LIFE CYCLE ASSESSMENT

BATTERY MANAGEMENT SYSTEM

PULSETRAIN

As the first European venture capital fund, Planet A relies on its own scientific team to assess the environmental and climate impact of an innovation. Prior to an investment, a life cycle assessment, like this one, is conducted and integral part of the investment decision. All assessments as well as the methodology are published for maximum transparency.

Terminology, units and abbreviations

ADP	Abiotic Depletion Potential
BEV (or EV)	Battery Electric Vehicles (or Electric Vehicles)
BMS	Battery Management System
CO_2	Carbon dioxide
CO_2-eq.	Carbon dioxide equivalents
EoL	End of Life
EU	European Union
EF	Emission factor
Functional unit	Quantified performance of a product system for use as a reference unit
g	Gram
GHG	Greenhouse gas
ICE	Internal Combustion Engine
IEA	International Energy Agency
kg	Kilogram
kWh	Kilowatt-hour
km	Kilometre
LCA	Life Cycle Assessment
Mt	Million tonnes
t CO_2-eq.	tonne Carbon dioxide equivalents

About Pulsetrain

Pulsetrain is a German seed-stage startup pioneering innovative inverter and battery management system (BMS) technology to address today's electric vehicles (EV) challenges across multiple industries like construction, two-wheelers and automobiles. It is paving the way for the industry to accelerate the electric transition more efficiently and sustainably.

Version 1 - November 27, 2024

Summary

The transport sector poses a significant challenge in reducing greenhouse gas (GHG) emissions as it accounts for a staggering 30% of total global energy use and 23% of global CO_2 emissions (REN21 2023; UNECE 2024) - and emissions are still increasing (IEA 2023a).

While battery electric vehicles (BEVs) offer a promising solution for decarbonising the sector, their widespread adoption is hindered by several bottlenecks. Key barriers to electric vehicle (EV) adoption include limited charging infrastructure, concerns about vehicle range, and high upfront costs. Additionally, EV batteries' performance and efficiency remain challenging, affecting consumer confidence and overall vehicle practicality.

Pulsetrain's advanced Battery Management Systems (BMS), namely; Cellmate BMS and Pulsetrain BMS, offer a promising solution to address these challenges. More efficient BMS can revolutionise the EV industry by significantly improving powertrain efficiency (reducing power consumption), extending battery life (increasing material efficiency), and ultimately accelerating the transition to sustainable transportation. This innovation not only addresses range anxiety but also has the potential to decrease production and lifetime costs, making EVs more accessible to a broader consumer base.

In this study, we assessed the environmental impact of EVs over internal combustion engine (ICE) vehicles and the impact of Pulsetrain's Battery Management Systems over a standard BMS across three different industries and geographical regions.

In the global construction industry: The impact of deploying electric excavators over ICE (diesel) excavators in 2025 and 2034 (at normalised lifetimes for different technologies) and the impact when using Pulsetrain's BMS instead of Standard BMS, is shown below:

Year of deployment	Emission reduction over ICE excavator			Emission reduction over Standard BMS	
	Standard BMS	Cellmate BMS	Pulsetrain BMS	Cellmate BMS	Pulsetrain BMS
2025	95.3%	95.7%	96.6%	0.4%	51.1%
2034	96.3%	96.6%	97.3%	0.2%	50.6%

The substantially higher potential for a reduction in GHG emissions in the Pulsetrain BMS over the Cellmate BMS is due to them prolonging the operational lifetime of excavators and thus increasing powertrain (energy consumption) efficiency.

In the global automotive industry: The impact of deploying BEVs over average ICE (petrol and diesel) cars in 2025 and 2034 and the impact when using Pulsetrain's BMS instead of Standard BMS, is shown below:

Year of deployment	Emission reduction over ICE car			Emission reduction over Standard BMS	
	Standard BMS	Cellmate BMS	Pulsetrain BMS	Cellmate BMS	Pulsetrain BMS
2025	54.9%	57.7%	62.0%	5.2%	13.0%
2034	61.0%	63.0%	66.6%	3.3%	9.2%

- In the two-wheeler industry (Indian case study): The impact of deploying BEV two-wheelers over average ICE (petrol) two-wheelers in 2025 and 2034 and the impact when using Pulsetrain's BMS instead of Standard BMS, is shown below:

Year of deployment	Emission reduction over ICE two-wheeler			Emission reduction over Standard BMS	
	Standard BMS	**Cellmate BMS**	**Pulsetrain BMS**	**Cellmate BMS**	**Pulsetrain BMS**
2025	56.2%	60.4%	65.0%	7.4%	15.6%
2034	67.0%	69.6%	73.0%	4.0%	9.1%

The higher GHG emission reduction potential in the Pulsetrain BMS for both automotive and two-wheeler industries is due to the prolonged battery lifetime, which avoids battery replacement as well as the increased powertrain efficiency, leading to lower energy consumption. The decrease in the GHG emission reduction potential over the years, on the other hand, is due to the greening of the future electricity mix leading to lower embodied emissions in electricity consumed.

About this study

This study explores the significance of transitioning to battery-operated systems in the transport sector to support the global energy transition. It examines the impact of replacing internal combustion engine (ICE) vehicles with battery electric vehicles (BEVs) across various industries, with a particular focus on Pulsetrain's battery management systems (BMS) in the construction, two-wheelers, and automotive industries. The methodology used in the study, including the modelling of energy systems and the case study of European cars, is explained in the report. Finally, the study presents the results along with a discussion of the variables not considered in the study and the limitations.

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1. Introduction

The increasing concern over global warming, depletion of natural resources and biodiversity loss has brought into focus the significant challenges posed by internal combustion engine (ICE) vehicles. ICE vehicles, which primarily rely on fossil fuels, are responsible for a large portion of the world's energy demand and are major contributors to greenhouse gas emissions. The transport sector accounts for a staggering 30% of total global energy use and 23% of global CO_2 emissions. 78% of transport energy use (i.e. around 23.5% of total energy use) and 69% of transport sector GHG emissions (i.e. around 16% of total GHG emissions) stem from road transport (IRENA 2022; REN21 2023; UNECE 2024). In addition to carbon dioxide (CO_2), ICE vehicles emit other harmful pollutants, including nitrogen oxides (NOx), particulate matter (PM), and volatile organic compounds (VOCs), which contribute to air pollution and adverse public health outcomes (Ramacher et al. 2020). Furthermore, construction machines worldwide which run on diesel-powered ICE, emit around 400 Mt CO_2 annually, equivalent to the emissions from international aviation. Excavators alone account for 50% of these emissions (Chick 2023).

The need for an efficient transition

To address these critical issues a transition toward battery-electric vehicles (BEVs) is essential. BEVs, which are powered by electricity stored in batteries, represent a cleaner alternative, particularly when coupled with renewable energy sources such as wind, solar, and hydropower. The shift to BEVs has the potential to significantly reduce the transport sector's reliance on fossil fuels and their associated emissions. Declining costs of battery technology have accelerated the adoption of electric vehicles globally (Goldman Sachs 2024). Coupled with recent policy initiatives, such as The European Green Deal and U.S. Inflation Reduction Act 2022, BEV sales are expected to see exponential growth in the long term. Many countries have set ambitious targets for phasing out ICE vehicles in favour of BEVs. For instance, the EU aims to register only zero-emission vehicles from 2035 (BMUV 2023), Japan aims for 20-30% of all car sales to be BEVs and plug-in hybrid electric vehicles (PHEVs) by 2030, while the USA plans for 50% of new vehicles to be zero-emission by the same year (Whitlock 2024).

While the shift to BEVs represents a significant step towards sustainable transportation (and construction), there is a pressing need to make this transition more efficient and sustainable in terms of energy and material consumption. This is driven by several factors:

1. Resource Demand: The production of EVs, particularly their batteries, requires significant amounts of raw materials including critical metals like lithium, cobalt, and nickel, which pose environmental and social challenges. A recent study projects that the raw material demand for electric vehicles will triple by 2050. This increase in demand raises concerns about resource depletion, supply chain vulnerabilities, and the environmental impact of material extraction (Takimoto et al. 2024).

2. Lifecycle Emissions: Although BEVs produce zero tailpipe emissions, their overall environmental impact depends on factors such as the source of electricity used for charging and the emissions associated with battery production. Improving the efficiency of BEVs can help reduce their lifecycle emissions.

3. Economic Factors: Despite decreasing costs, EVs are still generally more expensive than comparable ICE vehicles. Improving efficiency and reducing material requirements can help make BEVs more affordable and accelerate their adoption.

4. Energy Efficiency: While EVs are more energy-efficient than ICE vehicles, there is still room for improvement. Enhancing the performance of the powertrain using battery management systems can lead to increased range, reduced charging times, and overall better performance of EVs.

5. Grid Integration: As EV adoption increases, there will be growing pressure on electrical grids. More efficient EVs can help mitigate this impact and potentially even contribute to grid stability through vehicle-to-grid technologies.

In light of these challenges and opportunities, there is a clear need for continued innovation in EV technology. The cost of a battery pack is about 41% of the cost of the BEV (Figure 1). Thus, focusing on the BMS has great potential to address these challenges.

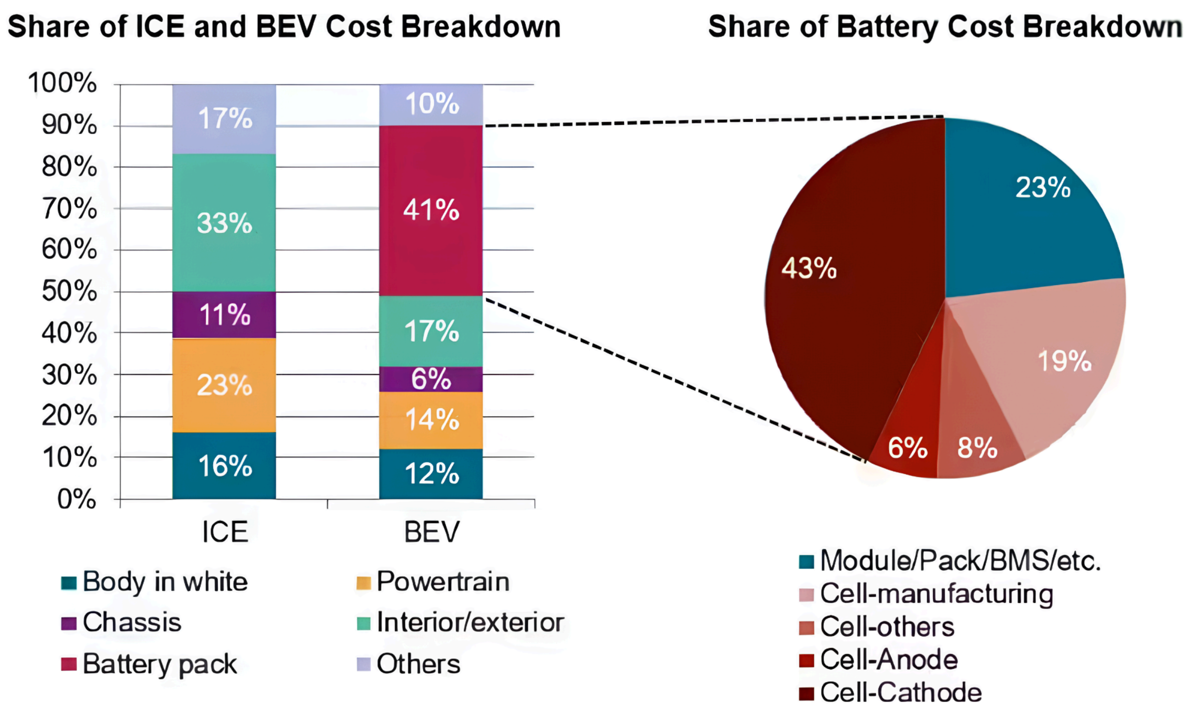


Figure 1: *Cost Breakdown of ICE and BEVs (Source: S&P Global Mobility Whitepaper 2023)*

A more advanced BMS can optimise battery performance, extend the lifespan of batteries, and improve energy efficiency, thereby reducing the overall environmental impact of EVs. Efficient BMS can also facilitate the integration of secondary-use applications, such as repurposing batteries for energy storage in stationary applications after their automotive life. By improving both the energy efficiency and material sustainability of EVs, innovations in BMS play a crucial role in accelerating the transition to a more sustainable transportation system.

2. Methods

This study assesses the impact of Pulsetrain's Battery Management Systems across different industries by considering the electricity mixes and the effect on lifecycle material consumption.

2.1. System description

This Life Cycle Assessment (LCA) study aims to assess the potential environmental impact of BEVs over ICE vehicles with a particular focus on deploying Pulsetrain's BMS, increasing powertrain efficiency and battery lifetime of EVs, compared to standard BMS technology across different industries; namely construction, automotive and two-wheelers. The system boundaries for all sectors are presented in Figure 2.

