# The optimal vehicle electrification level in a battery-constrained future

**Enquiries: ehsan.shafiei@concawe.eu**

In light of the EU's commitment to reduce greenhouse gas (GHG) emissions in Europe, there is considerable uncertainty as to whether battery production capacity will be able to meet the growing demand for batteries in Europe towards 2030. This article summarises the results of a study that explores the optimal passenger car sales composition that would minimise well-to-wheels GHG emissions as a function of battery production capacity.

## Introduction

As part of the European Green Deal, the European Union (EU) has committed to significantly reduce its greenhouse gas (GHG) emissions. A cut of 55% in 2030 compared to 1990 levels has been agreed by the European Commission, the European Parliament and the Council, to which passenger cars should contribute with a reduction of at least 37.5% in their $CO_2$ emissions between 2021 and 2030 (currently under revision and with the level of ambition likely to be raised in June 2021). This raises the obvious question for automotive manufacturers, energy providers, customers, regulators and other stakeholders: what is the best way forward to minimise GHG emissions from passenger cars?

For a given usage,[1] three main drivers play an important role in addressing this challenge:

1. The fleet mix, with four main technologies discussed in this instance (given in increasing order of electrification): vehicles powered solely by an internal combustion engine (ICEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and battery electric vehicles (BEVs).
2. The energy mix used for transport, i.e. the share of liquid and gaseous fuels or electricity used.
3. The carbon intensity of different combinations of feedstocks and conversion technologies used to supply energy carriers.

With a focus on the role of the fleet mix, many studies have been performed using a life-cycle assessment (LCA) approach to compare the merits of each of these four technologies.[2] Most of these studies carried out back-to-back comparisons of the life-cycle emissions of ICEVs vs BEVs expressed in terms of g $CO_2$eq/km or tonnes of $CO_2$eq along the whole lifetime of the vehicle in use, and concluded that, on an average C-segment basis in Europe, and using the average energy mix forecasted for the 2020–2030 time frame, BEVs would emit less GHG than ICEVs when no low-carbon fuels are considered.[3] The same conclusion in favour of BEVs is generally given when comparing HEVs with BEVs in an average European environment. The comparison of PHEVs with BEVs has received much less attention and there is no unanimous agreement in this regard. For example, IFPEN[2] concluded that PHEVs would emit less than BEVs over their life cycle, based on the assessment that the former has smaller batteries than the latter, which results in significantly lower GHG emissions over the vehicle life cycle, while keeping a high share of electric driving (referred to as the utility factor). However, ICCT[3] came to the opposite conclusion in their assessment that the real-world utility factor of PHEVs is overestimated by homologation measures, and is more likely to be in the range of approximately 20% for company cars and 50% for private vehicles, as users (especially those of company cars) do not charge them regularly enough. This results in higher $CO_2$ emissions in real use than those calculated during the homologation process. It is a fact that the LCA approach is often affected by many uncertainties, and the utility factor of PHEVs is among the most discussed topics along with the GHG emissions related to battery production.

1 For example, the number of cars sold each year, the mileage driven by each car, the occupation rate of the vehicles, etc.

2 For example, see Yugo (2018)[1] among many others.

3 This is an average result at the European scale, and does not necessarily apply in every European country as it depends on the energy mix of each country.

Notwithstanding the relevance of the aforementioned LCA studies, when a back-to-back comparison of, for example, an HEV with a BEV leads to the conclusion that the latter should replace the former in terms of sales, those studies all make the important — while often implicit — assumption that a bigger battery would be available to equip each and every new BEV vehicle sold.

But what if that was not the case? In such a scenario where, in 2030, the raw material availability and battery manufacturing capacity are still constrained, would it be preferable to allocate all the available materials/batteries to BEVs, with the consequence of having the rest of the sales as ICEVs? Or would it be more efficient for mitigating GHG emissions to spread the available batteries in different portions among HEVs, PHEVs and BEVs? [4]

The purpose of the present work is to answer the question, *'What would be the optimal sales mix to minimise GHG emissions from passenger cars in a battery-constrained environment in the same 2020–2030 time frame, according to a number of different analysts?'* (see the section entitled *Batteries: forecasted demand and production capacities* on pages 46–48). To answer this question, we need to move away from the back-to-back LCA comparison paradigm described above, and shift to a systemic view that takes account of constraints on battery availability, such that batteries allocated to BEVs may result in batteries no longer being available for HEVs and PHEVs, leading to an increase in sales of ICEVs.

To address this question, the authors performed an optimisation of the sales mix to reduce well-to-wheels (WTW) $CO_2$ emissions of passenger cars for different levels of battery production capacity. At this stage it is worth noting that, for each level of battery production capacity, it is assumed that the GHG emissions related to vehicle production are not influenced by the composition of vehicle sales, as all of the batteries produced are fully allocated to all vehicles sold that utilise electrified powertrains (xEVs).[5] This assumption results in a significant simplification compared to the full LCA method and justifies the use of a simpler WTW approach.

It could be argued that this study will be of limited use, being that automotive manufacturers should already be in the process of minimising the $CO_2$ emissions of their vehicles sold in a — potentially — battery-constrained environment. However, this is only partly true. As with any private corporation, vehicle manufacturers aim to maximise profits under certain constraints (reaching their $CO_2$ targets being a particularly important constraint). This means that they also have to account for vehicle costs, customer acceptance, long-term strategy, investments, etc., which makes optimisation far more complex — and different — from the work presented here. Manufacturers also have to face non-optimal regulations, for example the fact that GHG emissions are regulated only on a tank-to-wheels (TTW) basis and not on a WTW basis, or the fact that low-emission vehicles can benefit from double counting (super-credits).

[4] With the underlying assumption that HEVs, PHEVs and BEVs all use the same lithium-ion (Li-ion) battery technology.

[5] In a simplified approach, the emissions related to the production of vehicles is the sum of the emissions from the production of the car and those from the production of the batteries. As the number of cars and batteries produced is constant for each level of battery production whatever the fleet mix, one concludes that the emissions related to the production of vehicles does not depend on the fleet mix. To be more accurate, one should also account for the number and type of powertrains produced, which varies with the fleet mix. However, this was assumed to have a negligible effect on the life-cycle emissions.

These regulations can result in a suboptimal sales mix, in terms of minimising the global GHG emissions of passenger cars. For these reasons, the ultimate purpose of this article is to open a debate with automotive manufacturers and regulating authorities to identify, and hopefully also eliminate, any barriers that could lead to suboptimal WTW $CO_2$ emissions from passenger cars.

## Batteries: forecasted demand and production capacities

How likely is it that the next decade is going to be battery-constrained with respect to passenger cars? To assess the likelihood of this assumption, Concawe has collected data from the literature regarding forecasted demand and production capacities, and observed whether there are any gaps between the two.

### Forecasted demand

There are considerable uncertainties regarding the demand for batteries used for transport in 2030, as this depends heavily on the level of electrification of the vehicles sold, which in turn depends on regulations, customer preferences, vehicle manufacturers' strategies, etc. Added to this, the share of electrified vehicles has evolved quickly in recent years, and forecasts are somewhat sensitive to this dynamism.

