Optimal electrification level of passenger cars in Europe in a battery-constrained future

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A B S T R A C T

Recent forecasts for the rapid electrification of the road transport sector towards 2030 have given rise to considerable uncertainty associated with battery production capacity and whether it will be able to meet the growing demand in Europe. In view of this uncertainty and the potential implications for greenhouse gas (GHG) emissions, this paper explores the optimal electrification level of passenger cars for minimising well-to-wheels (WTW) GHG emissions as a function of battery production capacity. The findings indicate that plug-in hybrid electric vehicles (PHEVs) could be the key components of the optimal sales mix in a battery-constrained future; especially the lower-range PHEVs with smaller batteries would be preferable over hybrid electric vehicles (HEVs) and battery electric vehicles (BEVs). To ensure the best utilisation of the available battery resources, the longer-range PHEVs require far higher levels of utility factor to be able to play a role in the optimal sales mix.

1. Introduction

1.1. The context

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 GHG emissions compared to 1990 levels has provisionally been agreed by the European Commission, the European Parliament and the Council. In order to reach this new climate target, reducing emissions in the transport sector will be a key element and, as an example, an increase in the level of ambition for the current CO_2 emission standards for passenger cars would be expected. This raises the obvious question for automakers, energy providers, customers, regulators and other stakeholders: what is the best way forward to minimize the overall GHG emissions from passenger cars as a way to contribute to the climate ambition goal?

Many previous comparative analyses were performed using life-cycle assessment (LCA) to compare the merits of each of vehicle technologies— see e.g. (Carbone 4, 2018; Cox et al., 2020; ICCT, 2020; IEA, 2020a; Ricardo Energy & Environment, 2020; Yugo, 2018). Most of these studies carried out back-to-back comparisons of the life-cycle emissions of ICEVs vs BEVs expressed in terms of gCO_2eq/km or tonnes of CO_2eq 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

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Nomenclature

BEV	Battery Electric Vehicle
B7	Fuel with max 7 %v (volume) blending of FAME into diesel
CO_2eq	Carbon dioxide equivalent
DoD	Depth of Discharge
E10	Fuel with max 10 %v (volume) blending of bio-ethanol into gasoline
E100	Fuel with 100% bio-ethanol
FAME (B100)	Biodiesel fuel with 100% Fatty Acid Methyl Ester
GHG	Greenhouse Gases
HDV	Heavy-Duty vehicle
HEV	Hybrid Electric Vehicle
HVO	Hydrotreated Vegetable Oil
LCA	Life-Cycle Assessment
NEDC	New European Driving Cycle
xEV	Stands for HEV, PHEV, and BEV
PHEV	Plug-in Hybrid Electric Vehicle
TTW	Tank-to-Wheels
WLTP	Worldwide Harmonised Light Vehicle Test Procedure
WTT	Well-to-Tank
WTW	Well-to-Wheels

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low-carbon fuels are considered.[1] 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 (IFPEN, 2018) 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, UF). However, ICCT (ICCT, 2020) 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.

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 could still be constrained (see Section 2), 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?[2]

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 potentially European battery-constrained environment in the same 2020–2030 time frame, according to a number of different analysts?***' (see *Batteries: forecasted demand and production capacities* in Section 2). 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 additionally takes account of the composition of vehicle fleet mix and the 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.

1.2. Scope

Inspiring from the Kaya identity (Kaya and Yokobori, 1997), the annual GHG emissions from passenger cars can be expressed as a multiplication of the following key factors:

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[1] 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.
[2] With the underlying assumption that HEVs, PHEVs and BEVs all use the same lithium-ion (Li-ion) battery technology.

$$\sum_{\substack{heat \\ elec}} \left(Emission\ Intensity \left[\frac{gCO2eq}{MJ_{heat/elec}}\right] *Powertrain\ Efficiency\left[\frac{MJ_{heat/elec}}{MJ_{mech}}\right] *Glider\ Efficiency\left[\frac{MJ_{mech}}{km_{heat/elec}}\right] *Mode\ Share\left[\frac{km_{heat/elec}}{km_{total}}\right] \right.$$

$$\left. *Distance\left[\frac{km_{total}}{vehicle}\right] \right) *Vehicle\ Number \hspace{4cm} (1)$$

  i) the GHG emission intensity of the energy carriers
 ii) the powertrain efficiency
iii) the glider efficiency as a representative of the vehicle weight and design in addition to the traffic conditions
 iv) the share of electric/thermal driving mode in total distance travelled in case of multi-power source vehicles
  v) the total distance travelled by car
 vi) the number of cars required to meet passenger travel demand

It is often understood that the first two items of the above factors (GHG intensity for each energy carrier and powertrain efficiency) represent the technical drivers which impact GHG emissions from passenger cars, while the last two items (v) and (vi) represent the societal/behavioural drivers. The items (iii) and (iv) are both technical (e.g. vehicle weight or electric driving range) and societal/behavioural (e.g. traffic conditions or consumer recharging patterns) drivers. The current study, specifically, focuses on the analysis of the following factors:

- The GHG intensity of the energy carriers, represented in this work in either the use of liquid fuels or electricity, with different combinations of feedstock and conversion technologies to produce them;
- The powertrain efficiency, represented in this work by the fleet mix and technology improvement, 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).
- the driving mode of multi-power-source vehicles, considering the possible variations in the share of electric driving mode in total distance travelled for PHEVs.
- the number of cars, represented in the current study as scenarios for future sales of passenger cars, influencing the number of xEVs (i.e. HEVs, PHEVs, and BEVs) and, thus, the expected demand for batteries.

Within this context, the authors performed an optimisation of the sales mix to minimise the well-to-wheels (WTW) GHG emissions of passenger cars for different levels of battery production capacity. In this framework, for each level of battery production capacity, it is assumed that the GHG emissions related to vehicle production are not significantly influenced by the composition of vehicle sales, as all of the batteries produced are fully allocated to the sold xEVs and the embedded emissions for the non-battery manufacturing are assumed to be pretty similar for all vehicle types. Complementary to this simplified WTW emissions analysis, the implications of a full LCA of emissions for the optimal sales mix are also examined — taking into account the differences in the emissions associated with vehicle and fuel cycles.

It could be argued 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). 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 automakers and regulating authorities to identify, and hopefully also eliminate, any barriers that could lead to suboptimal WTW CO$_2$ emissions from passenger cars.

To guide the readers through the paper, the forecasted demand and production capacities of batteries are briefly reviewed in Section 2. In Section 3, the modelling framework to determine optimal vehicle sales mix under battery supply constraint is introduced. Section 4 describes the key assumptions and data for vehicles and energy carriers and, then, identifies the key influential factors and sensitivity cases. The main results of optimal sales mix are compared and discussed in Section 5. Section 6 presents the extended model for the simultaneous optimisation of vehicle sales mix and the battery size of PHEVs. Section 7 explores the significance of the results and the synthesis of the research findings, and then opens a discussion on a broader life-cycle modelling approach. Finally, the paper is concluded in Section 8, highlighting the key takeaway points and prospects for future research.

2. 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 in Europe, and observed whether there are any gaps between the two.

2.1. Forecasted demand in Europe

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) (Batteries Europe ETIP, 2020). *McKinsey & Company* has also shared forecasts which anticipate demand ranging between approximately 0.3 and 0.7 TWh/year in 2030 (McKinsey & Company, 2019).

To deal with uncertainties about battery supply, this study aims to explore the potential impact of a broad range of possibilities up to the most extreme case regarding battery demand, being defined by a 100% share of BEVs in the new vehicle sales mix by 2030, with an annual sale of 16 million passenger cars in Europe (Yugo et al., 2021b), all of them being equipped, e.g. with a large battery size of 75 kWh. This extreme case results in a demand scenario of 1.2 TWh/year of battery supply capacity by 2030, which is far higher than the upper range of the aforementioned scenarios, without taking into account the demand from other sectors such as heavy-duty transportation or energy storage. Therefore, the current study should not be considered as an attempt to forecast the future market uptake of electric vehicles but as an upper limit for the optimisation case to explore whether informative results could be derived when no constrains in terms of the share of electric vehicles are imposed to the system.

2.2. Forecasted production capacities in Europe

The forecasts regarding battery production capacities face the same level of uncertainty as for the demand:[3]

- *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 (Batteries Europe ETIP, 2020).
- *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 (PV Europe, 2020).
- 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(Reuters, 2021).
- Tsiropoulos *et al.,* on behalf of the *Joint Research Centre* of the European Commission (JRC), evaluated that European battery production capacity could be sufficient to meet a domestic demand for 2–8 million BEV sales (Tsiropoulos et al., 2018)— far from the expected annual sales of 16 million passenger cars.
- A recent report by *Ultima Media* predicts that the rising demand for electric vehicles, 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 (Ultima Media, 2021). 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 2020, the global battery capacity deployed amounted to 0.475 TWh/year, out of which 0.06 TWh/year were installed in Europe (Ultima Media, 2021). This is far from the levels of battery manufacturing capacity projected in the high-BEV demand scenario.

2.3. A battery-constrained environment?

In spite of all the uncertainties, the trends collected for battery production and demand show that Europe could encounter 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 be added to the one 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. 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

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[3] The figures presented here are from different sources. They are not necessarily consistent and cannot be summed up to derive a total value.

(EC, 2021). It may still need to rely on imports from other regions for some of its battery requirements in the studied time frame, but Europe considers local battery production to be a strategic goal, according to the strategic plan supporting the European Battery Alliance (EC, 2021). The likelihood of this battery-constrained scenario is also subject to the large uncertainties about reliable battery imports due to import challenges and sustainability standards as well as the future evolution of the demand/supply balance worldwide due to the growing battery demand in the rest of the world (e.g. see (IEA, 2021) for the regional battery demand forecast). 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 (Ultima Media, 2021). 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 minimize GHG emissions from passenger cars.

3. Method and modelling framework

To deal with uncertainties surrounding battery supply capacity and the potential implications for GHG emissions, an optimisation framework 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 options considered for the different levels of electrification of passenger cars include vehicles powered solely ICE engines, HEVs, PHEVs and BEVs; the potential impact of fuel cell electric vehicles is ignored in the 2030 passenger car fleet mix for the purpose of this study as the model aims to address the impact of battery resource constraints within 2020–2030 timeframe. In addition, any impact of possible competition among different transport modes in utilising battery resources is ignored in the timeframe considered because the electrification of medium- and heavy-duty vehicles (HDVs) would lag significantly behind that of passenger cars. For example, under the "Sustainable Development" scenario of IEA's Global EV Outlook 2020 (with ambitious electrification and a projected global battery demand of 3 TWh/year in 2030), modes other than passenger cars account for only 11% of overall battery demand in 2030, highlighting the centrality of electric passenger cars in the battery market towards 2030 (IEA, 2020a).

We have chosen two different frameworks to conduct a comprehensive evaluation around the role of different xEV configurations in

Table 1
Description of mathematical symbols.

