



Volume 132

2026

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: <https://doi.org/10.20858/sjsutst.2026.132.14>

Journal homepage: <http://sjsutst.polsl.pl>



Article citation information:

Pavlychenko, A., Lyashuk, O., Krivda, V., Sakno, O., Mironov, D., Kornilenko, K., Khoroshun, R. Impact of changes in the technical-operational performance of hybrid vehicles as a partially decarbonized technology on end-of-life treatment with regard to environmental requirements. *Scientific Journal of Silesian University of Technology. Series Transport*. 2026, 132, 267-283. ISSN: 0209-3324. DOI: <https://doi.org/10.20858/sjsutst.2026.132.14>

Artem PAVLYCHENKO¹, Oleg LYASHUK², Vitaliy KRIVDA³, Olha SAKNO⁴,
Dmytro MIRONOV⁵, Kostyantyn KORNILENKO⁶, Roman KHOROSHUN⁷

IMPACT OF CHANGES IN THE TECHNICAL-OPERATIONAL PERFORMANCE OF HYBRID VEHICLES AS A PARTIALLY DECARBONIZED TECHNOLOGY ON END-OF-LIFE TREATMENT WITH REGARD TO ENVIRONMENTAL REQUIREMENTS

¹ Department of Ecology and Environmental Protection Technologies, Dnipro University of Technology, D. Lavornyskoho Ave. 19, 49027 Dnipro, Ukraine. Email: pavlichenko.a.v@nmu.one.
ORCID: <https://orcid.org/0000-0003-4652-9180>

² Faculty of Engineering of Machines, Structures and Technologies, Ternopil Ivan Puluj National Technical University, Ruska 56 Street, 46000 Ternopil, Ukraine. Email: oleglashuk@ukr.net.
ORCID: <https://orcid.org/0000-0003-4881-8568>

³ Department of Automobiles and Automotive Engineering, Dnipro University of Technology, D. Lavornyskoho Ave. 19, 49027 Dnipro, Ukraine. Email: vitaliy.krivda@gmail.com.
ORCID: <https://orcid.org/0000-0002-8304-2016>

⁴ Department of Automobiles and Automotive Engineering, Dnipro University of Technology, D. Lavornyskoho Ave. 19, 49027 Dnipro, Ukraine. Email: sakno-olga@ukr.net. ORCID: <https://orcid.org/0000-0003-4672-6651>

⁵ Faculty of Engineering of Machines, Structures and Technologies, Ternopil Ivan Puluj National Technical University, Ruska 56 Street, 46000 Ternopil, Ukraine. Email: mironov.epz@gmail.com.
ORCID: <https://orcid.org/0000-0002-5717-4322>

⁶ Department of Automobiles and Automotive Engineering, Dnipro University of Technology, D. Lavornyskoho Ave. 19, 49027 Dnipro, Ukraine. Email: kornilenko.k@gmail.com.
ORCID: <https://orcid.org/0000-0003-0567-8534>

⁷ Faculty of Engineering of Machines, Structures and Technologies, Ternopil Ivan Puluj National Technical University, Ruska 56 Street, 46000 Ternopil, Ukraine. Email: roman_086@ukr.net.
ORCID: <https://orcid.org/0000-0002-1862-7640>

Summary. This article examines how changes in the technical and operational characteristics of hybrid vehicles, as an intermediate step in transport decarbonization, affect end-of-life treatment from an environmental standpoint. Life-cycle assessment and multifactor regression modeling are applied to evaluate the influence of traction battery capacity, battery chemistry, regenerative braking intensity and powertrain type on the integral end-of-life impact coefficient. The results show that BEVs carry an end-of-life burden approximately 3.5 times lower than PHEVs, while increasing battery capacity, though reducing in-use CO₂ emissions by up to 50%, proportionally raises recycling complexity and chemical load on processing facilities. The findings substantiate the need for standardized battery designs, regulatory end-of-life risk indicators, and integrated state-of-health monitoring to ensure safe and efficient processing of electrified vehicles.

Keywords: hybrid vehicles, technical-operational indicators; decarbonization, end-of-life treatment, batteries, environmental impact, recycling; ecology

1. INTRODUCTION

In the current context of a global shift to a low-carbon economy, the transport sector faces rising requirements to reduce CO₂ emissions. Hybrid vehicles (HEV/PHEV) serve as an intermediate step toward full electromobility, lowering in-use emissions relative to conventional ICE vehicles while preserving operational autonomy [1-2]. However, as high-voltage batteries and electronic systems are integrated, a new set of challenges emerges related to technical parameters and the environmental aspects of end-of-life treatment.

The main objective of this study is to analyze how changes in the technical and operational indicators of hybrid transport, in the context of decarbonization, affect end-of-life processes from the standpoint of environmental safety. The work applies life-cycle assessment (LCA, “cradle to grave”), which makes it possible to account not only for the use and production phases but also for end-of-life treatment of batteries and composite materials [3]. An LCA study of HEV/PHEV hybrids [4] found that although they have lower in-use emissions than ICE vehicles, battery manufacturing markedly increases their carbon footprint. Moreover, the extent of decarbonization in energy generation determines the environmental performance of hybrids, since under carbon-intensive grids the HEV/PHEV advantage narrows [1, 5].

The recycling rate for lithium-ion batteries remains low (<5%), which creates environmental risks when storing spent cells [6]. The main technologies include hydrometallurgy and pyrometallurgy, each with environmental constraints; pyrometallurgy is energy intensive and polluting, whereas hydrometallurgy requires substantial volumes of reagents. Recent studies report advanced methods such as direct regeneration and closed-loop recycling that support more sustainable resource use [7].

Beyond batteries, hybrids contain complex composite materials and electronics. At end-of-life, these constitute potential sources of heavy-metal contamination and electronic waste. Regulatory instruments focused on battery end-of-life, notably EU Directive 2006/66/EC, have raised collection and recycling rates for spent cells, particularly in countries with strong oversight [6].

