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# Environmental life cycle assessment of selected SUV passenger cars

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*This paper primarily aimed to conduct an environmental life cycle assessment of selected SUV passenger cars. The study focused on vehicles supplied with three dissimilar drive systems: BEV, petrol-powered PHEV, and ICEV. Two time ranges were considered: one for vehicles currently in use and another for those anticipated to be registered by 2050. The research employed the LCA method. Among the life cycle stages related to production and post-use management, the highest environmental repercussions were observed for currently used BEV vehicles, while the lowest impact was associated with ICEVs projected for 2050. During the operational phase, the ICEVs from 2020 exhibited the greatest level of environmental harm, whereas the BEVs from 2050 showed the least impact.*

Key words: *life cycle assessment, SUV, ICEV, PHEV, BEV*



## 1. Introduction

The new passenger automotive market in Europe enlarges by 0.9% in 2024, representing 12,909,741 registrations. Same year, SUVs accounted for 54% of all passenger car registrations in the European market, setting a historic record for the segment's share. The total number of SUVs sold amounted to 6.92 million vehicles, representing a 4% increase compared to 2023. The most popular models in this category were compact SUVs (C-SUVs), accounting for 42% of the total number of registrations in the segment. In second place were superminis, also known as small hatchbacks, versions (B-SUVs), along with a market share of 36%. Then again, the uppermost surge was recorded in the luxury SUV segment, where registrations increased by 13%, reaching 56,300 units (Fig. 1) [23].

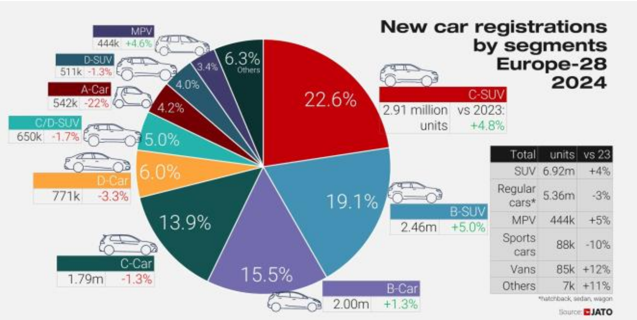


Fig. 1. New car registrations by segments (Europe-28, data for 2024) [23]

In connection with the above, the fundamental purpose of this paper was to conduct an environmental life cycle assessment of selected SUV passenger cars.

## 2. Materials and methods

### 2.1. Object and plan of the analysis

In this paper, materials and structural elements of SUV-class passenger vehicles rigged with three diverse drive systems: ICEV and PHEV as a petrol-powered representative, plus BEV. The LCA practice was chosen to assess the environmental impact. In accordance with ISO 14040 and ISO 14044 standards, it was decided that the life cycle analysis in this research shall divide the subject into the following: determination of goals and scope, life-cycle inventory, life-cycle impact assessment, and interpretation [16, 17, 25, 26, 33].

In the primary part of this paper, the purpose and spectrum of the analysis work was outlined (specifics are presented in part 2.2). During the ongoing research, the fundamental task was to assemble as much unquestionable and complete data as possible concerning the examined passenger vehicles. This task was carried out thanks to cooperation with manufacturers and recycling companies (specifics are presented in part 2.3). The following step aimed at conducting a life cycle analysis of the weighed SUV passenger vehicles. For this inquiry, calculations were created based on Sima-Pro 9.5 (with the Ecoinvent 3.9.1 database), based on the ReCiPe 2016 and IPCC 2021 models (specifics are presented in part 2.4). Acquired outcome, including thorough clarification, is given in parts 3 and 4.

### 2.2. Determination of goals and scope

The initial part of the life cycle analysis (LCA) consists of precisely defining its purpose and scope. The LCA was conducted to distinguish probable divergence in the environmental impact between three types of SUVs equipped with three different drive systems (ICEV, PHEV, BEV).

The systems of vehicles under study were designed to enable comparability in conditions of both the range and the detail of the performed research. In geographical terms, the area of the analysis aims to be a territory of Europe. The time horizon of this paper is 2020, up to 2050 (forecast). Transport processes were omitted from the analyses due to the significant variability of the potential locations of production plants and places of operation of the research objects, which could significantly disrupt the reliability of the results. A cut-off level of 0.1% was adopted in all assessments.

The studies conducted were categorized as bottom-up analyses, and that served to describe the existing reality (retrospective analysis), but also constituted a basis for modeling more sustainable solutions (prospective analysis).

Due to the high level of advancement, the conducted studies can be classified as detailed analyses. The data used was obtained directly from manufacturers and recycling companies, and when this was not possible, from SimaPro software databases. For the purposes of the conducted analyses, it was assumed that the cars would be used for an average period of 18 years. For an average annual mileage of approximately. 15,000 km/year, the range of their use was estimated at 270,000 km [3, 13, 22, 35].

## 2.3. Life-cycle inventory (LCI)

In the next phase of the appraisal, data collection and initial analysis take place. During this phase, assessable data is gathered to identify both the input and output data related to the object being tested. This is a crucial step in reaching the analysis goal and creating a life cycle model for the evaluated passenger vehicles. In this phase, input data such as energy and materials, as well as output streams such as waste and emissions, are identified and quantified [7, 28, 30, 37].