Symbol	Definition
$BCAP\left[\frac{GWh}{yr}\right]$	Upper limits for the total battery used in the sold xEVs [GWh/year]
$DoD_v^{[\%]}$	Depth-of-discharge for electric vehicle type v [share]
$EC_{v,f}\left[\frac{MJ}{km}\right]$	Energy consumption of vehicle type v using fuel f [MJ/km]
f	Fuel type index notation
$RANGE_v\left[\frac{km}{v}\right]$	Electric driving range of vehicle type v [km/vehicle]
$TOTSALE\left[\frac{Mv}{yr}\right]$	Total annual sales of vehicles [million vehicles/year]
$SALE_v\left[\frac{Mv}{yr}\right]$	Annual sales of vehicle type v [million vehicles/year]
$SHARE_v^{[\%]}$	Share of vehicle type v in new sales mix [percentage share]
$SIZE_v\left[\frac{kWh}{v}\right]$	Battery size of vehicle type v [kWh/vehicle]
$TTW_f\left[\frac{gCO2eq}{MJ}\right]$	Tank-to-Wheels (combustion) GHG emissions factor of fuel f [gCO$_2$eq/MJ]
$UF_v^{[\%]}$	Utility factor of vehicle type v [percentage share], only applicable to PHEVs
v	Vehicle type index notation
$VKT_v\left[\frac{km}{v}\right]$	Annual vehicle distance travelled for vehicle type v [km/vehicle]
$VKT_{v,f}\left[\frac{km}{v}\right]$	Annual vehicle distance travelled for vehicle type v using fuel f [km/vehicle]
$WTT_f\left[\frac{gCO2eq}{MJ}\right]$	Well-to-Tank GHG emissions intensity of fuel type f [gCO$_2$eq/MJ]
$WTW_{v,f}\left[\frac{gCO2eq}{km}\right]$	Well-to-Wheels GHG emissions intensity for vehicle v using fuel f [tCO$_2$eq/km]
$WTW_{v,f}\left[\frac{tCO2eq}{yr}\right]$	Well-to-Wheels GHG emissions from vehicle type v using fuel f [tCO$_2$eq/year]

a range of cases constrained by different battery supply caps. First, in the following section, a linear programming approach is introduced to determine optimal vehicle sales mix by minimizing WTW GHG emissions under battery supply constraints assuming given battery sizes for xEVs. In Section 6, the model is extended to a non-linear optimisation framework to determine both optimal vehicle sales mix and battery size of PHEVs by minimizing WTW GHG emissions under battery supply constraints.

3.1. Optimal vehicle sales mix under battery resource constraint: Linear programming model

The main question in this proposed modelling 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 battery supply cap and annual vehicle sales constraints within a given (and fixed) set of battery sizes for each xEVs category.

The objective function in Eq. (2) is minimised subject to a set of constraints as expressed in Eqs. (3)–(9). The nomenclature of the variables, parameters, and symbols are explained in Table 1. According to Eq. (2), the objective function of the model— which is the total WTW GHG emissions (in tCO$_2$eq/year) over all vehicle types v and fuel types f — is minimized for each certain level of battery supply cap.

$$Min \sum_v \sum_f \left(WTW_{v,f}^{\left[\frac{tCO2eq}{yr}\right]} \right) : \forall BCAP^{\left[\frac{GWh}{yr}\right]} \in \left[0, SIZE_{BEV}^{\left[\frac{kWh}{v}\right]} * SALE^{\left[\frac{Mv}{yr}\right]} \right] \tag{2}$$

According to Eq. (3), the WTW emissions in gCO$_2$eq/km are calculated based on the energy consumption of vehicles (MJ/km) and fuel emission factors (gCO$_2$eq/MJ) for well-to-tank (WTT) and TTW parts.

$$WTW_{v,f}^{\left[\frac{gCO2eq}{km}\right]} = WTT_f^{\left[\frac{gCO2eq}{MJ}\right]} * EC_{v,f}^{\left[\frac{MJ}{km}\right]} + TTW_f^{\left[\frac{gCO2eq}{MJ}\right]} * EC_{v,f}^{\left[\frac{MJ}{km}\right]} \tag{3}$$

Where $TTW_f^{\left[\frac{gCO2eq}{MJ}\right]}$ represents TTW combustion emissions factor of fuel f in gCO$_2$eq/MJ, and $WTT_f^{\left[\frac{gCO2eq}{MJ}\right]}$ represents the emission intensity of production pathways for fuels and electricity.

Eq. (4) determines the WTW GHG emissions from the sold vehicle type v using fuel type:

$$WTW_{v,f}^{\left[\frac{tCO2eq}{yr}\right]} = WTW_{v,f}^{\left[\frac{gCO2eq}{km}\right]} * VKT_{v,f}^{\left[\frac{km}{v}\right]} * SALE_v^{\left[\frac{Mv}{yr}\right]} \tag{4}$$

The optimization process includes a group of individual optimization runs executed at different levels of battery supply cap ($BCAP^{\left[\frac{GWh}{yr}\right]}$). A broad range of battery supply caps, ranging from 0.0 to 1.2 TWh/year, are considered as the upper limits for the total battery used in the sold xEVs, as dictated by Eq. (5). The assumed upper end of 1.2 TWh/year in the chosen framework represents a relaxed battery supply in which the whole new sales may be composed of BEVs (assuming a large battery size 75 kWh and annual sale of 16 million passenger cars per year for demonstration purpose).

$$\sum_v \left(SALE_v^{\left[\frac{Mv}{yr}\right]} * SIZE_v^{\left[\frac{kWh}{v}\right]} \right) \leq BCAP^{\left[\frac{GWh}{yr}\right]} \tag{5}$$

The size of batteries for xEVs ($SIZE_v^{\left[\frac{kWh}{v}\right]}$) is a key parameter that has a significant impact on the optimal battery resource allocation. As expressed in Eq. (6), the battery size requirement is linked to the other technical parameters including the electricity consumption of PHEVs and BEVs ($EC_{v,electricity}^{\left[\frac{MJ}{km}\right]}$), depth-of-discharge of battery ($DoD_v^{[\%]}$) as the maximum share of battery capacity that can be utilised (see Table 3 in Section 4), and the required electric-driving range ($RANGE_v^{\left[\frac{km}{v}\right]}$). Compared to ICEVs, the energy consumption of xEVs depends less on the mass increase because they are able to recover a portion of the additional energy used with larger batteries during accelerations thanks to regenerative braking (IEA, 2020b). Hence, as a simplification and considering an average C-segment vehicle size, a fixed electricity consumption representing an average value for each of PHEVs and BEVs is assumed for all battery sizes (see Section 4 for the data).

$$SIZE_v^{\left[\frac{kWh}{km}\right]} * DoD_v^{[\%]} = EC_{v,electricity}^{\left[\frac{MJ}{km}\right]} * RANGE_v^{\left[\frac{km}{v}\right]} / 3.6^{\left[\frac{MJ}{kWh}\right]} \tag{6}$$

The decision variable in the linear programming model is the share of different vehicles in the sales mix ($SHARE_v^{[\%]}$). Eq. (7) determines the optimal sale of each vehicle type v ($SALE_v^{\left[\frac{Mv}{yr}\right]}$) based on the optimal shares within the sales mix and the total annual vehicle sales ($TOTSALE^{\left[\frac{Mv}{yr}\right]}$). In the baseline assessment, an average annual sale of 16 million passenger cars per year is assumed (based on (Yugo et al., 2021b) for the region including EU27, UK, Norway, Switzerland, and Iceland).

$$SALE_v^{\left[\frac{Mv}{yr}\right]} = SHARE_v^{[\%]} * TOTSALE^{\left[\frac{Mv}{yr}\right]} : \sum_v SHARE_v^{[\%]} = 1 \tag{7}$$

Assessing the GHG emissions for PHEVs strongly depends on their utility factor ($UF_v^{[\%]}$), which is defined as the share of km driven on the electricity mode. Eqs. (8) and (9) determine the split of annual vehicle km travelled between electricity ($VKT_{PHEV,elec}^{\left[\frac{km}{v}\right]}$) and non-electricity fuels ($VKT_{PHEV,fuel}^{\left[\frac{km}{v}\right]}$), respectively.

$$VKT_{PHEV,elec}^{\left[\frac{km}{v}\right]} = UF_{PHEV}^{[\%]} * VKT_{PHEV}^{\left[\frac{km}{v}\right]} \tag{8}$$

$$VKT_{PHEV,fuel}^{\left[\frac{km}{v}\right]} = \left(1 - UF_{PHEV}^{[\%]}\right) * VKT_{PHEV}^{\left[\frac{km}{v}\right]} \tag{9}$$

4. Key assumptions and data for vehicles and energy carriers

The main assumptions and input parameters used to calculate WTW GHG emissions are summarised in Table 2 (for vehicles), Table 3 (battery specifications) and Table 4 (for energy carriers, i.e. liquid fuels and electricity in this instance). 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 average estimate, as it is not fully representative of all new registrations.

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 estimated WLTP function, based on (ICCT, 2020) and (UNECE, 2017) shows that a WLTP range of 60 km returns a utility factor of about 80%. According to (ICCT, 2020), the real-world utility factors of PHEVs, on average, are assumed to be half the figures considered under WLTP (leading to the 40% utility factor reported in Table 2 and Table 3). For the baseline analysis in the current study, an average battery size of 12.5 kWh is assumed for the PHEV with a 60 km WLTP electric-driving range—assuming a depth-of-discharge (DoD) level of 70% according to Table 3. An average battery size of 1.54 kWh is assumed for HEVs. The battery size for the BEV with a WLTP range of 400 km is 58.4 kWh as the baseline case.[4]

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

- **Electric range of BEVs** varies from a short range of 200 km to a long range of 600 km, with the base case being at 400 km.
- **Electric range of PHEVs** varies from a short range of 20 km to a long range of 100 km, with the base case being at 60 km.
- **Utility factor** varies from 20% to 90% with the base case being at 40%, to cover a broad range of real-world and test-cycle values.
- **Annual vehicle sales** change 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 (gCO$_2$eq/MJ)** ranges from 0 (e.g. from wind-generated electricity, excluding emissions from infrastructure) to 76.4 gCO$_2$eq/MJ as of 2019 (average value) in the high case, with the base case value of 21 gCO$_2$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 (EEA, 2020).
- **Vehicle energy consumptions (MJ/km),** for the base case, were derived from 2025+ WLTP figures in the JEC TTW v5 study (JEC, 2020). To address the uncertainties with relative energy consumption of different powertrains, further sensitivity analysis is conducted (see Section 6.3).

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[4] All battery sizes represent the nominal maximum capacity. The usable battery sizes are calculated in the model with the help of depth-of-discharge parameters as introduced in Table 3.

Table 2
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	7,200[b]	4,800[b]	12,000	12,000
Energy consumption (MJ/km, WLTP)[a]	Gasoline + Electricity	1.41	1.03	1.15	0.52	0.90	0.45
	Diesel + Electricity[c]	1.30	1.08	1.14	0.51	0.89	0.45

Notes: All data for energy consumption and utility factor are based on the WLTP cycle (Worldwide Harmonised Light Vehicle Test Procedure).
[a]Data source: JEC TTW study v5 (JEC, 2020)—The energy consumptions data represent the state-of-the-art figures for the year 2030.
[b]Assuming 40% utility factor.
[c]This case has been defined for illustration of using low-carbon liquid fuels.

