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# Life cycle greenhouse gas emissions of retrofit electrification: Assessment for a real case study

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ABSTRACT

Nowadays fleet electrification appears the most concrete opportunity to reduce the environmental burdens of the transportation sector. However, Battery Electric Vehicle penetration has to deal with crucial challenges, such as new BEVs high price, customers' reluctant and scarcity of materials. In this regard, electric retrofit is emerging as a low-cost and short-term solution to deal with these issues. However, to date only few studies focus on regulatory framework of electric retrofit and fewer quantify the environmental benefits of a converted BEV used in a certain context. This paper analyses a retrofit industrial prototype made by a local start up with all features available for a future homologation and it proposes a comparative Life Cycle Assessment, stressing the significant environmental hotspots to suggests in which geographical context governments should promote retrofit conversion. Two scenarios composed by two time-related parts are evaluated: a vehicle replacement with a new Internal Combustion Engine Vehicle and a retrofit conversion process of a SmartForTwo W450. The production stage of conversion kit is assessed mainly through primary data, while operation consumption is calculated through an analytic model implemented in MATLAB- Simulink. A detailed sensitivity analysis is performed in which different options for electricity grid mix, energy consumption, battery pack maintenance and EoL pathways are combined, for a total of 274 scenario combinations. The results reveal that retrofit conversion allows achieving about 45 % Greenhouse Gases saving compared to new replacement, in particular when urban driving and renewable electricity grid mix are considered.

## 1. Introduction

In the last decades, climate change has become a critical and urgent issue for every government agency. As provided by the Intergovernmental Panel on Climate Change (IPCC), Greenhouse Gases (GHGs) must be drastically reduced to not exceed the global warming of 2 °C within 2030 [1]. When considering the climate context, the transportation sector plays a central role, as it accounts for 37 % of total CO2 emissions, with road transportation representing almost 71 % of those emissions [2]. Despite the significant decrease in GHG emissions caused by global COVID restrictions, a further reduction in transportation impact is necessary to achieve 90 % decrease within 2025, as provided by the European Environmental Agency [3]. Considering that EU passenger car fleet has continuously grown in the last years, by 1.2 % in the only 2020 [4], a dramatic growth in energy consumption and fuel demand is unavoidable, with a series of correlated negative implications, such as urban air quality, fossil fuels depletion and environmental issues. Currently, electrification is considered the most promising path to decarbonize the transportation sector and achieve independence from fossil fuels [5]. Among all varieties of Electric Vehicles (EVs), Battery Electric Vehicles (BEVs) appear to be the best option solution to reduce pollutants and corresponding consequences on human health [6]. That said, despite the undeniable environmental benefit in use stage, replacing every single Internal Combustion Engine Vehicle (ICEV) with an electric one would involve very severe effects in terms of resource depletion, energy demand and disposal of scrap materials; as a consequence, the overall net effect of electrification should be established by carefully balancing all correlated benefits and disadvantages. In the last years, public policy regulations have strongly promoted the penetration of EVs in the market through incentives and high taxes on cars emissions and fuels. In particular, the European Union is currently pursuing on the one hand the progressive ban of the sale of ICEVs and on the other hand

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the future development of EVs charging infrastructures. Nonetheless the electric transition must face some crucial points, such as high price of EVs, customers' reluctance to switch from old to new technologies and scarcity of some essential raw materials. As a consequence, the European car market is not ready yet to accomplish a future net-zero emission target, even if EVs registered are nearly doubled in the last two years, 93 % reduction from in the two years 2020–2021 [7]. Against this background, converting an ICEV into a BEV stands as a viable short-term solution by accelerating the transition to a green-mobility and by providing a second life to ICEVs with a lower-cost alternative [8]. Currently, only few companies and start-ups offer a vehicle retrofit kit for all car classes, mainly made up by an electric motor, a connecting flange, a battery pack, an inverter, and a controller. The conversion process consists in removing the ICE components, such as engine, exhaust system, fuel tank and front intercooler and replacing them with the retrofit kit, respecting the original weight distribution of the car. For what concerns regulations, almost all European national governments have their own rules and procedures to grant homologation for converted vehicles. In Italy, the 219/2015 Decree Law, also called "Retrofit Decree", defined in 2015 the conversion process of N and M1 vehicles categories [9]. This decree states in detail the components that compose the retrofit kit, the authorized conversion process and the security features required for a circulating car. A few papers in literature investigate the conversion of a traditional ICEV into a BEV. Among these studies, Hoeft [7], Watts et al. [10] and Kothuri et al. [11] are the most relevant ones. Hoeft [7] analyses the electrical retrofit as a business model in Germany, Watts et al. (2021) examines actual regulations and future administrative improvements in UK, while Kothuri et al. [11] quantifies the energy benefits of a proper controlframework for a retrofitted hybrid electric vehicle. These studies represent interesting examples of vehicle retrofitting, but they deal with only the design aspect, without evaluating the environmental implications of the conversion process. Extending literature research to sustainability in the electric mobility field, several studies deal with the environmental effects caused by BEVs by means of Life Cycle Assessment (LCA) methodology. The existing studies focus both on comparison between several types of vehicles (ICEV/BEV/HEV/PHEV) and on separated components such as battery pack [12], traction electric motor [13], power electronics [14,15], vehicle tires [16]. Although the LCA is a holistic approach, many of these papers explore one specific aspect of a vehicle's LC, including electricity production [17], use phase [2], End-of-Life (EoL) [18], renewable energy production [19] and regional heterogeneities [20]. All those research agree that GHG emissions of BEVs are substantially lower than those of ICEVs, especially when assuming that electricity consumed in use stage is produced through a low-impact grid mix. In this context, Hawkins et al. [21] and Girardi et al. [22] discuss the effect of different grid mixes for electricity production, showing a drastic reduction of emissions by using renewable sources. Other studies highlight the relevant quota of emissions from battery production, providing exhaustive inventories for different types of battery pack [23]. Another relevant point often discussed by literature is the large amount of inventory data necessary to carry out a LCA of an entire vehicle. Due to lack of transparent and available inventories, most of LCAs are based on aggregated inventory data coming from literature, for both vehicle manufacturing (such as materials extraction, production process, materials composition) and fuel/electricity consumption (use of standardized data and common assumptions): this makes that the significant discrepancies between different driving contexts are not taken into account, thus avoiding to properly assess the inherent features of carbon footprint of different case studies. Only a few papers deal with the environmental impacts of the electric retrofit. A didactical plug-in series hybrid conversion of a 1974 Volkswagen super Beetle is investigated by Strecker et al [24]. The study analyses the WtW (Well-to-Wheel) emissions and energy consumption of three different use modes (EV mode, hybrid mode, BEV mode) by means of experimental driving models. A solar photovoltaic electricity charging is evaluated, showing a reduction from around 200 gCO2_eq/km (US average electricity mix) to 150 gCO2_eq/km, mainly obtained by the introduction of renewable energy sources. Helmers et al. [25] and Helmers et al. [26] discuss the impact assessment of an electric conversion of a Smart ForTwo W450 within the context of a German research project. The papers outline the environmental advantages by focusing on different conversion scenarios and real-world inventory assumptions (such as energy grid mixes and fuel/energy consumption). Results show that electric conversion allows decreasing the climate change by 16 % with respect to a new BEV, and by 47 % when compared with a realistic renewable energy mix [1]. The last paper that deals with the environmental implications of electric retrofit is Rizzo et al. [27]), which assesses an EV and a solar energy hybrid vehicle converted with a kit developed by University of Salerno. The study highlights the environmental benefits of the two types of conversion mode, mainly due to the avoided production of car glider. In fact, the penetration of the conversion process as a business model, reaches a high degree of sustainability only if the electric energy used is mostly generated by renewable sources. The study includes also the cost analysis of vehicles retrofitting in comparison with new battery electric vehicle. The state of literature stresses that the vast majority of existing studies focuses on current regulatory frameworks and technical features of electric retrofits, with few papers dealing with the environmental advantages of electric retrofits compared to BEVs and ICEVs. That said, most of these provide analyses at modelling/simulation level, without the development of an industrial/laboratory prototype. In particular, only two studies Helmers et al. [25] and Rizzo et al. [27] assess distinct temporal segments of electric conversion (ICEV first life and converted BEV second life), while no paper presents the cumulative GHG emissions impact of both temporal parts. This paper proposes a comparative LCA of two options for the electric conversion of a Smart ForTwo W450 car model. The study investigates two scenarios: the electric conversion with a retrofit kit and the replacement with a new traditional combustion vehicle. The LCA covers all LC stages of the considered car model, whose inventory data are obtained from an industrial prototype. The main goal of the study is carrying out a detailed environmental assessment that best portrays a possible conversion process, mainly using primary data and using real-world assumptions, and evaluating the effect of relevant boundary conditions. Furthermore, this analysis stresses the significant environmental hotspots with the aim to suggests in which geographical context policymakers and governments should promote retrofit conversion.

