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METHODS ARTICLE

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BEVSIM

Battery electric vehicle sustainability impact assessment model

Rajesh Mehta | Milad Golkaram | Jack T. W. E. Vogels | Tom Ligthart | Eugene Someren | Spela Ferjan | Jelmer Lennartz

Netherlands Organization for Applied Scientific Research (TNO), Utrecht, The Netherlands

Correspondence
Milad Golkaram and Tom Ligthart, Netherlands Organization for Applied Scientific Research (TNO), Utrecht, The Netherlands.
Email: milad.golkaram@tno.nl and tom.ligthart@tno.nl

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Abstract

To achieve climate neutrality ambitions, greenhouse gas emissions from the transport sector need to be reduced by at least 90% by 2050. To support industry and policy makers on mitigating actions on climate goals it is important to holistically compare and reduce life cycle environmental impacts of road passenger vehicles. A web-based sustainability assessment tool named battery electric vehicle sustainability impact assessment model, BEVSIM, is developed to assess the environmental, circularity, and economic performance of the materials, sub-systems, parts, and individual components of battery electric vehicles and internal combustion engine vehicles. This tool allows to measure and compare impacts resulting from recycling technologies, end-of-life scenarios, and future scenarios resulting from changes in grid mixes. This paper explains the purpose of the tool, its functionality and design as well as the underlying assumptions.

KEYWORDS
battery electric vehicle (BEV), industrial ecology, internal combustion engine (ICE), life cycle assessment (LCA), life cycle costing, material circularity index

1 | INTRODUCTION

Transportation is a major contributor to several environmental issues, including air pollution and climate change. The International Energy Agency reported that 15% of the total greenhouse gas (GHG) emissions in Europe resulted from use of passenger cars, compared to 4% from aviation (IEA, 2019). The EU has set ambitious long-term goals to tackling GHG emissions by the transport sector. GHG emissions from the sector will need to be reduced by 90% by 2050 to reach climate neutrality (European Parliament & Council, 2022). It is of utmost importance to have a better understanding of the environmental impacts of road vehicles over their entire life cycle to support the industry and policy makers on mitigating actions for the automotive sector. Several studies have addressed the environmental impacts of automotive passenger transport using different system boundaries, life cycle inventories (LCIs), use phase methodology, level of detail in data collection, and modeling assumptions (Pero et al., 2018). Some research strived to have an overview of different parameters which affect the life cycle assessment (LCA) by designing tools such as GREET (Dai et al., 2015), VehiReLCA (Tu & Hertwich, 2021), "The European Aluminum/IAI Life Cycle Model for Cars" (Bertram & Bayliss, 2015), and UCSB Automotive Energy and Greenhouse Gas Model (Bulzer, 2018). Although these tools benefit from a large database and are designed by experts in different fields, they lack up-to-date LCIs, and they are not user-friendly for business managers, sustainability managers, and non-LCA experts. Further, these tools do not include life cycle cost (LCC) and material circularity assessments, thereby limiting their use to only life cycle

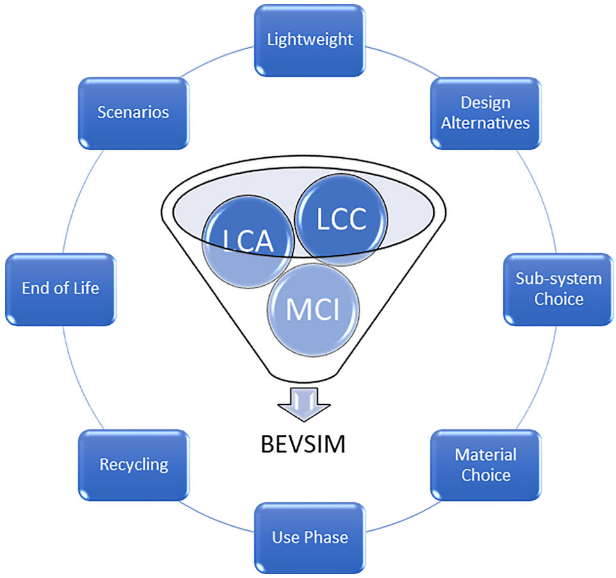

FIGURE 1 Schematic representation of battery electric vehicle sustainability impact assessment model capabilities.

environmental impacts. While GREET provides the user with a better overview on the sub-system/part level compared to the UCSB tool, both use an approach which involves materials and processes on an aggregated level. For instance, the process efficiencies are fixed and independent on the sub-system/part. Therefore, results are also on an aggregated level and do not provide insights on the individual sub-system/part level. In terms of life cycle stages, although GREET and UCSB tools focus on the use phase methodology, that is, driving cycles, they exclude vehicle maintenance and apply weak modeling for the end-of-life (EoL) stage. The waste treatment of materials, in these tools, also excludes the reuse fractions of the parts and the EoL scenarios are limited to disposal and mechanical recycling. Finally, the recycled content and a consistent allocation approach for materials going for recycling are missing in all these tools. To address these issues, we designed and developed a simplified tool named the battery electric vehicle sustainability impact assessment model (BEVSIM) for the automotive sector. The tool addresses several limitations of the existing application-specific tools and facilitates sustainability assessments for the automotive sector.