This study examined the life cycles of SUVs, focusing on the materials, energy consumption, and emissions involved in their production, operation, and end-of-life management (the so-called cradle to grave approach). In Europe, the average weight of SUVs registered in 2020 was 1537 kg. In the next 25 years, a reduction in vehicle weight by about 20% is expected. Currently, steel, polymers, and iron play a dominant role in the mass structure. Forecasts indicate that the share of high-strength steel, aluminum, and carbon fiber reinforced polymers will increase in the case of cars registered in 2050. At the same time, a decrease in the share of iron, other types of polymers, and other types of steel is expected (Fig. 2) [6, 14].

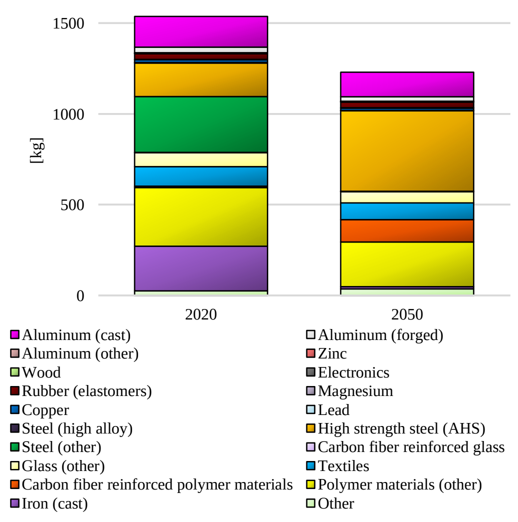


Fig. 2. Simplified material composition of SUV passenger cars registered in 2020 and 2050 (forecast) [personal study conducted through literature analysis and data gathered from manufacturers]

In the case of vehicles registered in 2020, a higher percentage of steel and iron in the total weight of the car is noticeable. Forecasts indicate that for cars to be registered in 2050, the dominant percentage will be characterized by high-strength steel and polymer materials (Fig. 3).

For battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) registered in 2020, the emission factors stemming from battery production were determined by the prevalent chemical composition, specifically NMC622 type batteries with graphite, along with the European battery market mix relevant for that period. For cars with forecast registration in 2050, the emission factors included NMC811-type graphite batteries manufactured in Europe [11].

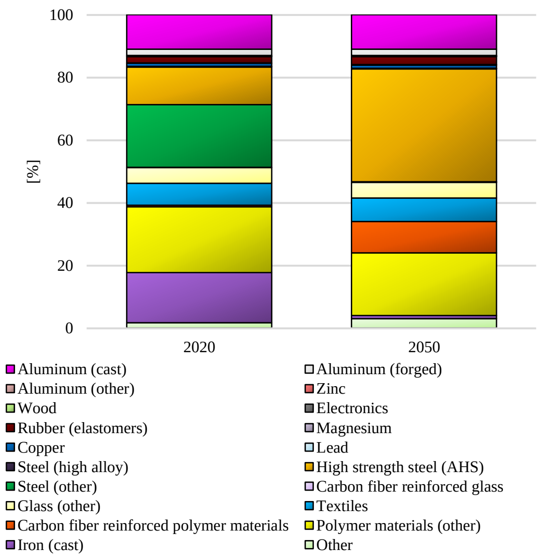


Fig. 3. Share of key materials in the construction of SUV passenger cars registered in 2020 and 2050 (forecast) [personal study conducted through literature analysis and data gathered from manufacturers]

## 2.4. Life-cycle impact assessment (LCIA)

The third phase of life cycle analysis encompasses the evaluation of the potential environmental impact associated with the subjects studied. This phase, known as life cycle impact assessment (LCIA), comprises both mandatory and optional components. The mandatory components involve the selection of impact categories, category indicators, characterization models, as well as the processes of classification and characterization. In contrast, the optional components consist of normalization, grouping, and weighting. In this research, both mandatory and optional elements were incorporated to provide a comprehensive analysis. The assessment was conducted utilizing SimaPro 9.5, supported by the Ecoinvent 3.9.1 database and the ReCiPe 2016 and IPCC 2021 models [1, 8–10].

Classification involves the process of assigning life cycle inventory (LCI) results to their corresponding impact categories. Characterization constitutes a process wherein LCI results are analyzed and converted by applying specific characterization parameters. These transformed results are subsequently expressed as relative contributions to each impact category. For this study, the ReCiPe and IPCC models were utilized to facilitate the characterization process. The normalization stage consists of relating the results of impact category indicators to established reference values. Grouping and weighting, on the other hand, are processes involving the assignment of weighting factors for each impact category and then multiplying them by the normalized values of the indicators [2, 12, 18, 32].

ReCiPe serves as one of the key models in life cycle impact assessment (LCIA), streamlining the transformation of life cycle inventory results into environmental impact indicators. These indicators quantify the potential magnitude of environmental impact across various impact categories. The model operates on two clearly delineated levels: 22 midpoint impact categories and 3 endpoint areas of influence. The midpoint categories focus on specific environmental issues, while the endpoint areas of influence represent a broader perspective of environmental effects, aggregated into three overarching dimensions: human health, ecosystem quality, and resource depletion. The ReCiPe 2016 model expresses grouping and weighting outcomes in environmental points (Pt). A total of 1000 points represents the average environmental repercussions attributed to a single individual over the span of one year [5, 15, 19, 31].