## 2. Materials and method

The study carries out a cradle-to-grave comparative evaluation of a feasible electric conversion (combustion engine to electric) and the corresponding conventional process of an ICEV substitution. The chosen functional unit is 1 km driven, which refers to two distinct operation scenarios (*Scenario A* and *Scenario B*). As shown, each scenario is divided into two time-related parts.

- *Scenario A*:
  - *Part 1*, ICE Smart ForTwo W450 travels 100000 km;
  - *Part 2*, ICE Smart ForTwo W450 is replaced with a new car, same model, covering a further 100000 km;
- *Scenario B:*
  - *Part 1*, ICE Smart ForTwo W450 travels 100000 km;
  - *Part 2,* ICE Smart ForTwo W450 is converted into an electric powered one another 100000 km lifetime is covered with electric propulsion.

The assumed lifetime scenarios are in line with literature [28]. The operational lifetime chosen for the present paper is 100000 km for each use phase and 200000 km for each scenario. Such a choice is mainly due to the need for coherently representing a typical conversion process that a local start up might have to support, based on the short operational lifetime usually driven by a city car [29]. The system boundaries include raw material extraction, production of both vehicle and conversion kit, use and EoL. More precisely, the operation stage also comprehends Well-to-Tank (WtT) (including fuel/energy feed-stocks extraction and energy/fuel production) and Tank-to-Wheel (TtW) (including energy conversion during operation). Use phase and EoL phase are modelled according to European standards. The Italian electricity mix is used in the base case, renewable and Polish grid mixes area assumed as opposite options in the sensitivity analysis. The assumptions made for material and energy production (electricity grid mix, vehicle materials composition and geographical locations) are the same for both vehicle substitution and retrofit processes. Table S1, in Supplementary Material 1, provides all vehicle specifications and scenario labels using the following parameters: electricity supply, fuel and electricity consumption, EoL modelling, maintenance and replacement of the LiFePO4 battery. The GREET software is used to calculate the GHGs emissions of both vehicle and fuel cycle, based on a model developed by the Argonne National Laboratory for the automotive sector [30,31].

### 2.1. Life cycle inventories

The Life Cycle Inventory (LCI) is structured into the following sections: manufacturing and assembly, use phase and maintenance, EoL. For the ICEV case study the inventory is based mainly on secondary data coming from literature and commercial databases, while the inventory data of the conversion kit are directly provided by the suppliers. Table 1 provides the list of the analysed assemblies.

### 2.2. Manufacturing and assembly

The vehicle is assessed separately for different components, subsystems and macro-systems. The chosen framework for such an analysis is the model provided by Hawkins et al. [21] (see Table S4, in Supplementary Material 1), on the basis of which material composition and production processes of each component are defined. When necessary, missing secondary data are obtained from GREET [32] and Ecoinvent database [33]. Table 2 summarizes the mass breakdown percentages of the sub-systems, and Table 3 reports the inventory percentage for material macro-groups. Nearly 20 % of the mass of the converted vehicle is allocated to the conversion kit, while the other sub-systems remain unchanged. In this specific prototype, the mass of the LiFePO4 battery pack is lower with respect to ICE vehicle configuration and the converted car benefits from this weight reduction. A detailed lists of literature references, physical correlation factors, material compositions for both configurations, and processes inventory are presents in the Supplementary Materials 1, from Table S2 to Table S9.

