensions are essential to support better-informed decisions and help industrial and public actors develop more sustainable business models for the energy transition.

CRediT authorship contribution statement

Joris Nguyen: Writing – review & editing, Writing – original draft, Visualization, Software, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Emmanuel Pion:** Writing – review & editing, Software, Resources, Investigation, Formal analysis, Data curation. **Ghada Bouillass:** Writing – review & editing, Supervision, Methodology, Conceptualization. **Michael Saidani:** Writing – review & editing, Supervision, Methodology,

Conceptualization. **Bernard Yannou:** Writing – review & editing, Supervision, Methodology, Funding acquisition, Conceptualization. **Hervé Ouisse:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition. **Pascal Graff:** Writing – review & editing, Supervision, Resources, Investigation, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Nguyen Joris reports financial support was provided by Manitou Group. Nguyen Joris reports financial support was provided by French government ministry of higher education and research. Nguyen Joris reports a relationship with Manitou group that includes: employment, non-financial support, and travel reimbursement. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.cesys.2026.100531.

Data availability

The data that has been used is confidential.

References

Allard, A., Castaignede, L., 2021. Etude Retrofit, ADEME. https://librairie.ademe.fr/mobilite-et-transport/4590-etude-retrofit.html. (Accessed 8 March 2024).
Altermaker. Ecodesign Studio: le logiciel pour l'éco-conception. https://altermaker.fr/ecodesign-studio/. (Accessed 4 November 2024).
T. Belin, C. Ponsa Sala, Rétrofit de véhicules : quel potentiel pour la décarbonation du secteur des transports ?, Carbon 4. https://www.carbone4.com/analyse-retrofit-vehicules (accessed 10 September 2024).
Biswas, A., 2016. A study of consumers' willingness to pay for green products. J. Adv. Manag. Sci. 4, 211–215. https://doi.org/10.12720/joams.4.3.211-215.
Biswas, W., 2013. Life cycle environmental benefits from the use of retrofit electric vehicles in Western Australia. In: ALCAS - the 8th Life Cycle Conference, Sydney, Australia.
Bocken, N.M.P., de Pauw, I., Bakker, C., van der Grinten, B., 2016. Product design and business model strategies for a circular economy. J. Ind. Prod. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.
Boyer, R.H.W., Hunka, A.D., Linder, M., Whalen, K.A., Habibi, S., 2021. Product labels for the circular economy: are customers willing to pay for circular? Sustain. Prod. Consum. 27, 61–71. https://doi.org/10.1016/j.spc.2020.10.010.
Classic Cars, Electric. The world's largest converter of classic cars. https://www.electricclassiccars.co.uk/. (Accessed 23 May 2024).
Dattero-Snell, D., 2023. Appraisal of Electric Vehicle Retrofit for Transport Decarbonisation Within Agriculture: Whole System Approach. Cardiff University. PhD thesis. https://orca.cardiff.ac.uk/id/eprint/168917/. (Accessed 30 May 2024).
Del Duce, A., Gauch, M., Althaus, H.-J., 2016. Electric passenger car transport and passenger car life cycle inventories in ecoinvent version 3. Int. J. Life Cycle Assess. 21, 1314–1326. https://doi.org/10.1007/s11367-014-0792-4.
Directorate for Legal and Administrative Information, Electric retrofit premium for a 2.3-wheel or motor quadricycle, service-public. https://www.service-public.fr/particuliers/vosdroits/F36877?lang=en (accessed 19 November 2024).
eBay. Complete engines for sale. https://www.ebay.com/b/Complete-Engines/259088/bn_7115800429. (Accessed 19 November 2024).
Ecoinvent, ecoinvent version 3.8. https://support.ecoinvent.org/ecoinvent-version-3.8. (Accessed 4 November 2024).
El Hannach, M., Ahmadi, P., Guzman, L., Pickup, S., Kjeang, E., 2019. Life cycle assessment of hydrogen and diesel dual-fuel class 8 heavy duty trucks. Int. J. Hydrog. Energy 44, 8575–8584. https://doi.org/10.1016/j.ijhydene.2019.02.027.
Elkafas, A.G., Rivarolo, M., Barberis, S., Massardo, A.F., 2023. Feasibility assessment of alternative clean power systems onboard passenger short-distance ferry. J. Mar. Sci. Eng. 11, 1735. https://doi.org/10.3390/jmse11091735.
European Commission. European platform on LCA. https://eplca.jrc.ec.europa.eu/LCDN/EF_archive.html. (Accessed 4 November 2024).
European Commission, 2021. Commission Recommendation (EU) 2021/2279 of 15 December 2021 on the use of the Environmental Footprint methods to measure and communicate the life cycle environmental performance of products and organisations. http://data.europa.eu/eli/reco/2021/2279/oj/eng. (Accessed 15 May 2024).
Franklin-Johnson, E., Figge, F., Canning, L., 2016. Resource duration as a managerial indicator for circular economy performance. J. Clean. Prod. 133, 589–598. https://doi.org/10.1016/j.jclepro.2016.05.023.
Guillard, V., Le Nagard, E., de Campos Ribeiro, G., 2023. A typology of consumers regarding perceived obsolescence: the paradox of eco-conscious consumers. J. Clean. Prod. 412, 137202. https://doi.org/10.1016/j.jclepro.2023.137202.