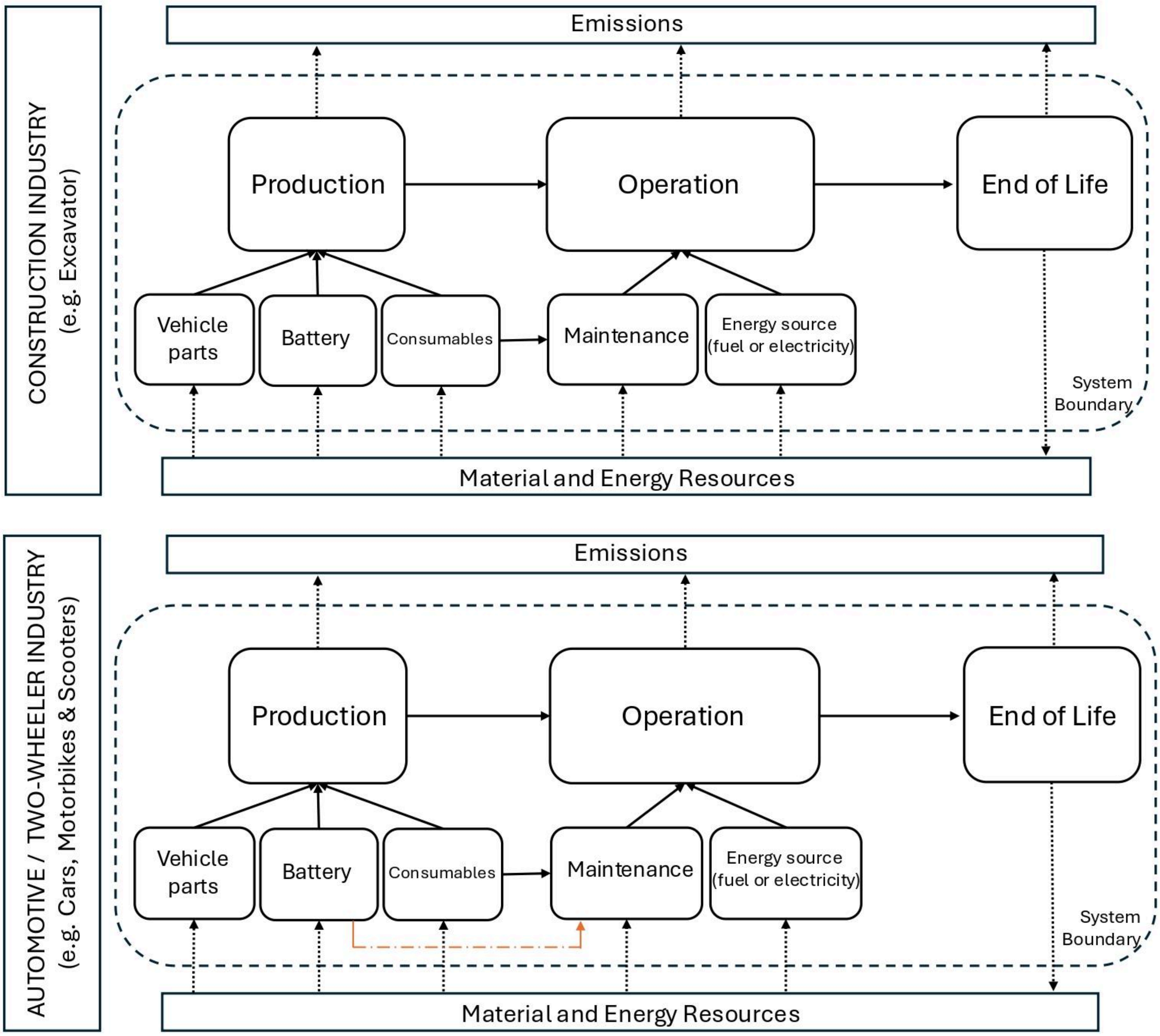


Figure 2: *System boundaries for construction, automotive and two-wheeler industries (The "Brown" line connecting the battery to maintenance in the automotive/ Two-wheeler industry system boundary indicates that battery replacement is a part of the maintenance of only some cases presented in this study).*

It is important to note that in reference to the EVs, this study focuses solely on the operational emission reduction resulting from deploying Pulsetrain's Battery Management Systems vs standard BMS; the difference in embodied emissions from the manufacturing of the BMS hardware is not considered due to two reasons: 1) lack of material and component data around the incumbent standard BMS systems being replaced by Pulsetrain and, 2) the impact of embodied emissions from the printed circuit board & electronic components installed on it is negligible compared to the lifetime energy and resource consumption in the EVs. Therefore, the results present lifetime emissions of ICE and BEV vehicles along with the emission reduction offered by Pulsetrain's BMS over standard BMS over their lifetime in different industries.

The two BMS from Pulsetrain evaluated in the study are:

1. **CellMate:** This is a basis BMS that provides a 14% powertrain efficiency improvement over a standard BMS.

2. **Pulsetrain:** This is a multilevel BMS capable of individually operating different cells in a battery pack. Thus, providing a 25% powertrain efficiency improvement compared to a Standard BMS and offering a 50% battery lifetime increase. Additionally, it also removes the need for a separate charger module, inverter and junction box, leading to about 120 kg weight reduction in the car.

For the construction industry, we analyse a 26-tonne excavator, for the automotive industry, we consider an average car, whereas for the two-wheelers we consider an average of scooters and motorbikes.

2.1.1. Functional unit and assessed indicators

This LCA comprises two types of vehicles, Internal Combustion Engine vehicles and Battery Electric Vehicles across the construction, automotive and two-wheeler industries. The BEVs have been further classified into three types based on the deployed BMS; a standard BMS and the two BMS by Pulsetrain. The functional unit used for the study is the complete life cycle of an ICE and battery electric vehicle over their respective lifetime in different industries, using different types of BMS.

The system was assessed using the indicator **global warming potential** from ReCiPe Midpoint (H) V1.1 (Huijbregts et al. 2017) for the construction industry. For the automotive and two-wheeler industries we used the indicator **climate change** based on IPCC 2013 (Stocker et al. 2014) for the assessment.

2.1.2. Data use

This study uses scientific literature and reports for referencing for ICE and standard BEVs across different industries; namely, construction i.e. excavator (Khan et al. 2023; Pérez 2022; Relion 2019), automotive (Bieker 2021; Dillman et al. 2020; Odysee mure 2019) and two-wheelers i.e. scooter & motorbikes (Anup et al. 2021; BGauss 2024; MORTH 2022). Global, EU and Indian average electricity mixes were modelled as explained in Section 2.2 of this report.

While the scientific literature and reports are based on the latest technology, they do not provide any disaggregated life cycle inventory data. This limits our ability to assess different impact indicators.

In updates of this LCA report, other indicators concerning material resource use, etc. will be assessed contingent on the availability of good quality and disaggregated life cycle inventory data.

2.1.3. Temporal scope

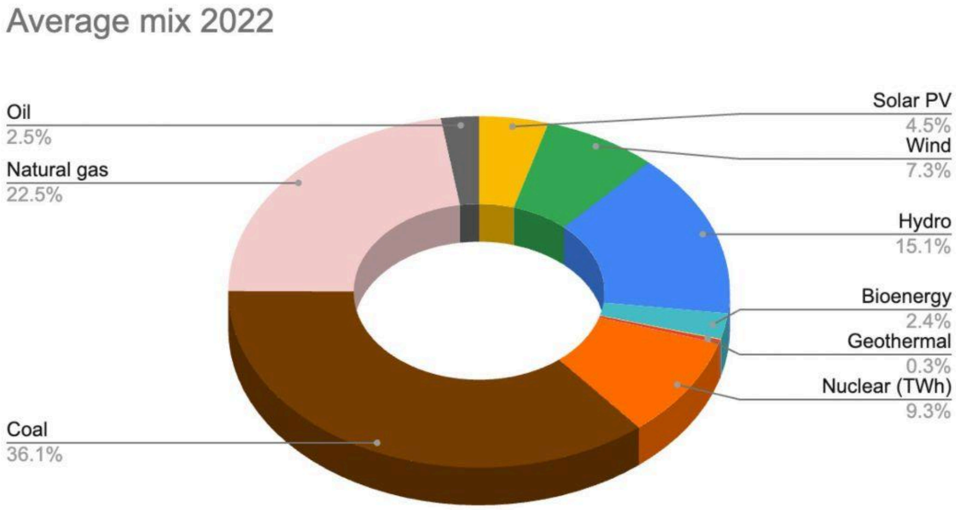
We evaluate the net change in the environmental impact of deploying Pulsetrain's systems over the next 10 years i.e. impact over the entire lifetime of the vehicles deployed between 2025 and 2034. Table 1 describes the operational life cycle of different vehicles (based on literature and policy information from Anup et al. 2021; Bieker 2021; Khan et al. 2023 etc.). The energy mix was projected into the future accordingly to cover the full operational lifetime of the vehicles.

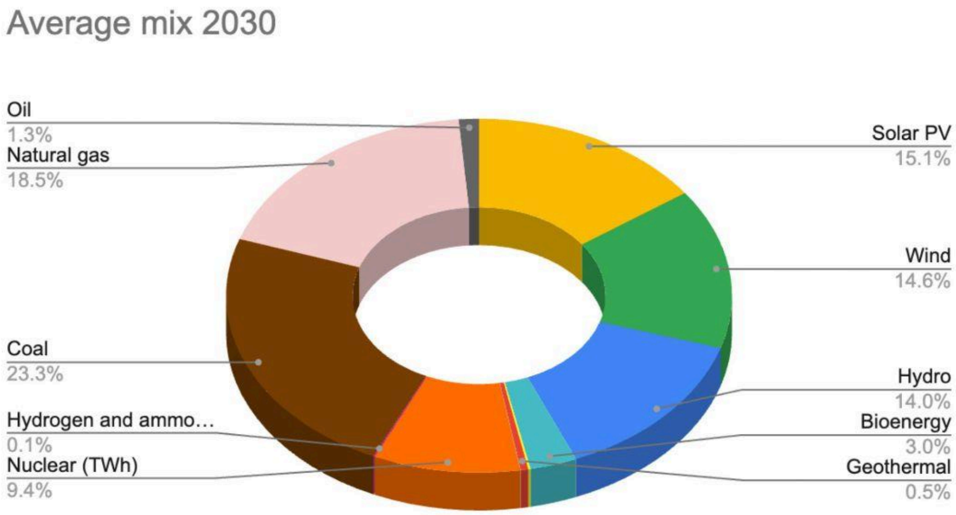
Table 1: *Operational lifetime of different vehicles considered in the study.*

Industry	ICE	BEV (Standard BMS)	BEV (CellMate BMS)	BEV (Pulsetrain BMS)
Construction (Excavators)	~ 5 years (9200 effective hours)	~ 5 years (9200 effective hours)	~ 5 years (9200 effective hours)	~ 7.5 years (13800 effective hours)
Automobiles (Cars)	18 years (217,000 km)	18 years (217,000 km & 1.5 batteries)	18 years (217,000 km & 1.5 batteries)	18 years (217,000 km & 1 battery)
Two-wheelers (scooters & motorbikes)	15 years (120,000 km)	15 years (120,000 km & 1.5 batteries)	15 years (120,000 km & 1.5 batteries)	15 years (120,000 km & 1 battery)

2.2. The electricity mix

The electricity consumed by battery electric vehicles operating in different regions of the world has a different emission factor (EF) depending on the share of electricity produced by different generation technologies. Global, EU and Indian electricity mixes were created based on the stated policy scenarios using data from IEA's World Energy Outlook and BP's Energy Outlook reports (BP 2024b, 2024a; IEA 2022, 2023) (Figure 3(a), (b) and (c)). Further, emission factors for different electricity generation technologies were used from the life cycle assessment of electricity generation options report from the United Nations (UNECE 2021).