**Table 1**
Inventory guide in an electric retrofit.

| Macro-assembly | Sub-components | New ICEV | Converted BEV |
|---|---|---|---|
| **Glider** | – | X | X |
| **Removed part in Powertrain ICEV** | Combustion Engine | X | |
| | Intercooler | X | |
| | Exhaust system ICEV motor | X | |
| | Power supply system ICE motor | X | |
| | Pb Battery | X | |
| | Fluids ICEV powertrain | X | |
| **Conversion Kit** | AC Electric motor | | X |
| | Electric motor controller | | X |
| | Battery LiFePO4 | | X |
| | BMS | | X |
| | Battery charger | | X |
| | DC/DC Converter | | X |
| | CAN device | | X |
| | Electric Motor connection flange | | X |
| | Miscellaneous wiring and sensors | | X |
| | Support system for battery pack | | X |

**Table 2**
Mass breakdown percentages of Smart ForTwo W450 ICE and Converted.

| Sub-System | Unit | ICE Smart ForTwo W450 | Converted Smart ForTwo W450 |
|---|---|---|---|
| Body | % | 45.3 | 48.5 |
| Chassis | | 23.8 | 25.5 |
| ICE Powertrain | | 21.7 | – |
| Transmission | | 5.1 | 5.4 |
| Fluids | | 4.1 | 0.7 |
| Battery Pack LiFePO4 | | – | 13.3 |
| Conversion Kit w/o Battery pack | | – | 6.6 |
| **Total Smart ForTwo mass** | kg | 780.1 | 728.1 |

**Table 3**
Inventory percentage for materials: Smart ForTwo W450 ICE and Converted.

| Material Macro-groups | Unit | Smart ForTwo W450 ICE | Smart ForTwo W450 Converted |
|---|---|---|---|
| Ferrous materials | % | 64.7 | 61.6 |
| Aluminum | | 7.5 | 5.7 |
| Non-Ferrous materials | | 2.4 | 3.1 |
| Plastics | | 12.9 | 14.6 |
| Other materials | | 12.5 | 15.0 |

The electric motor installed in the prototype is an asynchronous induction type, this type prevents modelling the environmental impact of permanent magnets (REE) [34]. The battery pack is composed of a LiFePO4 prismatic battery and a Battery Management System (BMS), both placed in the lower part of the vehicle; the remaining components of the conversion kit are installed in the luggage rack [9]. As regards the inventory of battery production, an available source that treats a battery with same chemistry and structure (LiFePO4 and prismatic cells) is chosen [35,36], even if less consistent in terms of time and geography representativeness. Lastly, for each material group a waste factor is defined as the amount of waste material in a specific manufacturing process (see Table S10 in Supplementary Material 1).

### 2.3. Use phase and maintenance

Use stage evaluates the exhaust emissions during operation, including upstream emissions of WtT cycle and vehicle maintenance. Fuel and energy consumption is modelled according to the Worldwide Harmonized Light Vehicles Test Procedure (WLTP) [37]. The fuel consumption declared by the manufacturer is used for the Smart ForTwo W450 car model, applying a linear correlation factor to convert NEDC standard to WLTP consumption level [38], from 4.7 l/100 km to 5.3 l/100 km. An analytic model implemented in MATLAB-Simulink environment is developed to calculate the energy consumption of the converted Smart ForTwo W450. The full layout of the modelling is shown in Fig. 1 and a detailed description of the main model sections are provided by Del Pero et al. [39]. Each sub-model is developed and characterized based on specifications of the converted car. It is assumed that the converted vehicle operates in one gear only (as an automatic transmission car), despite the gearbox is not altered during the conversion to electric. In this regard, it is worthy to note that there is still no guideline to develop specific driving cycles for retrofit vehicles. The MATLAB-Simulink analysis is carried out varying both the gear engaged and the driving cycles. The considered driving cycle are the following: NEDC, WLTP1 (Class 1), WLTP2 (Class 2), WLTP3 (Class 3),

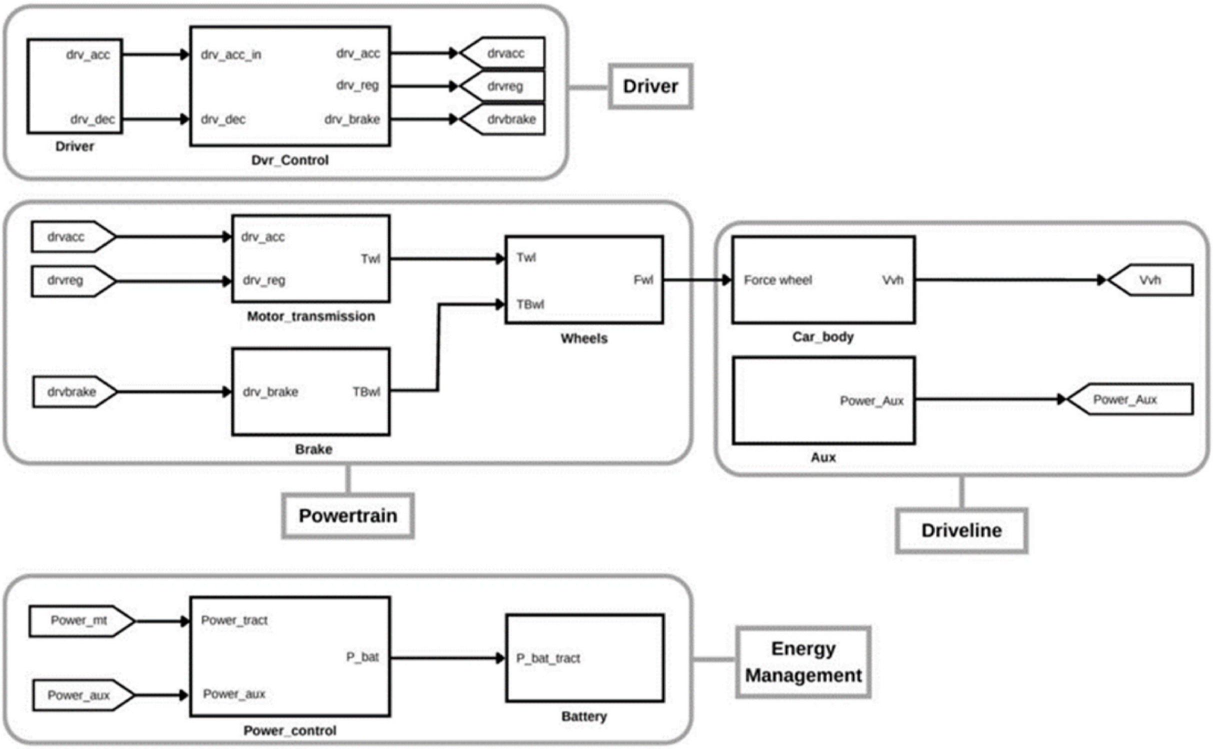

**Fig. 1.** Main sections of MATLAB-Simulink model. Adapted from Del Pero et al. [39].

ASTERICS-Twizy. The ASTERICS-Twizy is a cycle that reflects driving conditions in the Tuscan area developed by Berzi et al. [40].