Batteries Europe ETIP forecasts an annual demand of 0.44 TWh of batteries by 2030, in a context where the global demand for batteries would be multiplied by 14 between 2018 and 2030, initially driven by demand in China (1.12 TWh).[4] McKinsey & Company has also shared forecasts which anticipate demand ranging between approximately 0.3 and 0.7 TWh/year in 2030.[5]

In the work presented here, the most extreme case regarding battery demand assumes that 100% of new vehicle sales will be BEVs by 2030, with an annual sale of 16 million passenger cars in Europe,[6] all of them being equipped with a 50 kWh battery. This results in a demand scenario of 0.8 TWh/year of batteries, which is already in the upper range of the aforementioned scenarios, without taking into account the demand from other sectors such as heavy-duty transportation or energy storage.

### Forecasted production capacities

The forecasts regarding battery production capacities face the same level of uncertainty as for the demand:[6]

- Batteries Europe ETIP reports that there are a total of 25 announced projects for Li-Ion factories in Europe, ranging from pilot plants to 'gigafactories' which, if realised, will add approximately 0.5 TWh/year to total production capacity in Europe by 2030.[4]
- PV Europe mentions an expected 0.3 TWh/year of battery production capacity by 2029, with large uncertainties, and refers to the meta-study, 'Batteries for electric cars: Fact check and need for action' commissioned by VDMA and carried out by the Fraunhofer Institute for Systems and Innovation Research ISI, which suggests that production capacities of 0.3 to 0.4 TWh/year could be achieved by 2025.[7]
- Volkswagen recently announced its plan to build six battery cell factories in Europe by 2030, corresponding to a production capacity of up to 0.24 TWh/year.[8]
- Tsiropoulos *et al.*, on behalf of the Joint Research Centre of the European Commission, evaluated that European battery production capacity could be sufficient to meet a domestic demand for 2–8 million BEV sales[9] — far from the expected annual sales of 16 million passenger cars.
- A recent report by Ultima Media predicts that the rising demand for EVs, the introduction of regulations supporting local battery production, and the number of factories under construction or announced will lead to considerable growth in European battery manufacturing capacity of up to 0.95 TWh/year by 2030.[10] However, the report indicates that there is no guarantee that all of the announced capacities or stated ambitions can be realised.

For the sake of comparison, in the second half of 2020, the global battery capacity deployed in all newly sold passenger xEVs combined (HEVs, PHEVs and BEVs) amounted to 0.093 TWh/year, out of which 0.037 TWh/year were used in Europe.[11] This is far from the levels of battery manufacturing capacity projected in the high-BEV demand scenario.

### A battery-constrained environment?

In spite of all the uncertainties, the trends collected for battery production and demand undoubtedly show that we will be living in a battery-constrained environment during the next decade, as the demand that would result from a high-BEV electrified scenario could not be met by the forecasted production capacity. Even when reaching the 2030 horizon, meeting the overall battery demand remains highly uncertain; not only does the forecasted production capacity vary widely, but the demand from other sectors, such as heavy-duty vehicles and energy storage, could add to the demand originating from passenger cars. Recycling of batteries could help to alleviate this constraint, but the role of recycling is expected to be limited in this decade due to the level of technology development still required and because demand is expected to grow too fast to allow recycled batteries to have a significant share of sales by 2030.

[6] The figures presented here are from different sources and are not necessarily consistent; they should not, therefore, be combined in an attempt to derive a total future value for battery production capacity.

Even though an accelerated demand for batteries could incentivise the expansion of battery production capacity in the future, it is expected that, within the time frame up to 2030, battery supply in the EU would need time before it is able to keep pace with the accelerated demand due to the potential constraints on both raw material availability and production capacity.

The EU's ambition is to become a global leader in sustainable battery production and use by developing its own production capacity.[12] It may still need to rely on imports from other regions for some of its battery requirements, but Europe considers local battery production to be a strategic goal, according to the strategic plan supporting the European Battery Alliance.[12] Hence, it is assumed that Europe will not rely on imports as an important source of battery supply, not least considering its ambitious target of 100% sourcing from its local battery production capacity.[10] It is, therefore, fully justifiable to conduct a study under an assumption of battery constraints, and to investigate the best sales mix in this environment to minimise GHG emissions from passenger cars.

## Method and key assumptions

To deal with uncertainties surrounding battery supply capacity, and the potential implications for GHG emissions, a linear programming model was developed to explore the optimal passenger car sales composition, minimising WTW GHG emissions as a function of battery production capacity. The model determines the optimal mix among all feasible combinations of powertrains. The scope of the analysis is limited to ICEV, HEV, PHEV and BEV powertrains; the potential impact of fuel cell electric vehicles (FCEVs) is ignored in the 2030 passenger car fleet mix. Furthermore, the modelling framework does not aim to evaluate the impact of other barriers that could hinder the penetration of xEVs (e.g. the availability of recharging points in Europe). In addition, any impact of possible competition among different transport modes in utilising battery resources is ignored, mainly due to the expected centrality of electric passenger cars in the battery market towards 2030.[13]

The main question in the optimal framework is how to make the best use of a certain level of battery production cap (TWh/year) to minimise WTW GHG emissions of newly registered cars EU-wide in 2030. In this framework, the analysis explores the optimal vehicle sales mix to minimise GHG emissions subject to the following constraints:

- Battery supply cap, ranging from 0.0–0.8 TWh/year, being the upper limits for the total battery supply used in the xEVs sold.
- Annual sale of 16 million passenger cars per year (based on Yugo *et al.,* 2021).[6]

The main assumptions and input parameters used to calculate WTW GHG emissions are summarised in Table 1 (for vehicles) on page 49, and Table 2 (for energy carriers, i.e. liquid fuels and electricity in this instance) on page 50. TTW emissions in g $CO_2$eq/km are calculated based on the energy consumption of vehicles (MJ/km) and fuel emission factors (g $CO_2$eq/MJ). Vehicle energy consumptions (MJ/km based on the Worldwide Harmonised Light Vehicle Test Procedure (WLTP) cycle) for the base case were derived from 2025+ figures in the JEC TTW study v5.[14] In a higher-energy consumption case, a 50% increase is applied to the energy consumption of all powertrains to show the sensitivity of results.

It is worth noting that a C-segment passenger car is used as the reference vehicle in this study. The efficiency data should therefore be considered as an estimate, as it is not fully representative of all new registrations.