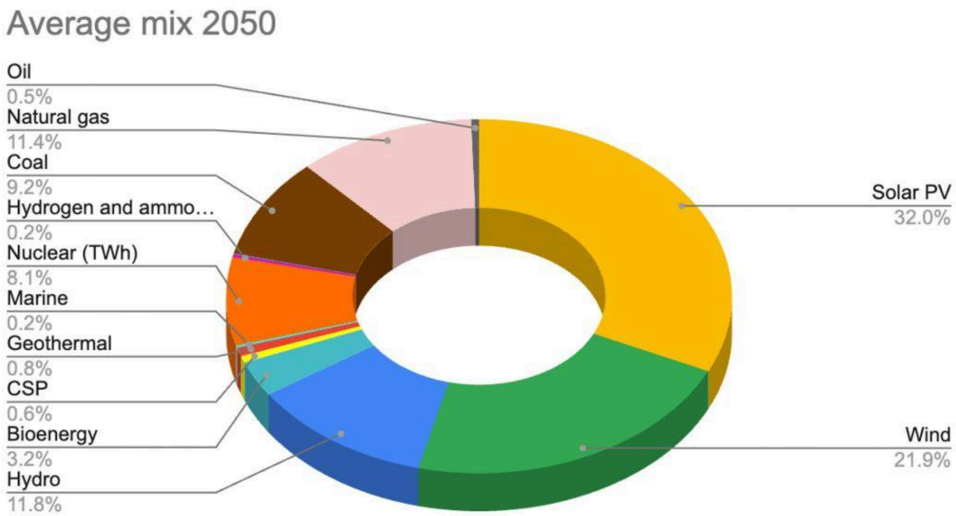


Figure 3(a): *Global electricity mix for 2022, 2023 and 2050*

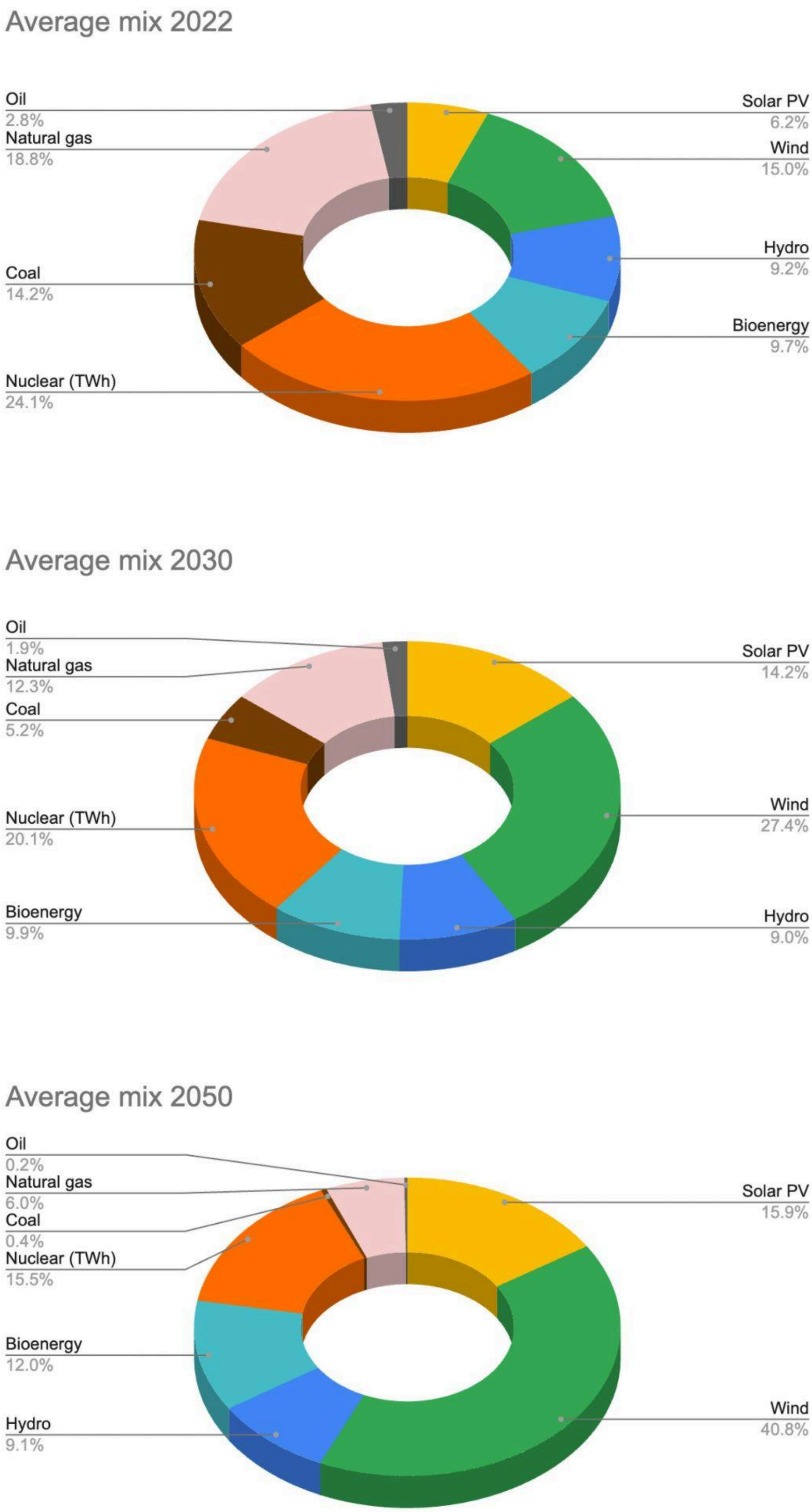


Figure 3(b): *EU electricity mix for 2022, 2030 and 2050*

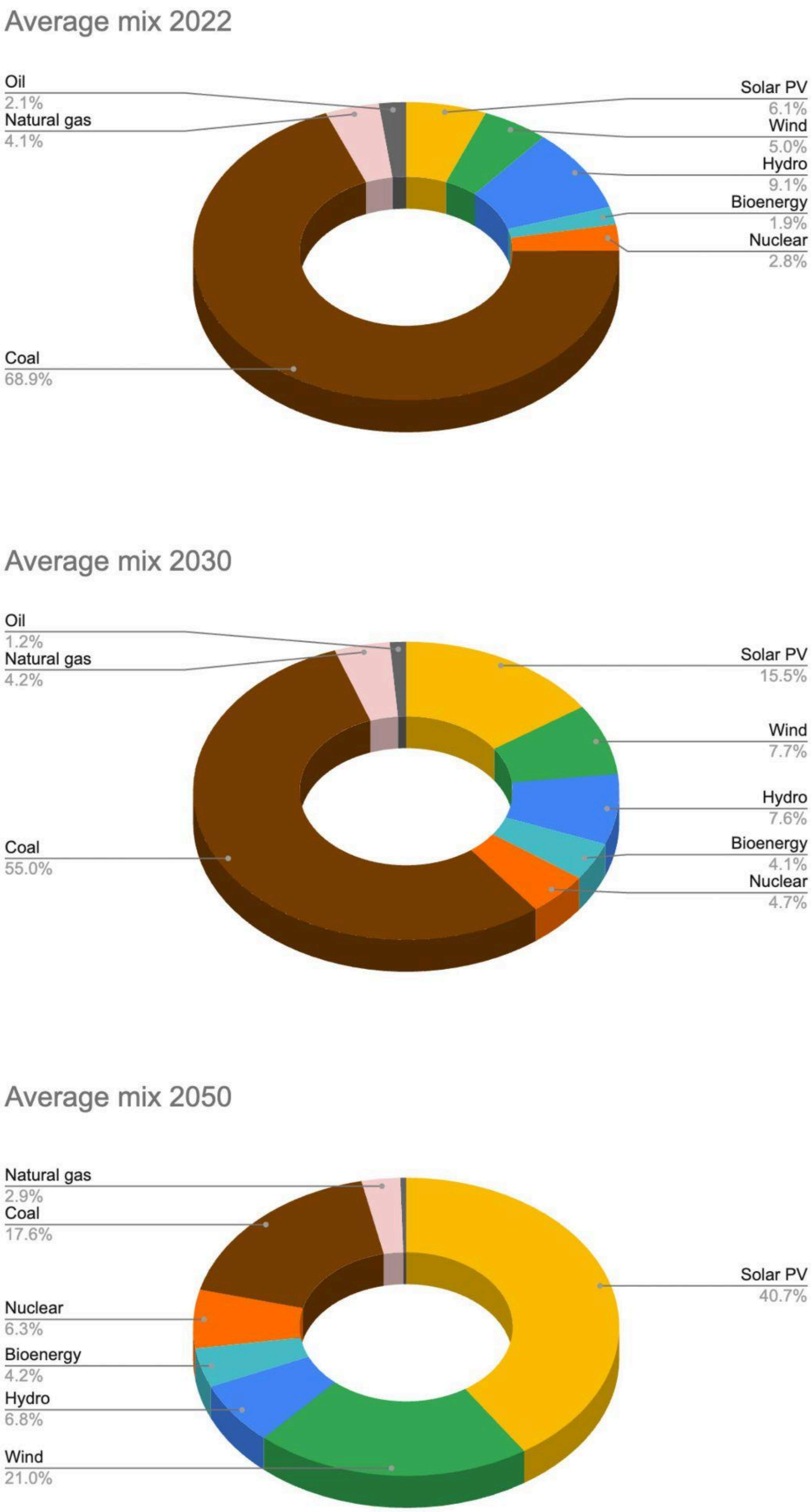


Figure 3(c): *Indian electricity mix for 2022, 2030 and 2050*

We interpolated the share of electricity generated using different technologies between 2022, 2030 and 2050. This interpolation along with the emission factors from UNECE 2021 was used to create yearly emission factors for electricity grid mixes in different regions (Figure 4(a), (b) and (c)).

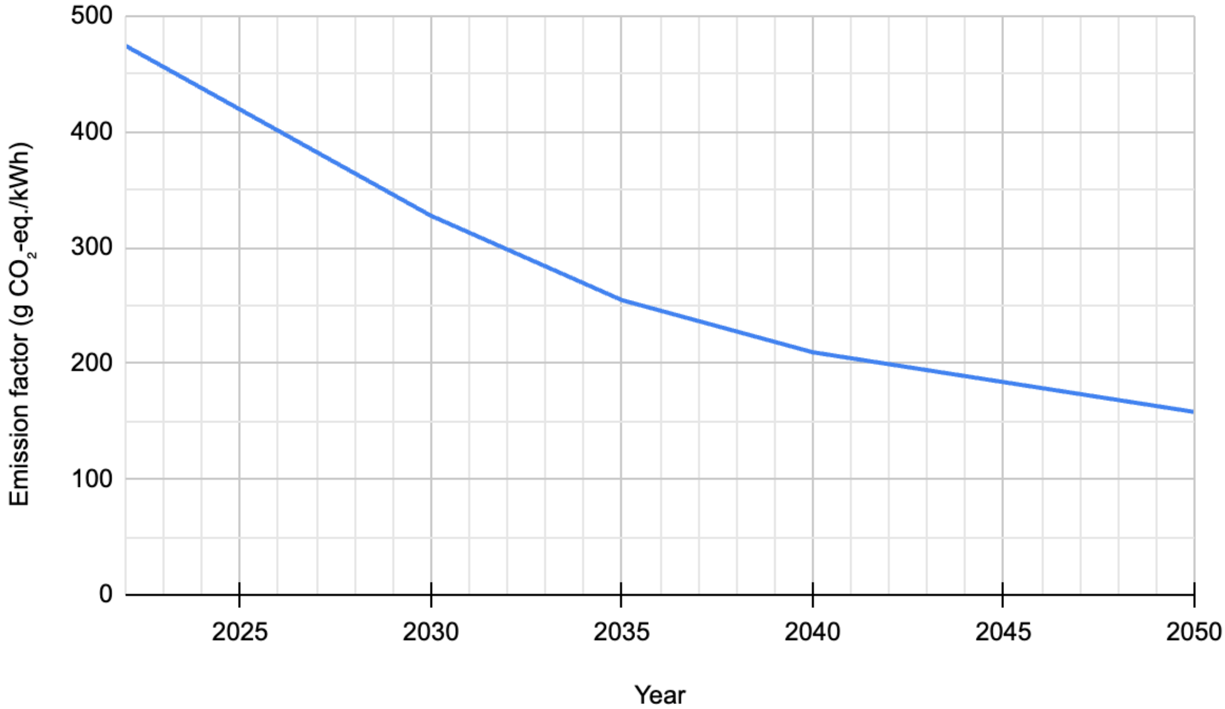


Figure 4(a): *Yearly emission factors (in g CO_2-eq./kWh) for global electricity grid mix from 2022 to 2050.*

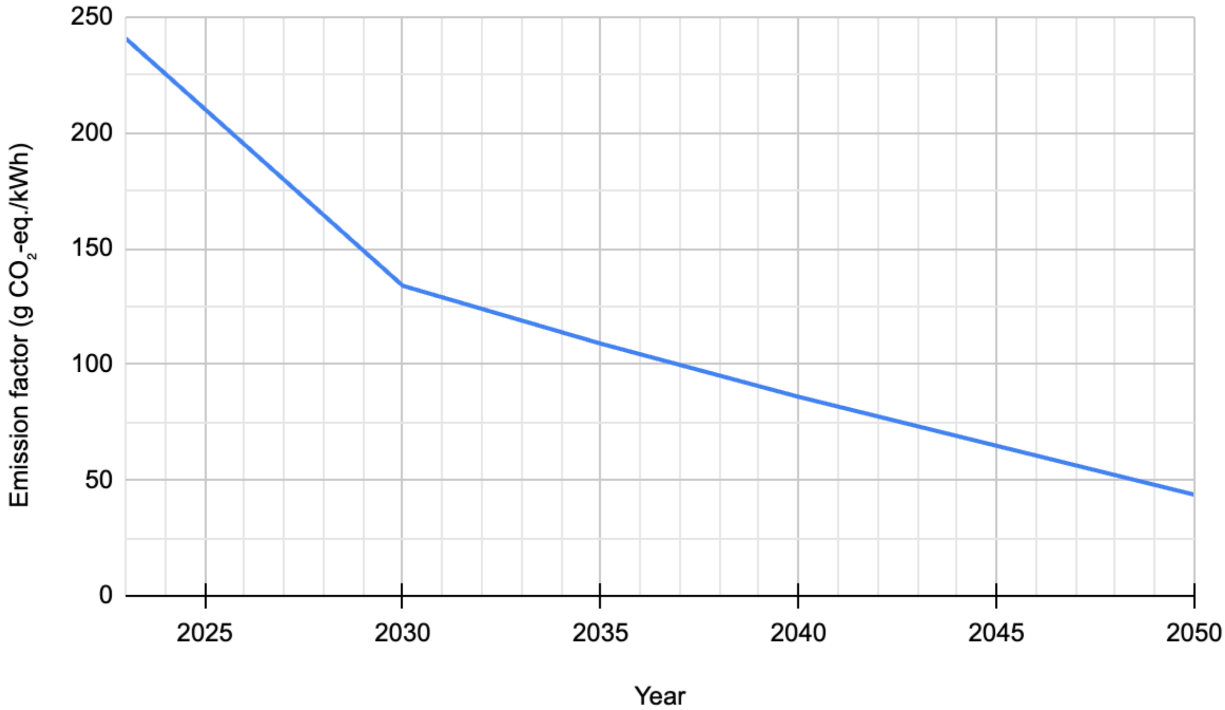


Figure 4(b): *Yearly emission factors (in g CO_2-eq./kWh) for EU electricity grid mix from 2022 to 2050.*

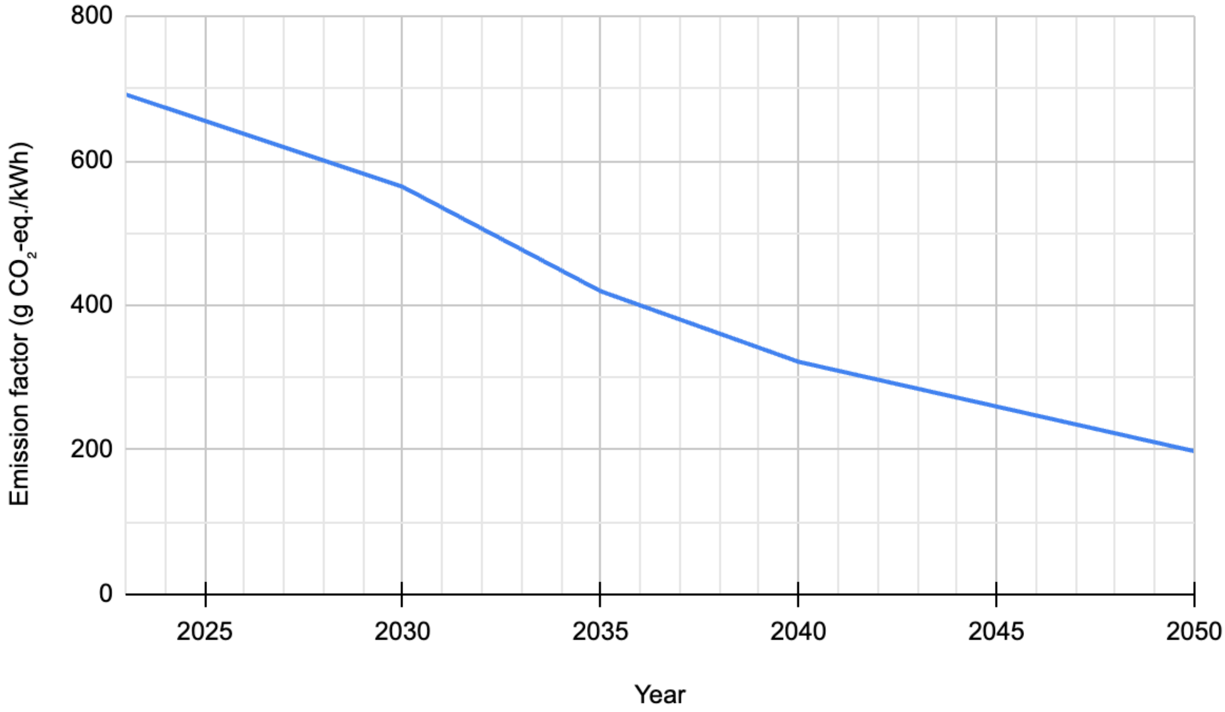


Figure 4(c): *Yearly emission factors (in g CO_2-eq./kWh) for the Indian electricity grid mix from 2022 to 2050.*

3. Results

Here we present the environmental impact of Pulsetrain's innovation in terms of global warming potential (in tonnes CO_2-eq.) for the construction industry and climate change (in tonnes CO_2-eq.) for automobile and two-wheeler industries. Further, a commentary has been made on the effect of EV transition on material consumption and human toxicity indicators.