It is necessary to underline that for NEDC and WLTP3 the converted vehicle does not cover the entire distance for all the gears engaged. In fact, the conversion kit does not have the sufficient power to reach the peak speed provided by the extra-urban and motorway phases, as shown in Supplementary Material 2, from Fig. S4 to Fig. S10. The choice of the gear in which the driving route is covered does not influence the energy consumption: the most noticeable gear variations data from the 4th gear occur for NEDC, WLTP3 and ASTERICS-Twizy cycles, as provided in the last of column of Table 4. Such a point can be associated with both the inability of reaching the target distance due to not sufficient power of the converted powertrain and the high acceleration and deceleration imposed by the driving cycle. Among driving cycles for which the vehicle is able to achieve the peak speed, the ASTERICS-Twizy is the one whose consumption is more sensible to the gear input, as it provides a bigger quota of entire route in extra-urban and rural driving contexts. To validate test results, data on energy consumption of the converted city car are checked in literature. Helmers et al. [25] estimates 10.6 kW/100 km the urban electricity consumption using a personal driving cycle, while Helmers et al. (2012) provides a 14.5 kW/100 km consumption for an inter-urban and highway test route. The differences between consumption values from literature and consumption values obtained by this study (less than 10 %) are considered acceptable. The main reason for such differences is the use of a custom-made driving cycle, which prevents from reproducing real-world driving conditions. As a confirmation, no energy consumption for a converted city car obtained from a standardized cycle can be found in literature. So, for the baseline scenario the WLTP2 4th gear driven cycle is chosen. In addition, renewable electricity grid mix and polish electricity grid mix are also analysed, to quantify the effect of two opposite environmental scenarios for electricity production. Maintenance is modelled relying on Burnham et al. [32]: the baseline model assumes that the battery LiFePO4 lifetime exceeds the operational lifetime of the converted vehicle, 100000 km, and the alternative one evaluated a possible battery LiFePO4 substitution after 50000 km (Schulz-Mönninghoff et al., 2023). Detailed information of electricity production mix and maintenance inventory are summarized in Supplementary Material 1, Table S12 and Table S13.

**Table 4**
Energy Consumption of the Smart ForTwo W450 varying driving cycle and gear engaged. Sign X the Converted vehicle manages to complete to target distance in the time imposed by the driving cycle. In green the baseline driving cycle chosen.

| Driving Cycle | Gear Engaged | Target Distance | Energy Consumption | Unit | Gear Variation Data |
|---|---|---|---|---|---|
| NEDC | 3rd | – | 11.74 | kWh/ | −2.98 % |
| | 4th | | 12.10 | 100 | 0.00 % |
| | 5th | | 12.93 | km | +6.86 % |
| WLTP1 | 3rd | X | 8.65 | kWh/ | −0.23 % |
| | 4th | X | 8.67 | 100 | 0.00 % |
| | 5th | X | 8.72 | km | 0.058 % |
| WLTP2 | 3rd | X | 11.25 | kWh/ | −0.2 7 % |
| | 4th | X | 11.28 | 100 | 0.00 % |
| | 5th | X | 11.48 | km | +1.77 % |
| WLTP3 | 3rd | – | 13.40 | kWh/ | −3.74 % |
| | 4th | | 13.92 | 100 | 0.00 % |
| | 5th | | 14.96 | km | +7.47 % |
| ASTERICS-Twizy | 3rd | X | 13.12 | kWh/ | −2.24 % |
| | 4th | X | 13.42 | 100 | 0.00 % |
| | 5th | X | 14.19 | km | +5.74 % |

## 2.4. Disposal and End-of-life

The EoL phase is modelled according to 2000/53/EC Directive (2000) [41], in order to model specific EoL scenarios related to the European context. The allocation approach is applied, considering the environmental effects produced by reuse, recycling, recovery, and landfilling emissions. GaBi6 database [42] is used as source for secondary data. The EoL destination of the LiFePO4 battery is assumed as stationary use for energy storage purposes. According to different literature sources [43], the environmental credits due to the avoided production of new batteries involves a 50 % reduction in the GHGs impact. In the base case, the environmental credits provided by the secondary use are excluded from the analysis, according to a more conservative scenario. Details of EoL scenarios are reported in Table 5 and Table 6.

## 3. Results and discussions

### 3.1. Base case scenario

The total impact of the electric retrofit process (*Scenario B*) is about 39 tCO2_eq, 45 %, which is lower than *Scenario A*. As shown in Table 7, the two scenarios have almost the same GHGs impacts in *Part 1* (*Scenario B* involves a GHGs reduction of about 4 % with respect to *Scenario A*). More specifically, the ICEV operation is the most critical LC stage (being around 83 % bigger than manufacturing and assembly), while the effect of EoL is negligible (307 and −435 kgCO2_eq respectively for *Scenario A* and *Scenario B*).

The major environmental difference between LC phases is found when comparing *Part 2*.

- the impact of use phase *Part 2* in *Scenario B* is 6.7 tCO2_eq, which is 58.8 % lower than use phase *Part 2* in *Scenario A*, mainly thanks to avoided emissions related to BEV TtW stage and the limited impact associated with electricity production and distribution;
- the conversion process allows saving 60.7 % of GHGs emissions in manufacturing, due to glider reuse and low number of components required for the conversion kit;
- EoL effect is negligible with respect to total LC (less than 1 %).