The analysis also used the IPCC 2021 GWP model, which allowed for the estimation of the greenhouse potential (GWP). This model is based on carbon dioxide as a reference compound, against which the greenhouse potential of other gases is determined. The findings from the analyses were expressed in terms of kilograms of carbon dioxide equivalent (kg $CO_2$ eq), as referenced in prior studies [21, 24, 27].

### 2.5. Interpretation

Interpretation serves not merely as the concluding phase of life cycle assessment but constitutes a fundamental component embedded within each preceding step of the process. The primary objective of this stage is to critically assess the derived results and ensure their alignment with the initially established objectives and scope of the study. Within this framework, the analysis underwent scrutiny for completeness, culminating in a favorable outcome. The results of the assessment, together with their interpretation, are presented in detail in sections 3 and 4 [4, 20, 36].

## 3. Results

### 3.1. Life cycles of materials, components, and work units

The analysis assessed the potential impact of SUV vehicles on the environment, considering three different drive systems: petrol-powered ICEV, petrol-powered PHEV, and BEV. Two distinct scenarios for managing post-consumer materials were thoroughly evaluated, focusing on two key approaches: the option of storage and the alternative strategy of recycling. Each scenario was carefully examined to understand its implications, benefits, and potential challenges in addressing waste management effectively. Two-time horizon scenarios were also adopted, covering cars registered in 2020 and a forecast referring to cars to be registered in 2050. Section 3.1 presents an assessment performed exclusively of the life cycles of materials, components and working assemblies of the vehicles considered. The results obtained for fuel and energy cycles are presented in Section 3.2.

#### 3.1.1. ReCiPe 2016

The key findings of the research, analyzed using the The ReCiPe 2016 model is expressed in units of environmental points (Pt). Figure 4 illustrates a comprehensive analysis of grouping and assigning weight to the anticipated environmental impacts associated with each stage of the life cycle for materials, components, and functional assemblies used in the production of the evaluated passenger vehicles within the SUV class. This assessment specifically excludes any environmental consequences arising from fuel consumption and energy generation processes, focusing solely on the broader materials and manufacturing systems. Passenger vehicles registered in 2020 are expected to have a more harmful effect on the environment over their lifespan than those set to be registered three decades later. When evaluating the life cycles of these vehicles, assuming they are disposed of through storage after use, their environmental impact is significantly more severe than if they were managed through recycling. The highest level of harmful impacts is noted for BEV vehicles, whose materials, components, and working assemblies would be designated for landfill ($6.21{\cdot}10^3$ Pt for those registered in 2020 and $5.22{\cdot}10^3$ Pt – in 2050). Implementing recycling practices can substantially minimize the overall negative repercussions throughout their entire lifecycle ($-5.23{\cdot}10^3$ Pt for cars from 2020 and $-4.34{\cdot}10^3$ Pt for those from 2050). The main reason for this situation was the impact on the environment of the production and post-consumer management of their batteries.

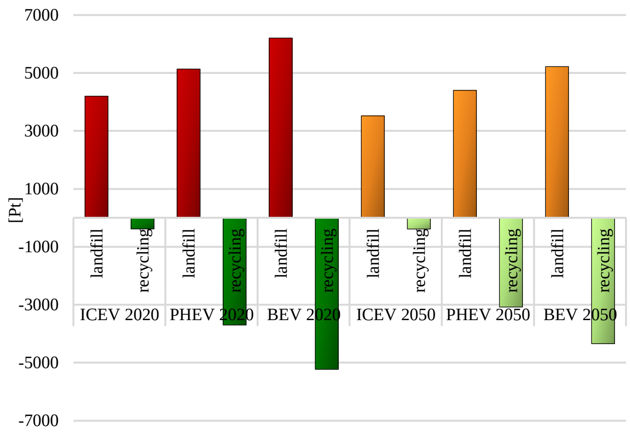


Fig. 4. The outcomes of categorizing and assigning weight to the anticipated environmental impacts throughout the life cycle of the analyzed SUV passenger vehicles, which vary based on their drive systems, while considering various post-consumer management scenarios, have been assessed using the ReCiPe 2016 model

Table 1 and Fig. 5 illustrate the outcomes of categorizing and evaluating the predicted environmental repercussions occurring throughout the life cycle of materials, components, and functional units associated with the analyzed passenger vehicles. Particular attention is given to three key impact areas: human health, ecosystems, and raw material depletion. Among these, the most significant adverse effects were identified in the areas of human health, while the least impact was observed in relation to raw material resource depletion. Notably, the life cycle of battery electric vehicles (BEVs) exhibited the highest number of negative effects, particularly when considering their storage requirements ($6.21{\cdot}10^3$ Pt for those registered in 2020 and $5.22{\cdot}10^3$ Pt – in 2050, within the realm of effects on human health, $5.81{\cdot}10^3$ Pt for cars from 2020 and $4.88{\cdot}10^3$ Pt for those from 2050). Recycling would reduce the destructive environmental consequences over their entire life cycle (–5.23·$10^3$ Pt for those registered in 2020 and –4.34·$10^3$ Pt in 2050, within the realm of effects on human health –4.62·$10^3$ Pt for cars from 2020 and –3.84·$10^3$ Pt for those from 2050). The least negative impacts were recorded in the case of ICEV life cycles.