3.1. Construction industry

In addition to the system description (chapter 2.1), it is important to note that only a 90% improvement factor for powertrain efficiency improvement was considered in the excavators, assuming that 10% of energy is consumed in independent auxiliary systems.

3.1.1. Global Warming Potential

Carbon footprint: The lifetime GHG emissions of the diesel excavator operated for 9,200 effective hours is 5192 tonnes CO_2-eq./excavator, dominated by the emissions from diesel consumption over its lifetime. BEV excavators deployed in 2025 and operated for the same number of effective hours over their lifetime, using a Standard BMS emit 243 tonnes CO_2-eq./excavator and using the Cellmate BMS emit 224 tonnes CO_2-eq./excavator. The lifetime of the excavator is extended by 50% to 13,800 hours using the Pulsetrain BMS, producing GHG emissions of 266 tonnes CO_2-eq./excavator over the prolonged operational period (Figure 5).

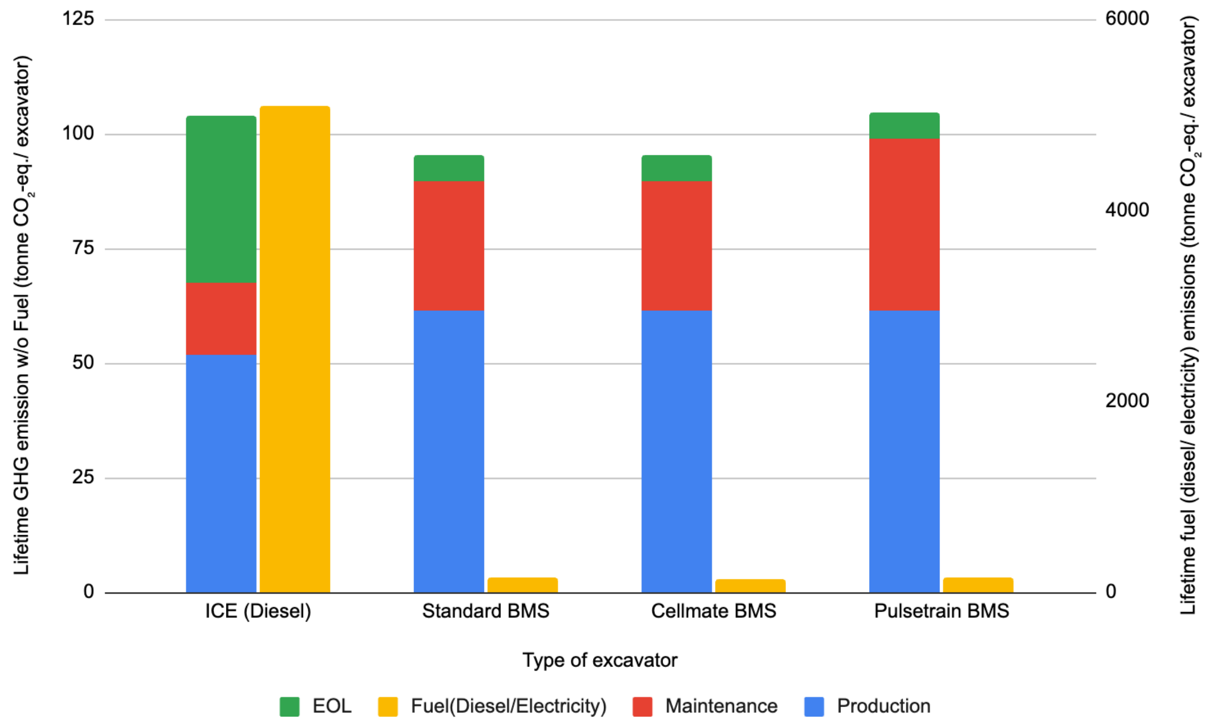


Figure 5: *Lifetime GHG emissions of ICE and BEV excavators over their respective lifetime operational hours (9,200 hours for ICE, Standard BMS & Cellmate BMS and 13,800 hours for Pulsetrain BMS).*

GHG emission reduction compared to ICE excavators: All BEV excavators have slightly higher production emissions but result in net GHG emission reduction over the ICE (diesel) excavator due to the replacement of fuel sources from diesel (higher embodied emissions) to electricity (lower embodied emissions). Having the same operational lifetime hours as the ICE excavator, using the standard BMS results in a reduction of 4,948 tonnes CO_2-eq./excavator deployed in 2025 and 5,001 tonnes CO_2-eq./excavator in 2034. **The Cellmate BMS results in a reduction of 4,967 tonnes CO_2-eq./excavator deployed in 2025 and 5,013 tonnes CO_2-eq./excavator in 2034.** The higher savings from Cellmate BMS is due to the higher powertrain efficiency, leading to reduced power consumption. **The Pulsetrain BMS results in a reduction of 7,477 tonnes CO_2-eq./excavator deployed in 2025 and 7,533 tonnes CO_2-eq./excavator in 2034.** These savings in Pulsetrain BMS are achieved due to the prolonged operational lifetime of the excavator, leading to lower material emissions and increased powertrain efficiency, leading to reduced power consumption (Figure 6).

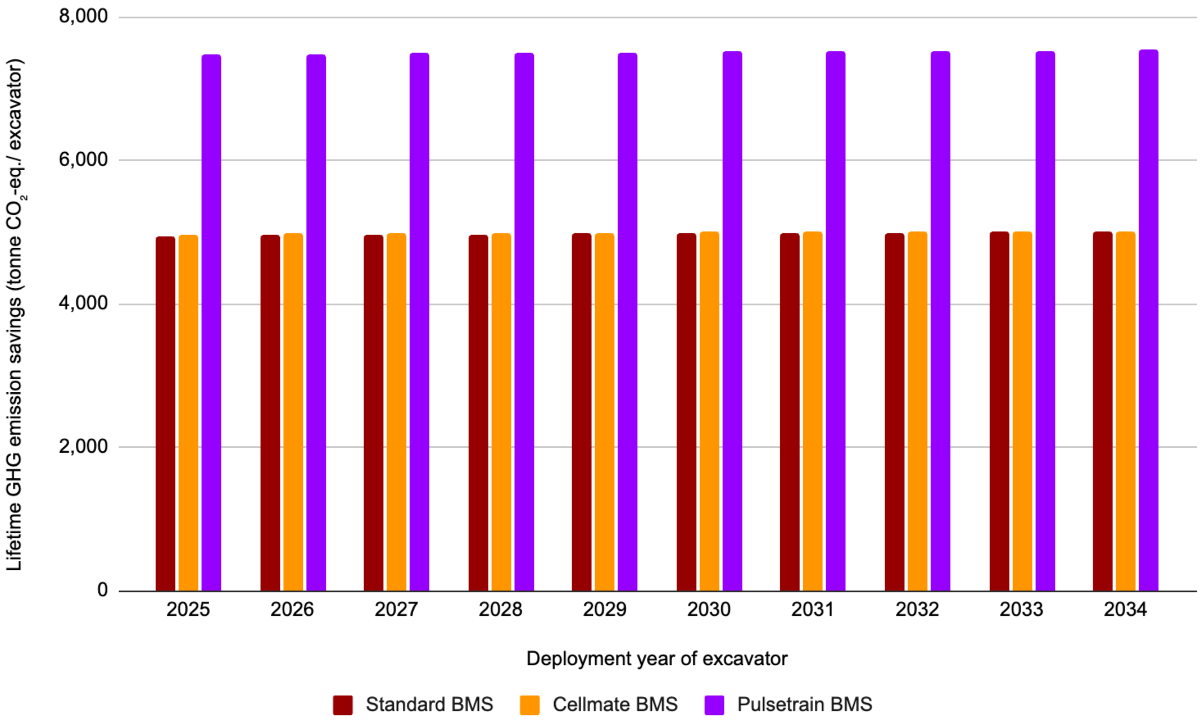


Figure 6: *Lifetime GHG emissions reduction of BEV excavators over their respective lifetime operational hours (9,200 hours for ICE, Standard BMS & Cellmate BMS and 13,800 hours for Pulsetrain BMS) over an ICE excavator.*

GHG emission reduction compared to a standard BMS: Comparing the lifetime GHG emission reduction by replacing a Standard BMS with a Pulsetrain's BMS, **the Cellmate BMS results in an emissions reduction of 19 tonnes CO_2-eq./excavator deployed in 2025 and 12 tonnes CO_2-eq./excavator deployed in 2034**. The decrease in savings over the years is due to the greening of the future electricity mix leading to lower GHG emissions per kWh of electricity consumed.

Pulsetrain BMS results in an emission reduction of 2,528 tonnes CO_2-eq./excavator deployed in 2025 and 2,532 tonnes CO_2-eq./excavator deployed in 2034. The substantially higher GHG emission savings are due to the prolonged operational lifetime, leading to a reduction in effective material consumption. Whereas, the marginal increase in GHG emission reduction observed from 2025 to 2034 is due to the increase in the share of material (production) emissions in the lifetime excavator emissions as the greening of the electricity grid mix leads to reduced operational emissions (Figure 7).

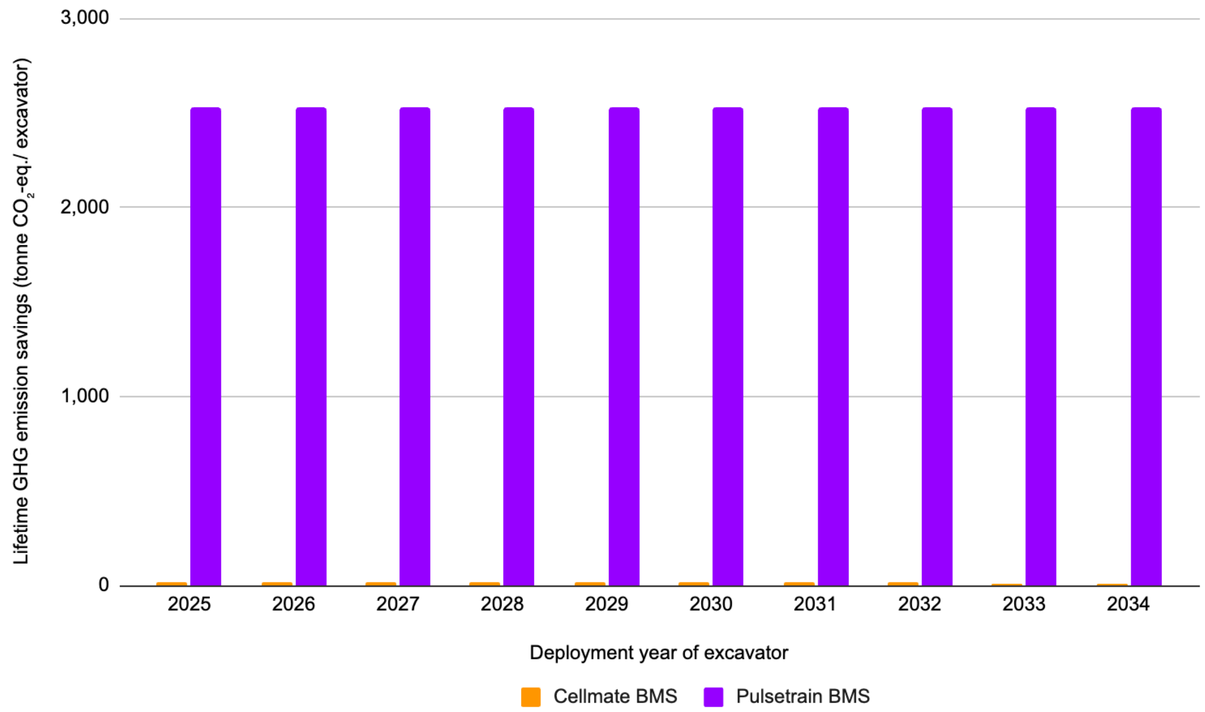


Figure 7: *Lifetime GHG emissions reduction of excavators using Pulsetrain BMS in comparison to Standard BMS over their respective lifetime operational hours (9,200 hours for Standard BMS & Cellmate BMS and 13,800 hours for Pulsetrain BMS).*

3.2. Automotive industry

Two cases were studied, the global car industry and the European car industry.

3.2.1. Global

Carbon footprint: The lifetime GHG emissions of different vehicles (ICE and BEVs) deployed in 2025 and operated for 217,000 km over 18 years is 41 tonnes CO_2-eq./vehicle for diesel ICE cars, dominated by the emissions from diesel consumption over its lifetime whereas petrol ICE cars result in 61 tonnes CO_2-eq./vehicle due to a much higher petrol consumption owing to their lower fuel efficiency. For BEVs, the GHG emission using standard BMS is 23 tonnes CO_2-eq./BEV and using Cellmate BMS is 21.6 tonnes CO_2-eq./BEV. The Pulsetrain BMS results in 19.4 tonnes CO_2-eq./BEV (Figure 8), since, in addition to increasing powertrain efficiency, it extends the battery lifetime by 50%, which prevents replacement of the battery during the operation lifetime of the BEV. This avoids emissions from battery replacement during the maintenance phase and reduces emissions from electricity consumption during the operation phase.