Taken together, the review shows that while hybrid vehicles contribute to lower CO₂ during operation, they introduce new environmental challenges at end-of-life. It is therefore appropriate to investigate how changes in technical and operational indicators affect component lifetimes and the corresponding treatment requirements.

The aim of this study is to examine how changes in the technical and operational characteristics of hybrid vehicles, arising from partial decarbonization, shape end-of-life treatment under current environmental requirements. As hybrid designs become more complex, primarily through the integration of high-voltage traction batteries, electronic control systems and advanced composite materials, there is a need to clarify the environmental risks associated with decommissioning. The study seeks to establish the relationship between lower in-use emissions and the rising complexity of end-of-life procedures, and to substantiate the need for technological solutions that ensure safe and efficient processing of such vehicles. Particular attention is given to the life cycle of hybrid components, their durability, options for second-use, and the regulatory framework that governs end-of-life management amid the sector's ecological transition.

2. MATERIALS AND METHODS

One of the key directions for improving hybrid transport in terms of energy efficiency and compliance with decarbonization requirements is increasing the capacity of traction battery packs. A higher nominal capacity substantially extends all-electric driving range, which in turn reduces reliance on the conventional internal combustion engine and helps cut CO₂ emissions over the duty cycle. Raising battery capacity, for example from 1 kWh to 3 kWh, yields an approximately 2.5 to 3 times increase in zero-emission range, depending on operating conditions and vehicle mass characteristics. According to studies by Scania Group that assessed the carbon footprint of hybrid heavy-duty transport, boosting electric range by even 20 to 30 km in an urban cycle can reduce daily CO₂ emissions by up to 40% compared with an equivalent ICE vehicle, provided the electricity comes from renewable sources [8].

However, the technical advantages of higher capacity are accompanied by operational constraints. A larger stored-energy volume requires more cells, which increases traction battery mass, complicates cooling systems, raises costs and can lower fuel efficiency in blended operation. In addition, a higher depth of discharge and more frequent charge cycles intensify degradation processes in electrochemical cells, which over time shortens the practical service life of the battery and necessitates more frequent pack replacement (Table 1) [9].

Tab. 1

Comparative analysis of technical-operational indicators for minimum and maximum battery capacity in hybrid vehicles

Parameter	Minimum capacity (1 kWh)	Maximum capacity (3 kWh)
All-electric range	20-30 km	60-90 km
Reduction in CO ₂ emissions	~20 %	~40-50 % depending on the electricity source
Battery degradation rate	~2-3 % over 2 years	~5-7 % over the same period
Toxic load	Minimal	3 times more materials required, including lithium, cobalt, etc.

From an environmental perspective, increasing the capacity of battery systems creates new end-of-life challenges. Higher-capacity packs contain larger amounts of rare-earth and toxic elements, including lithium, cobalt, nickel and manganese. Their presence complicates

mechanical dismantling and the chemical recovery of materials during recycling. The actual recycling rate for lithium-ion batteries, according to recent ICCT reports, remains critically low at less than 5% globally [10].

Thus, although a larger traction battery is an effective way to cut in-use emissions, it is accompanied by a marked rise in environmental burden at the end-of-life stages of the vehicle. In the absence of effective infrastructure for second-use and recycling, this trend can have a counterproductive environmental effect in the long term. For this reason, expanding the electric operating autonomy of hybrid transport should go hand in hand with the development of second-use technologies, the introduction of circular end-of-life policies and the standardization of battery platforms to facilitate dismantling and recycling [11].

One approach to optimizing the design of a hybrid vehicle is to reduce the nominal capacity of the traction battery. This decision is usually driven by cost considerations, the need to reduce vehicle mass and production simplification. A smaller battery entails fewer electrochemical cells, which lowers the mass of the energy module, reduces loads on the chassis and cooling systems, and decreases the vehicle's production cost as a whole.

From an engineering standpoint, reducing battery capacity directly limits electric range. Hybrids with small batteries up to 1 kWh can provide 20-30 km of autonomous EV-mode driving, which constrains extended zero-emission use. As a result, the share of time the vehicle operates solely on electric traction decreases, which leads to more frequent ICE engagement and, consequently, a smaller overall environmental effect during the use phase (Table 2). Fully electric vehicles and plug-in hybrids charged from the grid have zero tailpipe emissions, yet electricity generation at power plants can produce emissions. In regions where electricity is generated from relatively low-polluting sources, fully electric vehicles and grid-charged plug-in hybrids usually have a pronounced life-cycle emissions advantage over comparable gasoline or diesel vehicles [11].

Considering improving environmental safety and the reliability of transport energy systems, it is appropriate to compare lithium-ion (Li-ion) and nickel-metal hydride (NiMH) batteries with the same nominal capacity of 10 kWh. The evaluation considers durability, explosion hazard, degree of degradation, thermal stability, and recycling efficiency.

Analysis of the service life of Li-ion batteries reveals a longer lifetime of about 1500 full charge-discharge cycles, roughly 50% higher than the corresponding NiMH figure of up to 1000 cycles. This follows from the higher electrochemical stability of lithium cells and their lower internal resistance. Degradation analysis indicates an average capacity loss after 1000 cycles of about 20% for Li-ion batteries, whereas NiMH batteries lose up to 25%, so lithium cells are more stable under sustained operating load. The explosion-hazard assessment identifies the most critical characteristic for Li-ion batteries: high thermal reactivity and a risk of ignition under mechanical damage or overcharge. The notional explosion-hazard score is 8 out of 10, while for NiMH it is 4, which points to greater safety in transport and use. Thermal-stability analysis shows that NiMH batteries have a wider operating temperature range, up to 90 °C, which makes them more resistant to overheating, whereas Li-ion systems begin to degrade at temperatures above 60 °C.