Table 1. The outcomes of categorizing and assigning weight to the anticipated environmental impacts throughout the life cycle of the analyzed SUV passenger vehicles, which vary based on their drive systems and three areas of repercussions while considering various post-consumer management scenarios, have been assessed using the ReCiPe 2016 model [unit: Pt]

| Areas of influence | | | Human health | Ecosystems | Resources |
|---|---|---|---|---|---|
| 2020 | ICEV | landfill | 3.88·$10^3$ | 3.12·$10^2$ | 9.86·$10^0$ |
| | | recycling | –3.02·$10^2$ | –9.04·$10^1$ | 7.66·$10^0$ |
| | PHEV | landfill | 4.77·$10^3$ | 3.39·$10^2$ | 1.61·$10^1$ |
| | | recycling | –3.28·$10^3$ | –4.34·$10^2$ | 1.21·$10^1$ |
| | BEV | landfill | 5.81·$10^3$ | 3.68·$10^2$ | 2.46·$10^1$ |
| | | recycling | –4.62·$10^3$ | –6.33·$10^2$ | 1.91·$10^1$ |
| 2050 | ICEV | landfill | 3.24·$10^3$ | 2.64·$10^2$ | 8.48·$10^0$ |
| | | recycling | –3.16·$10^2$ | –7.90·$10^1$ | 6.58·$10^0$ |
| | PHEV | landfill | 4.08·$10^3$ | 2.94·$10^2$ | 1.38·$10^1$ |
| | | recycling | –2.74·$10^3$ | –3.60·$10^2$ | 1.04·$10^1$ |
| | BEV | landfill | 4.88·$10^3$ | 3.19·$10^2$ | 2.12·$10^1$ |
| | | recycling | –3.84·$10^3$ | v5.22·$10^2$ | 1.66·$10^1$ |

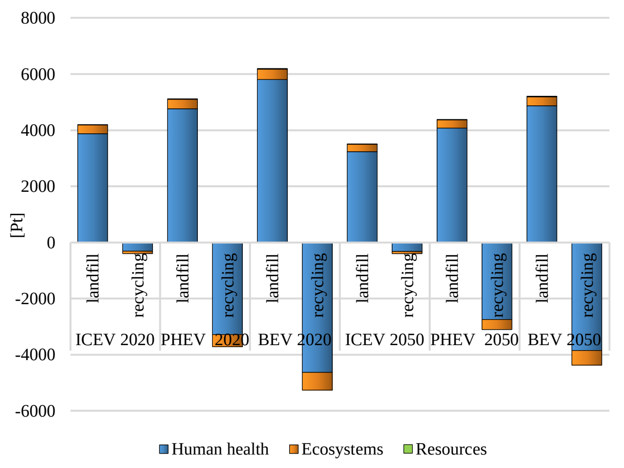


Fig. 5. Summarized outcomes of categorizing and assigning weight to the anticipated environmental impacts throughout the life cycle of the analyzed SUV passenger vehicles, which vary based on their drive systems and three areas of repercussions, while considering various post-consumer management scenarios, have been assessed using the ReCiPe 2016 model

### 3.1.2. IPCC 2021

During the second phase of the research, the IPCC 2021 model served as the foundation for analysis, with the results expressed in kilograms of $CO_2$ equivalent. Figure 6 provides a concise overview of the GHG emissions generated across the life cycles of materials, components, and operational assemblies for the examined SUV passenger vehicles. The findings highlight that the most significant environmental impacts occur when post-use waste is managed through landfill disposal, whereas the smallest impacts are observed in cases where recycling is implemented. Life cycles of vehicles to be registered in 2050 would cause lower greenhouse gas emissions compared to those in 2020. The maximum level of destructive impacts again characterized the life cycle of BEV cars, including their storage (2.00104 kg $CO_2$ eq for those registered in 2020 and 1.68104 kg $CO_2$ eq in 2050). The life cycles of all assessed vehicles, which include landfilling instead of recycling, result in higher GHG emissions. In this case, the life cycles of ICEVs also had the lowest level of hazardous environmental impact.

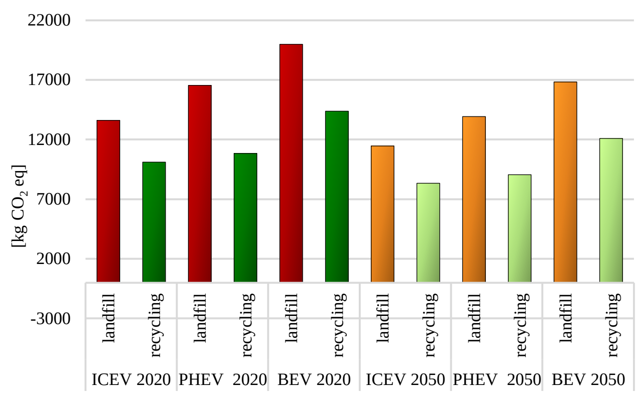


Fig. 6. Characterization results of greenhouse gas emissions throughout the life cycle of the analyzed SUV passenger vehicles, differentiated by their drive system types and considering various post-consumer management possibilities, have been evaluated based on the IPCC 2021 model