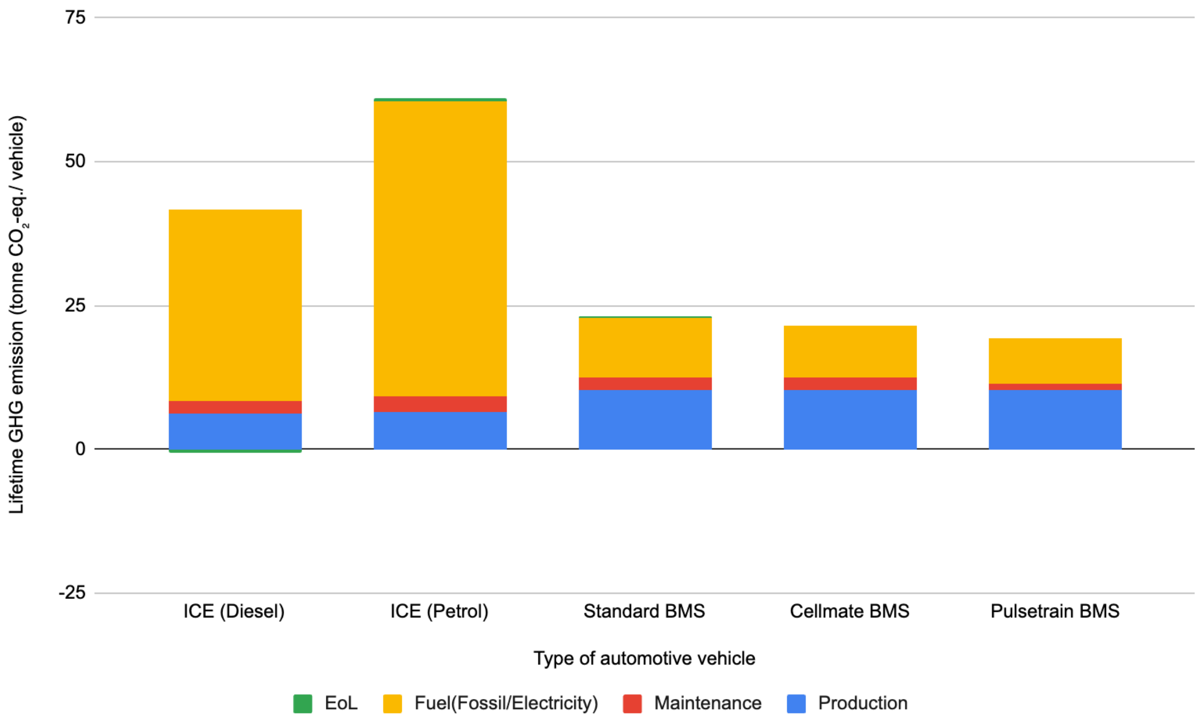


Figure 8: *Lifetime GHG emissions of ICE vehicles and BEV, operating globally.*

GHG emission reduction compared to ICE vehicles: All BEV cars have higher production emissions but result in net GHG emission reduction over the ICE diesel and ICE petrol cars due to the replacement of fuel sources (diesel and petrol) with higher embodied emissions due to electricity having lower embodied emissions. The standard BMS results in a reduction in emissions of 28 tonnes CO_2-eq./BEV deployed in 2025 and 31 tonnes CO_2-eq./BEV in 2034. **The Cellmate BMS results in a reduction in emissions of 29 tonnes CO_2-eq./BEV deployed in 2025 and 32 tonnes CO_2-eq./BEV in 2034.** The higher savings from Cellmate BMS is due to the higher powertrain efficiency, leading to reduced power consumption. **The pulsetrain BMS results in a reduction in emissions of 32 tonnes CO_2-eq./BEV deployed in 2025 and 34 tonnes CO_2-eq./BEV in 2034.** These savings in Pulsetrain BMS are achieved due to the prolonged operational lifetime of the battery, which avoids battery replacement, and the increased powertrain efficiency, which leads to reduced power consumption (Figure 9).

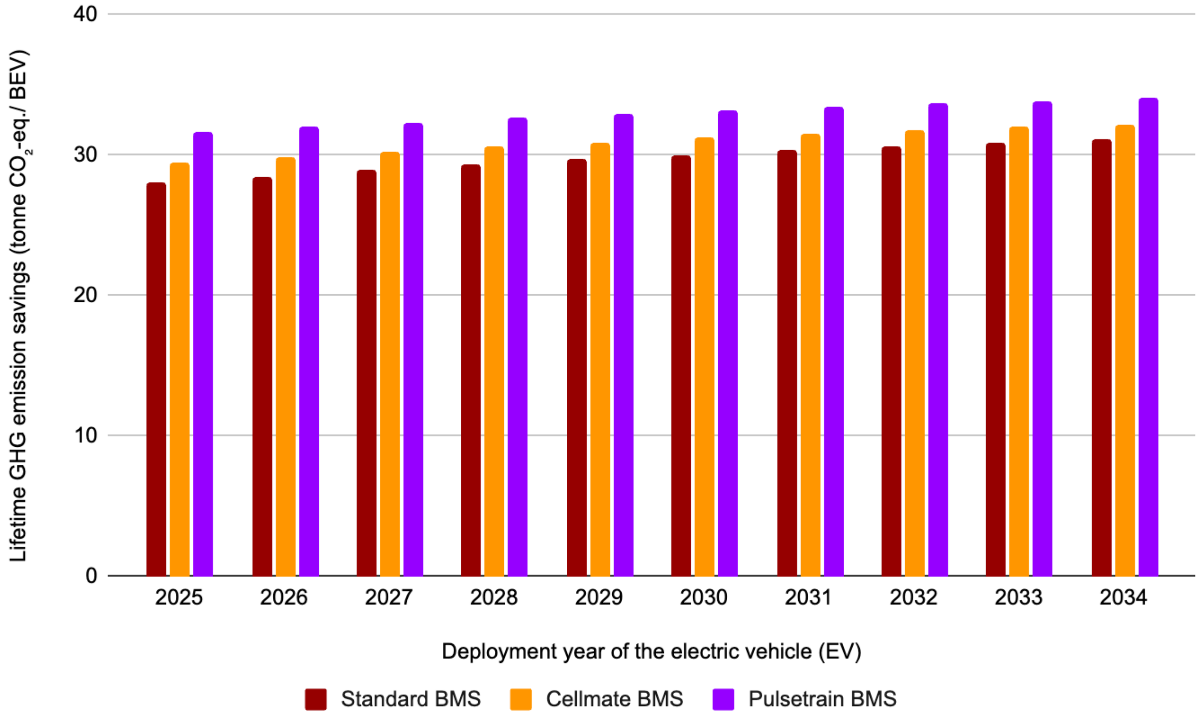


Figure 9: *Lifetime GHG emissions reduction of BEVs over an average ICE car, operated globally.*

GHG emission reduction compared to a standard BMS: Comparing the lifetime GHG emission reduction by replacing a Standard BMS with Pulsetrain's BMS, deploying the **Cellmate BMS reduces GHG emissions by 1.5 tonnes CO_2-eq./BEV deployed in 2025 and 1 tonnes CO_2-eq./BEV in 2034.** The reduction in savings over the years is due to the greening of the future electricity mix leading to lower GHG emissions per kWh of electricity consumed. On the other hand, the deployment of the **Pulsetrain BMS results in a reduction in emissions of 3.7 tonnes CO_2-eq./BEV deployed in 2025 and 2.9 tonnes CO_2-eq./BEV in 2034.** The higher GHG emission reduction is due to the prolonged battery lifetime, which avoids battery replacement and to the increased powertrain efficiency, which leads to reduced power consumption as explained above (Figure 10).

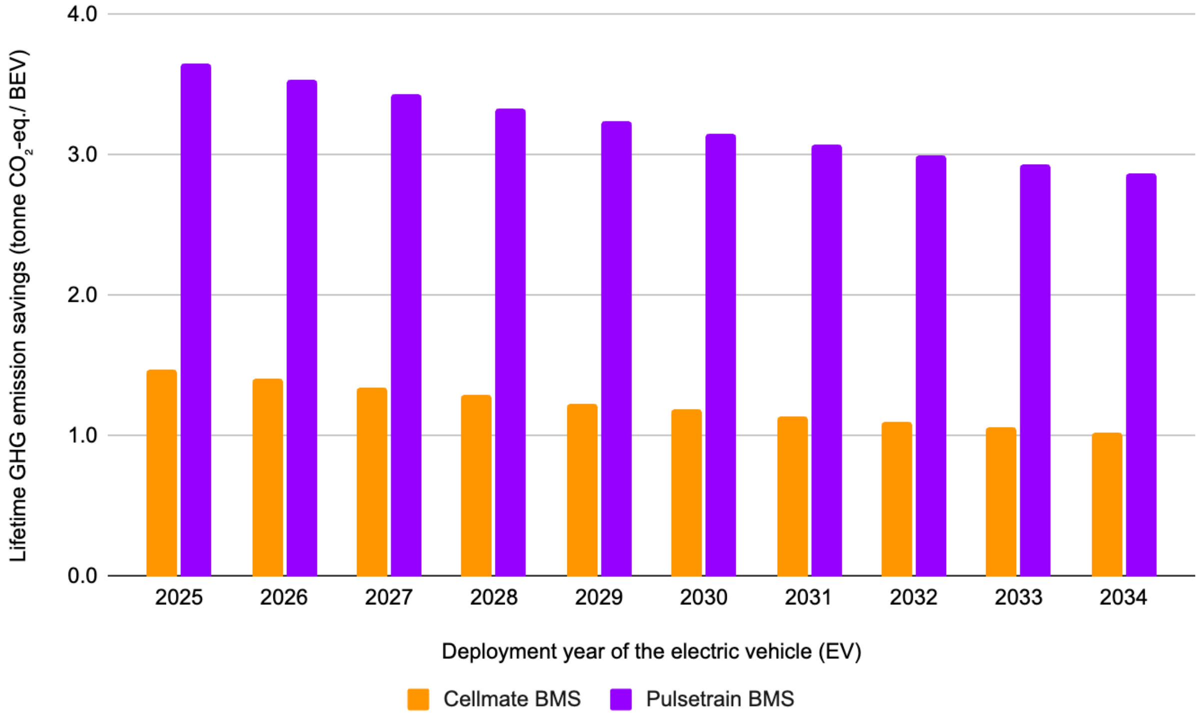


Figure 10: *Lifetime GHG emissions* reduction *of BEVs using Pulsetrain BMS in comparison to Standard BMS.*

3.2.2. European Union

Carbon footprint: We calculated the lifetime GHG emissions of the different vehicles (ICE and BEVs) deployed in 2025 and operated for 217,000 km over 18 years in the EU. The emissions for ICE vehicles were the same as the global counterparts assuming a globalised supply chain and simplicity in calculation of the operational emissions from fuel consumption. For BEVs, the GHG emission using standard BMS is 17.1 tonnes CO_2-eq./BEV and using Cellmate BMS is 16.5 tonnes CO_2-eq./BEV. The Pulsetrain BMS results in 15 tonnes CO_2-eq./BEV (Figure 11). The reason for the increase in emission reduction by the deployment of Pulsetrain's BMS is the same as described in section 3.2.1.

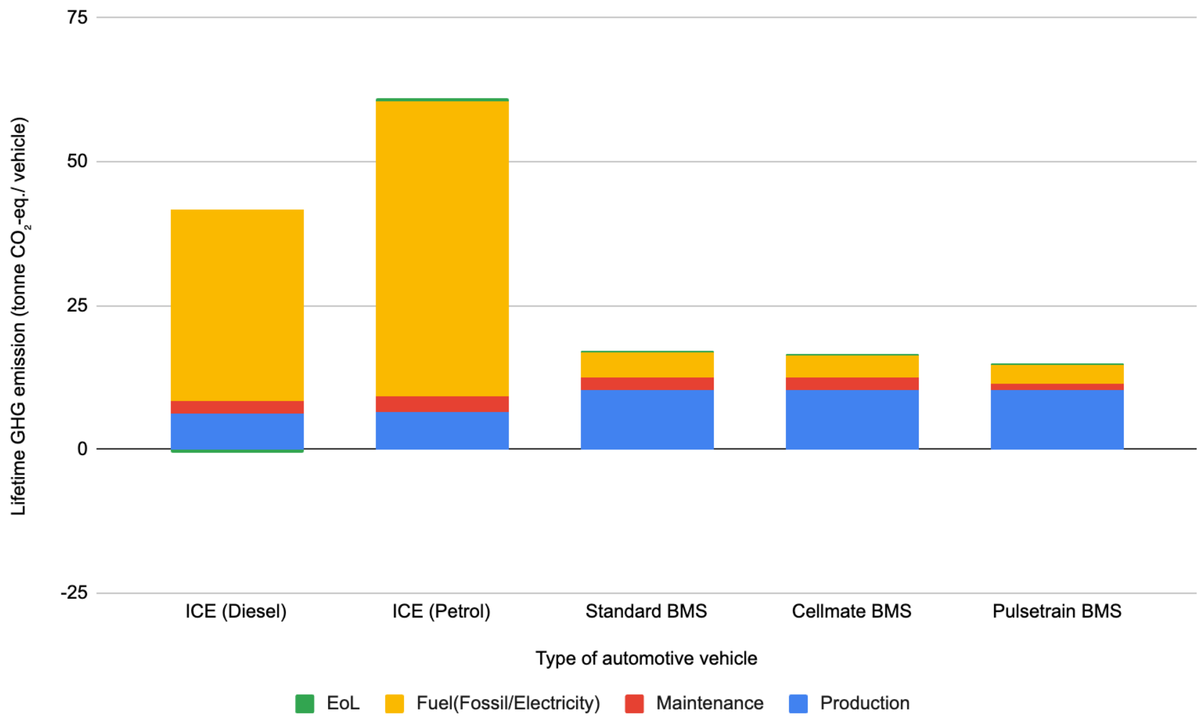


Figure 11: *Lifetime GHG emissions of ICE and BEV cars, operating in the EU.*

GHG emission reduction compared to ICE vehicles: Similar to the trend observed in section 3.1.1, all BEV cars in the EU have higher production emissions, resulting in net GHG emission reduction over their ICE counterparts due to replacing fuel with electricity which has lower embodied emissions. The standard BMS results in a reduction of 34 tonnes of CO_2-eq./BEV deployed in 2025 and 36 tonnes CO_2-eq./BEV in 2034, and **the Cellmate BMS results in a reduction in emissions of 35 tonnes CO_2-eq./BEV deployed in 2025 and 36 tonnes CO_2-eq./BEV in 2034. The Pulsetrain BMS results in a reduction in emissions of 36 tonnes CO_2-eq./BEV deployed in 2025 and 37 tonnes CO_2-eq./BEV in 2034** when cars have their operation and EoL phase only in the EU (Figure 12). The reason for the change in emission reduction using different Pulsetrain's technology over various time periods is the same as explained in section 3.1.1.