Table 3
Battery specifications for PHEVs and BEVs.

PHEV					BEV		
Battery Range (km)	DoD[a] (%)	Battery Size (kWh)	Utility Factor (% WLTP)[b]	Utility Factor (% Real-World)[c]	Battery Range (km)	DoD[a] (%)	Battery Size (kWh)
20	65.0%	4.5	46%	23%	200	80.0%	31.0
40	67.5%	8.6	69%	34%	300	82.5%	45.2
60[d]	**70.0%**	**12.5**	**80%**	**40%**	**400**	**85.0%**	**58.4**
80	72.5%	16.1	86%	43%	500	87.5%	71.0
100	75.0%	19.4	90%	45%	600	90.0%	82.8

[a]It is assumed that DoD increases linearly with battery size. The defined range of DoDs are based on data in JEC TTW report v5 (JEC, 2020) with modifications.
[b]WLTP-based utility factor data are based on the functions introduced in (Transport UNECE, 2017) and (ICCT, 2020).
[c]According to (ICCT, 2020), the real-world utility factors of PHEVs, on average, are assumed to be half the figures considered under WLTP.
[d]Baseline.

Table 4
Key assumptions for the energy carriers.

Fuel	Combustion emission factor[a] gCO_2eq/MJ (TtW)	WTT emission intensity[a] gCO_2eq/MJ	Biogenic credits[a] gCO_2eq/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)	–	21.0	–
Low (Wind)	–	0.0	–
High (2019 EU mix)	–	76.4	–

[a]Data source for liquid fuels: JEC WTW study v5 (Prussi et al., 2020a), assuming total theoretical combustion of the fuel. Biogenic credits accounting for the amount of CO_2 captured by the plant during its growth equivalent to the CO_2 released when burnt.
[b]Assuming 50% share of hydrotreated vegetable oil (HVO) in energy term to replace diesel fuel (B7 fuel grade).
[c]Source: (EEA, 2020).

- **Use of low-carbon fuels:** The purpose of this sensitivity case is to assess the robustness of the conclusions due to potential changes in the carbon intensity of the liquid fuels used in the mix. As a theoretical exercise, this analysis is not intending to represent any market forecast regarding the potential uptake of different type of sustainable biofuels or e-fuels (*low-carbon fuels*) and, for simplification purposes, one single type of low-carbon fuel (i.e. HVO) has been selected as a representative of alternative fuels based on its high compatibility as a drop-in fuel with conventional fossil ones (Yugo et al., 2021b). Within this context and as a theoretical example, this analysis explores an example of partial replacement of oil-based fuels by low-carbon fuels for the 50% of diesel passenger car sales in 2030, acknowledging that multiple pathways and combination of different production capacities beyond one single route would be required to meet the volumes of low-carbon fuels considered in this sensitivity case.

5. Main results of the linear programming model

5.1. The optimal sales mix to minimise GHG emissions

Fig. 1 displays the optimal sales composition for different levels of battery supply cap in 2030. The results are presented for the baseline condition, but are compared under three illustrative levels of utility factors for PHEVs with 60 km electric range—i.e. low (20%), medium/baseline (40%), and high (90%) utility factors. This wide range of utility factor has been chosen to be able to evaluate the robustness of the results as well as the validity of potential conclusions under extreme conditions. The corresponding minimised WTW and TTW GHG emissions (for the first life year when new cars are sold) at each level of battery supply cap are shown by the line graphs and can be read on the right axis.

When the utility factor of PHEVs is low (below 30%), the optimal sales mix would include **BEV**+**HEV** (with no PHEV playing a role), as shown on the left chart of Fig. 1 under the illustrative utility factor of 20%. The results under medium/high utility factors show that, below the battery cap of 0.20 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 WTW GHG emissions. 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 with medium/high utility factor appears to be a key technology for decarbonizing transport, as it is present in all the partially electrified scenarios, from a 0.05 TWh/year to a 0.90 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 about 0.93 TWh/year, assuming the annual sale of 16 million passenger cars per year).

The sensitivity analysis around the utility factor of PHEVs showed that the optimal mix remains unchanged for utility factors above 30%, while having a very significant impact on decreasing WTW GHG emissions. It indicates that, in the battery cap scenarios up to about 0.55 TWh/year in 2030, the PHEV with 60 km electric driving range would be the key component of the optimal solution, with a share of the sales mix higher than 50%.

The sensitivity analysis with respect to a change in annual sales of +/-25%, as demonstrated in Fig. 2, 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 decarbonizing the new sales.

Fig. 3 shows the corresponding results in terms of the optimal allocation of battery resources to different xEVs. Due to the smaller battery size of PHEVs versus BEVs, the optimal share of battery resource allocated to PHEVs—at each certain level of battery supply cap—is significantly lower than the respective share of PHEVs in the sales mix.

5.2. 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:

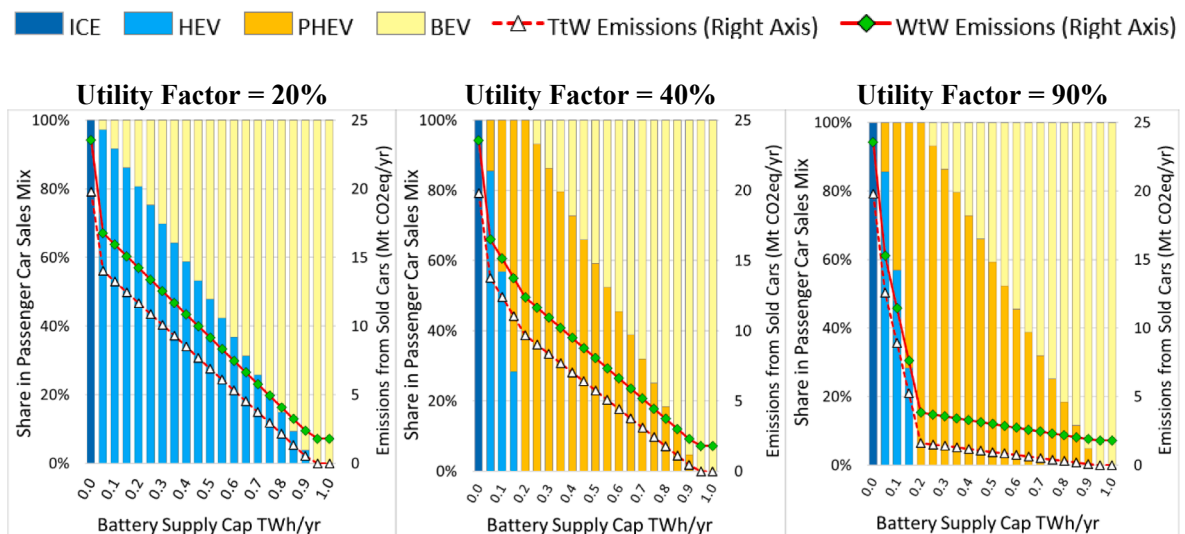- **BEV+ICE:** The vehicle choice set is restricted to BEVs and ICEVs.

Fig. 1. Optimal vehicle sales mix minimizing WTW GHG emissions subject to battery supply cap in 2030 with break-even point being 30% — Baseline results assuming fixed battery sizes of 1.54 kWh (HEV), 12.5 kWh (PHEV-60), and 58.4 kWh (BEV-400).
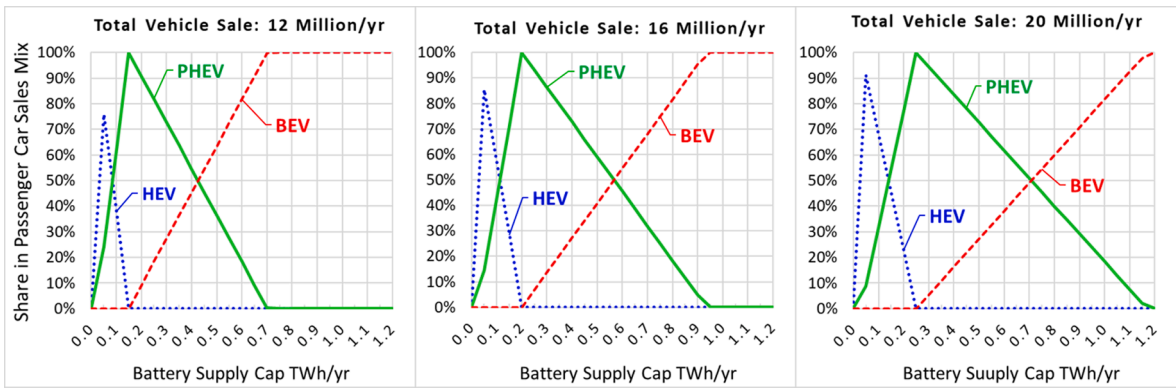
Fig. 2. Impact of total sales volume on the optimal share of xEVs in 2030 — under the fixed baseline battery size assumption and the utility factors above 30%.
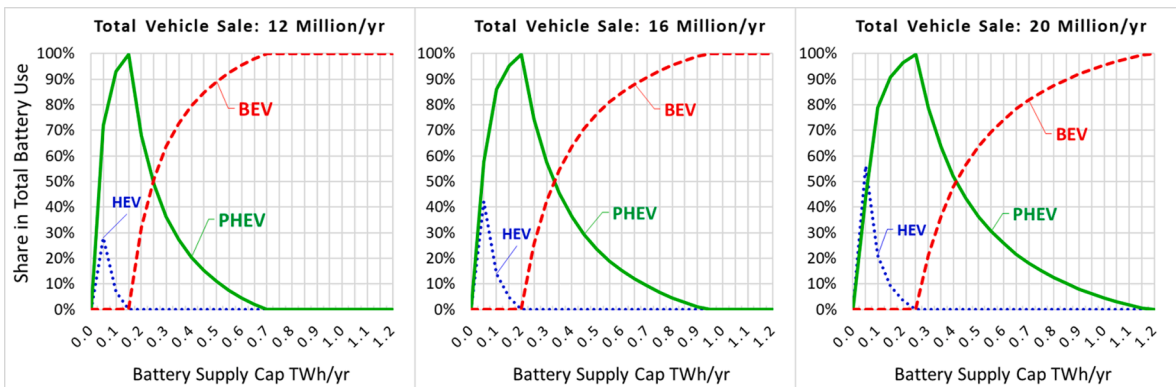