### 3.2. Fuel and energy cycles

During the next phase of the research, a comprehensive analysis was conducted on the fuel and energy life cycles for all the vehicles assessed in the study. This analysis was carefully framed within the context of two separate future time scenarios: one set in the year 2020 and the other projected for 2050. Within this timeframe, the GHG emissions associated with these fuel and energy cycles were systematically divided into two primary stages, allowing for a more structured and detailed examination of their environmental repercussions. The initial phase, known as well-to-tank (WTT), involves the comprehensive process of producing fuel and generating electricity, covering a wide range of activities from start to finish. This stage begins with the creation or extraction of the primary energy source, whether it be petroleum-based fuels like petrol and diesel or other forms of energy such as electricity. It extends through various intermediate steps, culminating in the efficient delivery of the fuel to its intended destination. This destination could range from an electric vehicle charging station to a fuel distributor or supplier, ensuring the necessary resources are made available for subsequent use. The second stage in the process, commonly referred to as tank-to-wheel (TTW), specifically addresses the emissions generated directly from the combustion of fuel. This phase begins at the moment when the energy, in its usable form, is accessed, whether sourced from a charging station supplying electricity or a fuel distributor providing gasoline or diesel, and concludes with the energy being expended during vehicle operation. At its core, this stage encapsulates the quantity of fuel consumed by the vehicle and the resulting emissions released as a consequence of driving. The analytical framework for this study was structured using the IPCC 2021 model. Within this framework, the outcomes of the analysis were quantified and presented in terms of kilograms of carbon dioxide equivalent (kg $CO_2$ eq), providing a standardized metric for assessing environmental impact.

Vehicles registered during the year 2020 are notable for exhibiting significantly higher levels of greenhouse gas emissions throughout their fuel production and energy consumption cycles when compared to the anticipated emissions of vehicles that are expected to be registered by the year 2050. This difference underscores the gradual shift toward more sustainable and environmentally friendly transportation technologies and practices projected to evolve over the coming decades. The maximum total level of greenhouse gas emissions was recorded for ICEVs, while the minimum – for BEVs. For example, cars with an internal combustion engine, the TTW stage covering emissions from fuel combustion causes more destructive environmental consequences compared to the WTT stage, taking into account the production of the above types of fuels. PHEVs registered in 2020 generate more GHG as part of the WTT stage, and those to be registered in 2050 – during the TTW stage. Changes in the European energy mix would reduce the level of greenhouse gas emissions over the next 30 years for BEVs (Fig. 7).

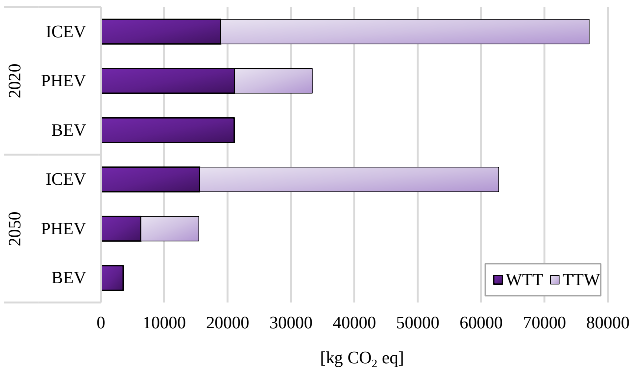


Fig. 7. Analysis of greenhouse gas emissions across the fuel and energy life cycles for SUV passenger vehicles with varying drive systems under different time horizon possibilities has been conducted, including assessments of emissions from the fuel and electricity production phase (WTT) as well as those resulting from fuel combustion during vehicle operation (TTW), based on the IPCC 2021 model

Balancing environmental priorities, it is crucial to address the levels of harmful emissions generated during both the production and consumption phases of fuel and electricity, commonly categorized as well-to-tank (WTT) and tank-to-wheel (TTW) emissions. Equally significant, however, is the need to mitigate destructive environmental impacts stemming from other key lifecycle stages, namely production (P), maintenance (M), and end-of-life (EoL) processes. Recognizing this dual importance, further in-depth analyses of greenhouse gas emissions across all these stages were undertaken to ensure a more comprehensive understanding and targeted approach to emission reduction.

The life cycle analysis reveals that internal combustion engine vehicles (ICEVs) exhibit the highest total greenhouse gas (GHG) emission levels, reflecting significant environmental drawbacks. For vehicles registered in both 2020 and 2050, the tank-to-wheel (TTW) phase emerges as the primary contributor to these harmful emissions, underscoring its critical environmental impact. Conversely, battery electric vehicles (BEVs) achieve the lowest cumulative GHG emission levels across their life cycle, demonstrating their relative advantage in reducing emissions. For BEVs registered in 2020, the emission levels during both the production and operation phases show a roughly comparable contribution to the overall carbon footprint. However, for vehicles set to be registered three decades later in 2050, a notable shift is expected. By this time, advances in technology and cleaner energy sources will likely result in significantly reduced emissions during the operation phase, while production remains the dominant source of GHG releases within the BEV life cycle. Overall, SUVs registered in 2050 are projected to produce lower total greenhouse gas emissions than those registered in 2020. However, for SUVs from 2020, the operation phase contributes substantially more to the intensification of the greenhouse effect compared to their production phase. This distinction clearly illustrates the evolving dynamics in vehicle lifecycle emissions and the environmental benefits of transitioning to more sustainable vehicular technologies (Fig. 8).