2 | THE BATTERY ELECTRIC VEHICLE SUSTAINABILITY IMPACT ASSESSMENT MODEL

BEVSIM is a sector and application-specific web-based tool developed as a part of the European project, Advanced Light Materials and Processes for the Eco-Design of Electric Vehicles (ALMA). BEVSIM contains LCA models for materials production, processing, the use phase, EoL fate, and recycling processes. The LCA tool is customizable to the level of the sustainability study, it can model a full car, a sub-system, that is, body, chassis, powertrain, interior, electrical, closure, or exterior or a part, BEVSIM offers integrated assessments by measuring environmental life cycle impacts, life cycle costing, and circularity assessments. The comparison is facilitated between battery electric vehicles (BEV) and internal combustion engine vehicle (ICE) passenger cars within the segment C and D categories, according to the definition by Oostvogels (2017). BEVSIM can in principle also be used for the full range of segments, from A to SUVs. The BEVSIM tool is designed for early screening of design alternatives in the research and development phase and for full LCA, LCC, and circularity assessment of a commercial product (Figure 1). The tool is designed for the following target value chain players and user groups: automotive manufacturers (OEMs), Tier 1—2 suppliers, materials manufacturers (Tier 3), service companies, research institutes and universities, automotive engineers, product developers, product designers, sustainability, and LCA experts.

The main benefits of the BEVSIM tool are significant savings in effort and time for performing LCA studies, consistency across LCA, LCC, and circularity assessment studies, lower total cost of ownership compared to full suite LCA software that requires LCA experts. BEVSIM can perform the following types of impact assessments: life cycle hotspot analysis, environmental impact assessment, circularity assessment using the material circularity indicator (MCI) and LCC analysis of the Ellen MacArthur foundation.

The BEVSIM tool allows to measure and compare impacts resulting from: design alternatives such as light weight designs, material choice, sub-system choice, process types and changes or choice, change in product lifetime, and change in recycled content of plastics. It also allows to compare impacts resulting from change in the allocation method for plastics going into recycling stream (cut-off, avoided product, 50:50 approach), recycling technologies for plastics and composites (mechanical, pyrolysis, and solvolysis), and EoL scenarios. As choice of grid mix is expected to have a major impact on BEV life cycle impacts, grey and green electricity grid mixes for 15 relevant countries are included together with future electricity scenarios for EU. Most up-to-date LCIs gathered from industry and literature for specific materials and processes.

3 | METHODS

3.1 | Functional unit

BEVSIM takes a consistent functional unit approach that allows comparison of the user design with reference design based on comparative functionality performance. The functionality comparison or equivalence principle is a key attribute when performing a life cycle assessment study. The functional unit is use of a segment C or D passenger car (BEV or ICE), its sub-system, or a part for its service life. For consistent comparison across the LCA studies, BEVSIM considers a default functional unit for comparison of the passenger cars. The functional unit can be changed in BEVSIM based on the vehicle or part lifetime. The default functional unit for comparison is defined as 245,000 km of vehicle, segment C or D car, driven in Western Europe with an average vehicle lifetime of 15 years. If the part or sub-system has a different individual lifetime, part-specific lifetime is selected to match the functionality equivalence, for example, car tires have approximately 40,000 km lifetime (Zhu et al., 2021) and must be replaced four to five times during the vehicle life.

The bill of materials and processing of the designs could be changed depending on the selected design. For consistent comparison of unique designs, it is assumed that the same number of sub-systems is compared in both user and reference design. It is also assumed that safety requirements and specifications of the studied design are the same and do not change. The user needs to ensure that the functionality equivalence is indeed valid and supported by design data, technical datasheets, or industrial test data.

3.2 | Impact assessment methods

In BEVSIM, three environmental impact assessment methods are used, namely ReCiPe 2016 Midpoint (H), Cumulative Energy Demand V1.11, and IPCC 2013 GWP 100a version 1.03. Climate change is the most understood impact category and the characterization factors come from the inter-governmental panel on climate change (IPCC).

For certain materials, specific EoL allocation methodologies are applied based on guidelines, or recommendations from industry associations. For BEVSIM, wherever required, we have aligned with respective industry guidelines and best practices. For plastics, the choice of cut-off, avoided product, and 50:50 approach exist in the tool. For plastics in BEVSIM we use the default and recommended allocation method, a form of system expansion—avoided product—including recyclate quality consideration.

3.3 | Life cycle inventories

BEVSIM includes 294 environmental profiles (result of each impact category for a certain process or material per respective unit, e.g., 3.19 kg CO_2/kg ABS) on material, processes, assembly, use phase, and EoL treatment. Most of the life cycle environmental impacts profiles are taken from Ecoinvent 3.6, a well-known global LCA database. For the raw materials phase, Industry 2.0 LCI database is used for plastics, while for steel and aluminum, World Steel (World Steel, 2021) and European Aluminum Association (EAA, 2018) are used, respectively. Material processing phase includes environmental profiles of typical processes for processing of raw materials such as plastics, steel, aluminum, and glass into finished parts. Paint processing and manufactured part processing are also included in the processing phase. The data on the processing of SMCs and steel is provided by Ford and BATZ. The data for recycling technologies such as mechanical recycling (Volk et al., 2021), solvolysis (La Rosa et al., 2018), and pyrolysis (Fivga & Dimitriou, 2018) were collected from literature. The rest of the LCI was collected from literature (see Supporting Information). The use of different inventories for different materials was chosen to use the most recent and relevant data. However, to a certain extent this may lead to differences in the way secondary materials are being treated in the inventories and in differences in cut-off rules. We assume that these differences have a limited impact on the results and should be seen as part of the uncertainty in the LCI data, because of this small uncertainty, <20%, differences in vehicle alternatives should be seen as less significant. All the emission factors per 1 kg (unless stated otherwise) are estimated in SimaPro and are used as datasets in BEVSIM. The emission factors are then multiplied by the amount/kg based on the user input.

BEVSIM considers a set of raw materials including commodity plastics (e.g., polyolefins) as well as engineering plastics (e.g., SAN, polycarbonate, and so on), different steel grades (e.g., hot dipped galvanized, HDG), and aluminum (e.g., extruded aluminum, automotive grade) products, and a large list of manufactured parts. This includes but is not limited to brake rotor, brake pad, exterior lightening, cables, fluids, lead-acid battery, nickel-manganese cobalt and lithium ion manganese oxide (NMC/LMO) battery, NMC111 battery, inverter, traction motor, tire, fuel tank (steel), and fuel tank (plastic). The references for the material LCI can be found in the Supporting Information. The user can choose a specific material depending on the applicability to a certain part. Moreover, for plastics, it is possible to choose a certain recycled content.