Fig. 3. Impact of total sales volume on the optimal allocation of battery resources to different xEVs in 2030 — under the fixed baseline battery size assumption and the utility factors above 30%.
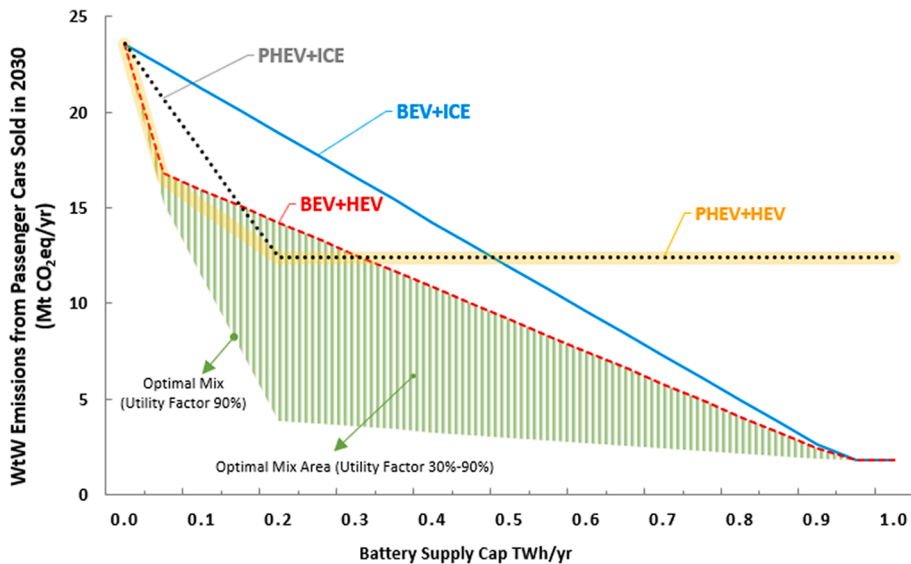

Fig. 4. Minimum WTW GHG emissions subject to battery supply constraint and break-even analysis of different sales combinations (patterned green area represents the sensitivity of 'Optimal Mix' case with utility factor ranging from 30% to 90%). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

- **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 optimized without exogenous constraints on the vehicle choice set (as presented in Fig. 1 for the certain levels of utility factor).

In all of the above cases, the WTW GHG emissions of passenger car sales are minimised subject to the battery supply cap constraints. Fig. 4 demonstrates the key comparisons and break-even points, mainly under the baseline conditions defined in Table 2, Table 3, and Table 4 (using fossil-based fuels for this initial comparison). A more detailed comparison of the minimum achievable emissions in different cases, including a comprehensive sensitivity analysis around the utility factor and the carbon intensity of electricity supply, is presented in Fig. 5. 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 Fig. 4). The gap is narrowed by increasing the battery supply up to the break-even point of 0.95 TWh/year with 'Optimal Mix'.
- Assuming the base case utility factor of 40% for PHEV, the **BEV+ICE** case could be advantageous over both the **PHEV+ICE** and **PHEV+HEV** cases only if the battery supply cap exceeds 0.50 TWh/year. This advantage is reduced as the utility factor for PHEV increases. Regarding these **PHEV+ICE/HEV** cases, it is worth noting that they would not fully utilise the available battery cap.
- The green shaded area represents the emissions related to the optimum mix (as described in Fig. 1 for a utility factor above 30%). The upper line of the green shaded area, resulting from the optimisation model for utility factors below 30%, is equivalent to a pure **BEV+HEV** case.
- The green shaded area in Fig. 4 shows also the sensitivity of the minimised emissions with respect to utility factor, changing from 30% 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.
- For utility factors above 30%, the **PHEV+HEV** case appears to be the most effective option to reduce GHG emissions for a battery cap below 0.20 TWh/year.
- The emissions level would reach a lower plateau in the **PHEV+ICE** and **PHEV+HEV** cases for the battery supply cap exceeding 0.20 TWh/year. The reason is that the whole new passenger car mix would be composed of 100% PHEVs with 12.5 kWh battery size.
- It is worth noting that a sales mix case involving **PHEV+BEV** would not be a feasible option for the battery cap below ~ 0.20 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 ~ 0.20 TWh/year (see also Fig. 1).

Fig. 5 summarises the results of a sensitivity analysis around the utility factor (i.e. 20%–90%) and the carbon intensity of electricity supply (i.e. 0–76.4 gCO$_2$eq/MJ) for all considered sales mix cases. According to the left-hand chart in Fig. 5, 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. For the

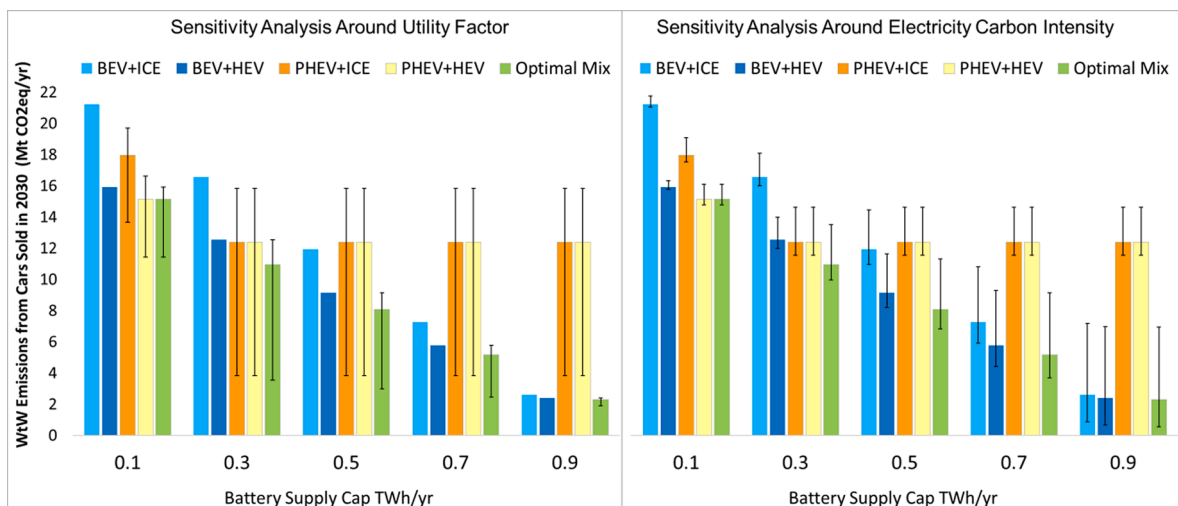**Fig. 5.** Comparison of minimized WTW GHG emissions subject to battery supply cap in different sales mix scenarios (left chart: error bars show the sensitivities with respect to utility factor ranging from 20% to 90%; right chart: error bars show the sensitivities with respect to the carbon intensity of electricity supply mix ranging from 0 to 76.4 gCO$_2$eq/MJ) — Note: the baseline composition of 'Optimal Mix' is defined in Fig. 1.

higher levels of battery cap up to ~ 0.80 TWh/year, only upper utility factors could make **PHEV+ICE** preferable. For the battery cap below ~ 0.20 TWh/year, the baseline results for **PHEV+HEV** are identical to the 'Optimal Mix' solution. The magnitude of the error bars is, however, narrower in the 'Optimal Mix' solution over the battery supply cap because PHEVs with low utility factors are excluded in the optimal mix.

Further sensitivity analysis around electricity supply emission factors ranging from 0 gCO$_2$eq/MJ to 76.4 gCO$_2$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 the right-hand chart in Fig. 5 for the details). The main difference is that, under the upper emission factor of 76.4 gCO$_2$eq/ MJ, the break-even utility factor (for changing the role of PHEV in the optimal fleet mix as defined in Fig. 1) increases to 36%, compared to 30% in the baseline analysis.

5.3. Minimum utility factor required to maintain the role of PHEVs

From the results and discussions above, it is evident that the utility factor of PHEVs is a key factor influencing the optimal sales mix and GHG emissions. For the certain values of energy consumption and battery size for PHEVs, the utility factor in real-world condition is largely dependent on the driving and recharging behaviours of consumers. Thus, to deal with the broad range of real-world and test-cycle utility factors, an extensive sensitivity analysis was performed to evaluate the minimum utility factor required to maintain the role of PHEVs in the new fleet mix. To do so, different possible combinations of battery sizes for PHEVs and BEVs are defined, each of which is separately executed and optimized. According to the battery specification data in Table 3, the total number of cases for the baseline is 25. To assess the impact of electricity supply carbon intensities, additional 50 optimisation cases are defined to present the results under lower and higher carbon intensities.

For each of the defined 75 cases, further sensitivity analyses were performed to determine the break-even utility factors. Fig. 6 recaps the results of the extensive sensitivity analysis, demonstrating the break-even utility factors— below which PHEV does not appear in the optimal sales mix and above which it does appear in the optimal mix. The findings indicate that the optimised break-even utility factor would increase with the battery size of PHEVs. Conversely, increasing the battery size of BEVs would reduce the break-even utility factor. The degree of sensitivities would increase substantially when larger battery sizes are assumed for PHEVs. For instance, the break-even utility factor in the case of PHEV-20 (i.e. 20 km battery range) varies between 15 and 21%, depending on the range of BEVs. The corresponding range of variations for PHEV-100 would be 32–67%.

One important insight from the results is that under shorter BEV ranges (i.e. less than 400 km), the break-even utility factors of PHEVs with longer electric ranges (i.e. 60–100 km) would be higher than the corresponding baseline real-world utility factors as presented in Table 3. It indicates that the minimum required utility factor to maintain the role of PHEVs in these cases must be above the average estimated/observed real-life utility factors. This comparison provides important insights into the potential role of PHEVs in decarbonising the road transport sector. While it is generally recommended that vehicle manufacturers should increase the electric range of PHEVs in future—because of the positive effect of electric range on fuel consumption (ICCT, 2020)— the current analysis reflects that, at least, a caveat must be made under a battery-constrained future: **longer-range PHEVs could contribute to WTW emissions reduction efficiently only if they can be utilised with higher (than average) utility factor, otherwise HEV+BEV**
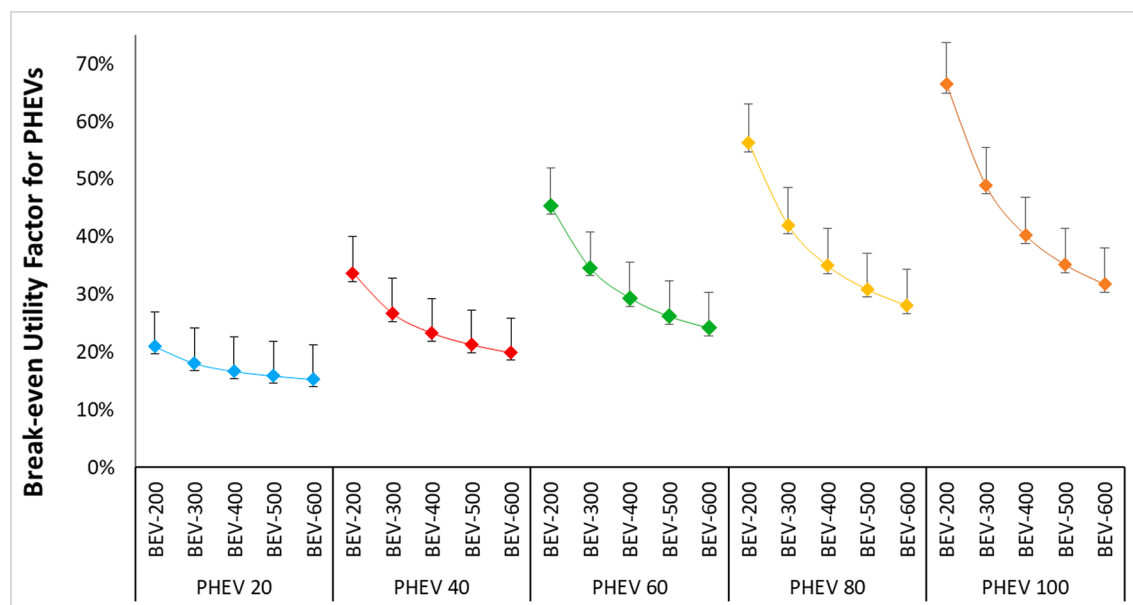

Fig. 6. Minimum level of utility factor required to bring PHEVs to the optimal sales mix (i.e. break-even utility factors). Note: error bars show the sensitivities with respect to the carbon intensity of electricity supply mix ranging from 0 to 76.4 gCO$_2$eq/MJ.

would become superior.