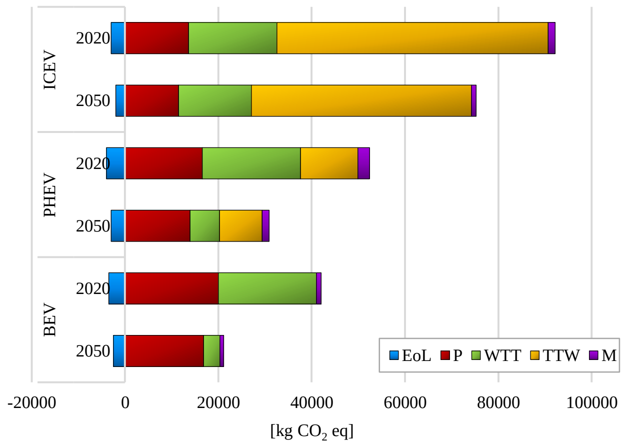


Fig. 8. Life cycle greenhouse gas emissions for analyzed SUV passenger vehicles, varying by drive system, were assessed across different time horizon scenarios, while key stages considered include: end-of-life (EoL), production (P), fuel/electricity production (WTT), fuel combustion emissions (TTW), and maintenance (M), using the IPCC 2021 model

## 4. Summary and conclusions

SUVs are the most frequently purchased cars on the European market. Depending on the drive system used, their life cycle has a different level of impact on the environment. Transport is the only sector of the economy where greenhouse gas emissions are increasing rather than decreasing. In particular, light vehicles, including passenger cars, represent a large part (approx. 50%) of energy demand in the transport sector [29, 34].

The study successfully accomplished its primary goal by performing an environmental life cycle assessment of selected SUV passenger cars. This assessment focused on internal combustion engine vehicles (ICEV) and plug-in hybrid electric vehicles (PHEV) using gasoline, as well as battery electric vehicles (BEV). It considered two scenarios for post-use management: storage and recycling, alongside two different temporal contexts: one for vehicles currently in use and another for those expected to be registered by 2050. The analyses were conducted using the life cycle assessment (LCA) method, including the ReCiPe 2016 model and IPCC 2021 guidelines.

Based on the obtained results, the following relationships were noted:

- all SUVs registered in the year 2020 contribute notably more to environmental degradation when compared to the SUVs anticipated to be registered by 2050. This significant disparity is primarily evident in their higher greenhouse gas emissions. The data highlights the environmental progress anticipated in vehicle technology and regulatory standards over these three decades, reflecting efforts to minimize the ecological footprint of future SUV models (Table 1, Fig. 4–6)
- Life cycles that rely on post-use management strategies, such as landfilling rather than adopting recycling methods, contribute to significantly more harmful environmental impacts. This approach leads to higher levels of GHG emissions, exacerbating climate change and putting additional strain on ecological systems. By depositing waste into landfills instead of processing materials for reuse, valuable resources are squandered, and the potential for reducing energy consumption and pollution through recycling is lost. Furthermore, the long-term effects of landfill accumulation, including soil and water contamination, further amplify ecological degradation, making this practice an unsustainable option for waste management (Table 1, Fig. 4–6)
- The maximum level of total destructive impacts was recorded for the BEV life cycle, assuming their storage after the end of their use. Recycling would enable a significant reduction of hazardous repercussions in the perspective of their whole life cycle (Fig. 4)
- The most significant number of adverse effects was observed regarding the influence of all tested SUVs on human health, highlighting a critical area of concern. In contrast, the smallest impact was identified in relation to the depletion of raw material resources, indicating a comparatively minor issue in this particular domain (Table 1, Fig. 5)
- Across all examined time horizons and end-of-life scenarios, internal combustion engine vehicles (ICEVs) powered by gasoline consistently result in higher greenhouse gas emissions when compared to vehicles with alternative drive systems. This holds true particularly when assessing their impact based on fuel production and energy consumption cycles (Fig. 7–8)
- The lowest total GHG emissions are noted for the life cycle of BEVs due to be registered in 2050 (Fig. 7–8)
- In the case of ICEV, the TTW stage causes more greenhouse gas emissions compared to the WTT stage (Fig. 7–8)
- BEVs do not cause GHG emissions in the TTW area because they are powered by electricity. From the perspective of the next 30 years, the level of GHG emissions in the scope of their WTT will decrease if the assumed changes in the European energy mix are implemented, among others, by expanding the share of renewable sources in energy production.

Based on the foregoing considerations, it becomes evident that for all evaluated SUV class vehicles, it is essential to implement targeted strategies designed to mitigate their adverse effects while enhancing their beneficial contributions to the environment. For internal combustion engine vehicles (ICEVs), these efforts should predominantly focus on reducing environmental impact during their operational phase. Meanwhile, for battery electric vehicles (BEVs), the primary emphasis should be placed on addressing environmental concerns arising during their production process.

In today's rapidly evolving automotive industry, it is becoming increasingly imperative to address the significant challenges related to reducing both material and energy consumption alongside minimizing harmful emissions throughout every stage of the life cycle of SUV class vehicles. This includes the design, manufacturing, usage, and eventual disposal phases. To accomplish this, there is a pressing need to significantly enhance the proportion of renewable energy sources integrated into these life cycles, particularly during the stages where battery electric vehicles (BEVs) and plug-in hybrid electric vehicles (PHEVs) are in operation. Moreover, continuous efforts are required in researching and developing materials and vehicle components that are not only environmentally sustainable but also economically feasible. These materials must meet rigorous standards of quality while maintaining desirable mechanical and technical parameters essential for their specific roles within various operational systems. Additionally, advancing battery technology remains a cornerstone of this sustainability drive. It is crucial to focus on creating batteries that are not only more efficient in terms of energy storage and usage but also possess an extended service life. These batteries should ideally be constructed from materials that allow for easy recycling, thereby supporting a circular economy and reducing environmental repercussions.