Helmers, E., Dietz, J., Hartard, S., 2017. Electric car life cycle assessment based on real-world mileage and the electric conversion scenario. Int. J. Life Cycle Assess. 22, 15–30. https://doi.org/10.1007/s11367-015-0934-3.
Hensher, D.A., Shore, N., Train, K., 2014. Willingness to pay for residential electricity supply quality and reliability. Appl. Energy 115, 280–292. https://doi.org/10.1016/j.apenergy.2013.11.007.
Hoeft, F., 2021. Internal combustion engine to electric vehicle retrofitting: potential customer's needs, public perception and business model implications. Transp. Res. Interdiscip. Perspect. 9, 100330. https://doi.org/10.1016/j.trip.2021.100330.
Innocenti, E., Berzi, L., Del Pero, F., Delogu, M., 2024. Life cycle greenhouse gas emissions of retrofit electrification: assessment for a real case study. Results Eng. 23, 102454. https://doi.org/10.1016/j.rineng.2024.102454.
ISO, 2006a. ISO 14040:2006 Environmental management - life cycle assessment - principles and framework. https://www.iso.org/standard/37456.html. (Accessed 4 November 2024).
ISO, 2006b. ISO 14044:2006 Environmental management - life cycle assessment - requirements and guidelines. https://www.iso.org/standard/38498.html. (Accessed 4 November 2024).
ISO, 2024. ISO 59020:2024 circular economy - measuring and assessing circularity performance. https://www.iso.org/standard/80650.html. (Accessed 24 June 2026).
Kiloutou Group, Manitou Group and Kiloutou sign an exclusive partnership agreement on their first retrofit project. https://www.kiloutou.com/group/en/press-releases/manitou-group-and-kiloutou-sign-an-exclusive-partnership-agreement-on-their-first-retrofit-project/(accessed 16 October 2024).
Kitzmann, N., et al., 2025. Planetary Health Check 2025: a Scientific Assessment of the State of the Planet. Potsdam Institute for Climate Impact Research. https://planetaryhealthcheck.org/. (Accessed 9 July 2026).
Kolahchian Tabrizi, M., Cerri, T., Bonalumi, D., Lucchini, T., Brenna, M., 2024. Retrofit of diesel engines with H2 for potential decarbonization of non-electrified railways: assessment with lifecycle analysis and advanced numerical modeling. Energies 17, 996. https://doi.org/10.3390/en17050996.
Kozłowski, M., Czerepicki, A., 2023. Quick electrical drive selection method for bus retrofitting. Sustainability 15, 10484. https://doi.org/10.3390/su151310484.
N. Le-Boucher, Going from combustion to electric through retrofitting, Renault Group. https://www.renaultgroup.com/en/news-on-air/news/retrofit-transform-a-combustion-motor-car-into-a-full-electric-car/(accessed 23 May 2024).
Moraga, G., et al., 2019. Circular economy indicators: what do they measure? Resour. Conserv. Recycl. 146, 452–461. https://doi.org/10.1016/j.resconrec.2019.03.045.
Napoli, G., et al., 2022. Technical and environmental assessment of diesel lightweight truck retrofitting by hydrogen. In: 2022 AEIT International Annual Conference, pp. 1–6. https://doi.org/10.23919/AEIT56783.2022.9951772.
Nguyen, J., Bouillass, G., Saidani, M., Yannou, B., 2025. When and how can electric retrofit of vehicles be beneficial? A critical review of environmental. Circularity, and Economic Performances unpublished results.
Oxford English Dictionary. Retrofit, n.: meanings, etymology and more. https://www.oed.com/dictionary/retrofit_n. (Accessed 23 October 2024).
T. Phillips, Car scrappage schemes for 2024, BuyaCar. https://www.buyacar.co.uk/car-deals/car-scrappage-schemes/(accessed 11 December 2024).
Plevin, R.J., Delucchi, M.A., Creutzig, F., 2014. Using attributional life cycle assessment to estimate climate-change mitigation benefits misleads policy makers. J. Ind. Ecol. 18, 73–83. https://doi.org/10.1111/jiec.12074.
Pohl, J., Hilty, L.M., Finkbeiner, M., 2019. How LCA contributes to the environmental assessment of higher order effects of ICT application: a review of different approaches. J. Clean. Prod. 219, 698–712. https://doi.org/10.1016/j.jclepro.2019.02.018.
Retrofleet, mona by retrofleet. https://www.retrofleet.fr. (Accessed 12 March 2024).
Rizzo, G., Tiano, F.A., 2020. Life cycle assessment study for different options of sustainable mobility, including vehicle conversion. Int. J. Powertrains 9, 122–149. https://doi.org/10.1504/IJPT.2020.108431.
Sanchez, S.T., et al., 2012. Accounting for indirect land-use change in the life cycle assessment of biofuel supply chains. J. R. Soc. Interface 9, 1105–1119. https://doi.org/10.1098/rsif.2011.0769.
Santis, M.D., Regis, F., 2021. Modeling, simulation, and techno-economic analysis of a retrofitted electric vehicle. In: 2021 IEEE International Conference on Environment and Electrical Engineering and 2021 IEEE Industrial and Commercial Power Systems Europe, pp. 1–6. https://doi.org/10.1109/EEEIC/ICPSEurope51590.2021.9584594.
Slorach, P.C., Jeswani, H.K., Cuéllar-Franca, R., Azapagic, A., 2020. Environmental sustainability in the food-energy-water-health nexus: a new methodology and an application to food waste in a circular economy. Waste Manag. 113, 359–368. https://doi.org/10.1016/j.wasman.2020.06.012.