To model the processing of material until the gate stage, BEVSIM includes the life cycle profile for plastic processing (e.g., injection molding,), steel processing (cold stamping, hot stamping), aluminum processing (stamping), and the production of the manufactured parts (see Supporting Information).

For the assembly operations, the energy consumption is estimated based on the literature (Giampieri et al., 2020). The corresponding contribution per sub-system is based on the weight percentage of the sub-system in the overall design. The total energy required for assembly operations consists of 36% painting and 74% for the rest of the processes. The HVAC, lighting, and heating during the assembly phase are also included based on the literature (Sato & Nakata, 2020) and their contribution is also allocated proportionally to the weight fraction of the studied part (see Supporting Information).

The LCC has two perspectives, the first is that of the consumer and includes the costs for buying the vehicle acquisition, its use and maintenance plus EoL costs; the second perspective is that of the producer and includes design and manufacturing (materials, processes, and assembly) costs, distribution costs, and costs during the use of the vehicle such as take back costs. Data for the consumer perspective were among others based for purchase/registration tax and road tolls and vignettes on Schroten et al. (2019) and for insurance, repair, and maintenance and ownership tax on Peplow, & Eardley (2021). For the electric vehicle, the price of electricity was based on that for medium size households in 19 European countries for 2020 weighted by the population size (Eurostat, 2021). Fuel prices for the consumer were taken from the weekly Oil Bulletin (European Commission, 2021) and also weighted for population size of the member states. Data for the producer's perspective are for other than the material costs very scarce and even for the material costs few producer-specific cost data, for example, Khoonsari (2009), were available. Websites with material prices were used for more general prices, that is, LME (2021) and Plastiker (2015). Material and process costs in BEVSIM are therefore only a first indication, users can edit the prices in BEVSIM, for details see cost tables in the Supplementary Materials, to make these specific for their own case.

3.4 | Use phase methodology

The use phase of the ICEs and BEVs in BVSIM are modeled based on the existing literature, following the MILE21 project conducted by TNO (de Ruiter et al., 2019). Both the real-world fuel consumption and the real-world electricity consumption of data for 900,000 vehicles were collected from the Dutch fuel card and charge pass provider Travelcard Nederland BV. In this subset there are 226,000 petrol vehicles, 273,000 diesel vehicles, 26,000 petrol hybrid vehicles, 7000 petrol plug-in hybrid vehicles, 2000 diesel plug-in hybrid vehicles, and 3100 full electric vehicles.

3.4.1 | ICE

The use phase energy consumption for the ICE vehicle is modeled using multiple linear regression. The factors are combined to give the preliminary CO_2 prediction.

$$\text{For petrol} - \text{based ICE vehicles, the fuel consumption in kg petrol per km driven is equal to} = \frac{0.75 \times (aW + b\,(t))}{(23.7 \times 100)} \quad (1)$$

where, a is the mass factor (0.0812 1/km), $b(t)$ (53.8 g CO_2/km) is the build year contribution (which depends on the year the vehicle is built), W is the vehicle mass, and 0.75 is the density of petrol (kg/L) (Speight, 2011).

$$\text{For diesel} - \text{based ICE vehicles, the fuel consumption in kg diesel per km equals to} = \frac{0.85 \times (aW + b\,(t))}{(26.5 \times 100)} \quad (2)$$

where, $a = 0.1194$ 1/km), $b(t)$ (20.9 g/km) (Speight, 2011).

The 2370 and 2650 g CO_2/L are the conversion (emission) factors for petrol and diesel, respectively (de Ruiter et al., 2019). Thus, the result shows the fuel or electricity consumption per km drive.

The above use phase exhaust emissions correlations were derived from segment C and D cars sold and operated in Europe. The exhaust emissions for European geography, during the use phase are based on Ecoinvent for a small size EURO 5 passenger car (emissions, petrol, EURO 5 {RER}| transport, passenger car, small size, petrol, EURO 5 | APOS, U).

3.4.2 | BEV

For BEV, the electricity consumption (low voltage) including charging losses in kWh per km driven is calculated as:

$$\text{Electricity consumption (kwh/km)} = \frac{aW + b\,(CdA) + cPC + d}{100} \quad (3)$$

TABLE 1 BEV electricity consumption factors used (de Ruiter et al., 2019)

Factor	Value	Unit
a	0.0118	kWh/kg km
b	8.27	kWh/km m^2
c	−0.0982	1/km
d	−0.44	kWh/km

TABLE 2 Maintenance of the parts needed during the use phase of the battery electric vehicles and internal combustion engine vehicles. Numbers represent the number of necessary replacements during one life cycle

Maintenance item	Replacements per life cycle (BEV)	Replacements per life cycle (ICE)	Comment
Paint	1	1	
Battery	1	–	
Battery (acid)	3	3	
Tires	6	6	
Bumpers	1	1	Due to accident
Lights (headlight/taillight bulb)	1	1	Due to accident
Air conditioner refrigerant	2	2	
Coolant/antifreeze	4	4	
Windshield wiper fluid	37	37	
Brake pads	4	4	
Brake rotors	2	2	
Brake fluid	7	7	
Glass	1	1	Due to accident
Panels	1	1	Due to accident
Motor oil	–	8	
Power steering fluid	–	6	
Material	**Amount per lifetime**	**Unit**	**Comment**
Wax	0.30	kg	This assumes 10 g per application and twice a year
Water	12,300	kg	Around 12.3 m^3 water is needed per life cycle

where, W is vehicle mass (kg), CdA is aerodynamic drag area (m^2) = 0.52, cPC is net (usable) power capacity of the battery (kWh) = 47.5, the factors *a*, *b*, and *c* can be found in Table 1.