6. Model extension: Optimal battery sizes for PHEVs

6.1. Mathematical formulation: Non-linear programming model

As discussed previously in Fig. 6, the size of batteries chosen are deemed to have a significant impact on the fleet mix. In this section, the initial linear optimization model, with the decision variable of sales mix ($SHARE_v^{[\%]}$), is extended to consider the optimum size of batteries for PHEVs (i.e. $SIZE_{PHEV}^{\left[\frac{kWh}{v}\right]}$) as a second decision variable. Hence, the model is reformulated as a non-linear optimisation model. The main objective is to **determine the optimal sizing of batteries together with the optimal sales mix to best utilise the available battery resources**. It is important to note that the current modelling framework intends to deal with the battery size of PHEVs, which influences the utility factor as a key determinant of optimal sales mix. Therefore, assuming an average C-segment vehicle size in the current study, only the battery size for PHEVs is endogenized and the impact of different battery sizes (rang) of BEVs is investigated through sensitivity analysis.

By considering the battery size of PHEVs (i.e. $SIZE_{PHEV}^{\left[\frac{kWh}{v}\right]}$) as a new decision variable with its lower/upper bounds being set to those presented in Table 3, the utility factor, which is linked to the battery size through electric driving range ($RANGE_{PHEV}^{\left[\frac{km}{v}\right]}$), is determined by the following functional form:

$$UF_{PHEV}^{[\%]} = U\left(RANGE_{PHEV}^{\left[\frac{km}{v}\right]}\right) \tag{10}$$

In order to specify the utility function $U(.)$ in Eq. (10) under WLTP test-cycle condition, we have used the data and functional form proposed in (UNECE, 2017) and (ICCT, 2020). Since the WLTP-based utility factors have been overestimated compared to real-world values and they do not incorporate consumer behaviours, additional estimation, based on (ICCT, 2020), is considered in which the real-world utility factors of PHEVs, on average, are assumed to be half the figures considered under WLTP. The resulting graphs for both functions are presented in Fig. 7. In order to deal with the EU emissions target regulations (see supplementary materials for details), the NEDC (New European Driving Cycle) utility factor is also estimated using the following Equation and displayed in Fig. 7, where $RANGE_{PHEV}^{\left[\frac{NEDCkm}{v}\right]}$ is all-electric range of PHEVs in NEDC terms. Based on (ICCT, 2020), the WLTP electric range of PHEVs is assumed to be three-quarters of the NEDC range.
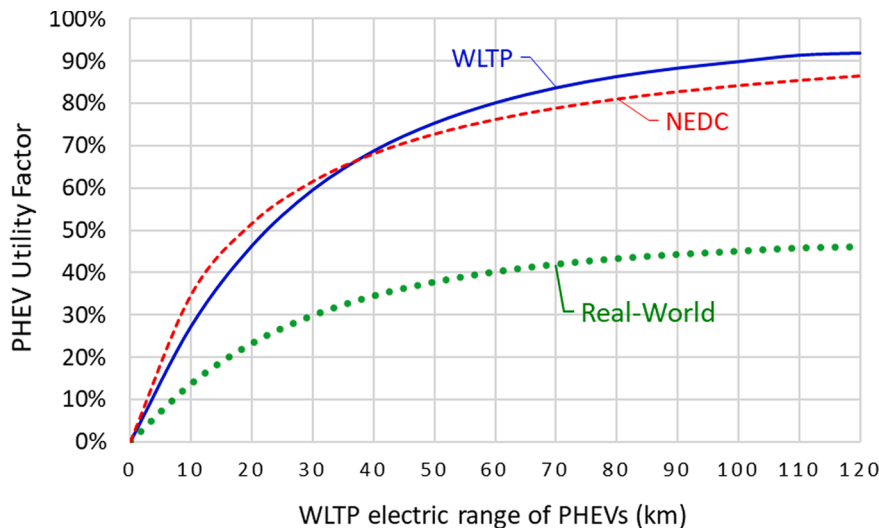
Fig. 7. WLTP-based and real-world utility factors of PHEVs as a function of WLTP electric driving range—based on data in (UNECE, 2017) and (ICCT, 2020).

$$UF_{PHEV}^{[NEDC\%]} = \frac{RANGE_{PHEV}^{\left[\frac{NEDCkm}{v}\right]}}{RANGE_{PHEV}^{\left[\frac{NEDCkm}{v}\right]} + 25} \qquad (11)$$
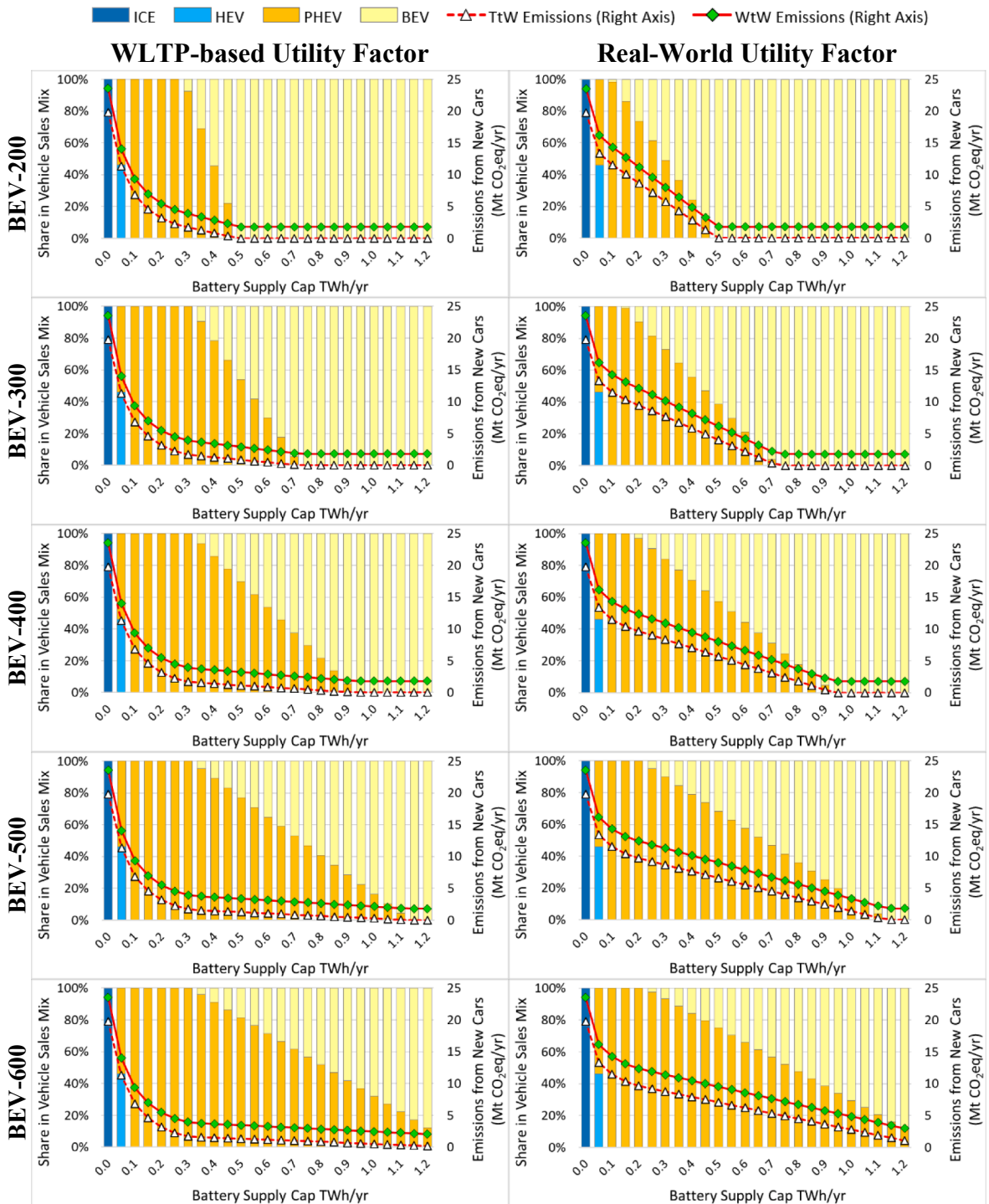

Fig. 8. Optimal vehicle sales mix minimizing WTW GHG emissions subject to battery supply cap in 2030—Results of the extended non-liner optimisation model.

It is worth noting that, in reality, it is expected that a higher annual distance travelled for PHEVs leads to a reduction in their actual utility factor — if all other factors remain constant (ICCT, 2020). However, given a fixed annual mileage assumed in the current analysis, this effect has not been taken into account.

6.2. Optimal vehicle sales mix and battery sizes of PHEVs

Fig. 8 displays the results of the non-linear optimisation model for the optimal vehicle sales mix under different levels of battery supply cap, given that the battery size and utility factor of PHEVs are endogenously examined. Since the chosen function for utility factor (as illustrated in Fig. 7) can have a significant impact on the findings, all results are presented and compared for WLTP-based versus real-world utility factor functions.

Fig. 8 demonstrates that considering the WLTP-based utility factor function (optimistic when compared with real world use) leads to a higher share of PHEVs in the sales mix regardless of the assumed battery range for BEVs. GHG emissions under WLTP-based utility factor function show steeper decline when battery supply cap is low. Fig. 9 shows the corresponding results for the optimal share of battery resources allocated to PHEVs. The assumption on BEV range has a large impact on this allocation: the larger the size of BEVs, the larger the share of PHEVs in utilising battery resources. Moreover, especially under the real-world utility factor, having BEVs with bigger batteries leads to delay (in terms of battery production capacity on the x-axis) the moment when the WTW and TTW emissions reach their floor level.