**Table 5**
EoL pathways for components and materials. Energy recovery credits is proportional to Italian grid mix.

| EoL Phase | Component/Material | Pathway |
|---|---|---|
| **Depollution** | Catalytic converter | Recycling |
| | Oil & Fluids | Incineration |
| | Fuel | Reuse |
| | Battery Pb | Recycling |
| | Battery LiFePO4 | Secondary use |
| **Dismantling** | Tyres | Recycling 87 %, Energy recovery 12 %, Landfilling 1 % |
| | Wheels | Reuse |
| | Wires | Reuse |
| | Sensors | Reuse |
| | Steering wheel | Reuse |
| | Brakes disc | Reuse |
| | Glass Scarps | Reuse 50 %, Incineration 30 %, Landfilling 20 % |
| | AC Electric | Recycling 97 %, Landfilling 3 % |
| | Conversion Kit w/o Battery pack and Electric Motor | Recycling 87 %, Energy recovery 12 %, Landfilling 1 % |
| **Shredding** | | |
| **Post-Shredding** | Ferrous | Recycling 97 %, Landfilling 3 % |
| | Aluminum | Recycling 97 %, Landfilling 3 % |
| | Other Non-ferrous metal (e.g. Cu, Brass) | Recycling 99 %, Landfilling 1 % |
| | Plastic | Recycling 87 %, Energy recovery 12 %, Landfilling 1 % |
| | Rubber | Recycling 87 %, Energy recovery 12 %, Landfilling 1 % |
| | Fiber Glass | Incineration |
| | Remaining ASR | Landfilling |

**Table 6**
List of the EoL scenarios analysed.

| | Pathways | Baseline scenario | Qualitative Description |
|---|---|---|---|
| **EoL Vehicle** | Best Recycling | X | High recycling rate, see Table 5. |
| | Mid Recycling | | Reuse and Recycling rate high enough to reach the limit imposed by European regulations (85 %). Methodology from Berzi et al.[41]. |
| | Worst Recycling | | Low recycling rate and excluded energy recovery. |
| | Reuse | | Smart ForTwo W450 ICE replaced after the first part of *Scenario A*, is allocated to reuse pathway. Environmental credits are assumed to be 70 % of the avoided environmental impact of vehicle production. |
| **EoL LiFePO4 Battery** | Secondary Use – No Credits | X | Stationary secondary use excluding environmental credits. |
| | Secondary Use - Credits | | Stationary secondary use including environmental credits. Credits are assumed to be 50 % of the avoided impact of battery production [1]. |
| | Energy demand Disposal | | Energy demand for the hydro-pyrometallurgical treatment method is modelled, according to Tagliaferri et al. [18]. Material recycling is excluded from the system boundary. |

**Table 7**
GHGs emissions for *Scenario A* and *Scenario B*. All the specific impacts are allocated to 100000 km driven by each vehicle.

| | Life Cycle Phase | *Scenario A* | kgCO2_eq | *Scenario B* | kgCO2_eq |
|---|---|---|---|---|---|
| ***Part 1*** | Manufacturing | *1 ICE* | 2844 | *1 ICE* | 2844 |
| | Use phase | *1 ICE* | 16375 | *1 ICE* | 16375 |
| | EoL | *1 ICE* | 307 | Removed Components | −435 |
| | **Total *Part 1*** | ***Scenario A*** | **19526** | ***Scenario B*** | **18784** |
| ***Part 2*** | Manufacturing | *1 ICE* | 2844 | Conversion Kit | 1118 |
| | Use phase | *1 ICE* | 16375 | *5.1 CONV IT* | 6750 |
| | EoL | *1 ICE* | 307 | *5.1 CONV IT* | 280 |
| | **Total *Part 2*** | ***Scenario A*** | **19526** | ***Scenario B*** | **8147** |
| **Total** | | ***Scenario A*** | **39052** | ***Scenario B*** | **26931** |

A detailed analysis of the manufacturing phase (Fig. 2) exhibits that the body (34.9 %) and chassis (25.8 %) are the most impactful subsystems for the ICE configuration, mainly because they present a preponderant share of vehicle weight. At the same time a lower quota of the impact is allocated to other sub-systems, such as powertrain (15.2 %) and assembly (11.3 %). As expected, the impact caused by the production of the conversion kit (7.62 kgCO2_eq/kgvehicle) is far higher than the ICEV one (3.65 kgCO2_eq/kgvehicle), due to production of LiFePO4 battery pack (51.7 %) and electric motor/power electronics (48.3 %). In this regard, electric conversion and glider reuse represent a feasible solution to reduce the environmental burdens associated with the manufacturing of BEVs [2]. Fig. 3 shows the main contributions of the different EoL pathways. For ICEV and converted BEV, the recycling emissions are the biggest due to the high recycling rate provided by the base case. The impact of the other EoL pathways (namely landfill, incineration, and energy recovery) is very low as a consequence of the reduced weight of components which are allocated to such EoL scenarios. Instead, if the EoL impact of both *Part 1* and *Part 2* is evaluated, the environmental credits are associated with *Scenario B*, thus resulting in −0.002 kgCO2_eq/km. Such a credit is mainly associated with the

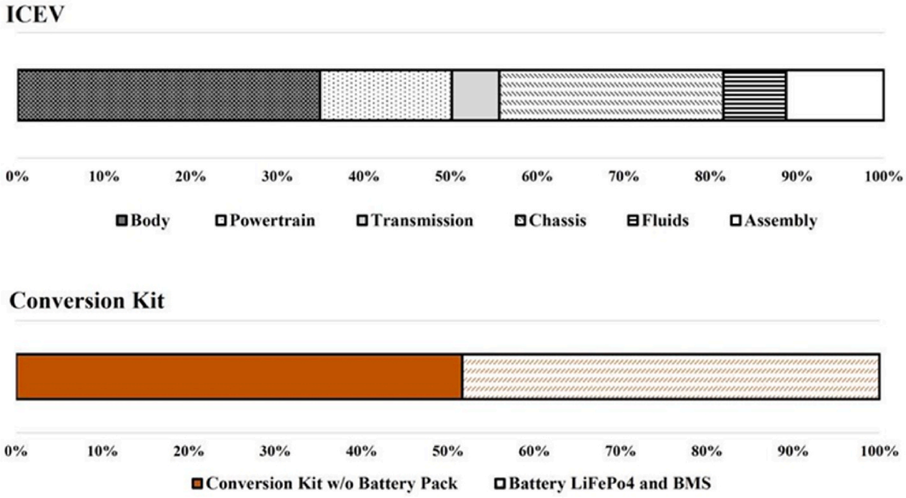

**Fig. 2.** Percentage contribution of each macro-system in the Manufacturing phase emissions.

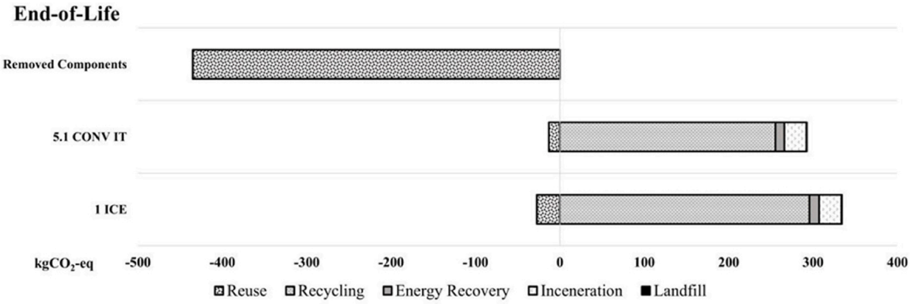

**Fig. 3.** Emission contributions of EoL pathways to ICE, Converted BEV, and Removed Components during the conversion process.

reuse of the removed components and the secondary use of the LiFePO4 battery pack.