These energy consumption formulas were also used in the LCC to calculate the energy costs during use of a vehicle.

In the BEVSIM tool, appropriate electricity grid models can be chosen as per the BEV use phase country and grid mix (see Supporting Information). The tool also allows scenario analysis using in-built future electricity grid mix datasets for different geographies.

Both BEV and ICE also emit certain non-CO_2 substances during the use phase. The non-exhaust emissions are modeled based on the literature (Thompson et al., 2004) and includes the tire wear, brake wear, clutch wear, road surface wear, and corrosion of chassis. The abrasion and corrosion of tires, brakes, clutch, road, and chassis can lead to the deposition of particles on the road surface.

3.5 | Maintenance

Finally, the maintenance of the car and its parts are required in both BEV and ICE cars which can be seen in Table 2. Among those, lights, bumpers, glass, and panels are changed due to accidents. The probability of accidents per car per year is estimated based on the total accidents in Germany in 2020 divided by the number of cars in Germany on the same year (Statista, 2020), fluids (coolant/antifreeze, air conditioner refrigerant, windshield

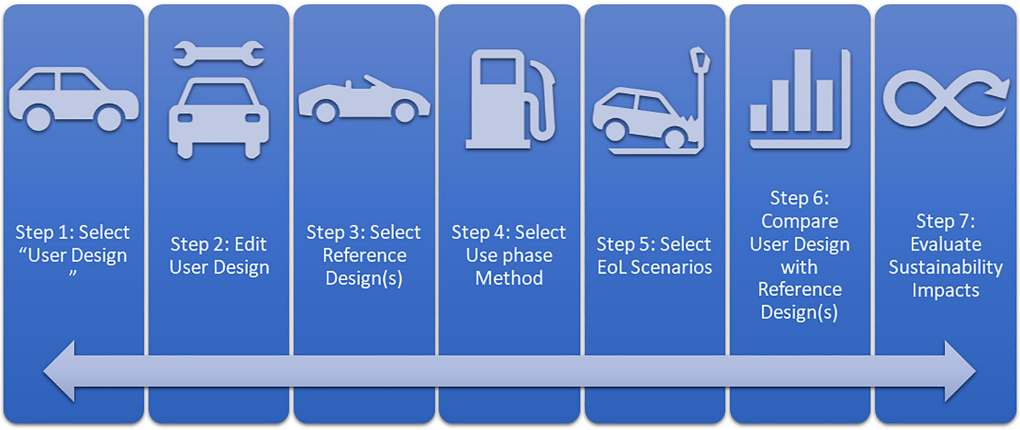

FIGURE 2 Product system of end-of-life vehicle treatment, based on Soo et al. (2017).

wiper fluid, brake fluid) also need regular change, whereas each car needs wax and water for polishing and washing on a regular basis (Table 2). Replacement value 1 means one new part or material and one replacement during the use phase.

3.6 | End-of-life

The EoL treatment of the vehicles follows the process described in Figure 2. First, the fluids and batteries are dismantled (depollution). After depollution, the reusable parts are stored for resale (see Supporting Information for the reuse fractions). The disassembled vehicle is then shredded for recovery of metals, after which the residues are sorted to recover heavy metals and plastics. The residue that cannot be sorted further is sent to a waste-to-energy plant.

For the batteries two scenarios are considered, (1) a mixture of NMC/LMO battery with stockpiling as the EoL fate and (2) NMC111 battery with EoL treatment including hydro-/pyrometallurgy and recovery of heavy metals.

After the separation, the separated materials are recycled accordingly. In BEVSIM customizable scenarios are included, whereby plastics and SMCs can be recovered mechanically and thermochemically (pyrolysis and gasification). Additionally, SMCs have the option of solvolysis. These alternative recycling methods are envisioned to be more dominant in the future. The EoL treatment of six typical steel products (wires, plates, engineering steel, HDG steel, finished cold rolled coil [FCRC], and pickled hot rolled coil [PHRC]) was modeled based on the data received from World Steel (2021). The world steel data shows the net credit for recycling, which includes the environmental burdens in addition to the credits associated with the recycling of post-consumer steel products. Each recycling method involves a set of assumptions which helps simplify the modeling. These assumptions can be found in the Supporting Information.

4 | BEVSIM WORKFLOW

Figure 3 explains the workflow of conducting a LCA, LCC, and circularity assessment in the BEVSIM tool. In Step 1, the BEVSIM user needs to select a user design for a new car, sub-system, or a part. The user can select his or her design either from the BEVSIM database or create a new car or part design from entirely scratch. In Step 2, the user can edit the design called "User Design" by modifying materials and processes per part, sub-system or at car level. In Step 3, the user is expected to select one or more reference designs from the database. The reference design can also be modified by selecting and editing it as a user design in Steps 1 and 2 and later re-selecting it as reference design. In Step 4, the user is expected to select a relevant use phase methodology, including geographical location for the user design and reference design(s). In Step 5, the user needs to select EoL scenarios for different materials of the car and parts under investigation. In Step 6, the user can compare the bill of materials of the design with reference design(s). Step 6 gives valuable information to the user to check if the created designs are correct and comparable before proceeding forward for sustainability assessments. Finally, in Step 7, the user can evaluate sustainability impacts, that is, LCA, LCC, and circularity performance of the user design using different impact assessment methods. A comparison is possible with reference design(s).

Figure 4 shows a selected screenshot of the user interface of BEVSIM tool for reader's familiarity with the tool. The user can simultaneously compare the modified and the original design and upgrade the design via changing the mass, processes, recycled content, allocation approach, and the process efficiency. Examples of the sample results are provided in the Supporting Information to show the versatility of the impact assessment.