Comparing this with the results of the sole optimization of the sales mix presented in Section 5.1, the extended model shows that the lower-range PHEVs with smaller batteries would be the preferable options over HEVs in reducing WTW GHG emissions. It can be seen that HEV is included in the optimal mix only under the battery supply cap of 0.05 TWh/year, taking less than half of the sales mix. The reason is that, according to Fig. 10, the lower-range PHEVs are recommended in the optimal sales mix to make the best use of the limited battery resources, while still taking the advantage of more efficient powertrains.

Fig. 10 shows that, under WLTP-based utility factor, when the battery supply cap exceeds the level of ~0.30 TWh/year, the optimal battery size would reach a plateau of approximately 19.4 kWh (equivalent to 100 km electric range, corresponding to the saturation of the model constraint). The case optimised under the short-range BEV-200 assumption would plateau at a slightly lower level of 17.8 kWh (equivalent to 90 km electric range). Under the real-world utility factor, the model reflects smaller battery sizes. This can be explained by the findings from Fig. 6 discussed in Section 5.3, indicating that the longer-range PHEVs require far higher levels of utility factor to be able to play a role in the optimal sales mix. Hence to ensure the best utilisation of the available battery resources—while minimizing WTW GHG emissions— the optimal battery sizes are lower than those of WLTP-based utility factor.

6.3. The impact of higher fuel consumption and low-carbon fuels

To address the uncertainties regarding the energy consumption of different powertrains (in MJ/km), the following sensitivity cases were defined:

- **High energy consumption (50%):** Based on the JEC TTW study v5 (JEC, 2020), the energy consumption figures for gasoline ICEVs and HEVs in 2015 are approximately 42% and 53% higher than the corresponding values in 2030 (all converted to WLTP). To define a simplified sensitivity case, a 50% increase is applied to the baseline energy consumption (MJ/km) of all powertrains—i.e. ICEVs, HEVs, PHEVs, and BEVs— as an illustrative example of the impact of not deploying or achieving further improvements versus the current efficiency levels.
- **High energy consumption (10–40% variable depending on each powertrain):** The energy consumption of vehicles in real world would be affected by climate conditions and ambient temperature. Especially, BEVs would have much higher energy
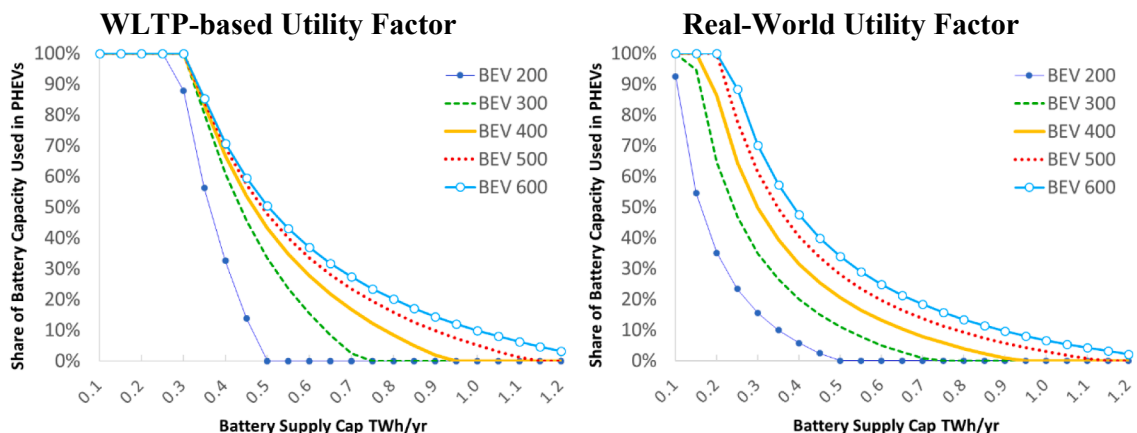
Fig. 9. Optimal allocation of battery resources to PHEVs.

WLTP-based Utility Factor   Real-World Utility Factor
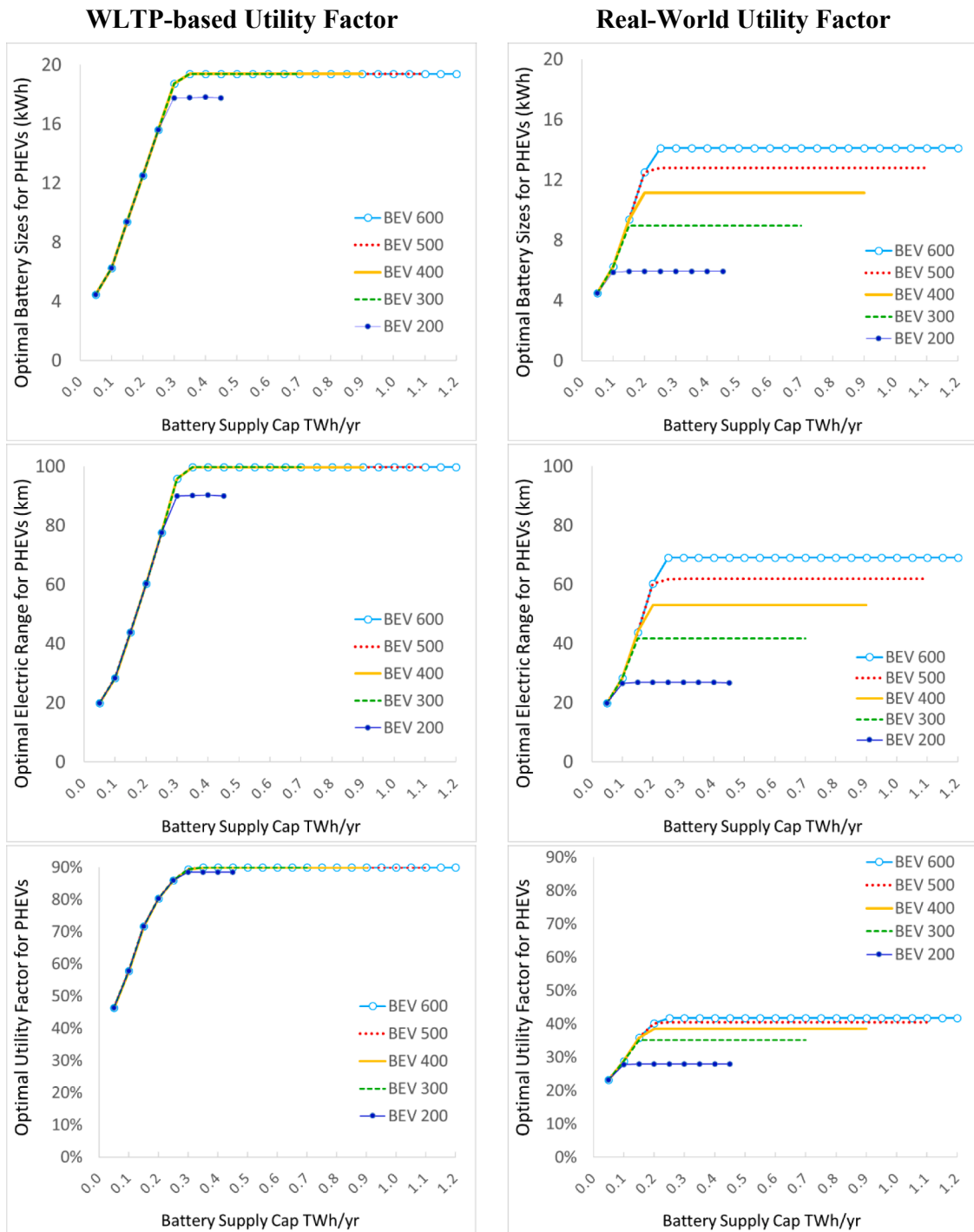
Fig. 10. Optimal battery sizes, electric-driving ranges, and utility factors for PHEVs as a function of battery supply cap.

consumption as ambient temperature deviates from the normal test-cycle conations. To address such differences due to the climate impact on the energy consumption of different vehicles, based on data from (Wu et al., 2019), this sensitivity case is defined in which ICEV, HEV, PHEV and BEV have increased energy consumption by 10%, 20%, 25% and 40%, respectively, compared to the baseline figures presented in Table 2.

The results of the sensitivity analysis in Fig. 11 show that, under WLTP-based utility factor, the higher energy consumptions for vehicles would not change the optimal sales mix significantly, compared to the baseline. However, the total WTW emissions of the new
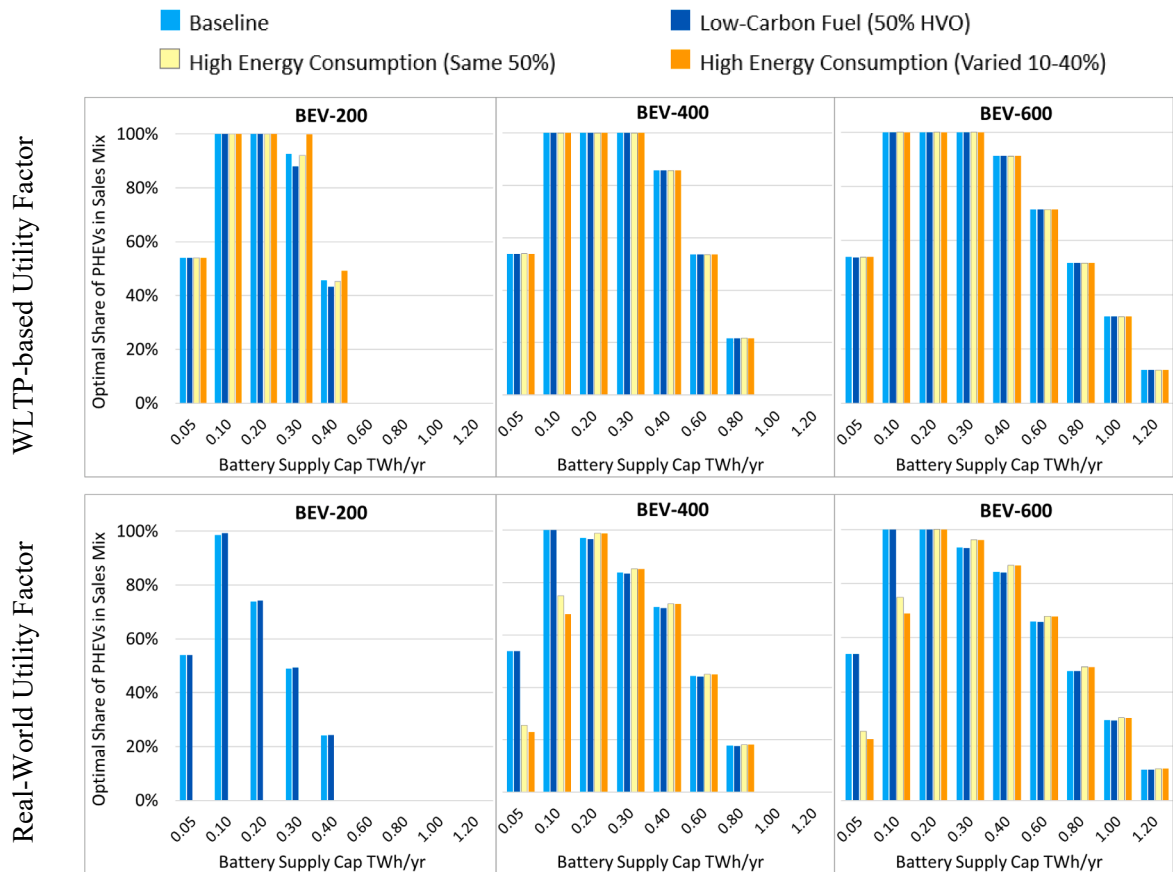
Fig. 11. Impact of low-carbon fuel and higher energy consumption on the optimal share of PHEVs in the sales mix.

cars would go up —proportionally to the higher energy use— as shown in Fig. 12. The results under the lower levels of real-world utility factor differ meaningfully in the following circumstances:

i) If the assumed range for BEVs is low (i.e. BEV-200), PHEV is eliminated from the optimal mix in both explored cases for higher energy consumption.

ii) If the assumed range for BEVs is medium/high (i.e. BEV-400 and BEV-600) and also the battery supply cap is below 0.2 TWh/year, then the higher energy consumption would reduce the optimal share of PHEVs, replacing with HEVs.