Table 1: Key assumptions for the selected vehicles

| | ICEV | HEV | PHEV-f (fuel mode) | PHEV-e (e-mode) | PHEV (average)[b] | BEV |
|---|---|---|---|---|---|---|
| **Vehicle mileage (km/vehicle/year)** | 12,000 | 12,000 | 4,800[b] | 7,200[b] | 12,000 | 12,000 |
| **Battery size (kWh)** | -- | 2 | -- | 20 | -- | 50 |
| **Energy consumption (MJ/km, WLTP)[a]** | | | | | | |
| Baseline: Gasoline + Electricity | 1.41 | 1.03 | 1.15 | 0.52 | 0.77 | 0.45 |
| High: Gasoline + Electricity | 2.11 | 1.54 | 1.73 | 0.79 | 1.16 | 0.67 |
| Low-carbon fuel illustration: Diesel + Electricity | 1.30 | 1.08 | 1.14 | 0.51 | 0.76 | 0.45 |
| **WLTP/NEDC[d] emission ratio (g $CO_2$/km)** | 1.15 | 1.32 | -- | -- | 1.00[c] | 1.26 |

Notes:
All data for energy consumption and utility factor are based on the WLTP cycle.
[a] Data source: JEC TTW study v5.[14]
[b] Assuming 60% utility factor.
[c] Data source: Tsiakmakis *et al.*, 2017.[15] The conversion factor of 1.0 is applied to the PHEV in its combined mode.
[d] NEDC: New European Driving Cycle.

The average vehicle mileage is assumed to be 12,000 km/year for all vehicle types. For PHEVs, the annual mileage in electric-driving mode (e-mode) is determined by the utility factor. The JEC TTW v5 data suggests that, with an increased battery size allocation of about 20 kWh for PHEVs, the range using electric drive should be approximately 90% of the distance travelled by 2030 (WLTP). In addition, the estimated WLTP function, based on ICCT (2020)[3] and UNECE (2017),[16] shows that a WLTP range of 100 km returns a utility factor of about 90%. In Concawe's evaluation, an average battery size of 20 kWh is assumed for the PHEV with a 100 km WLTP e-driving range (assuming a depth-of-discharge level of about 70–75%). An average battery size of 2 kWh is assumed for full HEVs. The battery size for the BEV with a WLTP range of 400 km is 50 kWh.

Table 2: Key assumptions for the energy carriers

| FUEL | Combustion emission factor [a] g $CO_2$eq/MJ (TTW) | Well-to-tank (WTT) emission factor [a] g $CO_2$eq/MJ | Biogenic credits [a] g $CO_2$eq/MJ |
|---|---|---|---|
| **Gasoline (fossil-based)** | 73.4 | 17.0 | 0.0 |
| **Ethanol (E100)** | 71.4 | 44.2 | -71.4 |
| **Gasoline (E10)** | 73.3 | 18.9 | -4.9 |
| **Diesel (fossil-based)** | 73.2 | 18.9 | 0.0 |
| **FAME (B100)** | 76.2 | 38.7 | -76.2 |
| **HVO** | 70.8 | 27.6 | -70.8 |
| **Diesel (B7)** | 73.4 | 20.2 | -4.9 |
| **B7(50%) + HVO(50%)** [b] | 72.1 | 23.9 | -37.9 |
| **Electricity** [c] | | | |
| Base (2030 EU mix) | 0.0 | 21.0 | 0.0 |
| Low (Wind) | 0.0 | 0.0 | 0.0 |
| High (2019 EU mix) | 0.0 | 76.4 | 0.0 |

Notes:

[a] Data source for liquid fuels: JEC WTW study v5,[17] assuming total theoretical combustion of the fuel.

[b] Assuming 50% share of hydrotreated vegetable oil (HVO) in energy term to replace diesel fuel (B7 fuel grade).

[c] Source: EEA, 2020.[18]

A range of sensitivity analyses have been conducted around the following key parameters:

- **Utility factor:** varies from 30% to 90% with the base case being at 60% (all using the WLTP cycle).
- **Total sales:** changes in annual vehicle sales within +/- 25% around the baseline sale of 16 million cars (i.e. 12 million cars in the low case and 20 million cars in the high case).
- **Electricity supply carbon intensity (g $CO_2$eq/MJ):** ranges from 0 (e.g. from wind-generated electricity, excluding emissions from infrastructure) to 76.4 g $CO_2$eq/MJ as of 2019 (average value) in the high case, with the base case value of 21 g $CO_2$eq/MJ representing indicative intensity levels that would allow the EU to achieve a net 55% reduction in GHG emissions by 2030, compared with 1990.[18]
- **Vehicle energy consumption (MJ/km):** 2025+ numbers in the JEC TTW report v5 are considered as the base case assumption for 2030, and a 50% increase in fuel consumption is considered for the sensitivity analysis.
- **Use of low-carbon fuels:** HVO is considered as a partial replacement for the 50% of diesel passenger car sales in 2030. (It is important to note that other low-carbon fuel alternatives such as pyrolysis gasoline from waste resources can also be considered in the sensitivity analysis. However, for simplicity in the current analysis, HVO is considered as the illustrative case for low-carbon fuels because of its higher replacement potential for fossil fuels[6]).

## Results

### The optimal sales mix to minimise GHG emissions

Figure 1 displays the optimal sales composition for different levels of battery supply cap in 2030 when the utility factor is above 45%. The corresponding minimised WTW GHG emissions at each level of battery cap is shown by the diamonds and can be read on the right axis. The results show that, below the battery cap of 0.30 TWh/year, the combination of 'PHEV+HEV' would be the most effective option towards a low-carbon sales mix when pursuing the ultimate goal of reducing GHG emissions (WTW). When the available battery capacity rises to 0.55 TWh/year, the PHEV would still be the most attractive technology, with its share remaining higher than the BEV. For battery supply capacities greater than 0.55 TWh/year, BEVs would have the dominant share over PHEVs in all the sensitivity cases explored. Overall, the PHEV appears to be a key technology for decarbonising transport, as it is present in all the partially electrified scenarios, from a 0.05 TWh/year to a 0.75 TWh/year battery production cap. PHEVs are excluded from the optimal sales mix in only two cases: the non-electrified case (ICEVs only, with no battery production — a scenario that would not comply with future TTW $CO_2$ emissions limits) and the 100% BEVs case (enabled by a battery production capacity of 0.8 TWh/year, assuming the annual sale of 16 million passenger cars per year). The sensitivity analysis with respect to a change in annual sales of +/-25%, as demonstrated in Figure 2 on page 52, confirms the key contribution of PHEVs in the optimal fleet sales mix: the higher the vehicle sales, the higher the expected contribution of PHEVs to decarbonising the new sales mix.

**Figure 1: Optimal vehicle sales mix minimising WTW GHG emissions subject to a battery supply cap in 2030 when the utility factor is greater than 45%**

Note: WTW emissions are calculated at a 60% utility factor.