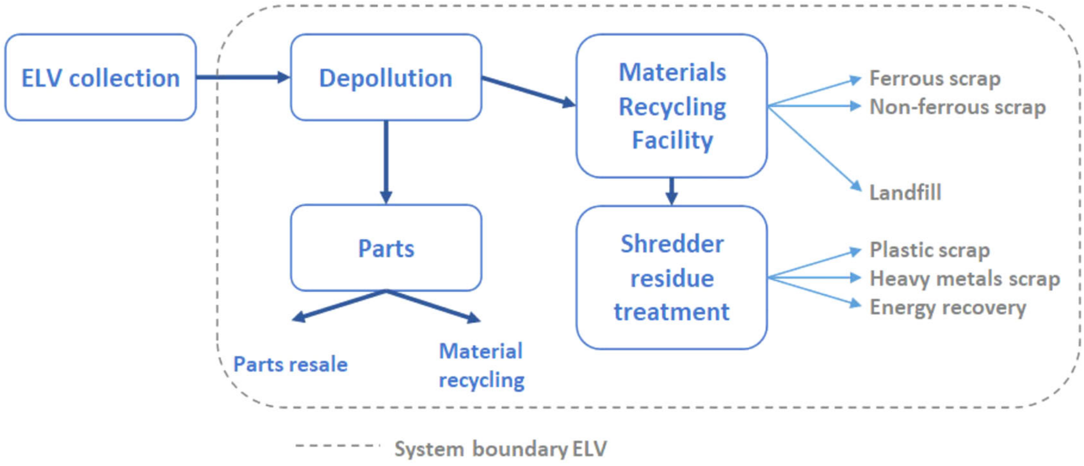

FIGURE 3 The workflow of conducting a life cycle assessment, life cycle cost analysis, and circularity assessment in the battery electric vehicle sustainability impact assessment model tool.

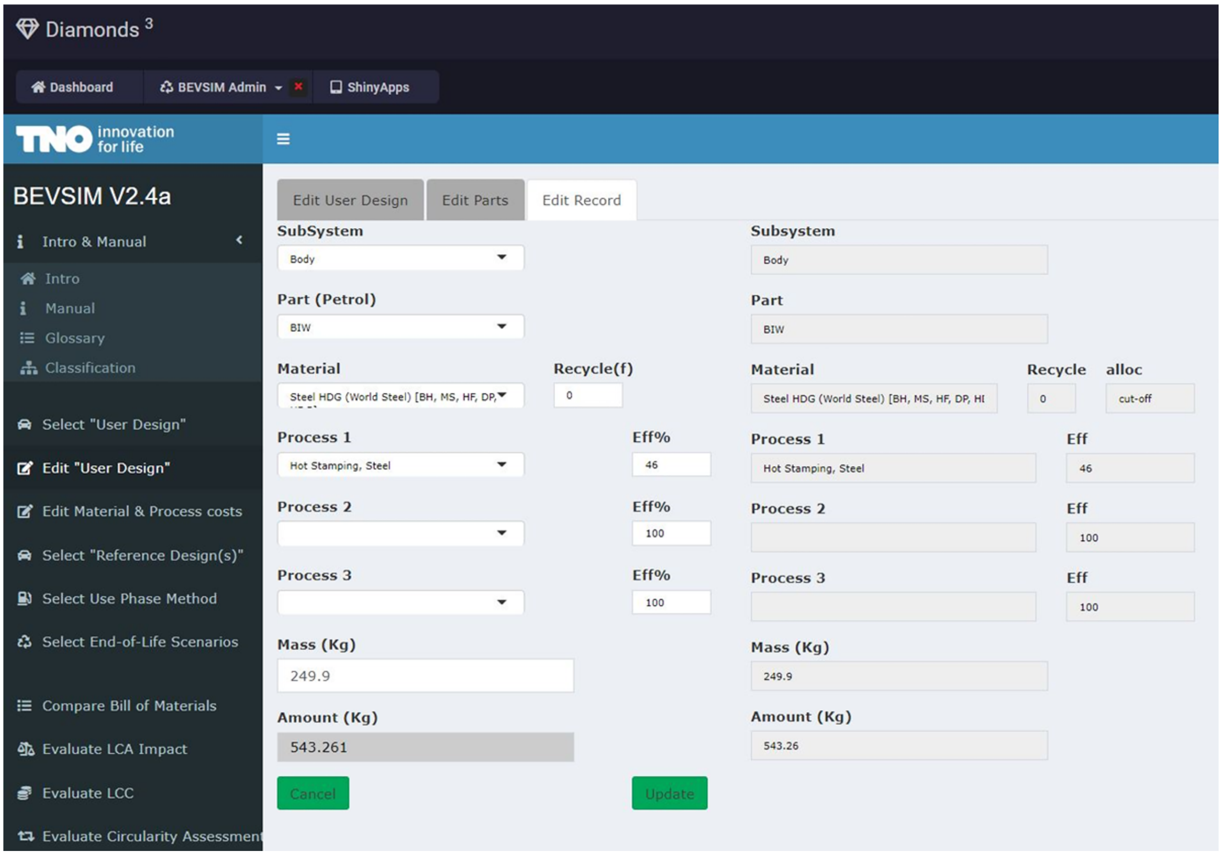

FIGURE 4 Overview of battery electric vehicle sustainability impact assessment model tool; edit options for a specific sub-system/part by modifying the material, process, mass, recycled content, allocation approach, processing efficiency, and multiple processing steps. In the same screen on the right side, the original design is shown for comparison.