Tab. 2

Comparison of traction-battery characteristics with analytical coefficients

Parameter	Reduced-capacity battery (1 kWh)	Nominal-capacity battery (3 kWh)	Coefficient / formula	Scientific rationale
All-electric range	20-30 km	60-90 km	$K_p = \text{range/capacity}$	Battery energy efficiency
Battery mass	≈ 60 kg	≈ 180 kg	$K_m = \text{mass/capacity}$	Specific-mass assessment
Battery cost	≈ 1000 USD	≈ 3000 USD	$K_c = \text{cost/capacity}$	Cost normalised by capacity
Service life (cycles)	≈ 1500 cycles	≈ 1500 cycles	$K_d = \text{cycles/capacity}$	Durability-to-capacity ratio
Grid well-to-wheel CO ₂	Lower (higher efficiency in coal-intensive regions)	Higher (greater electricity consumption)	$E = e_{\text{grid}} \cdot L / \text{efficiency}$	Analysis per NREL/AFDC
Life-cycle CO _{2e}	Lower (less manufacturing)	Higher (battery manufacturing)	$L_{CA\text{effect}} = L_{CA\text{net}} - L_{CA\text{proddiff}}$	ICCT and IPCC methodologies
End-of-life load	Lower (fewer toxic components)	Higher (lithium, cobalt, mass)	$U = \text{mass} \times \text{toxicity} \times \text{complexity}$	Aggregate impact on recycling and the environment

where K_p is the travel-efficiency metric (distance per 1 kWh) useful for comparing technological solutions; K_m is the ratio of battery mass to capacity, an indicator of gravimetric energy density; K_d is the ratio of charge-discharge cycles to battery capacity, a measure of lifetime normalized to size; $L_{CA\text{effect}}$ is the net life-cycle benefit or burden that accounts for both in-use emission reductions and manufacturing-related emissions; U is the end-of-life load index that combines battery mass, component toxicity and technological complexity during recycling.

Hence, under current decarbonization policy, the deployment of battery systems in transport should be considered not only through the lens of energy efficiency but also about their full life cycle and environmental impact. Comparing lithium-ion and nickel-metal hydride batteries makes it possible to assess the environmental burden of each technology at different stages of use. At the manufacturing stage, Li-ion batteries exhibit a higher carbon footprint due to the energy-intensive processing of lithium, cobalt and nickel, which are often mined in regions with weak environmental oversight. Cobalt extraction is associated with significant harm to water resources and biodiversity. While NiMH batteries contain fewer critically toxic components, their production is less energy intensive, which lowers the initial carbon footprint.

During the use phase, although both battery types have the same nominal capacity, the longer service life of Li-ion systems reduces replacement frequency and therefore cuts total resource demand per unit distance traveled. Their elevated thermal reactivity, however, creates a risk of uncontrolled release of hazardous substances in the event of fire or damage, which directly affects environmental safety.

At end-of-life, NiMH batteries have an advantage: higher effective recycling rates up to 60%, fewer constraints in waste handling and lower toxicity upon disposal. By contrast, Li-ion recycling remains technologically complex, costly and environmentally risky given the danger of electrolyte leakage, thermal reactions and the challenge of material recovery. Accordingly, the environmental suitability of NiMH batteries is more evident within closed-loop material cycles and safe end-of-life treatment, whereas Li-ion technologies, despite higher performance, require further development of recycling capacity and regulatory support to meet sustainability criteria (Table 3).

Tab. 3

Comparative table of technical and environmental indicators for Li-ion and NiMH batteries

Parameter	Li-ion	NiMH
Capacity, kWh	10	10
Service life, cycles	1500	1000
Average degradation, %	20	25
Explosion hazard, 1-10	8	4
Thermal stability, °C	60	90
Recycling efficiency, %	50	60

However, this trade-off has advantages at end-of-life. Fewer lithium cells mean a lower toxic load on waste-processing systems. Reducing battery mass lowers the need for energy-intensive pyrometallurgical or hydrometallurgical processes, which makes it possible to use more accessible, even manual, dismantling methods. In addition, a simplified battery configuration supports the standardization of dismantling and component sorting, which in turn raises recycling efficiency within the existing processing infrastructure [Sigma Earth, 2024].

From an environmental perspective, this strategy can be no less effective than a focus on maximizing electric range. Where full recycling infrastructure is lacking, a prudent reduction in battery energy intensity can mitigate risks of chemical pollution and help reduce the volume of complex waste. This is especially relevant in countries or regions where systems for collecting and processing spent traction batteries are at an early stage of development. Hence, although lowering battery capacity runs counter to the prevailing trend of increasing energy content, it can be an environmentally sound choice in the context of sustainable resource management.

A particularly relevant line of inquiry is the comparison of plug-in hybrids (PHEV), which combine an internal combustion engine with an electric motor, and battery-electric vehicles (BEV), which operate solely from a traction battery. The study conducts a comparative environmental analysis of hybrid and fully electric powertrains, assessing how different powerplant types perform in the decarbonization of the transport sector by comparing environmental impacts during use, as well as at the stages of manufacturing and end-of-life.

During the use phase, PHEVs reduce CO₂ emissions but do not eliminate them. Depending on the frequency of ICE operation, average mixed-mode emissions are about 40-60 g CO₂/km. BEVs, in turn, produce no emissions in operation, which makes them more suitable for environmentally sensitive areas and urban agglomerations. BEV battery packs have much higher energy content than those of PHEVs, which leads to a higher manufacturing-phase carbon footprint, about 11 t CO_{2e} for BEV versus 8 t CO_{2e} for PHEV. This reflects not only the quantity of materials but also the complexity of producing large battery modules. Fully electric vehicles are quieter, with average levels around 45-50 dB, which significantly reduce acoustic

load in urban environments compared with hybrids that generate 65-70 dB due to the ICE and transmission.

The absence of a complex transmission, gearbox and ICE in BEVs simplifies dismantling and component sorting at end-of-life. The structural uniformity and modularity of battery packs also promote standardization and automation of recycling. Based on expert assessment, the end-of-life burden for BEVs scores at 6 out of 10, whereas for PHEVs it is 8 out of 10, which reflects the greater complexity of handling mixed assemblies and materials.

The paper also examines the optimization potential of regenerative braking systems. In electric and hybrid vehicles, these systems enable generator mode in the traction motor, converting vehicle kinetic energy into electrical energy and storing it in the battery. This reduces traction energy demand, lowers mechanical load on conventional friction brakes and decreases ICE wear in hybrid configurations [13].