Looking at the results of the Base case scenario, several potential footprint mitigation strategies emerge across different phases of the LC.

- Manufacturing phase: To reduce emissions during the production of sub-systems, such as the conversion kit, alternative materials and optimized manufacturing processes appear to be feasible solutions. Key strategies include:
  - Recycled or low impact materials, replacing high-impact materials with recycled or low impact alternatives can significantly reduce emissions associated with material extraction and processing. For example, aluminium and plastic components in the conversion kit could be replaced with recycled alternatives to minimize environmental impact.
  - Innovative production process, implementing innovative production techniques can minimize energy consumption and waste generation during manufacturing. For instance, utilizing additive manufacturing for the support system of the battery pack could maximize customization of the conversion kit for different vehicle segments and propose lightweight solutions.
- Well-to-Wheel phase: The transition to renewable energy sources for electricity production can substantially reduce emissions during the use phase. The main points that need to be addressed are:
  - Different electricity mixes, analysing and transitioning to renewable energy sources in the electricity mix can significantly reduce the carbon footprint associated with EV operation (see the following sections).
  - Deployment of charging infrastructure, installing charging infrastructure throughout the Italian territory is crucial to support the adoption of retrofitted solutions in the Italian territory.
- EoL phase: Although the phase has a low overall impact, implementing circular economy principles can reduce the need for critical raw material extraction (e.g., cobalt for battery pack production) and maximize resource efficiency and cost savings. Some possible approaches are described below:
  - Disassembly and reuse design, developing vehicles for easy disassembly and component reuse can extend product lifespan and reduce the need for new material extraction. For example, designing LiFePO4 battery packs for easy disassembly could facilitate their reuse in secondary applications.
  - Closed-loop recycling processes, implementing closed-loop recycling systems can facilitate the recovery of valuable materials from EoL vehicles and minimize waste generation, as described in the Best Recycling pathway.
  - Component remanufacturing, establishing processes for remanufacturing and refurbishing vehicle components can further extend product lifespan and minimize waste (e.g., battery pack and ICE powertrain as evaluated in *Reuse and Secondary Use – No Credits EoL* pathways).

### 3.2. Sensitivity analysis

The effects of the variation of a single parameter of the base case are firstly evaluated, while the combination of all alternative scenarios is analysed later. As shown in the previous paragraph, the operation is the most critical stage for all powertrain configurations considered, whose emissions are correlated to electricity supply chain and energy consumption. As expected, Fig. 4 stresses that the greater benefits arise when considering the renewable energy mix (0.0006 kgCO2_eq/km) and the WLTP1 urban driving cycle (0.052 kgCO2_eq/km). On the other hand, assuming the Polish grid mix and the WLTP3 extra-urban driving cycle involves higher emissions (respectively 0.095 and 0.08374 kgCO2_eq/km), but however lower than the ones caused by the ICEV. When assuming the real-world ASTERCS-Twizy driving cycle, the impact of the converted BEV increases to 0.080 kgCO2_eq/km [40], with the variation associated with the gear being very small for all the scenarios. Actually, the lack of guidelines for developing driving cycles of converted BEVs and the inability to reach the target distance enhance the uncertainty of the emission results obtained. In term of break-even analysis, each vehicle configuration provides a break-even point between *Scenario A* and *Scenario B*. The results of maintenance of LiFePO4 battery pack are reported in Fig. 5: a 54.7 % increase GHG emissions is obtained, which corresponds to a 2.2 % increase when considering both *Part 1* and *Part 2* of *Scenario B*. That said, assuming literature data for battery lifetime and maintenance rate [44], it is unlikely that a battery replacement is needed during the 100000 km vehicle operational lifetime. Fig. 6 highlights that the choice of EoL vehicle modelling does not affect significantly GHG emissions, with the exception of Reuse for ICEV configuration, for which the environmental credits (−1684 kgCO2_eq) arise from the allocation of the Smart ForTwo W450 ICE to the reuse pathway (around 5.8 % with respect to the base case of *Scenario A*). It derives that the assumptions on geographical and temporal boundary conditions of EoL vehicle treatment are less relevant than assumptions on where and when the conversion process and the use phase occur (Fig. 6 A): this result is completely in line with Tagliaferri et al. [18], which assesses two different recycling scenarios in a cradle-to-grave LCA of BEV and ICEV circulating in Europe.

As expected, when considering the overall LC impact of *Scenario B*, the variability in GHG emissions due to battery EoL modelling is very low (respectively +0.16 % and −1.0 % compared to the base case for Energy Demand Disposal and Secondary Use-Credits *Scenario B*). That said, the relative influence on GHGs of EoL battery pathways is unknown, since empirical data on the specific conversion process, such as cell conversion rates, state of health, and refurbished lifetime span for repurposing applications, are not available [45].