BEVs have the potential to significantly diminish GHG emissions in the coming years if powered by renewable energy sources. In this case, they have around 80% lower life-cycle greenhouse gas emissions than their combustion-powered counterparts.

The relationship between cars and their impact on the surrounding environment is intricately multifaceted, presenting a challenging task in evaluating the full extent of their environmental consequences. Addressing these challenges in search of an optimal solution requires a multi-pronged approach. This process involves designing vehicles with features and structural elements that harmonize with the goal of producing a high-quality product while simultaneously focusing on refining operational and production processes. These refinements must aim to minimize energy consumption and material usage throughout every phase of the vehicle's life cycle, from initial manufacturing through its ultimate disposal or recycling.

## Nomenclature

| | |
|---|---|
| BEV | battery electric vehicles |
| EoL | end-of-life |
| GHG | greenhouse gas |
| GWP | global warming potential |
| ICEV | internal combustion engine vehicles |
| LCA | life cycle assessment |
| LCI | life cycle inventory |
| LCIA | life cycle impact assessment |
| M | maintenance |
| P | production |
| PHEV | plug-in hybrid electric vehicles |
| SUV | sport utility vehicle |
| TTW | tank-to-wheel |
| WTT | well-to-tank |

## Bibliography


[1] Bałdowska-Witos P, Piasecka I., Flizikowski J, Tomporowski A, Idzikowski A, Zawada M. Life cycle assessment of two alternative plastics for bottle production. Materials. 2021;14:4552. https://doi.org/10.3390/ma14164552

[2] Bare JC, Hofstetter P, Pennington DW, Udo de Haes HA. Midpoints versus endpoints: the sacrifices and benefits. Int J Life Cycle Assess. 2000;5:319-326. https://doi.org/10.1007/BF02978665

[3] Bäumer M, Hautzinger H, Pfeiffer M, Stock W, Lenz B, Kuhnimhof T et al. Driving performance survey – domestic mileage. Document of the Federal Road Research Institute (Bundesanstalt für Straßenwesen). Brema 2017. https://www.bast.de/DE/Publikationen/Berichte/unterreihe-v/2018-2017/v290.html

[4] Curran MA. Interpretation, critical review and reporting in life cycle assessment. Springer. Cham 2023. https://doi.org/10.1007/978-3-031-35727-5

[5] Dekker E, Zijp MC, van de Kamp ME, Temme EHM, van Zelm R. A taste of the new ReCiPe for life cycle assessment: consequences of the updated impact assessment method on food product LCAs. Int J Life Cycle Assess. 2020;25:2315-2324. https://doi.org/10.1007/s11367-019-01653-3

[6] Díaz S, Mock P, Bernard Y, Bieker G, Pniewska I, Ragon PL et al. European vehicle market statistics 2020/21. International Council on Clean Transportation Document. Beijing – Berlin – Brussels – San Francisco – Washington 2020. https://theicct.org/publication/european-vehicle-market-statistics-2020-21/

[7] Finkbeiner M, Inaba A, Tan R, Christiansen K, Klüppel HJ. The New International Standards for Life Cycle Assessment: ISO 14040 and ISO 14044. Int. J. Life Cycle Assess. 2006;11:80-85. https://doi.org/10.1065/lca2006.02.002

[8] Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S et al. Recent developments in life cycle assessment. J. Environ. Manag. 2009;91(1):1-21. https://doi.org/10.1016/j.jenvman.2009.06.018

[9] Fukushige S, Kobayashi H, Yamasue E, Hara K. Ecodesign for sustainable products, services and social systems II. Springer. Singapore 2024. https://doi.org/10.1007/978-981-99-3897-1

[10] Guinée J. Handbook on life cycle assessment: operational guide to the ISO standards. Springer. Dordrecht 2002. https://doi.org/10.1007/0-306-48055-7

[11] Harlow JE, Ma X, Li J, Logan E, Liu Y, Zhang N et al. A wide range of testing results on an excellent lithium-ion cell chemistry to be used as benchmarks for new battery technologies. J Electrochem Soc. 2019;166(13):3031-3044. https://doi.org/10.1149/2.0981913jes

[12] Hauschild MZ, Goedkoop M, Guinée J, Heijungs R, Huijbregts M, Jolliet O et al. Identifying best existing practice for characterization modeling in life cycle impact assessment. Int J Life Cycle Assess. 2013;18:683-697. https://doi.org/10.1007/s11367-012-0489-5

[13] Hesser F, Kral I, Obersteiner G, Hörtenhuber S, Kühmaier M, Zeller V et al. Progress in life cycle assessment. Springer. Cham 2021. https://doi.org/10.1007/978-3-031-29294-1

[14] Hill N, Amaral S, Morgan-Price S, Nokes T, Bates J, Helms H et al. Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA. Ricardo-AEA, IFEU and E4tech document for the European Commission. Brussels 2020. https://op.europa.eu/en/publication-detail/-/publication/1f494180-bc0e-11ea-811c-01aa75ed71a1

[15] Huijbregts MAJ, Steinmann ZJN, Elshout PMF, Stam G, Verones F, Vieira M et al. ReCiPe2016: a harmonised life cycle impact assessment method at midpoint and endpoint level. Int J Life Cycle Assess. 2017;22:138-147. https://doi.org/10.1007/s11367-016-1246-y

[16] ISO 14040:2006. Environmental Management – Life Cycle Assessment – Principles and Framework. International Organization for Standardization. Geneva. Switzerland. 2006.