Fig. 11 also demonstrates the impact of considering the assumed illustrative example of low-carbon fuels in 2030 as replacement for diesel fuel in new sales (i.e. with HVO having a 50% energy share in total liquid fuel use, as explained in Table 4). The sensitivity analysis around the share of HVO shows that the optimal sales mix does not differ markedly under different BEV range and utility factor categories. However, it results in a lower level of emissions, compared with the emissions from the similar sales mix in the baseline condition (see Fig. 12).

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 all diesel-fuelled vehicles, together with a high carbon intensity of the electricity supply (i.e. 76.4 gCO_2eq/MJ), **would lead to the 100% HEV share being the optimal case in minimising WTW emissions**. Assuming 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 WTW emissions (from HEVs and PHEVs).

7. Discussion and the significance of the analysis

7.1. Modelling framework and verification

The linear optimisation model introduced in Section 3.1 assumed only one certain electric range option as an average typical value
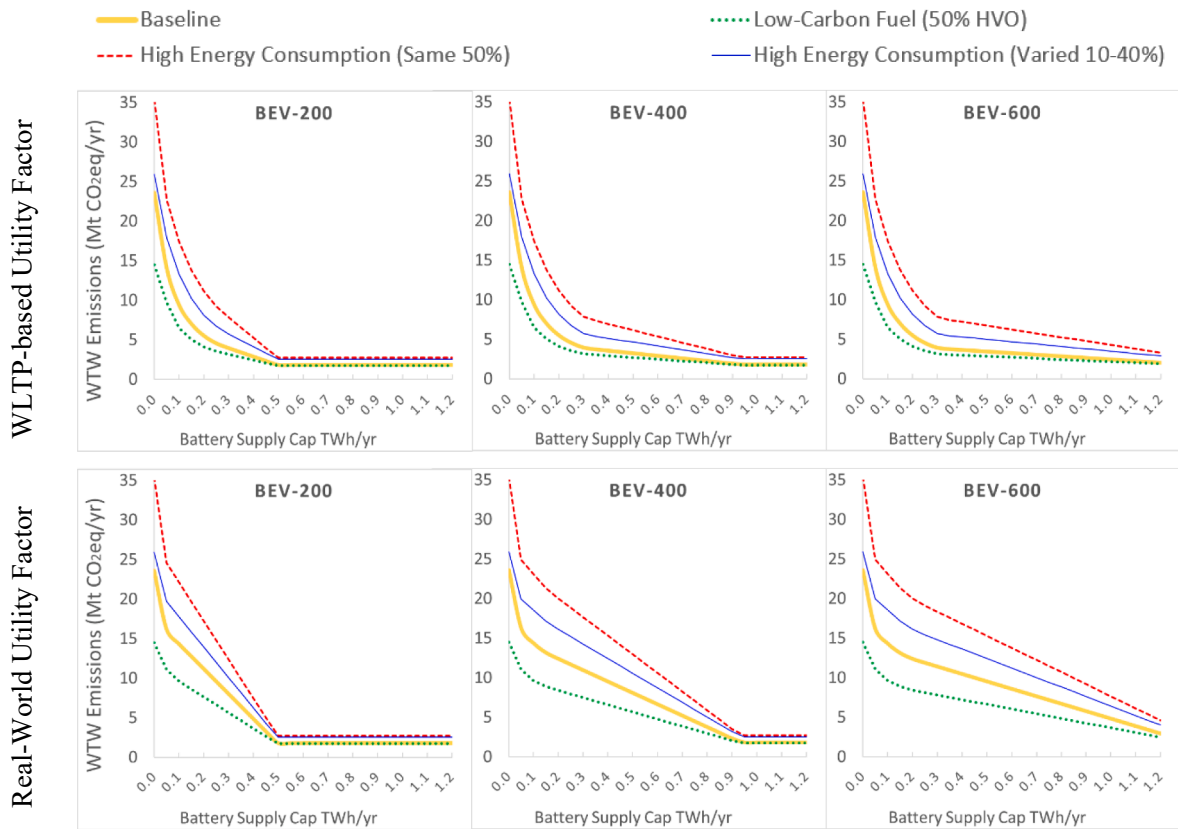
Fig. 12. The impact of higher energy consumption for vehicles and the use of low-carbon fuels (HVO as an illustrative example) on the minimised WTW GHG emissions.

for each of PHEVs and BEVs. To deal with a portfolio of battery sizes for both PHEVs and BEVs, a set of fragmented linear optimisation models was implemented based on a certain array of battery sizes as introduced in Table 3. Nevertheless, the assumed battery sizes in each case remained fixed over the different levels of battery supply cap. Thus, a single linear optimisation model is not able to address the optimal size of batteries along with the optimised vehicle sales mix. To deal with the optimal battery sizes under the linear optimisation framework, a two-stage optimisation process needs to be conducted as follows:

 i) First, a set of fragmented linear optimisation models—each one dealing with a certain battery size of electric vehicles— are executed and solved separately.
 ii) Next, the optimal results of the individual linear cases are compared for each level of battery supply cap to determine the best solution in minimizing WTW emissions.

Theoretically, increasing the number of linear cases would lead to more accurate results. It indicates that there can be the similarities between the results of applying the two proposed modelling approaches, as the nonlinear optimisation model is the direct extension of the linear one as explained in Section 6.

Although the linear programming model helps achieve the global optimal solution, however managing a large number of fragmented linear models would be cumbersome, particularly, when a variety of sensitivity cases should be managed as well. Hence, to address the cases related to optimal battery sizing properly, the non-linear optimisation approach was chosen as it was manageable under a large number of sensitivity cases while having returned more accurate results for the battery sizes. To guarantee (or raise the probability of) the convergence of the non-linear optimisation results to a global optimal solution, in addition to using a random multi-start points for the solver, the starting points for the optimisation were also motivated by the optimal solution of the approximated linear models.

7.2. Synthesis of the research findings to inform decision-making processes

Besides the rationalisation for using the two methodological approaches as discussed in Section 7.1, this study looked at the optimal electrification level of passenger cars from two angles:

i) A sole optimisation of vehicle sales mix with the aim of assessing the implications of a broad range of utility factors for a certain level of battery sizes for PHEVs and BEVs
ii) A simultaneous optimisation of vehicle sales mix and the battery size of PHEVs, with the aim of providing a comprehensive outline for the optimal electrification level.

The findings from the first analysis (linear sales mix optimisation) indicates that, 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. Fig. 13 provides a recap of the main findings for the optimal passenger car sales mix and break-even points with respect to battery production capacity, assuming the average battery ranges of 60 km for PHEVs and 400 km for BEVs. It should be noted that the market shares with less than 5% were omitted in aggregating the findings.

With regard to the outcome of the second aspect of the analysis (sales/battery size simultaneous optimisation), Fig. 14 sums up the key findings on the optimal electrification level of passenger cars, providing insights which will be especially relevant in the 2030 time frame.

Comparing the results of the sole optimization of the sales mix (linear programming model) with the results of the non-linear optimisation of both sales mix and battery sizes shows that the lower-range PHEVs with smaller batteries would be the preferable options over HEVs in reducing WTW GHG emissions. The following diagram in Fig. 15 provides a recap of the main findings for the optimal sizing of PHEVs over different levels of battery production capacity.

7.3. Potential impact of vehicle manufacturing emissions: The opening for a life-cycle modelling framework

A Cradle-to-Grave assessment, considering the life-cycle GHG emissions of fuels and vehicles, can substantially enrich the presented study. To open a discussion on the potential impact of life-cycle emissions on the optimal sales mix, a simplified test case is implemented complementary to the performed WTW emissions minimisation. In order to carry out such a preliminary analysis, the basic required data, as presented in Table 5, was utilized from the recent literature, particularly, the battery energy densities from (JEC, 2020), and the average battery production GHG emissions from (Ternel et al., 2021).

The assumed GHG emissions associated with the manufacturing of batteries were approximated based on the data adopted from (Ternel et al., 2021) and then adjusted proportionally with respect to the battery energy densities. There are considerable uncertainties with the emissions of battery production, mainly depending on the carbon intensity of electricity supply and the energy source of heating required in the production process— e.g. (Emilsson and Dahllöf, 2019) reported a range of 61–106 kgCO$_2$eq/kWh for BEVs. Hence, the assumed battery production emissions presented in Table 5 could not be necessarily consistent with the range of assumed electricity supply carbon intensities in this study and reflect the uncertainty about the origin of batteries imported from different countries. To address these uncertainties within the scope of this simple test case, the changes of +/-50% around the baseline values are taken into consideration for a sensitivity analysis.

Based on the above data, the average annual life-cycle emissions for the vehicle and battery productions are calculated assuming an average vehicle lifetime of 15 years. To calculate the Cradle-to-Tank emissions for the fuel-cycle part, the following assumptions are made:

- According to the projections of IEA Sustainable Development Scenario on 2030 EU electricity mix, the life-cycle emission intensity of 151.4 gCO$_2$eq/kWh (Yugo et al., 2021a) is assumed for the electricity used in PHEVs and BEVs.
- For the liquid petroleum fuels and biofuels, the material-related carbon intensities of 0.6 gCO$_2$eq/MJ and 5.0 gCO$_2$eq/MJ (Prussi et al., 2020b) are added, respectively, to the corresponding WTT figures introduced in Table 4.