More specifically, the recycling processes of LiFePO4 battery could increase substantially the GHGs of the EoL phase, while the battery secondary use could ensure definitely higher environmental benefits, separation efficiency rate, recovered material quality and energy consumptions, these latter for hydro-pyrometallurgical process [46]. In the light of previous considerations, it can be stated that the geographic location and the technical features of the EoL battery modelling could have a strong effect in terms of both environmental burdens and credits, thus representing a point of difference with respect to EoL assessment at vehicle level. The sensitivity analysis investigates also whether Scenario B is environmentally convenient against Scenario A even when considering all possible combinations of sensitivity parameters mentioned above. All vehicle configurations and corresponding labels are listed in Supplementary Material 1 Table S1, which provides a total of 274 ICEV and converted BEV models. To simplify the presentation of results, it is assumed that modelling assumptions (e.g., vehicle manufacturing specifications, energy/fuel consumption and EoL modelling) of Part 1 and Part 2 of each scenario remain the same; additionally, EoL assumptions for Part 1 in Scenario B are not specified, as removed components are permanently allocated to a probabilistic reuse pathway (e.g. the EoL of ICE powertrain Scenario B by ICEV +5.2 CONV RE against Scenario A 4 ICE +4 ICEV). Fig. 7 provides the impact for all considered car models. Data reveals that the worst configuration of Scenario B is ICEV +8.9 CONV PO, whose GHG missions do not exceed the best configuration of Scenario A (4 ICEV + 4 ICEV), with a percentage difference of about 4 %. Indeed, even if the worst configuration is chosen (Replacement in battery maintenance, WLTP3 energy consumption, Worst Recycling EoL vehicle modelling, Energy demand Disposal EoL battery modelling and Polish grid mix for electricity supply chain), the environmental profile of retrofit is still preferable than assuming the manufacturing of a new glider and the corresponding WtW use phase. Similar to sensitivity analysis based on single parameters, energy consumption level and electricity grid mix involve the highest impact variation, due to the crucial role of WtT phase on total LC emissions; on the other hand, battery maintenance, EoL vehicle and EoL battery modelling have a lower effect, approximately in a range of ±2 %. Numerical values are presented in Supplementary Material 3, see Table S9.

In addition, the sustainability aspects of this study can be evaluated through the lens of the 17 Sustainable Development Goals (SDGs) [47], established by United Nations General Assembly in 2015 as part of the 2030 Agenda for Sustainable Development. The study predominantly contributes to these points.

- SDG 7 - Affordable and Clean Energy: the focus on the EVs directly contributes to this goal by promoting the adoption of clean and renewable energy sources in the transportation sector. Also, by analysing the retrofitted process, the study supports the aim of providing affordable and sustainable energy for all.
- SDG 9 - Industry, Innovation, and Infrastructure: the emphasis on the retrofitted prototype data inventory and numerical analysis of energy consumption reflects an effort to enhance industrial processes and infrastructure, thus contributing to SDG 9's aim of promoting inclusive and sustainable industrialization.
- SDG 11 - Sustainable Cities and Communities: the retrofitting process can play a crucial role in the adoption of EVs, which is essential in creating sustainable cities and communities. Additionally,

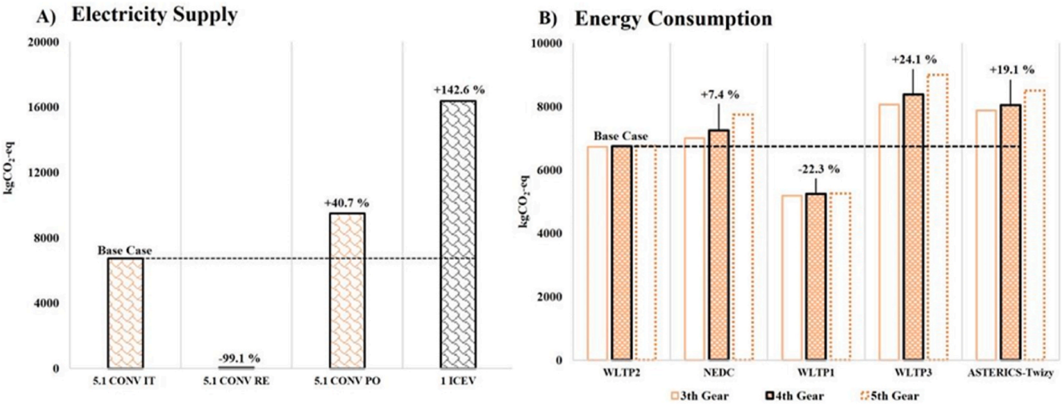

**Fig. 4.** Use Phase *Part 2 Scenario B* impact sensitivity analysis: A) electricity grid mix variation using WLTP2 driving cycle, B) energy consumption variation using Italian Grid Mix energy production.

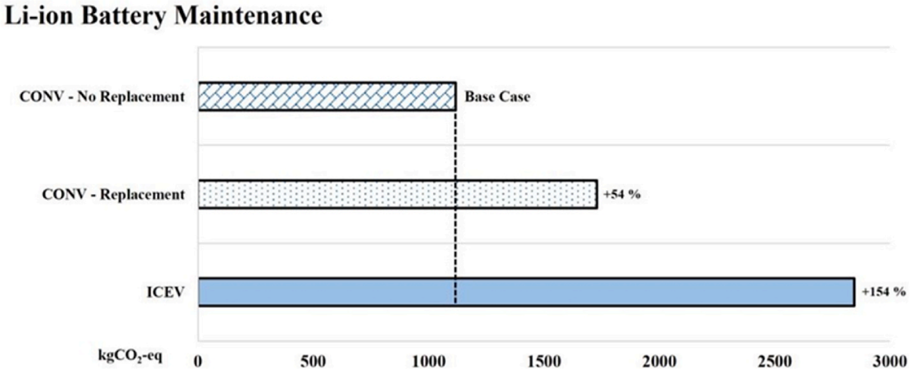

**Fig. 5.** Manufacturing *Part 2 Scenario B* sensitivity analysis.

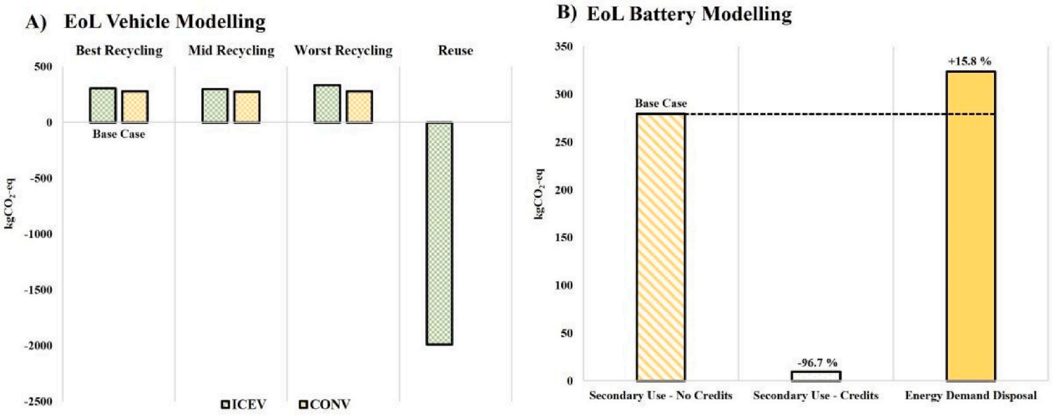

**Fig. 6.** EoL impact sensitivity Analysis: A) EoL vehicle modelling sensitivity using battery EoL Secondary Use-No credits, B) EoL battery modelling sensitivity using the Best Recycling for vehicle.