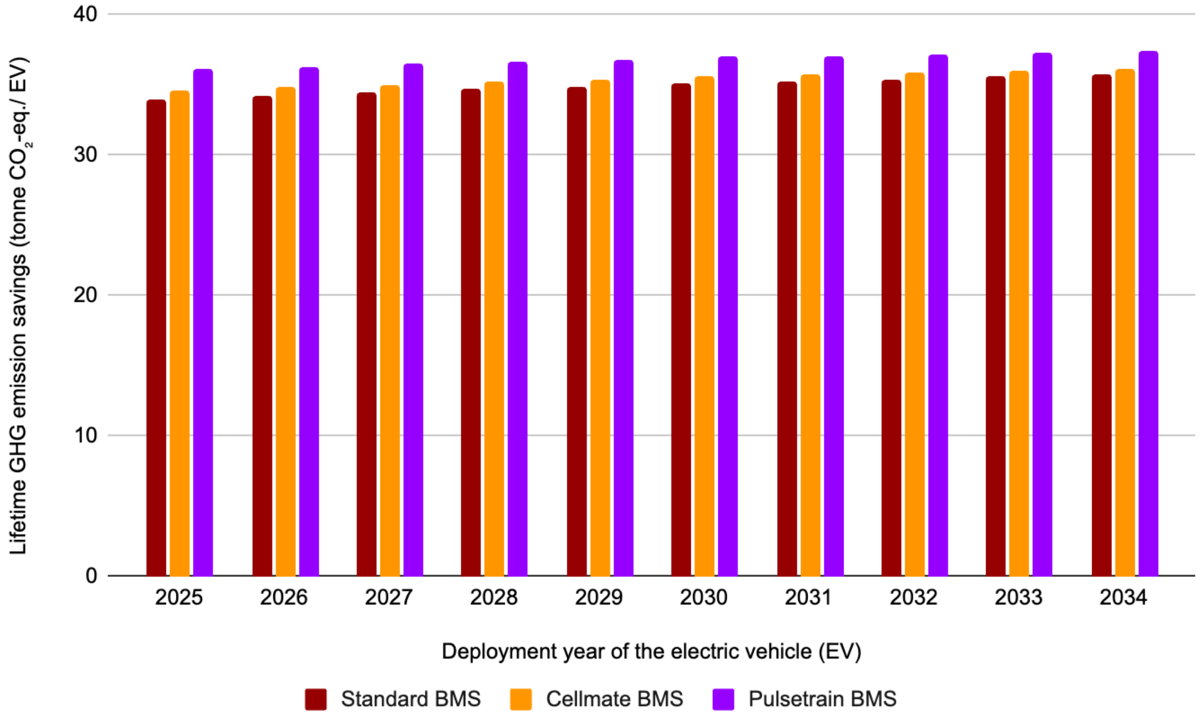


Figure 12: *Lifetime GHG emissions* reduction *of BEVs over an average ICE car, both operated and EoL in the EU.*

GHG emission reduction compared to a standard BMS: Comparing the lifetime GHG emission reduction by replacing Standard BMS with Pulsetrain's systems, the deployment of **Cellmate BMS results in an emission reduction of 0.6 tonnes CO_2-eq./BEV deployed in 2025 and 0.4 tonnes CO_2-eq./BEV in 2034. The deployment of Pulsetrain BMS results in an emission reduction of 2.2 tonnes CO_2-eq./BEV deployed in 2025 and 1.7 tonnes CO_2-eq./BEV in 2034** when cars have their operation and EoL phase only in the EU (Figure 13). The reason for the lower absolute reduction compared to those observed in section 3.1.1 is the greener grid in the EU. Whereas, the reason for the observed trend over the years is the same as explained in section 3.1.1 of this report.

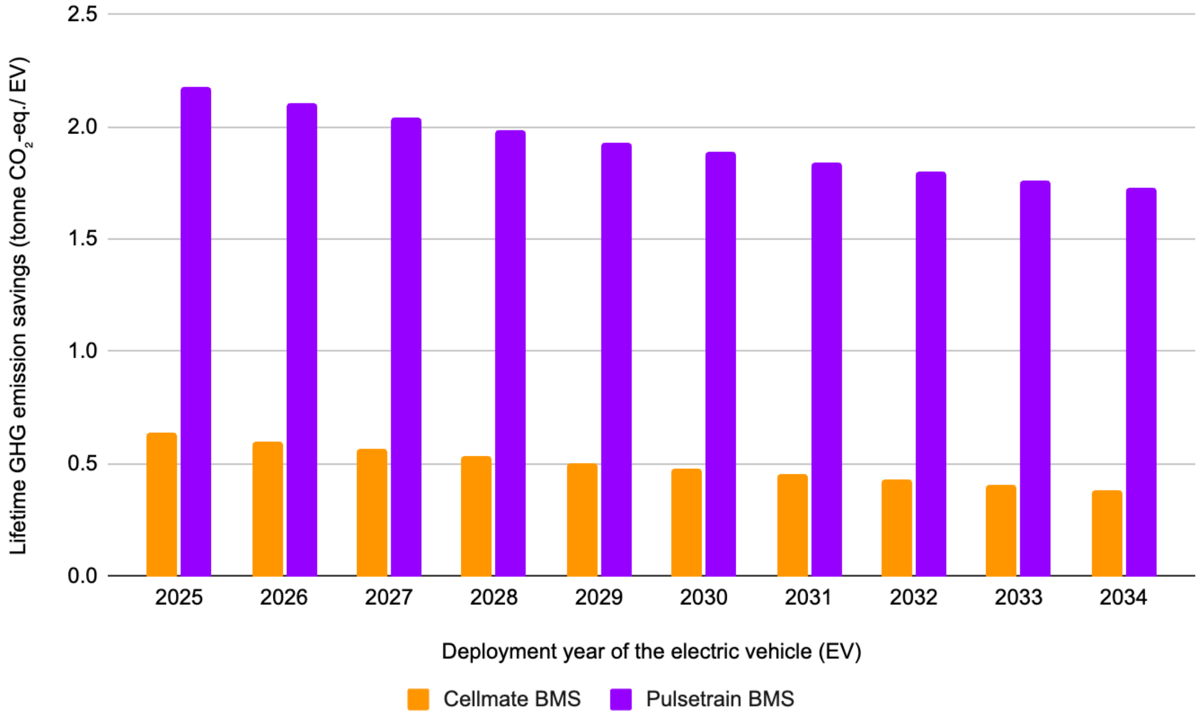


Figure 13: *Lifetime GHG emissions reduction of BEVs using Pulsetrain BMS in comparison to Standard BMS, both operated and EoL in the EU.*

Additionally, to fully comprehend the environmental impact of Pulsetrain's systems, we need to look at the bigger picture, accounting for the shares of changes in total EU vehicle stock. Scientific literature, reports and governmental statistics (Eurostat 2024; Held et al. 2021; Merkisz-Guranowska et al. 2022; UBA 2020; UNEP 2020) show that along with the retirement of vehicles, the vehicles are also exported to other countries outside the EU, whereas the EoL of a third of the total vehicle stock is unknown (Figure 14). For the purpose of the study, the unknown stock share has been adjusted by weighted average into export and retired shares.

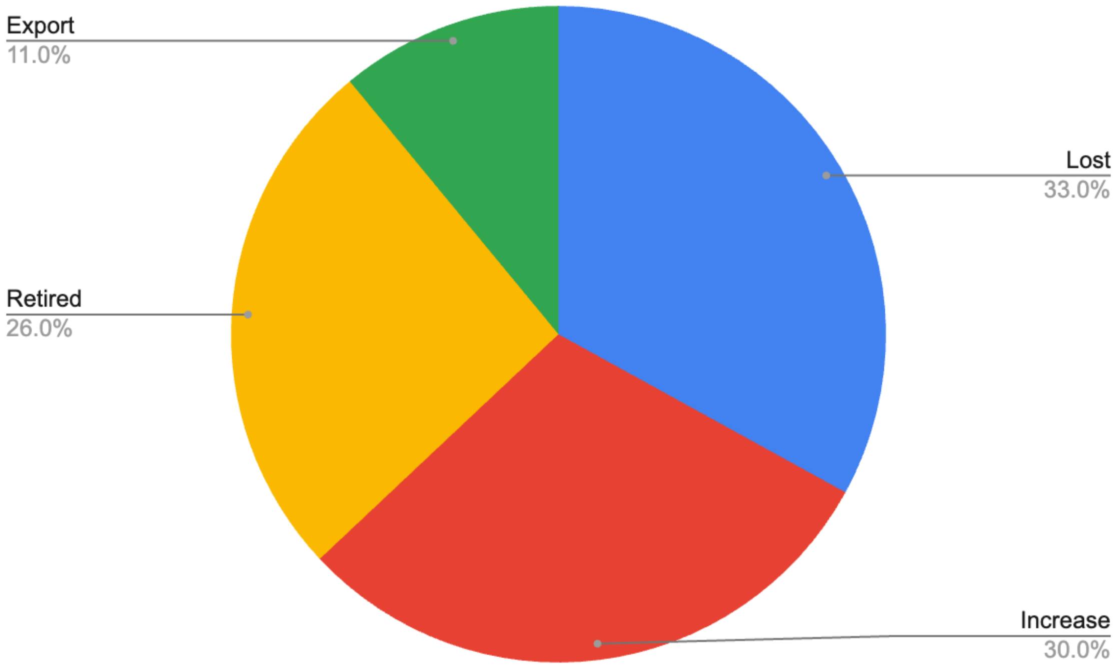


Figure 14: *Shares of change in total vehicle stock in the EU.*

After adjusting the 33% lost vehicles (Figure 14) in retired and exported categories, for every 100 new vehicles entering the (EU) market, 49% result in the retirement of old vehicles, 21% are exported and 30% are added to the stock. This implies:

- 49% of new EVs fully replace ICE vehicles: This is a net reduction in GHG emissions i.e. the GHG emissions emitted decrease in absolute terms.
- 30% do not replace ICE vehicles but are just added to the stock: These vehicles result in additional emissions in the transport sector. It could be assumed that these replace the new ICE vehicles entering the market. Thus, these EVs avoid emissions of ICE vehicles that would have entered the market instead. This is not a net reduction, but rather an increase in GHG emissions. The emissions would have just increased more by the use of ICE vehicles (hence, the "avoidance" or "avoided emissions").
- 21% are added to the stock outside the EU (through exports): These vehicles result in a net increase in emissions as ICE vehicles are still used elsewhere while more EVs have entered the system.

Table 2 shows the impact (net reduction and avoided emissions) from the deployment of Pulstrain's BMS and accounting for the shares of changes in total EU vehicle stock.

Table 2: *Net reduction and avoided emissions from the deployment of Pulstrain's BMS in the EU, after accounting for the shares of change in total EU vehicle stock.*

	Standard BMS		Cellmate BMS		Pulsetrain BMS	
Year of deployment	**Net reduction (t CO2-eq./BEV)**	**Avoided emissions (t CO2-eq./BEV)**	**Net reduction (t CO2-eq./BEV)**	**Avoided emissions (t CO2-eq./BEV)**	**Net reduction (t CO2-eq./BEV)**	**Avoided emissions (t CO2-eq./BEV)**
2025	8.0	10.2	8.6	10.4	10.2	10.8
2034	9.8	10.7	10.2	10.8	11.5	11.2

The reason for the higher GHG emission reduction potential by using Pulsetrain's systems and the trend for the change in savings over the years are the same as explained above in this section. It is also important to note that in absolute terms, the avoided emissions are higher than the net reduction in almost all cases since the net reduction is lowered due to a net increase from the export of vehicles.

On comparing the increase in savings by using Pulsetrain's systems over the standard BMS, the net reduction is the same as Figure 13, since the net improvement remains the same. The avoided emissions are 30% of the net reduction matching the share of vehicle stock increase (Figure 15).