In fully electric vehicles, regeneration can return about 15-30% of energy consumed in the urban cycle, which improves range and reduces charging frequency. Regeneration effectiveness depends on the programmed regeneration level, the drive layout (front, rear, or all-wheel) and the battery type.

On the other hand, intensive use of regeneration increases the number of charge-discharge events. This accelerates electrochemical degradation even when the depth of discharge is modest. In city use, the number of microcycles can rise by a factor of 1.5-2 relative to conventional operation (Fig. 1). This creates a need to optimize charging algorithms and cell balancing, and to adopt Second Life practices, where batteries are repurposed in stationary energy systems after their primary automotive service, according to the International Council on Clean Transportation (2021). In addition, higher stress on cells raises the requirements for cooling and state-of-health (SOH) monitoring, which complicates design but helps extend service life and enables timely retirement of the most vulnerable modules.

To assess the impact of regenerative braking on battery life, a cyclic loading coefficient is introduced in the analytical model.

$$K_r = \frac{N_{rec}}{N_{base}} = \frac{C_{rec} \cdot f_{city}}{C_{base} \cdot f_{highway}} \quad (1)$$

where C_{rec} is the number of microcycles in urban operation; C_{base} is the number of cycles under the standard duty; f_{city} , $f_{highway}$ are the shares of regeneration use in city and highway driving respectively.

When $K_r > 1.3$, adaptive energy-saving modes and enhanced SOH (state of health) monitoring are recommended.

Next, the paper presents the end-of-life impact equation. To formalize this impact, a conditional load coefficient U is introduced, calculated as [14]:

$$U = \frac{W_m \cdot T \cdot C}{E_r}; \quad (2)$$

where W_m is the mass of powertrain components, kg; T is material toxicity, a notional rating; C is disassembly complexity, a coefficient from 1 to 10; E_r is the recycling-efficiency coefficient, 0-1.

To compute the conditional end-of-life load, the following input data are used: for BEV – $W_m \approx 250$ kg, $T=5$, $C=2$, $E_r=0.7$; for PHEV – $W_m \approx 350$ kg, $T=6$, $C=3$, $E_r=0.5$.

Thus, the relative end-of-life load for BEVs is lower by a factor of approximately 3.5 (Table 4).

Tab. 4

Comparative indicators of relative end-of-life burden for PHEV and BEV

Parameter	Hybrid(PHEV)	Battery electric (BEV)
Presence of ICE and transmission	Yes	No
CO ₂ emissions in use, g/km	50	0
CO ₂ emissions in manufacturing, t	8	11
Energy burden of end-of-life, points	8	6
Acoustic burden, dB	68	48
Conditional end-of-life coefficient, U	0.45	0.3

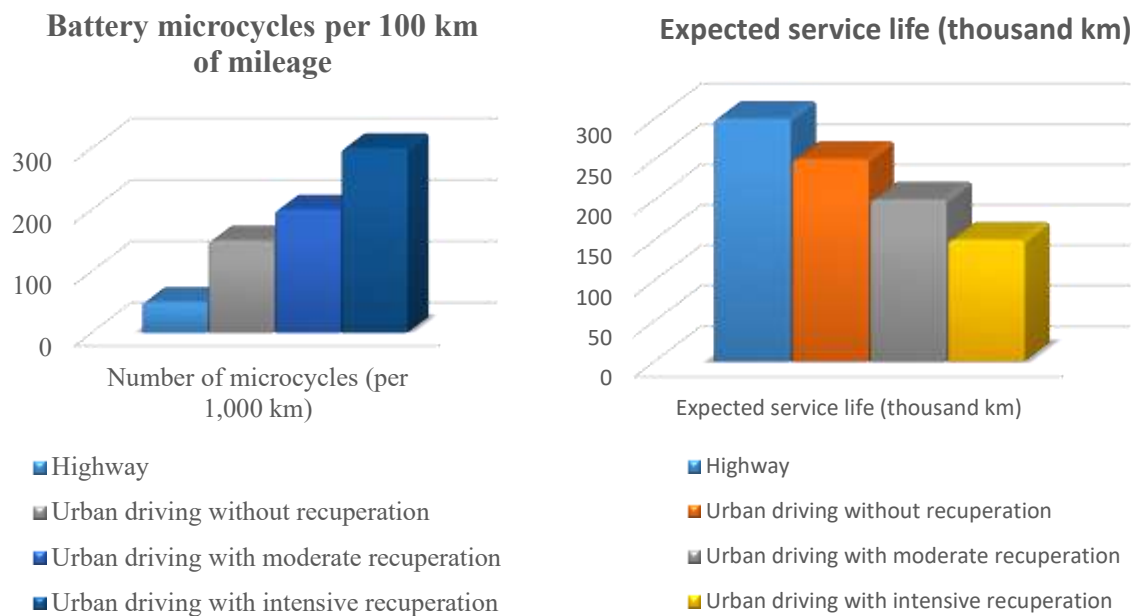


Fig. 1. Expected battery service life

BEVs have zero CO₂ emissions in use, which is critical for urban mobility. Despite higher manufacturing emissions of ≈ 11 t CO_{2e}, extended operation of BEVs offsets this footprint. Simplifying the vehicle architecture and reducing the number of assemblies streamlines end-of-life processing and raises reuse potential. By the aggregate end-of-life impact metric, the end-of-life burden for BEVs is at least three times lower for ecosystems. Although manufacturing is more energy intensive, BEVs present a more favorable environmental profile due to zero tailpipe emissions in operation, lower noise and an optimized recycling pathway. In the long run, as battery-recycling infrastructure develops and power generation decarbonizes, BEVs can deliver a substantial reduction in the transport sector's overall carbon footprint.

3. RESULTS AND DISCUSSION

Assessment and optimization of the factors that determine the integral end-of-life impact coefficient are crucial to the environmental performance of hybrid and battery-electric vehicles, since the magnitude of U aggregates the influence of key technical parameters and disposal scenarios on the level of environmental burden. To study the interactions and the individual contribution of each factor to the composite end-of-life indicator, a regression model was developed using a planned multifactor experiment [15]. In this study the response function is the integral end-of-life impact coefficient U , which enables a quantitative appraisal of trade-offs among the mass of power components, material toxicity, disassembly complexity and recycling efficiency. The principal parameters and their variation bounds used to determine U are given in Table 5.