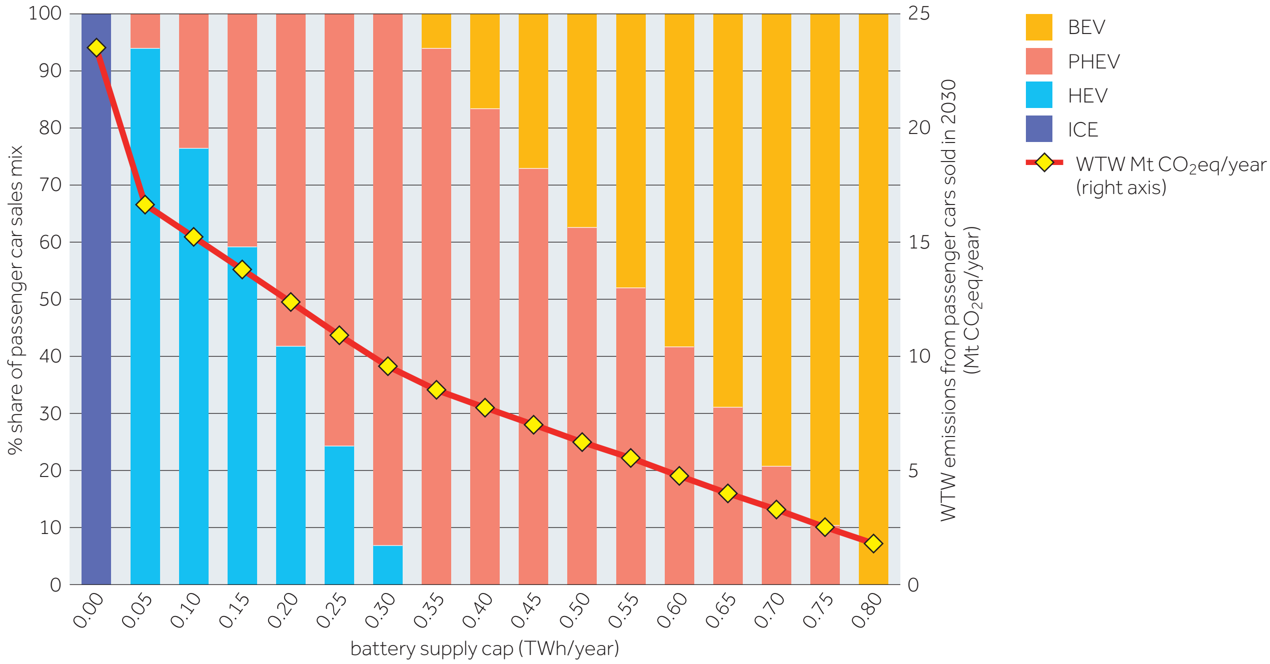
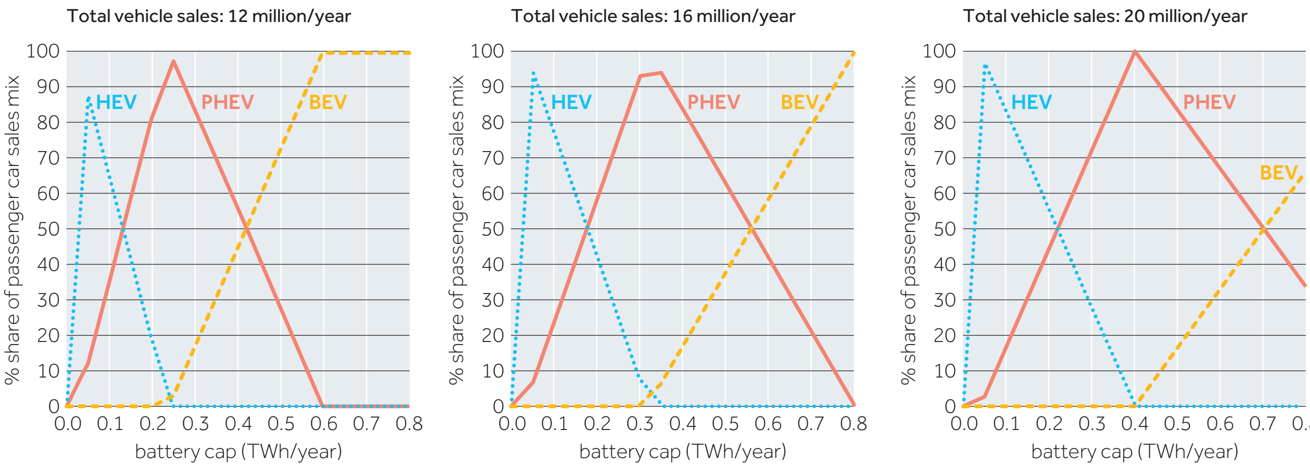
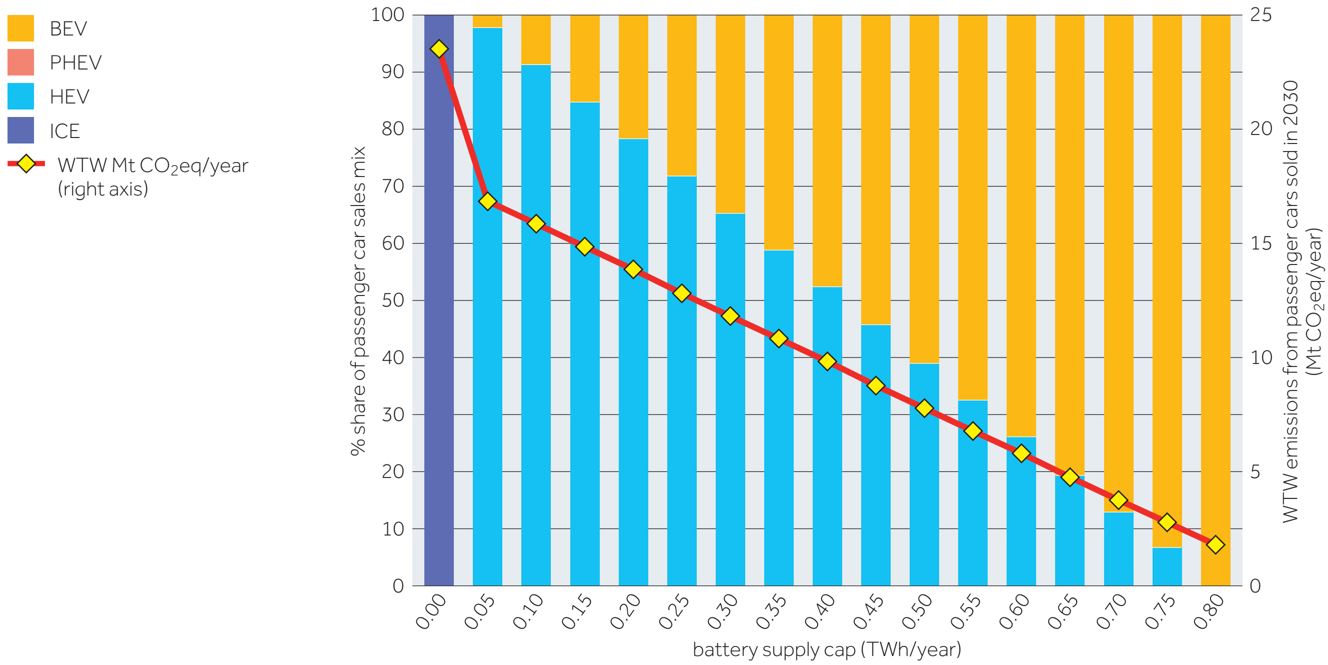


Figure 2: Optimal share of xEVs in 2030 sales: impact of total sales volume




The sensitivity analysis around the utility factor of PHEVs showed that the optimal mix remains unchanged for utility factors above 45%. It indicates that, in the battery cap scenarios up to about 0.55 TWh/year in 2030, the PHEV with 100 km electric driving range would be the key component of the optimal solution, with a share of the sales mix higher than 50%. However, when the utility factor of PHEVs is too low (below 45%), the optimal sales mix would include BEV+HEV (with no PHEV playing a role), as shown in Figure 3.