5 | ALPHA AND BETA TESTS

The BEVSIM tool has been tested at two levels: (1) alpha tests conducted internally by TNO experts, and (2) beta tests conducted by ALMA partners who were not part of the BEVSIM tool development. In December 2021, TNO released the first version of the BEVSIM tool for beta testing. To verify the BEVSIM tool, the results for alpha test 1 were compared with commercial LCA software (SimaPro V 9.2.0.1) as well as by manual calculations using Excel. The percentage difference between BEVSIM and SimaPro results is less than 0.06% for individual life cycle phases which proves the accuracy and completeness of the BEVSIM simulation calculations. Furthermore, the BEVSIM tool is also tested on two other impact assessment methods, ReCiPe midpoint (H), and cumulative energy dema (CED). The comparison of the BEVSIM results with SimaPro results for the ReCiPe and CED impact assessments can be found in the Supporting Information. All impact categories matched with high accuracy except a few with less than 0.05% error, which may come from rounding errors. Alpha test 1 LCA study showed that assembly operation is a contributor to the overall life cycle impacts and many times is excluded in LCA analysis due to lack of data and sufficient information. Further, LCC analysis in the alpha test 1 showed that two perspectives are required to help different stakeholders evaluate LCCs for the BEV and ICE vehicle or parts. A general lack of automotive cost data for the producer's perspective limits the quality of this type of LCC, however companies can edit the data and make it suited to their own cases.

The alpha test 2 was done for a sub-system/part of a petrol car (segments C and D) manufactured in Europe and used in France for a total of 200,000 km over a lifetime of 14 years. The EoL scenarios for plastic waste treatment consist of 60% incineration, 20% pyrolysis, and 20% mechanical recycling. The alpha test 2 was performed by a TNO LCA expert not involved in the ALMA project. The TNO LCA expert, internal reviewer, judged the performance of the BEVSIM tool with respect to SimaPro results as satisfactory. After the test was carried out the missing elements and issues in the calculations were identified and resolved (Supporting Information S4).

The alpha test 2 results showed that the BEVSIM results and the comparison to commercial LCA software (SimaPro V 9.2.0.1) and other impact assessment methods showed different accuracies. For example, IPCC results were comparable between the tools with a difference <0.2%, whereas ReCiPe results are comparable between the tools, with <0.1% difference.

Beta tests 1 and 2 were conducted by BATZ and CTAG to check the user-friendliness, the methodology, and simulation workflow of the tool. The beta testers provided several improvement suggestions which were addressed in the released version of the BEVSIM tool. Overall, the beta testers showed satisfaction on the technical aspects, data, and quality of the BEVSIM application. However, further investigation is necessary to extend the SMC processing steps as well as geographical scope. The latter shows its impact especially for the use phase of the BEV.

The alpha and beta testing provides quality assurance and ensures that LCA, LCC, and circular economy methodologies, datasets, and assumptions have been implemented correctly in the BEVSIM tool. The alpha and beta tests also checked the user-friendliness of the tool.

However, there are limitations to the applicability of BEVSIM which requires further improvements. First, BEVSIM does not use driving cycles and rather has a fixed fuel/electricity usage depending on the weight of the vehicle. This is not realistic as the energy consumption during the use phase depends on the acceleration/brake, wind speed, slope, etc. Second, BEVSIM does not provide the user with the option of different batteries such as LFP batteries which are growing in the market or different recycling options thereof. The non-exhaust emissions carry some degrees of uncertainty. To the best of our knowledge, accurate and comprehensive studies are missing in this area, which capture all the emissions in the use phase. These issues need to be considered during the use of the tool and will be studied in the future in more detail. Finally, the future research involves two use cases of BEV and ICE vehicles to compare the full cars from cradle-to-grave using different impact assessment methods (ReCiPe midpoint H, IPCC 100, and CED) as well as MCI and LCC.

6 | DISCUSSION

In this paper, we described the BEVSIM tool, a web-based sustainability assessment tool for embedding sustainability assessments in the technology development and product design cycle. BEVSIM can be used by value chain players such as automotive manufacturers, material suppliers, service companies, research institutes, and universities. BEVSIM is designed for simplifying sustainability assessments and related decision making for automotive engineers, product developers, product designers, sustainability, and LCA experts. BEVSIM follows a cradle-to-grave approach which is like comparable tools (e.g., carculator, GREET, UCSB, VehiReLCA, and the European Aluminum/IAI Life Cycle Model). However, these tools differ in their level of detail, LCI, data quality, flexibility, and robustness of assumptions. Table 3 lists the major differences and focus of each tool. In terms of design alternatives, BEVSIM provides simultaneous assessment (MCI, LCA, and LCC) of a considerable number of designs with a user-friendly platform made in the Shiny application. Each automotive design can be compared to a reference design, and can be copied and modified. This can also be done by the UCSB model which is limited in number of designs. The focus of IAI and GREET tools is on the light weight and thus the full life cycle cannot be truly compared.

BEVSIM allows selection of the level of detail the user wants to perform the sustainability assessment for the automotive value chain. For instance, the user can choose a full car, a sub-system, or a part. This functionality is absent in other tools. Although GREET has introduced the sub-systems and parts in the tool, the user does not have full access on the part or sub-system level during the life cycle impact assessment (LCIA).

BEVSIM also provides the choice of material processing datasets by which the user can select up to three subsequent processes for part production with default or customized efficiencies for individual processes. Although the USCB tool provides this option, the addition of multiple processes is not straightforward.