Given the optimization criteria and the number of factors, a full factorial first-order design of type 2^4 was selected. A design matrix was compiled with 16 runs (Table 6) that cover all possible combinations of the chosen factors. In this matrix, columns 2-5 contain the coded values of the corresponding factors, while the first column consists of ones corresponding to the intercept term. The sixth column records the response value U . To unify the heterogeneous physical parameters and the target indicator U , dimensional quantities were transformed into dimensionless quality indices using the Harrington desirability function [16], which enables comparison of optimization potential across disposal scenarios on a common scale.

Tab. 5

Ranges of variation for technical and technological factors

Level	Wm , kg	T , arb. units	C , dimensionless	E_r , dimensionless
Base level	300	5.5	2.5	0.6
Variation	50	0.5	1	0.1
Upper level	350	6	3	0.7
Lower level	250	5	2	0.5

Tab. 6

Fragment of the full factorial design planning matrix

Run No.	x_0	x_1	x_2	x_3	x_4	U
1	1	0.780	0.485	0.780	0.760	0.619
2	1	0.780	0.386	0.780	0.760	0.595
3	1	0.38	0.485	0.780	0.760	0.521

At the next stage, to simplify analysis and improve comparability of how individual parameters affect the integral end-of-life impact coefficient, all factors were converted to a dimensionless form by normalization. The value of each factor was computed using the equation:

$$\begin{aligned} x_{ib} &= x_{i0} + x_i \\ x_{in} &= x_{i0} - x_i \end{aligned} \quad (3)$$

where x_{ib} is the upper level of factor i , x_{in} is the lower level, x_{i0} is the zero (mid) level and x_i is the half-range of variation.

In addition, for a more comprehensive assessment of system effects, the initial full- factorial planning matrix was expanded by including terms that represent pairwise interactions between factors (rows 6-16) (Table 7).

Tab. 7

Fragment of the coded planning matrix for the full factorial experiment

<i>Run No.</i>	1	2	3
x_0	1	1	1
x_1	1	1	-1
x_2	1	-1	1
x_3	1	1	1
x_4	1	1	1
x_1x_2	1	-1	-1
x_1x_3	1	1	-1
x_1x_4	1	1	-1
x_2x_3	1	-1	1
x_2x_4	1	-1	1
x_3x_4	1	1	1
$x_1x_2x_3$	1	-1	-1
$x_1x_2x_4$	1	-1	-1
$x_1x_3x_4$	1	1	-1
$x_2x_3x_4$	1	-1	1
$x_1x_2x_3x_4$	1	-1	-1
U	0.676	0.663	0.514

The resulting matrix satisfies the requirements of symmetry with respect to the center of the experimental region, normalization and orthogonality among factors [15]. These conditions ensure independent and statistically reliable estimates of the influence of each parameter on the integral end-of-life impact coefficient. The regression model for U based on the full factorial experiment can be written in the form of a generalized equation:

$$U = b_0 + b_1 \cdot x_1 + b_2 \cdot x_2 + b_3 \cdot x_3 + b_4 \cdot x_4 + b_5 \cdot x_1 \cdot x_2 + \dots + b_{15} \cdot x_1 \cdot x_2 \cdot x_3 \cdot x_4 \quad (4)$$

The regression coefficients are determined by the following equation:

$$b_j = \frac{\sum_{i=1}^N y_i \cdot x_{ji}}{N}, \quad b_o = \bar{y}. \quad (5)$$

where x_j is the coded value of the j -th factor, y_j is the response of the j -th experiment and N is the number of experiments.

Coefficients whose absolute values exceed the confidence-interval threshold are considered statistically significant and are retained in the final model. This makes it possible to focus only on those factors and combinations that genuinely determine the integral end-of-life impact coefficient within the studied parameter range. As a result, the following regression equation was obtained:

$$U = 0.52324 + 0.0453 \cdot x_1 + 0.0412 \cdot x_2 + 0.0423 \cdot x_3 - 0.0404 \cdot x_4 \quad (6)$$

Model adequacy was assessed using Fisher's criterion, which tests the agreement between model variance and the experimental data:

$$F = \frac{S_{ad}^2}{S_{\{y\}}^2} \quad (7)$$

where S_{ad}^2 is the adequacy variance:

$$S_{ad}^2 = \frac{\sum_{i=1}^N (y_i - \hat{y}_i)^2}{f} \quad (8)$$

and $S_{(y)}^2$ is the reproducibility variance:

$$S_{(y)}^2 = \frac{\sum_{i=1}^N (y_i - \bar{y})^2}{N-1} \quad (9)$$

The calculated statistic was $F_{calcul} = 2.03541$ and the tabulated value was $F_{table} = 1.8874$. Since the condition $F_{calcul} < F_{table}$ is not satisfied, the obtained equation (6) cannot be considered statistically adequate for the entire factor space.

In view of these results, the experimental plan was extended by moving to a second-order orthogonal central composite design. This approach accounts for possible response curvature and refines optimization decisions without losing data obtained at earlier test stages (Table 8).