Figure 3: Optimal vehicle sales mix minimising WTW GHG emissions subject to a battery supply cap in 2030 when the utility factor is below 45%



With the optimised market share of different powertrains within the total new sales and corresponding NEDC TTW emissions intensities (calculated based on the WLTP/NEDC ratio presented in Table 1 on page 49), the average EU-wide new passenger car emissions (in NEDC TTW g $CO_2$/km) can be calculated and compared with the emission target of 59 g $CO_2$/km by 2030. Assuming the state-of-the-art efficiency figures for passenger cars in 2030, and regardless of the level of utility factor, the analysis shows that the optimised fleet mix in Figures 1 and 3 under the battery production capacity constraint above 0.05 TWh/year would be fully compliant with the emission target of 59 g $CO_2$/km by 2030.

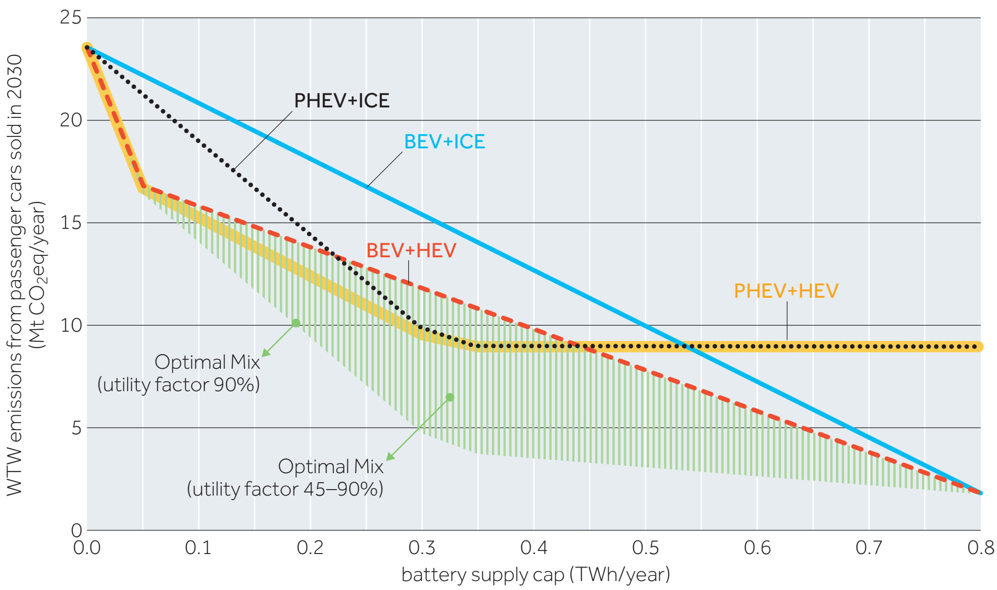
## Pairwise comparisons of different sales mix scenarios

This section summarises the outcomes of comparing the following cases in pairs to evaluate which sales mix would be preferable in terms of WTW GHG emission reductions:

- **BEV+ICE:** the vehicle choice set is restricted to BEVs and ICEVs.
- **BEV+HEV:** the vehicle choice set is restricted to BEVs and HEVs for a battery supply cap above 0.05 TWh/year.
- **PHEV+ICE:** the vehicle choice set is restricted to PHEVs and ICEVs.
- **PHEV+HEV:** the vehicle choice set is restricted to PHEVs and HEVs for a battery supply cap above 0.05 TWh/year.
- **Optimal Mix:** the sales mix is optimised without exogenous constraints on the vehicle choice set.

In all of the above cases, the WTW GHG emissions of passenger cars are minimised subject to the battery supply cap constraints. Figure 4 demonstrates the key comparisons and break-even points, mainly under the baseline conditions defined in Tables 1 and 2.

**Figure 4: Minimum WTW GHG emissions subject to battery supply constraints and break-even analysis of different sales combinations**




Note: the green shaded area on Figure 4 presents the sensitivity of the 'Optimal Mix' case with the utility factor ranging from 45% to 90%.

A more detailed comparison of the minimum achievable emissions in different cases, including a comprehensive sensitivity analysis around the utility factor, is presented in Figure 5 on page 55. The key messages from the findings are expressed as follows:

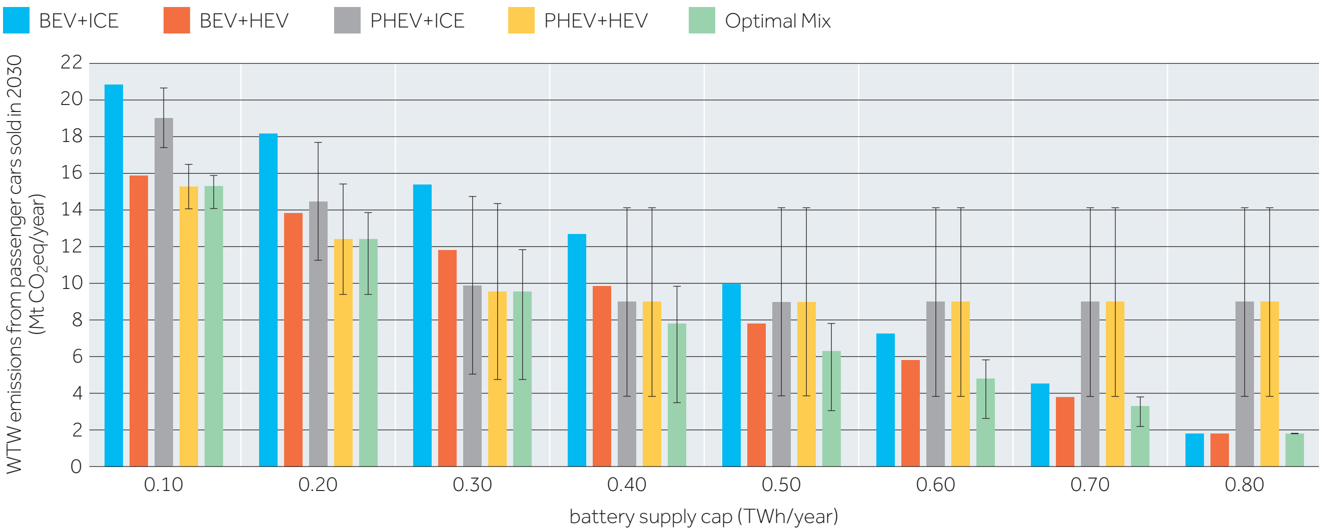
- Among the sales combination cases that fully utilise the available battery supply cap, the sales mix restricted to only BEV+ICE appears to be the worst combination when reducing GHG emissions, almost throughout the whole battery cap range explored, initially with a substantial gap compared to the other cases (see the blue line in Figure 4 on page 53). The gap is narrowed by increasing the battery supply up to the break-even point of 0.8 TWh/year with 'Optimal Mix'.
- Assuming the base case utility factor of 60% for PHEV, the BEV+ICE case could be advantageous over both the PHEV+ICE and PHEV+HEV cases (which would not fully utilise the available battery cap) only if the battery supply cap exceeds 0.55 TWh/year. This advantage is reduced as the utility factor for PHEV increases.
- The green shaded area on Figure 4 represents the optimal sales mix as described in Figure 1 (page 51) for a utility factor above 45%. The upper line of the green shaded area, resulting from the optimisation model for utility factors below 45%, is equivalent to a pure BEV+HEV case.
- For utility factors above 45%, the PHEV+HEV case appears to be the most effective option to reduce GHG emissions for a battery cap below 0.35 TWh/year.
- The emissions level would reach a floor in the PHEV+ICE and PHEV+HEV cases for the battery supply cap exceeding 0.32 TWh/year. The reason for this is that the whole new passenger car mix would be composed of 100% PHEVs.
- The green shaded area on Figure 4 shows the sensitivity of the minimised emissions with respect to the utility factor, changing from 45% to 90%: in these scenarios, it appears that increasing the utility factor of PHEVs is the most efficient way forward to decreasing GHG emissions from passenger cars.
- It is worth noting that a sales mix case involving PHEV+BEV would not be a feasible option for the battery cap below ~0.35 TWh/year (not shown in this instance). For the battery cap over this level, the results for this case are represented by the 'Optimal Mix'. This means that a sales mix made of PHEV+BEV would minimise GHG emissions for a battery cap above ~0.35 TWh/year.