The use of recycled content is particularly important for material suppliers and vehicle manufacturers to support their circularity ambitions. BEVSIM allows the users to evaluate the sustainability impact of varying recycled content on their design alternatives. The tool also lets the user

TABLE 3 Comparison of different tools for the circularity (life cycle assessment, life cycle cost analysis) assessment of road transport vehicles

#	Functionality	Classification	GREET	UCSB	VehiReLCA	IAI	Carculator	BEVSIM
1	Design alternatives	Tool feature	✗[a]	✓	✗	✗[a]	✓	✓
2	Material, sub-system choice	Tool feature	✗[c]	✗	✗	✗	✗	✓
3	Flexibility to use user defined process efficiencies for material processing	Tool feature	✓	✓	✗	✗	✗	✓
4	Change in vehicle lifetime	Methodology	✓	✓	✓	✓	✓	✓
5	Change in recycled content of plastics and steel		✓	✓	✗	✓	✗	✓
6	Change in the allocation method for plastics (cut-off, avoided, 50:50 approach)	Methodology	✗	✓	✗	✗	✗	✓
7	EoL scenarios (mechanical, pyrolysis and solvolysis)	Methodology	✗	✗	✗	✗	✗	✓
8	Number of electricity datasets	Tool feature	50	7	N/A	59[b]	Infinite	32
9	Future electricity grids (2030 and 2050)	Tool feature	✗	✗	✗	✗	✗	✓
10	Most up-to-date life cycle inventories gathered from industry and literature	Methodology	✗	✗	✗	✗	✓	✓
11	Vehicle types	Tool feature	5	5	3	5	4	3
12	Types of Assessments: LCA, LCC, material circularity indicator	Methodology	LCA	LCA	LCA	LCA	LCA	LCA, LCC, MCI
13	Number of environmental impact categories for LCA	Methodology	1	2	1	1	16	20
14	Use phase driving cycle	Methodology	✓	✓	✗	✓	✓	✗

[a]Limited to light weighting.
[b]In principle it is an infinite number as the user can also modify the grid mix.
[c]The tool is made using the sub-systems but the result is not shown independently.

choose the EoL allocation method for plastics recycling. This function is absent in all compared tools except the UCSB tool. For the metals, such as steel and aluminum, respective industry best practices are used for the EoL allocation.

EoL scenarios, including mechanical recycling, solvolysis and pyrolysis of plastics, and SMCs are extremely useful functionality for the contemporary progresses in plastics waste treatment. BEVSIM uses this versatile function to help the user in the selection of the best waste treatment options. Carculator among other tools, has the advantage of more up-to-date data inventory, is web based, and provides design alternatives and different driving cycles. Despite the level of sophistication this tool does not focus on recycling scenario or recycling content of the materials in the vehicle. Moreover, MCI and LCC are not the focus of the tool.

The LCC using the consumer perspective can be used by car designers to estimate whether the higher acquisition costs for a BEV compared to an ICE are balanced by lower use costs for the consumer. Energy costs and transport taxes tend to be lower for BEVs compared to ICEs in Europe. Other tax benefits currently also occur.

One of the key interests of vehicle manufacturers is the type of electricity used by the BEVs. Depending on the location of the vehicle use phase, the environmental impact of the vehicle can significantly change. BEVSIM is the only tool which uses predictive electricity grids in addition to 32 existing grids for BEV. Although the present scope of BEVSIM only includes BEV and ICE, its next version will include option to conduct sustainability assessments for plug-in hybrid electric vehicle (PHEV) and hybrid electric vehicle (HEV). This can simply involve the driving cycles present in the literature for more accurate estimation of the use phase emissions.

We demonstrated BEVSIM's capabilities in a real-world project, generating insights and feedback to the ALMA partners, including designers, on the environmental hotspots of the ALMA value chain. Furthermore, we generated detailed insights about the existing state of the recycling infrastructure and environmental performance for the car as a whole and individual materials. During the development cycle and alpha and beta testing phases, TNO shared information and ideas on improvement opportunities for increasing the circularity of the ALMA value chain for SMC and plastics materials. In 2022, TNO launched the BEVSIM tool for ALMA partners and for public.

7 | CONCLUSIONS

A web-based sustainability assessment tool named BEVSIM has been conceptualized and developed. The unique design of this tool empowers the LCA experts, non-experts, in academia and industry for consistent and holistic sustainability assessment of their design ideas, product designs, and products throughout their life cycle including EoL management and recycling. In this paper, BEVSIM was compared to other road transport impact assessment tools (GREET, UCSB, VehiReLCA, and IAI) via 13 separate functionality parameters. BEVSIM scored equivalent or higher than the other four studied tools except for the number of electricity datasets, number of vehicle types, and use phase driving cycle parameters. Furthermore, compared to excel-based LCA tools, BEVSIM allows standardized version control and dataset updates. The web-based platform approach of BEVSIM allows use of common database and data sharing across individual users while still allowing for restrictions for access of specific database, projects in case confidentiality is required. These features are generally available in full suite LCA software and not in light application-specific tool, a major advantage for BEVSIM. We performed two alpha and two beta tests on BEVSIM for quality assurance and stakeholder feedback before launching the tool.

BEVSIM can perform the following types of impact assessments: life cycle hotspot analysis, environmental impact assessment, circularity assessment using MCI and LCC. These unique features combined with the ability to analyze the effect of allocation methods, flexible recycled content, change of electricity grid mix, EoL scenarios, and latest LCI make BEVSIM superior to existing tools for LCA of vehicles. In the next phase of BEVSIM development, we plan to expand the tool applicability to other passenger vehicle types, commercial vehicles, other geographies, inclusion of driving cycle in the use phase methodology and specific composite materials.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available in the Supporting Information of this article.

ORCID

Milad Golkaram https://orcid.org/0000-0002-6627-4683

REFERENCES

Bertram, M., & Bayliss, C. (2015). Automotive life - Life cycle assessment model. Available from https://international-aluminium.org/resource/european-aluminium-iai-automotive-life-cycle-model/ Accessed September 9, 2021

Bulzer, R. (2018). UCSB energy and GHG model - WorldAutoSteel. Available from https://www.worldautosteel.org/life-cycle-thinking/ucsb-energy-ghg-model/ Accessed May 15, 2023

Dai, Q., Kelly, J. C., Burnham, A., & Elgowainy, A. (2015). Updated life-cycle assessment of aluminum production and semi-fabrication for the GREET model. http://www.osti.gov/servlets/purl/1224957/ Accessed September 9, 2021

Destatis. (2022). Accidents registered by the police by type of damage/location. Available from https://www.destatis.de/EN/Themes/Society-Environment/Traffic-Accidents/Tables/accidents-registered-police.html Accessed May 15, 2023

de Ruiter, J. M., van Gijlswijk, R. N., & Ligterink, N. E. (2019). *More information, less emissions - Estimating the real world CO_2 emissions of passenger cars based on vehicle properties*. TNO Publications.