Tab. 8

Fragment of the coded planning matrix for
the second-order orthogonal central composite design (OCCD)

Run No.	1	2	3	4
x ₀	1	1	1	1
x ₁	1	1	-1	-1
x ₂	1	-1	1	-1
x ₃	1	1	1	1
x ₄	1	1	1	1
x ₁₂ -α	0.2	0.2	0.2	0.2
x ₂₂ -α	0.2	0.2	0.2	0.2
x ₃₂ -α	0.2	0.2	0.2	0.2
x ₄₂ -α	0.2	0.2	0.2	0.2
x ₁ x ₂	1	-1	-1	1
x ₁ x ₃	1	1	-1	-1

x_1x_4	1	1	-1	-1
x_2x_3	1	-1	1	-1
x_2x_4	1	-1	1	-1
x_3x_4	1	1	1	1
$x_1x_2x_3$	1	-1	-1	1
$x_1x_2x_4$	1	-1	-1	1
$x_1x_3x_4$	1	1	-1	-1
$x_2x_3x_4$	1	-1	1	-1
$x_1x_2x_3x_4$	1	-1	-1	1
U	0.643	0.651	0.513	0.514

Applying the same procedures to the second-order OCCD planning matrix made it possible to build a refined regression model for the integral end-of-life impact coefficient. The resulting general equation accounts for linear, quadratic and interaction effects of the factors, which provides a better description of the dependence of U within the studied parameter range:

$$U = 0.52433 + 0.0421 \cdot x_1 + 0.03892 \cdot x_2 + 0.0383 \cdot x_3 - 0.0391 \cdot x_4 + 0.0311 \cdot x_1^2 + 0.0322 \cdot x_3^2 \quad (10)$$

Model adequacy was tested using Fisher's criterion. The calculated value was $F_{calcul} = 1.918$ and the tabulated value was $F_{table} = 1.96$. Since $F_{calcul} < F_{table}$, the model is considered statistically adequate for interpreting the experimental results.

To examine how the technical and technological parameters of end-of-life treatment affect the coefficient, response surfaces were plotted. The graphs were obtained by fixing two factors at the zero level and varying the remaining two.

Analysis of the quadratic regression equation (10) and the response surfaces (Fig. 2) identifies how the statistically significant factors influence the integral end-of-life impact coefficient of electrified vehicles. Increases in the mass of power components (Wm), material toxicity (T) and disassembly complexity (C) raise U , which reflects a higher environmental burden due to more difficult end-of-life processing, greater waste toxicity or higher mass of retired components. In contrast, higher recycling efficiency (Er) reduces U , since this factor enters the equation with a negative coefficient and its increase improves end-of-life performance from an environmental standpoint. The influence of the quadratic terms is moderate, evident as smoothed paraboloid shapes of the response surfaces for the Wm - C pair and individually for Wm and C , where the effect intensifies as a parameter deviates from the center toward its maximum.

To convert from coded to physical factor values, the inverse transformation was applied according to the following equation:

$$x_j = \frac{K_j \tilde{x}_j - K_{jo} \tilde{x}_{jo}}{I_j} \quad (11)$$

This yielded a polynomial regression model of the integral end-of-life impact coefficient for electric and hybrid vehicles suitable for forecasting and environmentally oriented system optimization. After normalization and inverse transformation, the following equation was obtained:

$$U = 0.5042 + 0.0465 \cdot x_1 + 0.0317 \cdot x_2 + 0.0322 \cdot x_3 - 0.0376 \cdot x_4 + 0.0306 \cdot x_1^2 + 0.0311 \cdot x_3^2 \quad (12)$$