### The impact of the utility factor in different cases

Figure 5 on page 55 summarises the results of a sensitivity analysis around the utility factor for all considered sales mix cases. According to the Figure, for a battery cap below ~0.35 TWh/year, PHEV+ICE would be a more effective strategy than BEV+ICE regardless of the utility factor considered (i.e. 30–90%). For the higher levels of battery cap up to ~0.70 TWh/year, only upper utility factors could make PHEV+ICE preferable. For the battery cap below ~0.35 TWh/year, the baseline results for PHEV+HEV are identical to the 'Optimal Mix' solution. The error bars are, however, narrower in the optimal sales mix solution because PHEVs with low utility factors are excluded from the 'Optimal mix'.

**Figure 5: Comparison of minimised GHG emissions subject to a battery supply cap in different sales mix scenarios (error bars show the sensitivities with respect to the utility factor).**

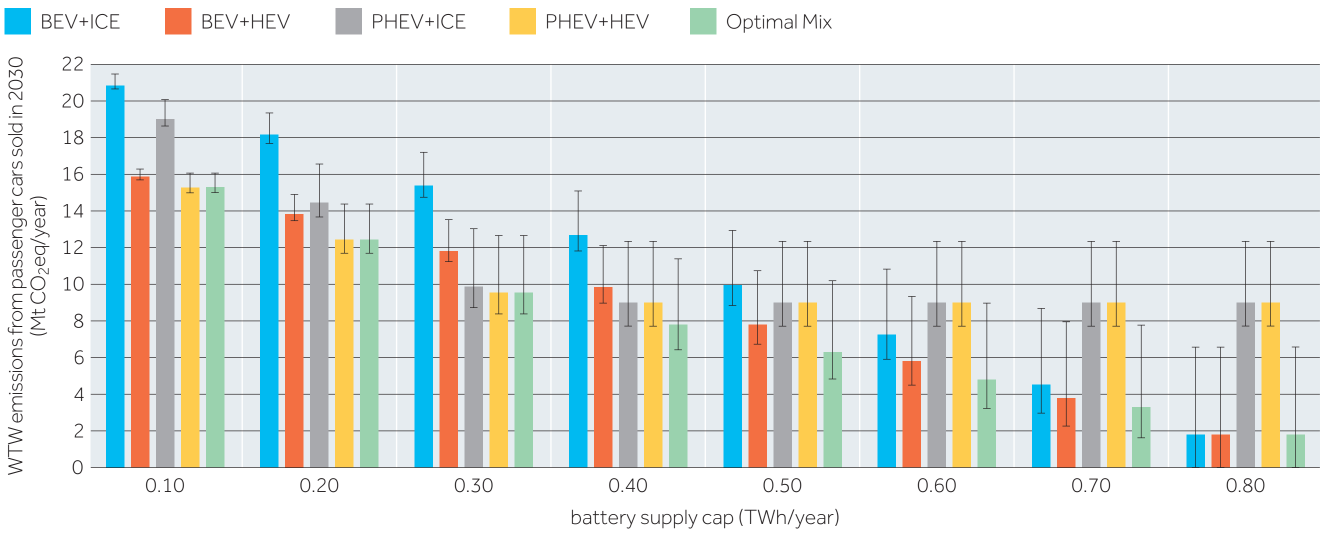
Note: The composition of 'Optimal Mix' is defined in Figure 1 (page 51) and Figure 3 (page 52).




## The impact of electricity supply carbon intensity

Further sensitivity analysis around electricity supply emission factors ranging from 0 g $CO_2$eq/MJ to 76.4 g $CO_2$eq/MJ (the average emission intensity of EU electricity generation mix in 2019) shows that the above conclusion about the role of the PHEV would still be valid (see Figure 6). The main difference is that, under the upper emission factor of 76.4 g $CO_2$eq/MJ, the break-even utility factor (for changing the optimal fleet mix as defined in Figures 1 and 3) increases to 52%, compared to 45% in the baseline analysis.

**Figure 6: Comparison of minimised GHG emissions subject to a battery supply cap in different sales mix scenarios (error bars show the sensitivities with respect to the carbon intensity of the electricity supply mix ranging from 0 to 76.4 g $CO_2$eq/MJ)**



## The impact of higher fuel consumption and low-carbon fuels

Further sensitivity analysis showed that assuming higher energy consumptions for vehicles according to Table 1 on page 49 (i.e. 50% higher MJ/km) would not change the optimal sales mix. Hence, owing to the unchanged sales mix, the total emissions of the new cars would go up proportionally by 50% compared to the baseline. Such differences are shown in Figures 7 and 8 for different levels of battery supply cap, utility factors and electricity supply emission intensity.