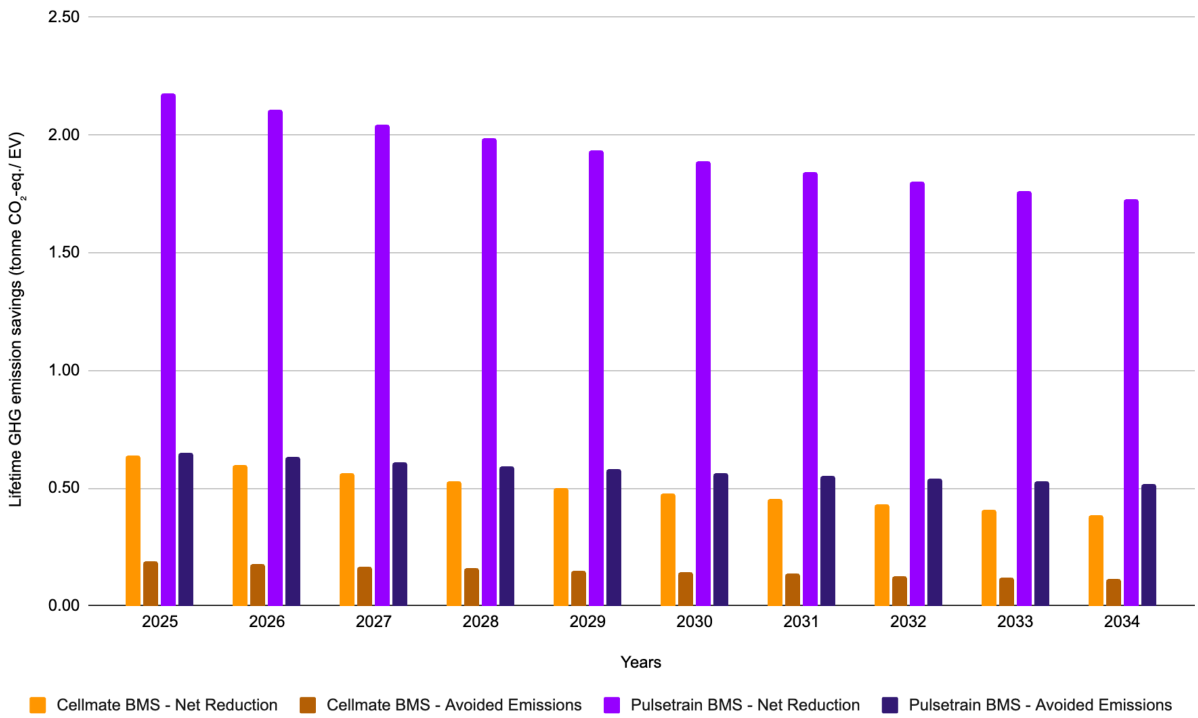


Figure 15: *Total GHG emissions savings considering both net reduction and avoided emissions from BEVs using Pulsetrain BMS over Standard BMS*

3.3. Two-wheeler Industry (India)

We chose to focus on the Indian market when analysing the two-wheeler industry, due to the enormous market share in the country (Figure 16). Also, India is projected to surpass China in terms of BEV two-wheeler sales where the market has already relatively matured, with BEV two-wheelers accounting for 70% of the two-wheeler sales (Counterpoint 2024; Mordor Intelligence 2023c, 2023b, 2023a). The calculations consider the various life cycle phases (production, manufacturing, operation, maintenance, and end-of-life) of the two-wheelers and the electricity grid mix in India.

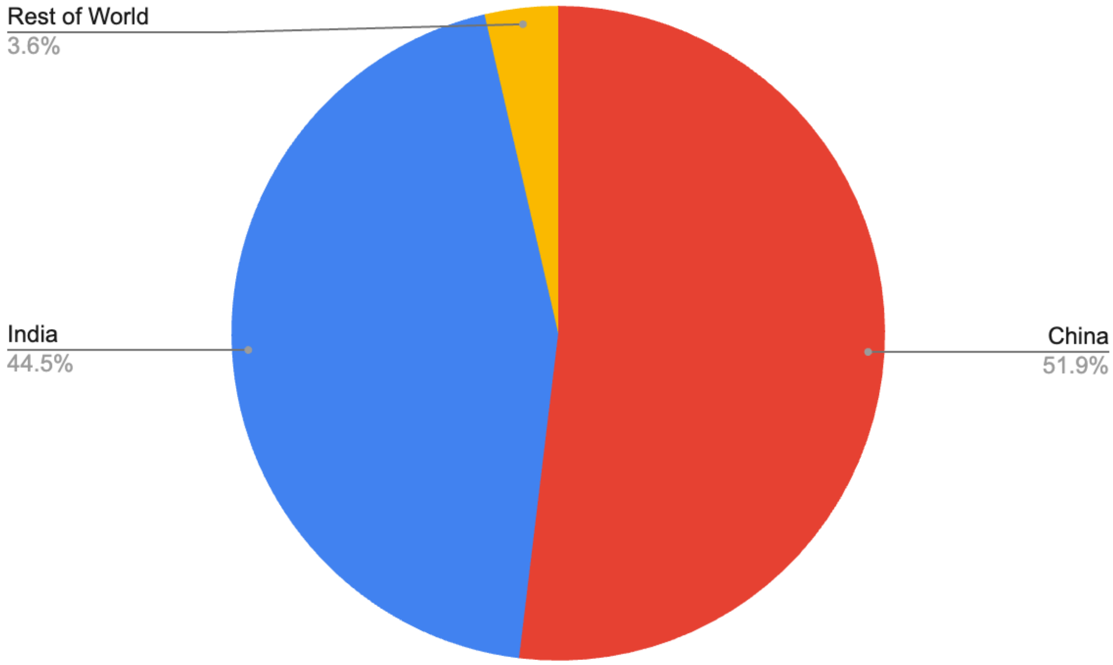


Figure 16: *Global Two-Wheeler Market Share by Country according to the monetary value of BEVs sold (Counterpoint 2024; Mordor Intelligence 2023c, 2023b, 2023a)*

Carbon footprint: We calculate the lifetime GHG emissions of an ICE petrol two-wheeler (average of motorbike and scooter) and BEVs deployed in 2025 and operated for 120,000 km over 15 years. The GHG emissions for ICE petrol two-wheelers is 7.9 tonnes CO_2-eq./ two-wheeler, dominated by the fuel consumption over its lifetime. For BEVs, the GHG emission using a standard BMS is 3.5 tonnes CO_2-eq./electric two-wheeler and using the Cellmate BMS is 3.2 tonnes CO_2-eq./electric two-wheeler. The Pulsetrain BMS results in GHG emissions of 2.8 tonnes of CO_2-eq. emissions/electric two-wheeler (Figure 17), since, in addition to increasing powertrain efficiency, it extends the battery lifetime by 50%, which prevents battery replacement during the BEV's operation lifetime. This avoids emissions from battery replacement during the maintenance phase and reduces emissions from electricity consumption in the operation phase.

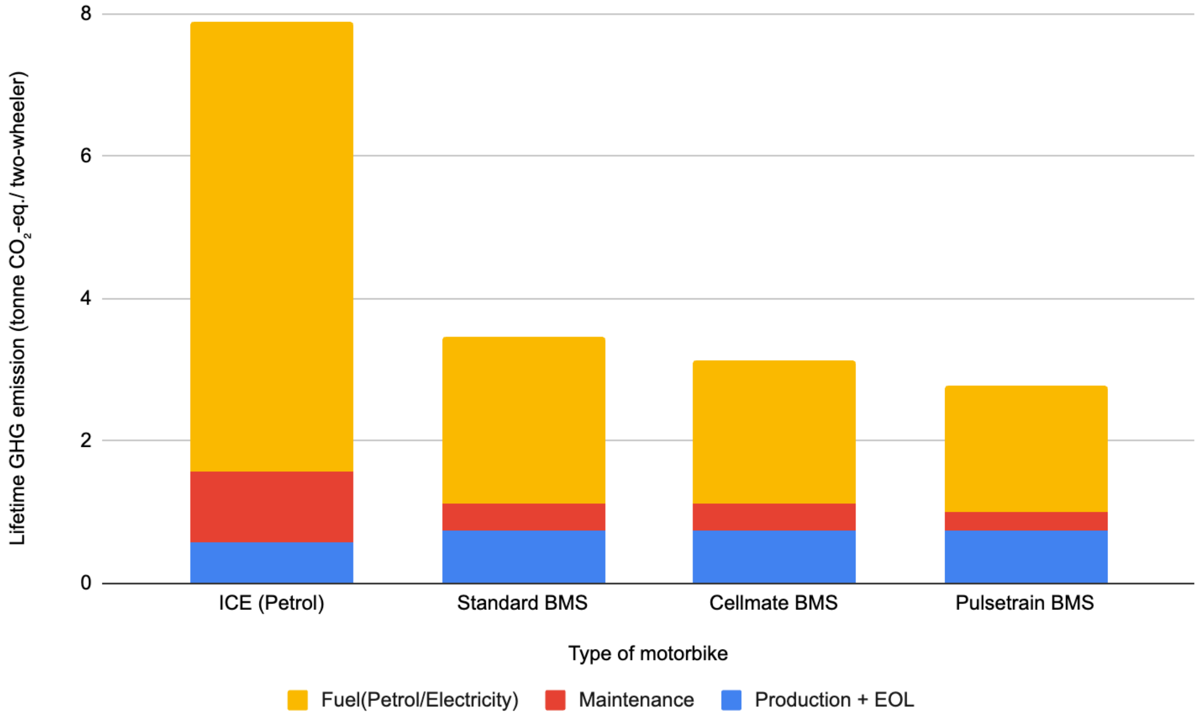


Figure 17: *Lifetime GHG emissions of ICE and BEV two-wheelers over their lifetime.*

GHG emission reduction compared to ICE vehicles: All BEV two-wheelers have slightly higher production emissions but result in net GHG emission reduction over ICE (petrol) two-wheelers due to electricity having lower embodied emissions. The standard BMS results in a reduction in emissions of 4.4 tonnes CO_2-eq./electric two-wheeler deployed in 2025 and 5.3 tonnes CO_2-eq./electric two-wheeler in 2034, and the Cellmate BMS results in a reduction in emissions of 4.8 tonnes CO_2-eq./electric two-wheeler deployed in 2025 and 5.5 tonnes CO_2-eq./electric two-wheeler in 2034. The higher reduction from the Cellmate BMS is due to the higher powertrain efficiency, leading to reduced power consumption. The Pulsetrain BMS results in a GHG emission reduction of 5.1 tonnes CO_2-eq./electric two-wheeler deployed in 2025 and 5.8 tonnes CO_2-eq./electric two-wheeler in 2034. These reductions are due to the prolonged operational lifetime of the battery, which avoids battery replacement and the increased powertrain efficiency, which leads to reduced power consumption (Figure 18).

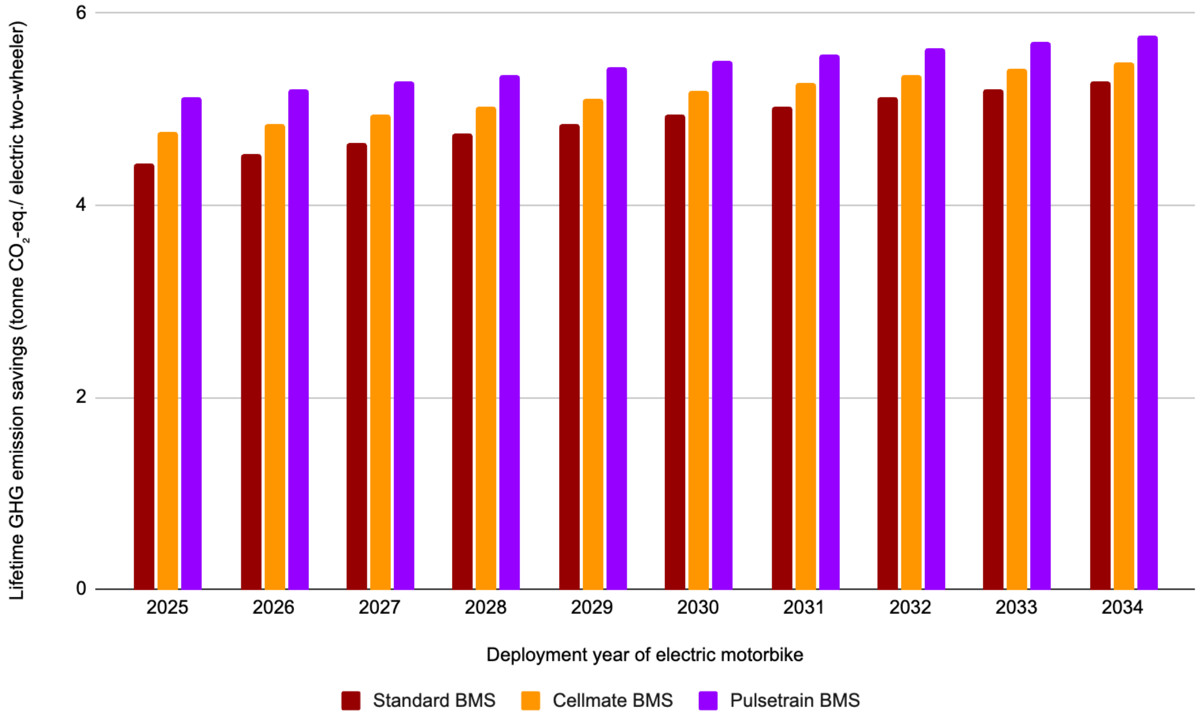


Figure 18: *Lifetime GHG emissions reduction of electric two-wheelers over an average ICE two-wheeler.*

GHG emission reduction compared to a standard BMS: Comparing the lifetime GHG emission reduction by replacing a Standard BMS with deploying the Cellmate BMS results in a net reduction of 329 kg CO_2-eq./electric two-wheeler deployed in 2025 and 210 kg CO_2-eq./electric two-wheeler in 2034. The decrease in reduction over the years is due to the greening of the future Indian electricity mix leading to lower GHG emissions per kWh of electricity consumed. On the other hand, deploying the Pulsetrain BMS results in a net reduction of 693 kg CO_2-eq./electric two-wheeler deployed in 2025 and 841 kg CO_2-eq./electric two-wheeler in 2034 compared to the standard BMS. This is due to the prolonged battery lifetime, which avoids battery replacement, and the increased powertrain efficiency, which leads to reduced power consumption as already mentioned above (Figure 19).