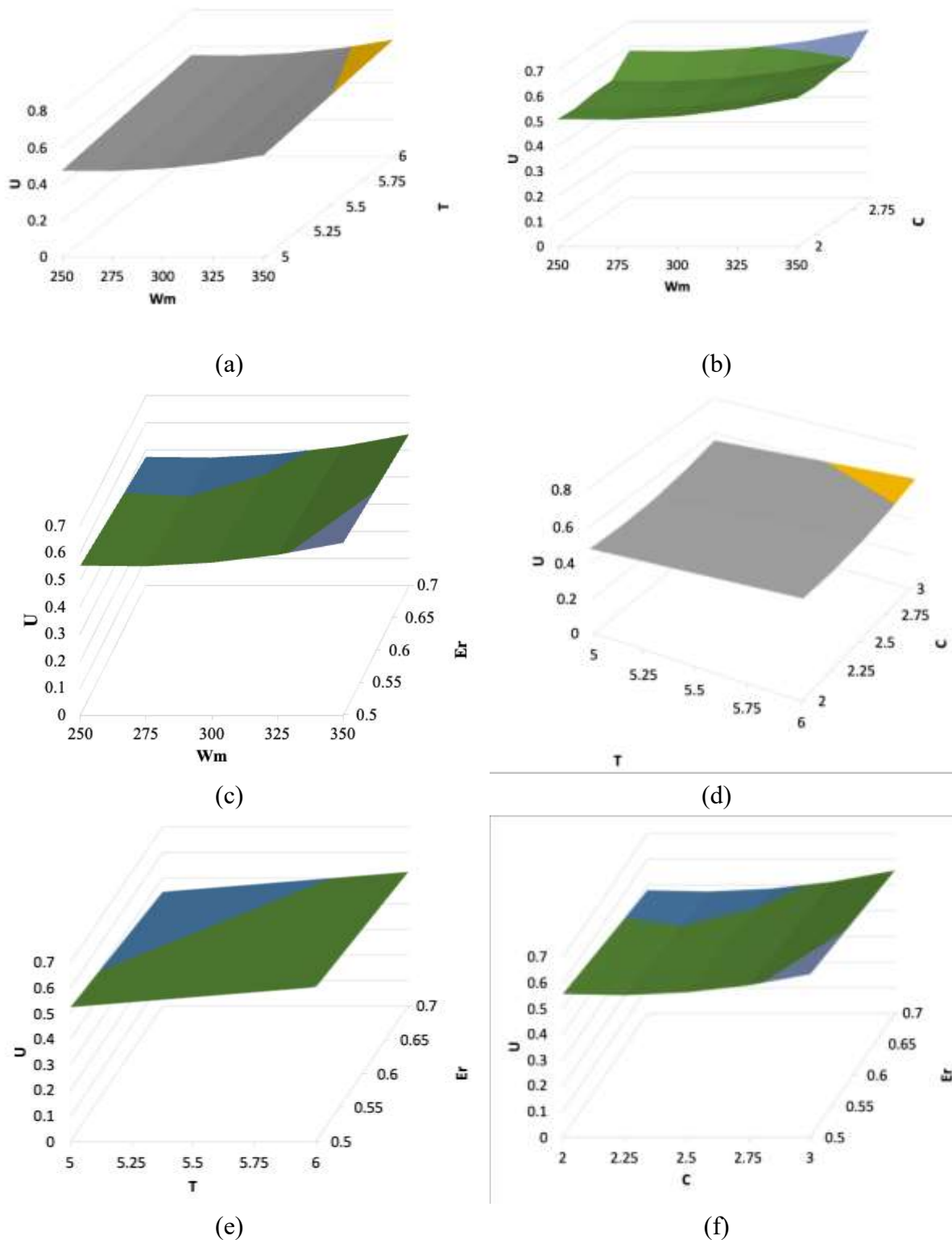


Fig. 2. Response surfaces of the model for the integral end-of-life impact coefficient as the factors vary: (a) mass of power components vs. material toxicity; (b) mass of power components vs. disassembly complexity; (c) mass of power components vs. recycling efficiency; (d) material toxicity vs. disassembly complexity; (e) material toxicity vs. recycling efficiency; (f) disassembly complexity vs. recycling efficiency

The developed polynomial models for U , both in coded form and using real data on mass, toxicity, disassembly complexity and recycling efficiency, provide a basis for automated systems of environmental monitoring and for forecasting end-of-life consequences of operating electrified vehicles. In addition to planning optimization measures for choosing the battery type, materials and recycling technologies, the model serves as a tool for rapid environmental assessment and for decisions that raise the level of environmental safety.

Thus, by substituting the values of the relevant factors into the model, one can compute the predicted integral end-of-life impact coefficient U for specific vehicle configurations. Based on real data obtained during operation and end-of-life processing, the model can be further adjusted or adapted to improve the accuracy and reliability of environmental evaluations, which is relevant for fleet modernization strategies and end-of-life planning.

4. CONCLUSION AND RECOMMENDATIONS

The type of powertrain is the primary determinant of end-of-life burden structure. BEVs, owing to the absence of an internal combustion engine and conventional transmission, show a conditional end-of-life coefficient U of approximately 0.30, compared with 0.45 for PHEVs. By the aggregate end-of-life burden metric, the load imposed by BEVs is approximately 3.5 times lower, which confirms their advantage in terms of dismantling accessibility and material homogeneity. However, the concentration of high-capacity battery packs in BEVs introduces a distinct waste category: energy-dense, high-voltage assemblies that require specialized neutralization and processing technologies not yet available at scale.

Traction battery capacity has a twofold effect on environmental outcomes. Increasing nominal capacity from 1 kWh to 3 kWh extends the EV-mode driving range from 20-30 km to 60-90 km and reduces CO₂ emissions by up to 40-50%, depending on the electricity source. At the same time, it increases battery mass approximately threefold, intensifies degradation from roughly 2-3% to 5-7% capacity loss over a two-year period, and substantially raises the chemical load on recycling facilities. Given that the global recycling rate for lithium-ion batteries currently remains below 5%, higher pack capacity proportionally escalates end-of-life environmental risk. These findings confirm that extending electric range must be accompanied by commensurate development of recycling infrastructure and closed-loop material policies.

Battery chemistry is a critical factor in determining end-of-life treatability. Comparative analysis of Li-ion and NiMH batteries at equal nominal capacity of 10 kWh shows that Li-ion cells deliver longer service life (~1500 cycles versus ~1000 cycles for NiMH) and lower degradation rates (~20% versus ~25% capacity loss after 1000 cycles). However, Li-ion batteries carry a significantly higher explosion-hazard rating (8/10 versus 4/10 for NiMH) and a lower thermal stability threshold (60°C versus 90°C), and their effective recycling rate (~50%) remains below that of NiMH (~60%). Among current Li-ion chemistries, lithium iron phosphate (LiFePO₄) offers the most favorable combination of thermal stability, low toxicity and cobalt-free composition, which simplifies secondary processing. These results indicate that battery chemistry selection must explicitly account for end-of-life treatability rather than in-use performance alone.

Regenerative braking intensifies battery microcycling. In urban driving, the number of charge-discharge microcycles increases by a factor of 1.5-2 relative to standard operation, as captured by the cyclic loading coefficient K_r . When K_r exceeds 1.3, adaptive energy-saving modes and enhanced state-of-health monitoring are required to prevent accelerated degradation of active electrode materials. Controlling regeneration intensity in relation to battery

temperature and SOH can meaningfully extend pack service life and defer end-of-life processing.

Manufacturing-phase carbon emissions remain substantial even for environmentally oriented BEVs, at 8-11 t CO_{2e} per vehicle – with the battery module accounting for the dominant share. Without explicit optimization of material choices, production processes and supply-chain logistics, the in-use emission advantage of PHEVs and BEVs may be partially offset by upstream environmental costs. Life-cycle assessment must therefore be embedded at the design and procurement stages rather than applied retrospectively.

The polynomial regression model of the integral end-of-life impact coefficient U , developed using a second-order orthogonal central composite design, is statistically adequate ($F_{\text{calcul}} = 1.918 < F_{\text{table}} = 1.96$). The model identifies the mass of power components Wm , material toxicity T and disassembly complexity C as factors that each exert a positive and statistically significant influence on U , while recycling efficiency Er reduces U when improved. Quadratic effects were identified for Wm and C , indicating a nonlinear response in the upper ranges of these parameters. The model, expressed both in coded form (Equation 10) and in physical units (Equation 12), enables quantitative prediction of end-of-life burden for specific vehicle configurations and can be integrated into design assessment or certification workflows.

The findings of this study point to several interconnected directions for improving end-of-life management of hybrid and battery-electric vehicles. Battery-module designs should be unified through the introduction of standardized form factors and communication interfaces, which would enable automated dismantling, reduce unidentified residues at recycling facilities and lower per-unit processing costs. Complementing this, a mandatory Battery Passport would support planned second use and recycling while enabling traceability of risk sources from the design stage onward. At the regulatory level, end-of-life risk indicators should be incorporated into state vehicle certification and environmental rating systems, with differentiated incentives such as reduced taxation for low-risk designs or mandatory recycling quotas where thresholds are exceeded, thereby creating a direct market signal for manufacturers. To manage the growing volume of retired traction batteries, a centralized registry consolidating data on residual capacity, service history and second-use potential would facilitate their integration into stationary backup-power systems and urban charging infrastructure, extending useful material life within closed-loop energy networks. Finally, AI-based and IoT-enabled monitoring should be integrated into battery management systems to enable real-time state-of-health prediction, adaptive adjustment of regeneration parameters and early identification of modules approaching critical degradation – both extending component service life and ensuring planned withdrawal from service before failure, which directly reduces the volume and unpredictability of end-of-life material streams.