Figure 7: The impact of higher energy consumption and use of low-carbon fuels on the minimised GHG emissions under the 'Optimal Mix' case (error bars show the sensitivities with respect to the utility factor)

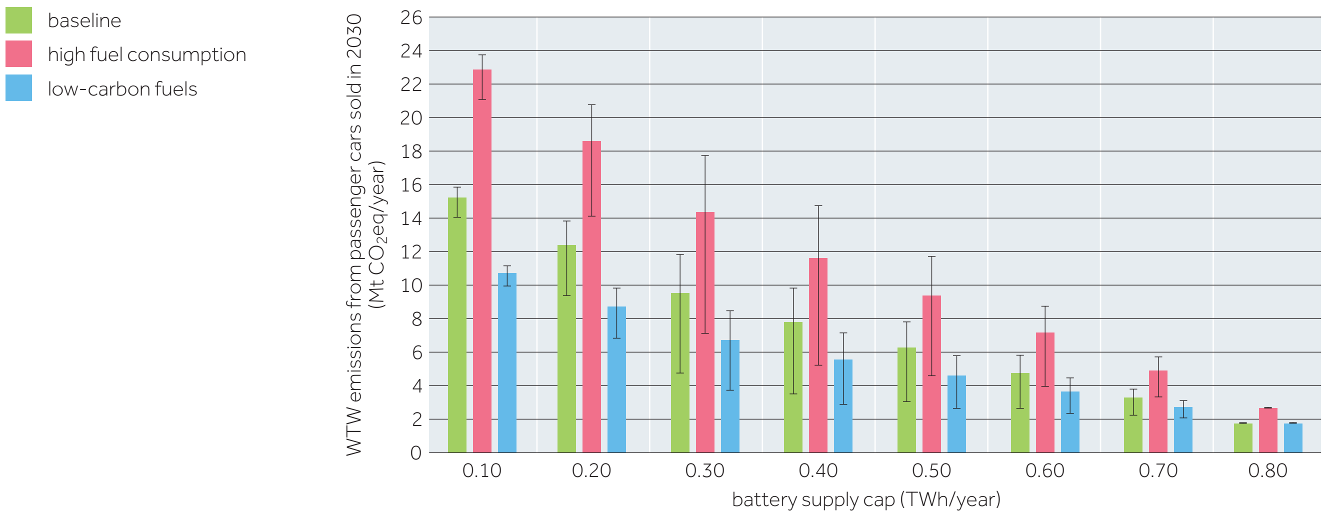
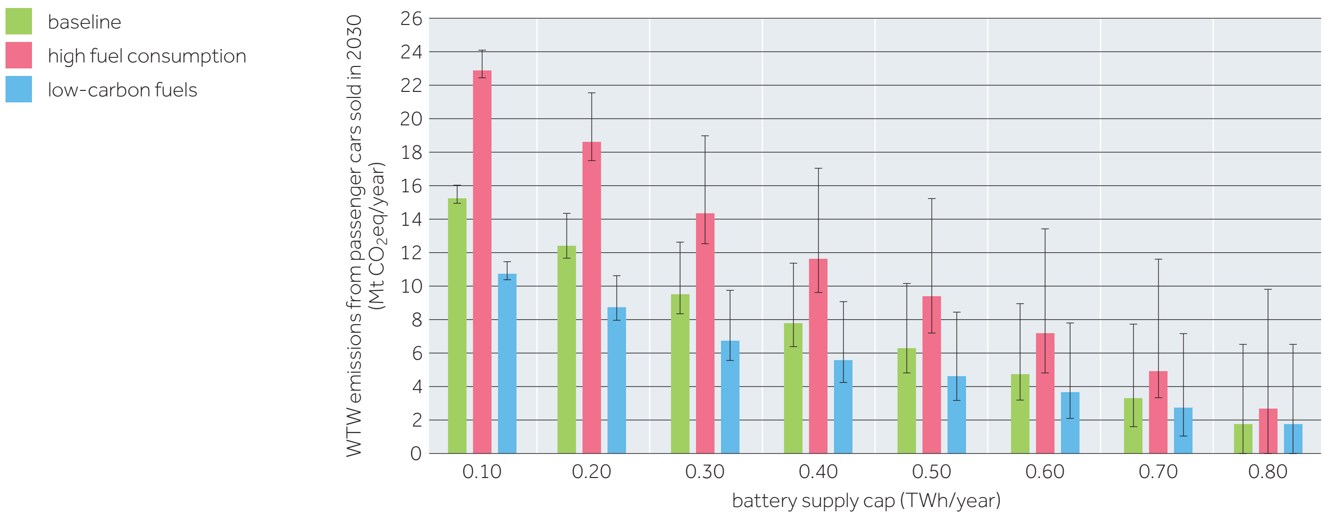



Figure 8: The impact of higher energy consumption and use of low-carbon fuels on the minimised GHG emissions under the 'Optimal Mix' case (error bars show the sensitivities with respect to the carbon intensity of the electricity supply mix ranging from 0 to 76.4 g $CO_2$eq/MJ)



Figures 7 and 8 also demonstrate the impact of considering the assumed illustrative example of low-carbon fuels in a 2030 time frame scenario (i.e. with HVO having a 50% energy share in total liquid fuel use, as explained in Table 2 on page 50) as replacement for diesel fuel in new sales. The sensitivity analysis around the share of HVO shows that it cannot change the optimal sales mix within the assumed range of utility factor and electricity supply carbon intensities. However, it results in lower WTW emissions from the same sales mix as in the baseline condition.

It is important to note that more optimistic scenarios for the share of HVO in total liquid fuels (as an illustrative example of low-carbon fuels) would be in favour of HEVs, especially when the carbon intensity of the electricity supply is high. For instance, further sensitivity analysis shows that, assuming an extreme case of a 100% HVO share of fuel used in diesel-fuelled vehicles, together with a high carbon intensity of the electricity supply (i.e. 76.4 g $CO_2$eq/MJ), would lead to the 100% HEV share being the optimal case in minimising WTW emissions.[7]

## Conclusions

This study addressed the key question in a future battery-constrained environment, i.e. how to make the best use of a certain level of battery production towards minimised WTW GHG emissions of EU-wide newly registered passenger cars in 2030. To deal with the uncertainties relating to battery supply capacity and the potential implications for GHG emissions, the study explored the optimal passenger cars sales composition that would minimise WTW GHG emissions as a function of battery production capacity. A wide range of possible cases were defined based on the sensitivity analysis around the key parameters, including the utility factor of PHEVs, the carbon intensity of the electricity supply, vehicle energy consumption and the use of low-carbon fuels. Other considerations such as the total cost of ownership are not considered in this analysis which focuses only on strategies to minimise WTW GHG emissions.

The findings confirm that individual comparisons of powertrains (e.g. 1 BEV vs 1 PHEV) are not always relevant, and a systemic analysis optimising the whole sales mix, given the amount of limited battery supply resources, leads to different conclusions. The findings indicate that under a low/medium battery production capacity and moderate/high levels of utility factor, a combination of HEV+PHEV sales is the most effective option for reducing GHG emissions. In addition, in the battery cap scenarios up to about 0.55 TWh/year in 2030, PHEVs with 100 km electric-driving range would be the key component of the optimal sales mix, with its share reaching the maximum of 94% at the battery supply capacity of 0.3–0.35 TWh/year. In the scenarios considered, increasing the utility factor of PHEVs is the most immediate and accessible way to decrease GHG emissions in the short term. Increasing the contribution of low-carbon fuels in the fuel mix and a decrease in the carbon intensity of the electricity mix will offer significant additional WTW savings, which are expected to be more significant in the period 2030+.

[7] This assumes that a 100% HVO share of fuel used changes the optimal sales mix only in the case of very high electricity carbon intensity. In all other cases (including baseline electricity carbon intensity) its main impact is on the significant reduction in total emissions (from HEVs and PHEVs).