T. Stobierski, Willingness to pay: what it is and how to calculate, Business Insight. Blog. https://online.hbs.edu/blog/post/willingness-to-pay (accessed 19 November 2024).
Strecker, B., Hausmann, A., Depcik, C., 2014. Well to wheels energy and emissions analysis of a recycled 1974 VW Super Beetle converted into a plug-in series hybrid electric vehicle. J. Clean. Prod. 68, 93–103. https://doi.org/10.1016/j.jclepro.2013.04.030.
Transport for London, scrappage scheme. https://www.tfl.gov.uk/modes/driving/ultra-low-emission-zone/scrappage-schemes. (Accessed 16 October 2024).
van Loon, P., Diener, D., Harris, S., 2021. Circular products and business models and environmental impact reductions: current knowledge and knowledge gaps. J. Clean. Prod. 288, 125627. https://doi.org/10.1016/j.jclepro.2020.125627.
Watts, R., Ghosh, A., Hinshelwood, J., 2021. Exploring the potential for electric retrofit regulations and an accreditation scheme for the UK. Electronics 10, 3110. https://doi.org/10.3390/electronics10243110.
Whitehead, J.C., 2006. Improving willingness to pay estimates for quality improvements through joint estimation with quality perceptions, South. Econ. J. 73, 100–111. https://doi.org/10.1002/j.2325-8012.2006.tb00759.x.
Zampori, L., Pant, R., 2019. Suggestions for updating the Product Environmental Footprint (PEF) method. EUR 29682 EN. Publications Office of the European Union, Luxembourg. https://doi.org/10.2760/424613.