References

1. *Sigma Earth*. Available at: <https://sigmaearth.com>.
2. Hawkins Troy, Ola M. Gausen, Anders H. Strømman. 2012. „Environmental impacts of hybrid and electric vehicles – a review”. *The International Journal of Life Cycle Assessment* 17(8): 997-1014. ISSN: 0948-3349. DOI: <https://doi.org/10.1007/s11367-012-0440-9>.

3. Laene Oliveira Soares, Ricardo Sodre Jose, Arismel Mancebo Boloy Ronney. 2025. „Lifecycle assessment and environmental impacts of hybrid electric vehicles fuelled by bioethanol and biogas”. *Renewable and Sustainable Energy Reviews* 216. No. 115652. ISSN: 1364-0321. DOI: <https://doi.org/10.1016/j.rser.2025.115652>.
4. Šimaitis Joris, Rick Lupton, Christopher Vagg, Isabela Butnar, Romain Sacchi, Stephen Allen. 2025. „Battery-electric vehicles have the lowest carbon footprint among passenger cars across 1.5-3.0°C energy decarbonisation pathways”. *Communications Earth & Environment* 6. No. 476. ISSN: 2662-4435. DOI: <https://doi.org/10.1038/s43247-025-02447-2>.
5. Ncars.com.ua. „Що роблять з батареями старих електрокарів”. Available at: <https://ncars.com.ua/media/shcho-robljat-z-batareiamy-starykh-elektrokariv>. [In Ukrainian: „What is done with the batteries of old electric cars”].
6. Redway Battery. „What Are the Environmental Impacts of Disposing AA and 21700 Batteries?”. Available at: <https://www.redwaybattery.com/what-are-the-environmental-impacts-of-disposing-aa-and-21700-batteries>.
7. Narisetty Venkata Sai Chandra Prasanth, Tejaswi Maddineni. 2024. „Powering the future: innovations in electric vehicle battery recycling”. *Nanotechnology Perceptions* 20(13): 2338-2351. ISSN: 1748-0140. DOI: <https://doi.org/10.48550/arXiv.2412.20687>.
8. Scania Group. 2024. Scania Annual and Sustainability Report 2024. Södertälje: Scania CV AB. Available at: <https://www.scania.com/content/dam/group/investor-relations/annual-review/download-full-report/scania-annual-and-sustainability-report-2024.pdf>.
9. Pavlovic Jelica, Adolfo Tansini, Jaime Suarez, Georgios Fontaras. 2024. „Influence of vehicle and battery ageing and driving modes on emissions and efficiency in plug-in hybrid vehicles”. *Energy Conversion and Management*: X 24. No. 100776. ISSN: 2590-1745. DOI: <https://doi.org/10.1016/j.ecmx.2024.100776>.
10. Hall Dale, Nic Lutsey. 2018. „Effects of battery manufacturing on electric vehicle life-cycle greenhouse gas emissions”. International Council on Clean Transportation. Available at: https://theicct.org/wp-content/uploads/2021/06/EV-life-cycle-GHG_ICCT-Briefing_09022018_vF.pdf.
11. Zhao Yinan, Fang Wang, Shaojun Zhang, Ye Wu, Jiming Hao. 2025. „Decarbonization potential of Chinese PHEVs: impact of increased battery range, power mix, and usage patterns”. *Energy* 331. No. 136986. ISSN: 0360-5442. DOI: <https://doi.org/10.1016/j.energy.2025.136986>.
12. Kelly, Jarod C., Elgowainy, Amgad, Isaac, Raphael, Ward, Jacob, Islam, Ehsan, Rousseau, Aymeric, Sutherland, Ian, Wallington, Timothy J., Alexander, Marcus, Muratori, Matteo, Franklin, Matthew, Adams, Jesse, & Rustagi, Neha. 2022. “Cradle-to-Grave Lifecycle Analysis of U.S. Light-Duty Vehicle-Fuel Pathways: A Greenhouse Gas Emissions and Economic Assessment of Current (2020) and Future (2030-2035) Technologies”. Argonne National Laboratory. Energy Systems Division. ANL-22/27. DOI: <https://doi.org/10.2172/1875764>.
13. Veza Ibhama, Muhammad Zacky Asy'ari, M. Idris, Vorathin Epin, I.M. Rizwanul Fattah, Martin Spraggon. 2023. „Electric vehicle (EV) and driving towards sustainability: comparison between EV, HEV, PHEV, and ICE vehicles to achieve net zero emissions by 2050 from EV”. *Alexandria Engineering Journal* 82: 459-467. ISSN: 1110-0168. DOI: <https://doi.org/10.1016/j.aej.2023.10.020>.

14. European Environment Agency. 2022. "Decarbonising Road Transport – the Role of Vehicles, Fuels and Transport Demand". *Transport and Environment Report 2022*. Copenhagen: European Environment Agency. DOI: <https://doi.org/10.2800/68902>.
15. Mroziak Małgorzata, Agnieszka Merkiś-Gurańska. 2024. „Modeling of material and energy inputs in the life cycle of a vehicle”. *Archives of Transport* 70(2): 117-136. ISSN: 0866-9546. DOI: <https://doi.org/10.61089/aot2024.vzsv6b46>.
16. Harrington E.C. 1965. „The desirability function”. *Industrial Quality Control* 21(10): 494-498.

Received 23.01.2026; accepted in revised form 03.06.2020



Scientific Journal of Silesian University of Technology. Series Transport is licensed under a Creative Commons Attribution 4.0 International License