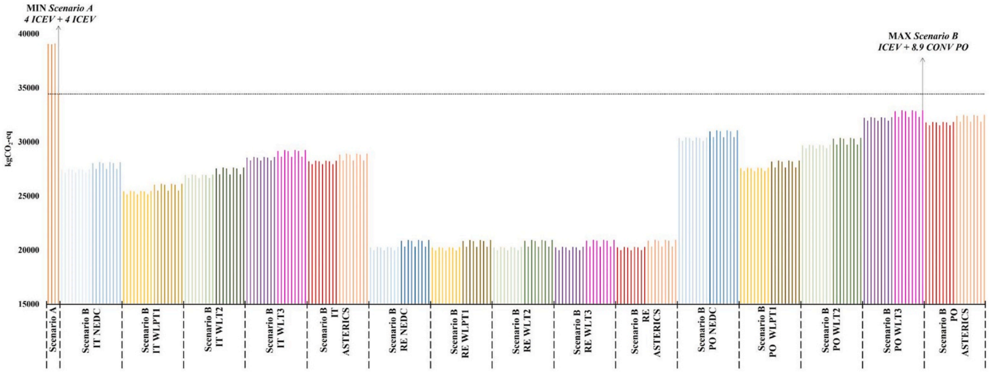

**Fig. 7.** GHGs LC impact calculate for 274 scenario models. Each scenario Label includes two sets of 9 vehicle configurations (different colour for Replacement and No Replacement LiFePO4 battery maintenance modelling) in which EoL Vehicle and EoL Battery are changed. The order in which the impacts are displayed correspond to the order used to list the results in Table S14 (see Supplementary Material 3). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

addressing driving cycles, electricity grid mixes and mileage patterns, helps to reduce the urban air pollution and make cities inclusive and sustainable.

- SDG 12 - Responsible Consumption and Production: this goal focuses on the sustainable production and consumption practises, which is reflected in the analysis of manufacturing and EoL phases of the retrofitted process, highlighting the possibility of reuse and reduction of waste.
- SDG 13 - Climate Action: the study directly supports SDG 13, showing the potential 45 % reduction of GHG emissions of a retrofitted vehicle compared to a replacement with a new ICEV.

## 4. Conclusions

This paper quantifies the GHG emissions reduction of an electric retrofitted vehicle, a new short-term solution for fleet electrification. A real-world modelling is proposed including industrial prototype data inventory, numerical analysis of energy consumption on MATLAB-

Simulink and EoL pathways. This study examines GHGs impact of a Smart ForTwo W450 electric conversion process carried out in the Italian context, and identifies recommendations for users, companies, policymakers in order to maximize the environmental benefits from an industrial point of view of the conversion process. Two conversion scenarios are compared: a retrofit using an industrial prototype of a Smart ForTwo W450 conversion kit (*Scenario B*) and vehicle substitution with the same ICE city car (*Scenario A*). The results show that the GHGs of *Scenario B* is 38.7 tCO2_eq, thus resulting into a 45 % lower impact than *Scenario A*. This outcome is mainly due to the reuse of the glider in the conversion process and to the lack of exhaust air emissions during electric operation. The analysis of manufacturing and assembly phases highlights that the higher impact of ICEV production is mainly caused by glider manufacturing, even if the specific impact of the conversion kit (in terms of kgCO2_eq/kg of component) is more than double. The breakdown of GHG emissions between materials reveals that this result is correlated to the intensive use of metals and chemicals in the production of LiFePO4 battery pack and electric motor. As expected, the lowest impact across LC phases is achieved by EoL in both scenarios. Moreover, this study analyses the environmental implications of a change in driving cycle (from base case to an urban cycle) and in electricity grid mix (from base case to a low-impact grid mix), highlighting respectively a 22.3 % and 99.1 % reduction in GHG emissions. That said, ICEV operation is proved to be the most impactful LC stage, even when assuming the worst choice in terms of driving pattern (WLTP3) and electricity grid mix (Polish grid mix). Also extended life-time of glider, urban driving context and renewable electricity mix are identified as key aspects to be developed by government agencies to turn electric retrofit into a more sustainable mobility strategy. Furthermore, the modelling of vehicle EoL has a negligible influence on the GHG emissions, evidencing the scarce relevance of assumptions on EoL geographical context. On the other hand, the lack of experimental data on EoL LiFePO4 battery pathways does not allow to properly quantify the effect of assumptions on temporal and geographical boundary conditions. As regards the combination of all sensitivity parameters considered, the results show that in all cases *Scenario B* involves a lower impact than *Scenario A*: the percentage variation ranges from a minimum of +4.4 % (increase of 1.5 tCO2_eq) to a maximum of +51 % (increase of 19.1 tCO2_eq). Taking into consideration both temporal segments (*Part 1* and *Part 2*), it appears clear that electric retrofit has the potentiality to drastically decrease the LC impacts of a potential electrification process, thus representing a valid alternative to vehicle replacement with a new ICEV. To achieve the greatest environmental benefits, the conversion process should be applied to cars operating mainly in city/urban context and in geographical areas where the fossil intensity of electricity grid mix is limited. Future development of the study can be oriented in the following directions: extension of the analysis to other vehicle segments, availability of experimental data (user driving habits in electric mode, the reliability of the conversion, real mileage), forecast on future improved scenarios in terms of reduced energy/fuel consumption levels (vehicle lightweighting, reduction of fossil source), reliable data on recycling and refurbishment LiFePO4 battery and expansion of the system boundary to include the comparison between a new EV and a retrofitted one.

## CRediT authorship contribution statement

**Eleonora Innocenti:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Lorenzo Berzi:** Software, Methodology, Investigation. **Francesco Del Pero:** Software, Supervision, Writing – review & editing. **Massimo Delogu:** Project administration, Funding acquisition, Conceptualization, Supervision.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

Data will be made available on request.

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## Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.rineng.2024.102454.

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