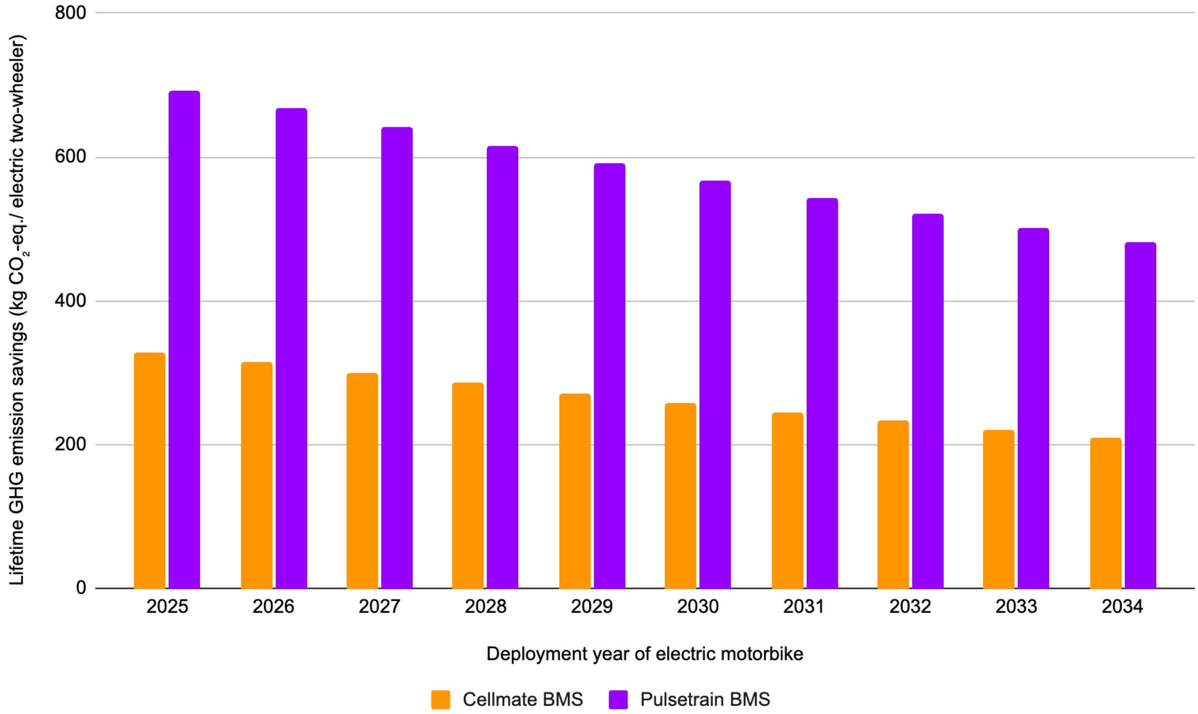


Figure 19: *Lifetime GHG emissions reduction of electric two-wheelers using Pulsetrain systems compared to a Standard BMS.*

3.4. Resource Consumption and Ecotoxicity Impact of EVs

The following section is based on the latest scientific literature and reports including (but not limited to) Betz et al. 2021; Khan et al. 2023; Kosai et al. 2021; McKinsey 2018; Oliveri et al. 2023; UBA 2024 etc.

Resource Consumption (Abiotic Depletion Potential)

The transition to electric vehicles has significant implications for resource consumption, particularly in terms of the abiotic depletion potential (ADP). Recent studies have shown that EVs tend to have a higher resource consumption compared to internal combustion engine vehicles mainly due to the following factors:

- Battery Production: The manufacturing of batteries and their associated electronic components, which form the backbone of EVs, requires substantial amounts of critical raw materials such as lithium, cobalt, nickel, and copper. This increased demand for metals and materials and the energy consumption in their extraction and processing contributes to a higher ADP for EVs in the production phase.

- Rare Earth Elements: Electric motors in EVs often use rare earth elements like neodymium and dysprosium, which are not typically used in ICE vehicles. The extraction and processing of these elements further contribute to the abiotic depletion potential of EVs.

- Electricity Generation Infrastructure: The transition to EVs necessitates an expansion of electricity generation and distribution infrastructure, which also impacts resource consumption.

However, it's important to note that the ADP impact of EVs can be mitigated through improved battery technologies and manufacturing processes, increased use of recycled materials in battery production and development of alternative battery chemistries that rely less on critical raw materials.

Environmental Ecotoxicity Indicators
The environmental ecotoxicity impacts of EVs present a complex picture when compared to ICEVs:

- Freshwater Ecotoxicity: LCA studies indicate that EVs can have higher freshwater ecotoxicity impacts compared to ICEVs. This is primarily due to the mining and processing of metals required for battery production, as well as the potential impacts of electricity generation from coal in some regions.

- Marine Ecotoxicity: Similar to freshwater ecotoxicity, EVs may show increased marine ecotoxicity impacts, particularly in regions where electricity is generated from fossil fuels.

- Terrestrial Ecotoxicity: The impacts on terrestrial ecosystems can vary depending on the specific materials used in EV production and the electricity mix. However, some studies suggest that EVs may have higher terrestrial ecotoxicity impacts compared to ICEVs.

For example, Khan et al. 2023 demonstrated that there is a general increase in Terrestrial Ecotoxicity, Human carcinogenic toxicity, Freshwater Eutrophication Potential and Marine Ecotoxicity by replacing ICE excavators with electric excavators. This is due to the use of rare earth metals both in manufacturing battery and electronic components for EVs and renewable electricity plants, along with a higher energy consumption in electrical components.

It's crucial to note that the ecotoxicity impact is also influenced by the electricity mix used to charge EVs, along with the efficiency of recycling and waste management processes.

As the transition to renewable energy progresses and battery technologies improve, the ecotoxicity impacts of EVs are expected to decrease. The increasing proportion of low-carbon electricity generation in Europe and key battery production locations (e.g., China, South Korea, and Japan etc.) is likely to reduce the environmental impacts associated with EV use and production. Furthermore, advancements in battery recycling technologies and the implementation of circular economy principles in the EV industry are expected to significantly reduce both resource consumption and ecotoxicity impacts in the future.

The effects of these changes/ improvements have been studied across resource consumption and ecotoxicity apart from global warming potential for 2020, 2030 and 2050 for passenger cars and heavy-duty vehicles in the German market context (UBA 2024). Readers are encouraged to read the UBA 2024 report for more information.

Pulsetrain's systems can positively influence these indicators i.e. reduce the negative impacts in comparison to an EV with standard BMS, that too, independent of the battery technology, electricity mix and EoL processes, as Pulstrain's systems help reduce the energy consumption and prolong the lifetime of the batteries.

4. Variables not considered in the study and limitations

The following variables have not been considered in the study but can positively influence the overall impact of Pulsetrain's BMSs:

- **Reduction in waste cells:** Pulsetrain's Pulstrain BMS technology can switch individual battery cells on and off, reducing the need for all cells to strictly meet or exceed standard performance parameters. Typically, about 20% of battery cells produced fall outside the acceptable range and are sent for recycling. Pulsetrain estimates that its BMS technology can lower this rejection rate to 11%, significantly reducing battery waste during manufacturing.
- **Enhanced Battery Formation Efficiency:** Battery formation refers to the initial cycles of charging and discharging, during which manufacturers use proprietary methods to optimise performance. Research indicates that pulsed charging can significantly improve the coulombic efficiency of batteries. Pulsetrain's Pulstrain BMS can be applied during the formation process to produce batteries with higher coulombic efficiency, resulting in improved performance and reduced resource consumption over the battery's lifetime.
- **Second lifetime of batteries:** The Pulsetrain BMS enables a seamless second-life use of the batteries in static applications due to reduced degradation, switching off weak cells in the pack to maintain optimum power output and the possibility of mixing of different cells. This lowers the impact over the lifetime of the battery but is outside the system boundary and the scope of this study.
- **Weight reduction of vehicles:** The Pulsetrain's BMS avoids the need for a separate charger module, inverter and junction box, achieving about 120kg weight reduction (see section 2.1). The impact of reducing this weight (and thus the embodied emissions in the materials) has not been considered in this study due to two reasons, first, the unavailability of component level BMS data, and second, the weight of cars has increased over the years and this weight reduction will most likely face a rebound effect, becoming another opportunity to fit in other components that will cover up for the weight reduction.
- **Manufacturing of BMS:** The emissions from the manufacturing of Pulsetrain's systems and Standard BMS were not critically studied in this report. This is due to the lack of data on individual components of the incumbent BMS systems. It is essential to note that a transition to electric systems involving batteries will need a lot of BMS systems and thus lead to a lot of electronic waste at the EoL of the batteries. There is a dire need to create transparency around the electronic components in battery packs to ensure that critical metals remain in recycling loops and a high material use efficiency is achieved.
- **Energy Burn in Standard BMS:** In conventional battery systems, cells age differently and require balancing. For cells wired in series, the same current flows through all, but weaker cells heat up more due to the I^2R effect, accelerating their aging. As per Arrhenius' law, every 10°C increase doubles the aging rate, creating a self-reinforcing cycle where weaker cells degrade faster. The Battery Management System (BMS) halts charging when the weakest cell—typically with the highest resistance and lowest capacity—is full. To balance the cells, the BMS burns off excess energy from fully charged cells through resistors, a process that occurs while the vehicle is stationary. This leads to energy losses that can also be potentially eliminated by Pulsetrain's technology.

The following points describe the limitations of the study. While these points have not been considered in this version of the study because of various reasons, they can influence the final result, if considered:

- The electricity grid emission intensity was only sourced for three points in time: the present, 2030, and 2050. For the years in between, a linear interpolation was used to project emissions. In reality, emissions are likely not to develop linearly as different sources of energy will change gradually at different rates.
- We assumed a global electricity grid mix for the construction and automotive industry due to the global deployment of these vehicles. However, the real impact potential will vary by region, depending on the electricity grid mix of the particular grid circles.
- We used exemplary vehicles like a 26-tonne excavator, average ICE petrol or diesel cars and average two-wheelers like motorbikes and scooters in the study. However, the real impact will vary depending on the exact size, type and class of the vehicle that is replaced by BEVs, including those using Pulsetrain's systems.
- We assumed the lifetime emissions of ICE cars for an average of different cars. In reality, these emissions can vary depending on the size and class of the car, leading to different production and operational emissions. Additionally, the geographical region where a car is assembled can also have an impact on the overall emissions. The emissions of ICE vehicles operating in different countries can thus vary slightly.
- The share of change in total EU vehicle stock (increase, retired, exported and lost) for BEVs in the EU has been assumed constant. This share can change over the years due to various factors like policy, material availability etc. This can change the net impact of the deployment of Pulsetrain's systems in vehicles used in the EU.
- For the vehicles that are exported outside the EU, we did not consider variables like the probability of change in the mode of transport (from public transport to car) or a car type (new EV vs old ICE) and attribution of production emissions over a longer time period and additional fuel consumption in second life. This was done with a view of the system boundary and to avoid overcomplexity in calculations.
- We assumed a specific (representative) operational lifetime for vehicles across different industries. While these lifetimes were chosen based on scientific literature, the actual lifetimes can vary based on factors like geography, maintenance schedules etc. This can change the operational and maintenance emissions leading to a change in the impact.
- In the study, emissions for LCA phases, particularly production and EoL, have been chosen based on scientific literature and considered static over the years. However, these emissions can vary due to an increase in production efficiency, material use, EoL methods and also the geographical region for production and EoL of the vehicles.
- Deploying Pulsetrain BMS provides extended battery lifetime along with powertrain efficiency improvement. The extended lifetime can reduce the total cost of ownership (TCOE) of the BEV and potentially accelerate the EV transition. This factor has not been accounted for in the study as there are multiple bottlenecks to EV transition which will need to be addressed to realise an accelerated transition.

5. Conclusion

In conclusion, Pulsetrain has the potential to create a significant positive environmental impact by reducing energy consumption in the operation of EVs and extending the operational lifetime of batteries, resulting in higher material use efficiency (Table 3).

Table 3: *Impact potential of BEVs over ICE vehicles and Pulsetrain BMS compared to ICE and Standard BMS*

		Emission reduction over ICE excavator (tonnes CO2-eq./ excavator)			Emission reduction over Standard BMS (tonnes CO2-eq./ excavator)	
Industry	**Year of deployment**	**Standard BMS**	**Cellmate BMS**	**Pulsetrain BMS**	**Cellmate BMS**	**Pulsetrain BMS**
Construction (Global)	2025	4,948	4,967	7,477	19	2,528
	2035	5,001	5,013	7,533	12	2,532
		Emission reduction over ICE car (tonnes CO2-eq./ BEV)			**Emission reduction over Standard BMS (tonnes CO2-eq./ BEV)**	
		Standard BMS	**Cellmate BMS**	**Pulsetrain BMS**	**Cellmate BMS**	**Pulsetrain BMS**
Automotive (Global)	2025	28	29	32	1.5	3.7
	2035	31	32	34	1.0	2.9
		Emission reduction over ICE car (tonnes CO2-eq./ electric two-wheeler)			**Emission reduction over Standard BMS (kg CO2-eq./ electric two-wheeler)**	
		Standard BMS	**Cellmate BMS**	**Pulsetrain BMS**	**Cellmate BMS**	**Pulsetrain BMS**
Two-Wheeler (India)	2025	4	5	5	329	693
	2035	5	5	6	210	481

This study found that the impact potential varies in the three different industries we analysed:

- The highest impact potential (on an individual BMS deployment level) was observed in the construction industry due to two reasons, firstly, the biggest battery size and therefore the highest electricity consumption and, secondly, extending the lifetime of complete excavators as the operational lifetime of the electric excavators is limited by their battery lifetime and no battery replacement is considered.

- The automotive industry has the second largest impact potential (on an individual BMS deployment level), due to comparatively lower production emissions, battery size and power consumption. Unlike excavators, the operational lifetime of the car is not limited by the operational lifetime of the battery, i.e. a battery replacement is planned for in the operating life of the car. Thus, in the automotive industry, only the material consumption efficiency and lifetime emissions of the battery are being affected. For the automotive industry in the EU, the net impact considering the change in vehicle stock is lower as not all vehicles are scrapped at the end of their life, but are exported and used in other countries.

- The two-wheeler industry has the lowest environmental impact (on an individual BMS deployment level), due to the lowest material consumption, smallest battery size and therefore least electricity consumption. In addition to this, the lifetime in km of an average two-wheeler is only 55% compared to an average car and the operational lifetime in years is 83%.

Pulsetrain's Battery Management Systems will find applications in various industries and have the potential to achieve a significant positive impact on climate mitigation while lowering the negative effects of electrification on other resource consumption and ecotoxicity parameters.

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