EAA. (2018). *Environmental profile report - European aluminium*. Available from https://www.european-aluminium.eu/resource-hub/environmental-profile-report-2018/ Accessed September 9, 2021

European Commission. (2021). Weekly oil bulletin. https://ec.europa.eu/energy/data-analysis/weekly-oil-bulletin_en

European Parliament and Council. (2022). Clean and sustainable mobility for a climate-neutral EU - Consilium. Available from https://www.consilium.europa.eu/en/policies/clean-and-sustainable-mobility/ Accessed September 9, 2021

Eurostat. (2021). Electricity prices by type of user (ten00117). https://ec.europa.eu/eurostat/web/main/data/database?p_p_id=NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_nPqeVbPXRmWQ&p_p_lifecycle=0&p_p_state=pop_up&p_p_mode=view&_NavTreeportletprod_WAR_NavTreeportletprod_INSTANCE_nPqeVbPXRmWQ_nodeInfoService=true&nodeId=1008572

Fivga, A., & Dimitriou, I. (2018). Pyrolysis of plastic waste for production of heavy fuel substitute: A techno-economic assessment. *Energy*, *149*, 865–874.

Giampieri, A., Ling-Chin, J., Ma, Z., Smallbone, A., & Roskilly, A. P. (2020). A review of the current automotive manufacturing practice from an energy perspective. *Applied Energy*, *261*, 114074.

IEA. (2019). Global EV Outlook 2019 – Analysis - IEA. Global EV Outlook 2019. IEA, Paris. https://www.iea.org/reports/global-ev-outlook-2019, License: CC BY 4.0

Khoonsari, S. H. M. (2009). Life cycle cost analysis for passenger cars: Steel versus composites. *9th Annual Automotive Composites Conference and Exhibition, ACCE 2009*, pp. 642–670.

La Rosa, A. D., Blanco, I., Banatao, D. R., Pastine, S. J., Björklund, A., & Cicala, G. (2018). Innovative chemical process for recycling thermosets cured with recyclamines® by converting bio-epoxy composites in reusable thermoplastic-an LCA study. *Materials*, *11*(3), 353.

LME. (2021). Metals. https://www.lme.com/Metals

Oostvogels, B. (2017). Duidelijkheid over autosegmenten. Available from https://autorai.nl/duidelijkheid-over-autosegmenten/ Accessed September 9, 2021

Peplow, L., & Eardley, C. H. (2021). Electric cars: Calculating the total cost of ownership for consumers. *Element Energy Limited*, Vol. 44.

Pero, F. D., Delogu, M., & Pierini, M. (2018). Life cycle Assessment in the automotive sector: A comparative case study of Internal Combustion Engine (ICE) and electric car. *Procedia Structural Integrity*, *12*, 521–537. https://doi.org/10.1016/j.prostr.2018.11.066

Plastiker. (2015). Raw Materials & Prices. http://plasticker.de/preise/preise_monat_single_en.php

Sato, F. E. K., & Nakata, T. (2020). Energy consumption analysis for vehicle production through a material flow approach. *Energies*, *13*, 2396.

Schroten, A., Scholten, P., van Wijngaarden, L., van Essen, H., Brambilla, M., Gatto, M., Maffii, S., Trosky, S., Kramer, H., Monden, R., Bertschmann, D., Killer, M., Greinus, A., Lambla, V., El Beyrouty, K., Amaral, S., Nokes, T., & Coulon, A. (2019). *Transport taxes and charges in Europe. An overview study of economic internalisation measures applied in Europe*. European Commission.

Soo, V. K., Peeters, J., Compston, P., Doolan, M., & Duflou, J. R. (2017). Comparative study of end-of-life vehicle recycling in Australia and Belgium. *Procedia CIRP*, *61*, 269–274. https://linkinghub.elsevier.com/retrieve/pii/S2212827116313919

Speight, J. G. (2011). 2 - Production, properties and environmental impact of hydrocarbon fuel conversion. In M. Rashid & B. T. Khan (Eds.), *Advances in clean hydrocarbon fuel processing* (pp. 54–82). Woodhead Publishing.

Statista. (2020). Germany - Total number of registered cars by brand - Car Sales Statistics. Available from https://www.statista.com/statistics/587764/number-of-registered-cars-germany Accessed May 15, 2023

Thompson, N., Ntziachristos, L., Samaras, Z., Aakko, P., Wass, U., Hausberger, S., & Sams, T. (2004). Overview of the European "Particulates" Project on the characterization of exhaust particulate emissions from road vehicles: Results for heavy duty engines. *SAE Transactions*, *113*, 1374–1386.

Tu, Q., & Hertwich, E. G. (2021). A mechanistic model to link technical specifications of vehicle end-of-life treatment with the potential of closed-loop recycling of post-consumer scrap alloys. *Journal of Industrial Ecology*, *26*, 704–717.

Volk, R., Stallkamp, C., Steins, J. J., Yogish, S. P., Müller, R. C., Stapf, D., & Schultmann, F. (2021). Techno-economic assessment and comparison of different plastic recycling pathways A German case study.

World Steel. (2021). Life cycle thinking. worldsteel.org.

Zhu, J., Han, K., & Wang, S. (2021). Automobile tire life prediction based on image processing and machine learning technology. *Advances in Mechanical Engineering*, *13*(3), https://doi.org/10.1177/16878140211002727

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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