However, when the utility factor of PHEVs is too low (below 45%), HEVs and BEVs would replace them in the optimal sales mix. Table 3 provides a recap of the main findings for the optimal passenger car sales mix and break-even points with respect to battery production capacity, providing a clear message for an open debate with automotive manufacturers and regulatory authorities, which will be especially relevant in the 2030 time frame.

Table 3: Passenger car sales mix minimising WTW GHG emissions with break-even points

Note: the vehicle type mentioned in parentheses represents the dominant option within each sales mix.

<table>
<tr><th></th><th colspan="6">BATTERY PRODUCTION CAPACITY CONSTRAINT (TWh/year)</th></tr>
<tr><th>PHEV UTILITY FACTOR</th><th>Low<br>0.05–0.15</th><th>Medium<br>0.15–0.3</th><th>High<br>0.3–0.4</th><th>High<br>0.4–0.55</th><th>Very high<br>0.55–0.8</th><th>Relaxed<br>>0.8</th></tr>
<tr><td>Low:<br>≤45%</td><td colspan="3">BEV+HEV<br>(HEV)</td><td colspan="2">BEV+HEV<br>(BEV)</td><td>BEV</td></tr>
<tr><td>Medium/high:<br>>45%</td><td>HEV+PHEV<br>(HEV)</td><td>HEV+PHEV<br>(PHEV)</td><td colspan="2">PHEV+BEV<br>(PHEV)</td><td>PHEV+BEV<br>(BEV)</td><td>BEV</td></tr>
</table>

Notes:
Current capacity in 2021: 0.037 TWh/year.
Range of expected capacity in 2030: 0.3–0.95 TWh/year.

## References


1. Yugo, M. (2018). 'Life-cycle analysis—a look into the key parameters affecting life-cycle $CO_2$ emissions of passenger cars.' In Concawe *Review*, Vol. 27, No. 1, pp. 17-30. https://www.concawe.eu/publication/concawe-review-27-1/
2. IFPEN (2018). *Cross-sector review of the impact of electrification by segment. E4T Project*. IFP Energies Nouvelles. https://www.ifpenergiesnouvelles.com/sites/ifpen.fr/files/inline-images/NEWSROOM/Communiqu%C3%A9s%20de%20presse/projet-e4t-bilan-impact-electrification-2018_version_anglaise.pdf
3. ICCT (2020). *Real-world usage of plug-in hybrid electric vehicles. Fuel consumption, electric driving, and $CO_2$ emissions*. International Council on Clean Transportation. https://theicct.org/publications/phev-real-world-usage-sept2020
4. Batteries Europe ETIP (2020). *Strategic Research Agenda for batteries 2020*. European Technology and Innovation Platform (ETIP). https://ec.europa.eu/energy/sites/default/files/documents/batteries_europe_strategic_research_agenda_december_2020__1.pdf
5. McKinsey & Company (2019). *Recharging economies: The EV-battery manufacturing outlook for Europe*. https://www.mckinsey.com/industries/oil-and-gas/our-insights/recharging-economies-the-ev-battery-manufacturing-outlook-for-europe
6. Yugo, M., Shafiei, E., Ellingsen, L. A. and Rogerson, J. (2021). *Concawe's Transport and Fuel Outlook towards EU 2030 Climate Targets*. Concawe Report no. 2/21. https://www.concawe.eu/wp-content/uploads/Rpt_21-2.pdf
7. PV Europe (2020). 'Battery manufacturing is coming to Europe.' Article published on the PV Europe website on 22 November 2020. https://www.pveurope.eu/energy-storage/green-economy-battery-manufacturing-coming-europe

8. Reuters (2021). 'Volkswagen takes aim at Tesla with own European gigafactories.' Article by Christoph Steitz and Jan Schwartz published on the Reuters website on 15 March 2021.
https://www.reuters.com/article/us-volkswagen-batteries-plants-idUSKBN2B71EW
9. Tsiropoulos, I., Tarvydas, D. and Lebedeva, N. (2018). *Li-ion batteries for mobility and stationary storage applications - Scenarios for costs and market growth*. EUR 29440 EN, Publications Office of the European Union, Luxembourg, 2018, ISBN 978-92-79-97254-6, doi:10.2760/87175, JRC113360.
https://publications.jrc.ec.europa.eu/repository/handle/JRC113360
10. Ultima Media (2021). *INSIGHT: Electric Vehicle Battery Supply Chain Report: How Battery Demand and Production Are Reshaping the Automotive Industry*.
https://new.abb.com/products/robotics/events/ev-battery-report
11. Adamas Intelligence (2021). *State of Charge: EVs, Batteries and Battery Materials*.
https://www.adamasintel.com/report/download-state-of-charge-evs-batteries-and-battery-materials-2020-h2/
12. EC (2021). 'European Battery Alliance' (European Commission website).
https://ec.europa.eu/growth/industry/policy/european-battery-alliance_en
13. IEA (2020). *Global EV Outlook 2020. Entering the decade of electric drive?*
https://www.iea.org/reports/global-ev-outlook-2020
14. Huss, A. and Weingerl, P. (2020). *JEC Tank-to-Wheels report v5: Passenger cars.*
Editors: Maas, H., Herudek, C., Wind, J., Hollweck, B., De Prada, L., Deix, S., Lahaussois, D., Faucon, R., Heurtaux, F., Perrier, B., Vidal, F., Gomes Marques, G., Prussi, M., Lonza, L., Yugo, M. and Hamje, H.
EUR 30270 EN, Publications Office of the European Union, Luxembourg, 2020, ISBN 978-92-76-19927-4, doi:10.2760/557004, JRC117560. https://ec.europa.eu/jrc/en/publication/jec-tank-wheel-report-v5-passenger-cars
15. Tsiakmakis, S., Fontaras, G., Cubito, C., Pavlovic, J., Anagnostopoulos, K. and Ciuffo, B. (2017). *From NEDC to WLTP: effect on the type-approval $CO_2$ emissions of light-duty vehicles*. EUR 28724 EN, Publications Office of the European Union, Luxembourg, 2017, ISBN 978-92-79-71642-3 doi:10.2760/93419, JRC107662. https://publications.jrc.ec.europa.eu/repository/handle/JRC107662
16. UNECE (2017). *Technical report on the development of Amendment 2 to global technical regulation No. 15 (Worldwide harmonized Light vehicles Test Procedures (WLTP)).* United Nations Economic Commission for Europe, Inland Transport Committee. https://unece.org/DAM/trans/doc/2017/wp29/ECE-TRANS-WP29-2017-099e.pdf
17. Prussi, M., Yugo, M., De Prada, L., Padella, M. and Edwards, R. (2020). *JEC Well-to-Wheels report v5*.
EUR 30284 EN, Publications Office of the European Union, Luxembourg. ISBN 978-92-76-20109-0, doi:10.2760/100379, JRC121213. https://publications.jrc.ec.europa.eu/repository/handle/JRC121213
18. EEA (2020). 'Greenhouse gas emission intensity of electricity generation' (website). European Environment Agency, published 8 December 2020. https://www.eea.europa.eu/data-and-maps/daviz/co2-emission-intensity-6#tab-googlechartid_googlechartid_googlechartid_googlechartid_chart_11111