[17] ISO 14044:2006. Environmental management – Life Cycle Assessment – Requirements and Guidelines. International Organization for Standardization. Switzerland. Geneva 2006.

[18] Jolliet O, Müller-Wenk R, Bare J, Brent A, Goedkoop M, Heijungs R et al. The LCIA midpoint-damage framework of the UNEP/SETAC life cycle initiative. Int J Life Cycle Assess. 2004;9:394-404. https://doi.org/10.1007/BF02979083

[19] Kjaer LL, Pigosso DCA, McAloone TC, Birkved M. Guidelines for evaluating the environmental performance of product/service-systems through life cycle assessment. J Clean Prod. 2018;190:666-678. https://doi.org/10.1016/j.jclepro.2018.04.108

[20] Kłos Z. Ecobalancial assessment of chosen packaging processes in food industry. Int J Life Cycle Assess. 2002;7:309. https://doi.org/10.1007/BF02978894

[21] Masson-Delmotte V, Zhai P, Pirani A, Connors SL, Péan C, Berger S et al. IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge. Cambridge University Press 2021. https://doi.org/10.1017/9781009157896

[22] Mehlhart G, Möck A, Goldman D. Effects on ELV waste management as a consequence of the decisions from the Stockholm Convention on decaBDE. Öko-Institut Document. Fryburg 2018. https://www.oeko.de/fileadmin/oekodoc/ACEA-DecaBDE-final-report.pdf

[23] Munoz F. European new car market growth in 2024 driven by hybrids and Chinese brands. https://www.jato.com/resources/media-and-press-releases/european-new-car-market-growth-in-2024-driven-by-hybrids-and-chinese-brands?utm_content=324341353&utm_medium=social&utm_source=facebook&hss_channel=fbp-141752974736982 (accessed on April 15, 2025).

[24] Muñoz I, Schmidt JH. Methane oxidation, biogenic carbon, and the IPCC's emission metrics. Proposal for a consistent greenhouse-gas accounting. Int J Life Cycle Assess. 2016; 21:1069-1075. https://doi.org/10.1007/s11367-016-1091-z

[25] Muthu SS. Life cycle sustainability assessment (LCSA). Springer. Singapore 2021. https://doi.org./10.1007/978-981-16-4562-4

[26] Nakamura S. A practical guide to industrial ecology by input-output analysis. Springer. Cham 2023. https://doi.org/10.1007/978-3-031-43684-0

[27] Nalau J, Gilmore E, Howden M. Improving adaptation assessment in the IPCC. NJP Clim Action. 2024;3:76. https://doi.org/10.1038/s44168-024-00155-9

[28] Palousis N, Luong L, Abhary K. An integrated LCA/LCC framework for assessing product sustainability risk. WIT Press. Southampton 2008. https://doi.org/10.2495/RISK080131

[29] Piasecka I, Tomporowski A, Piotrowska K. Environmental analysis of post-use management of car tires. Przem Chem. 2018;97(10):1649-1653. https://doi.org/10.15199/62.2018.10.4

[30] Proske M, Finkbeiner M. Obsolescence in LCA–methodological challenges and solution approaches. Int J Life Cycle Assess. 2020;25:495-507. https://doi.org/10.1007/s11367-019-01710-x

[31] Rashedi A, Khanam T. Life cycle assessment of most widely adopted solar photovoltaic energy technologies by mid-point and end-point indicators of ReCiPe method. Environ Sci Pollut Res Int. 2020;27:29075-29090. https://doi.org/10.1007/s11356-020-09194-1

[32] Reap J, Roma F, Duncan S, Bras B. A survey of unresolved problems in life cycle assessment. Int J Life Cycle Assess. 2008;13:290-300. https://doi.org/10.1007/s11367-008-0008-x

[33] Schmidt WP. Solutions for sustainability challenges. technical sustainability management and life cycle thinking. Springer. Cham 2024. https://doi.org/10.1007/978-3-031-63624-0

[34] Sikora A. European Green Deal – legal and financial challenges of the climate change. ERA Forum. 2021;21:681-697. https://doi.org/10.1007/s12027-020-00637-3

[35] Stoffels P, Kaspar J, Baehre D, Vielhaber M. Holistic material selection approach for more sustainable products. Procedia Manuf. 2017;8:401-408. https://doi.org/10.1016/j.promfg.2017.02.051

[36] Suppipat S, Chotiratanapinun T, Teachavorasinskun K, Hu AH. Design for enhancing eco-efficiency of energy-related products. The integration of simplified LCA tools in industrial design education. Springer. Cham 2023. https://doi.org/10.1007/978-3-031-15060-9

[37] Wang S, Su D. Sustainable product innovation and consumer communication. Sustainability. 2022;14:8395. https://doi.org/10.3390/su14148395



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