Having assumed the above-mentioned considerations, the sum of fuel-cycle and vehicle-cycle GHG emissions are minimised subject to the constraints introduced in Section 3.1. Fig. 16 displays the optimal vehicle sales mix minimizing the overall life-cycle GHG emissions subject to battery supply cap for the baseline battery sizes of 1.54 kWh (HEV), 12.5 kWh (PHEV-60), and 58.4 kWh (BEV-
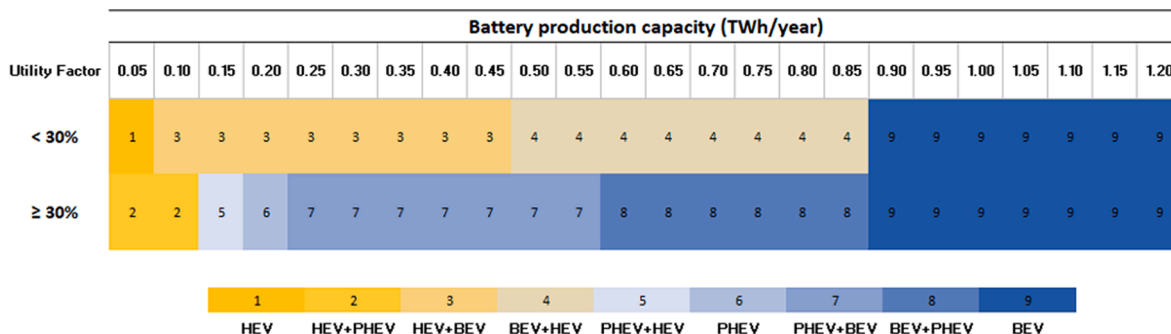

Fig. 13. Passenger car sales mix minimising WTW GHG emissions for different battery production capacity and using fossil-based fuels (Note: the first term in each combination, e.g. HEV in HEV+PHEV, represents the dominant option within each combination).
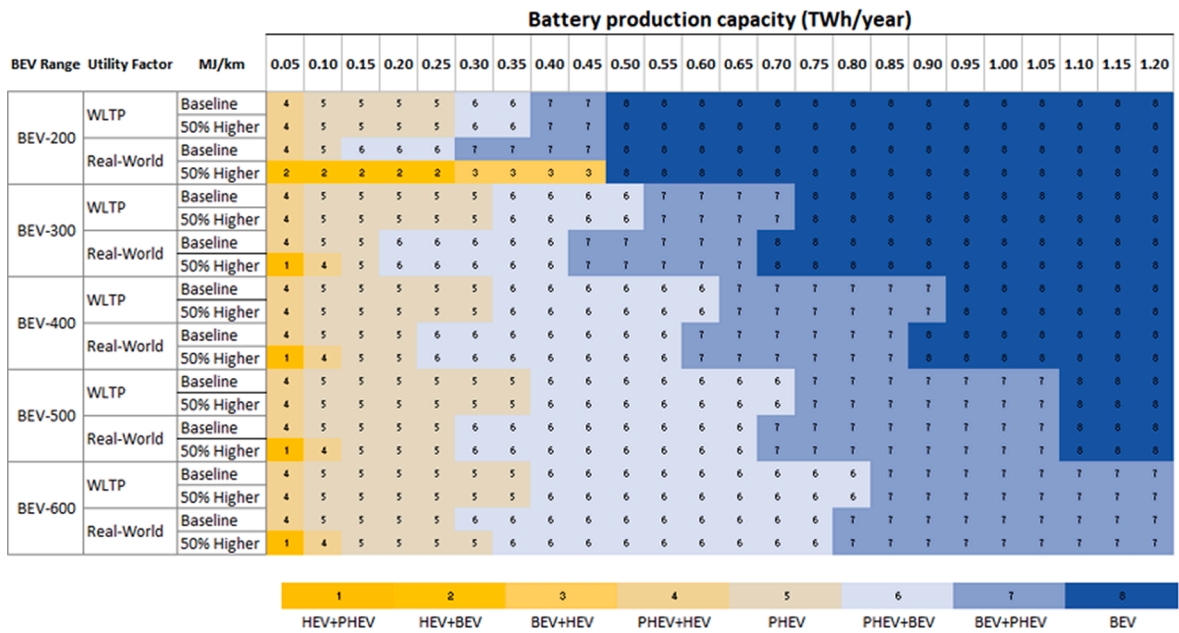
Battery production capacity (TWh/year)

BEV Range	Utility Factor	MJ/km	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45	0.50	0.55	0.60	0.65	0.70	0.75	0.80	0.85	0.90	0.95	1.00	1.05	1.10	1.15	1.20
BEV-200	WLTP	Baseline	4	5	5	5	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
		50% Higher	4	5	5	5	5	6	6	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
	Real-World	Baseline	4	5	6	6	6	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
		50% Higher	2	2	2	2	2	3	3	3	3	8	8	8	8	8	8	8	8	8	8	8	8	8	8	8
BEV-300	WLTP	Baseline	4	5	5	5	5	5	6	6	6	6	7	7	7	7	8	8	8	8	8	8	8	8	8	8
		50% Higher	4	5	5	5	5	5	6	6	6	6	7	7	7	7	8	8	8	8	8	8	8	8	8	8
	Real-World	Baseline	4	5	5	6	6	6	6	6	7	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8
		50% Higher	1	4	5	6	6	6	6	6	7	7	7	7	7	8	8	8	8	8	8	8	8	8	8	8
BEV-400	WLTP	Baseline	4	5	5	5	5	5	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8	8	8	8
		50% Higher	4	5	5	5	5	5	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8	8	8	8
	Real-World	Baseline	4	5	5	5	6	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8	8	8	8	8
		50% Higher	1	4	5	5	6	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8	8	8	8	8
BEV-500	WLTP	Baseline	4	5	5	5	5	5	5	6	6	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8
		50% Higher	4	5	5	5	5	5	5	6	6	6	6	6	6	6	7	7	7	7	7	7	8	8	8	8
	Real-World	Baseline	4	5	5	5	5	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	8	8	8	8
		50% Higher	1	4	5	5	5	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	8	8	8	8
BEV-600	WLTP	Baseline	4	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7
		50% Higher	4	5	5	5	5	5	5	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7
	Real-World	Baseline	4	5	5	5	5	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7
		50% Higher	1	4	5	5	5	5	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	7	7

1	2	3	4	5	6	7	8
HEV+PHEV	HEV+BEV	BEV+HEV	PHEV+HEV	PHEV	PHEV+BEV	BEV+PHEV	BEV

Fig. 14. The outline of the optimal level of vehicle electrification based on the vehicle sales mix, ignoring the market shares less than 5% (legend note: the first term in each combination, e.g. HEV in HEV+PHEV, represents the dominant option within each combination).
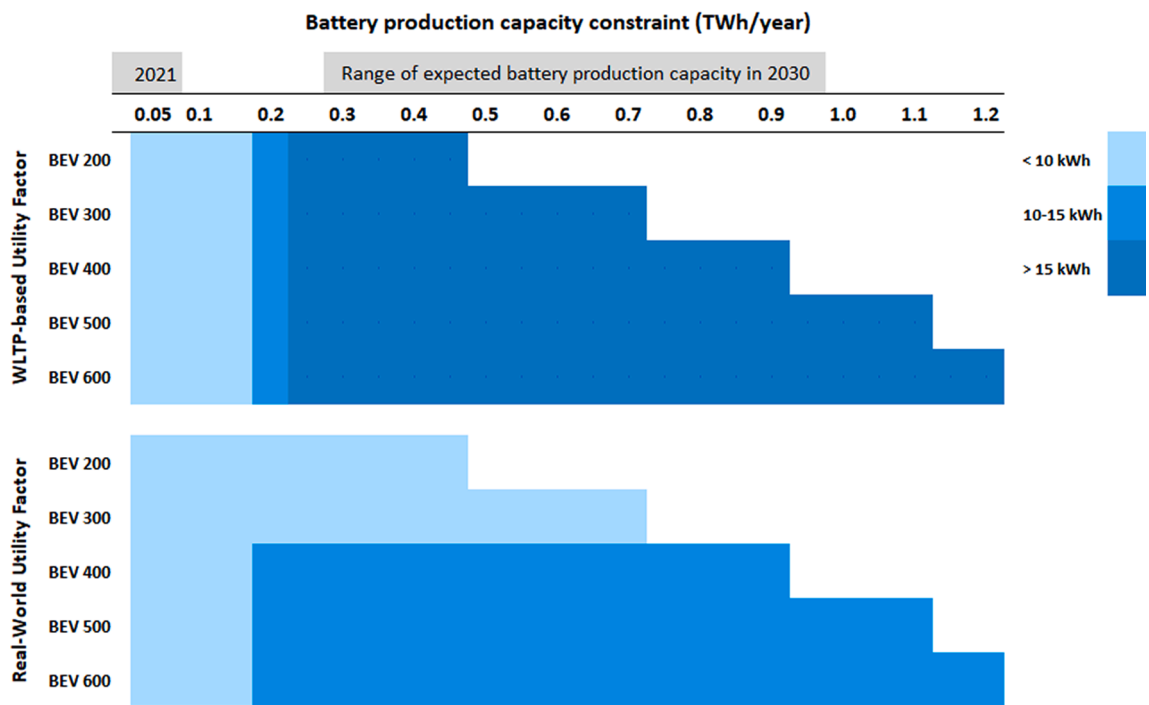

Fig. 15. Summary of the optimal battery sizing for PHEVs.

400). Fig. 16 also compares the minimised GHG emissions in fuel-cycle, vehicle-cycle, and overall life-cycle terms. The sensitivity analyses around the utility factor of PHEVs and the battery production GHG emissions indicate that the new objective function would not change the main conclusions on the key role of PHEVs in the sales mix. The only important difference is that, under the medium/high emissions intensities of battery production, the contribution of PHEVs can be strengthened — seizing the whole sales mix— if they can be utilised with a high level of utility factor.

Table 5

Life-cycle GHG emissions for the production of vehicles and batteries (baseline values).

Vehicles	Non-battery components [a] tCO$_2$eq/vehicle	Battery production [b] kgCO$_2$eq/kWh	Battery energy density [c] Wh/kg
ICE	4.40	—	—
HEV	4.82	257	60
PHEV	5.17	108	142
BEV	4.62	96	160

Note: End-of-life emissions or recycling credits have not been considered.

[a]Source of data: (Yugo et al., 2021a).

[b]Based on the average battery production emissions adopted from (Ternel et al., 2021) and then adjusted proportionally with respect to battery energy densities.

[c]Source of data: (JEC, 2020).

By increasing the optimal level of electrification, the fuel-cycle emissions show decreasing patterns. Conversely, the vehicle-cycle emissions increase with the level of electrification along with the relaxation of the battery supply cap. As a result, the slopes of the overall life-cycle emissions curves are still negative with respect to the electrification level, flattening out at the higher levels.

The results demonstrate that for the higher levels of utility factors, PHEVs could allow to reach quick win situations (and relieve the constraint on other resources) compared to BEVs. For instance, in the central case (i.e. baseline battery emissions combined with a 60% utility factor), around 80% of the life-cycle emissions reduction potential can be reached at around 0.2 TWh/year, with 100% share of PHEVs. Attaining the remaining 20% emissions reduction potential requires to produce additional battery capacity of about 0.8 TWh/year. Future studies would be required to explore the impact of influential factors in the context of a comprehensive life-cycle analysis.

8. Conclusions

This article 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 related to battery supply capacity and the potential implications for GHG emissions, this study explored the optimal passenger car sales composition that would minimise WTW GHG emissions as a function of battery production capacity. Given that battery size, utility factor and fuel consumption of vehicles are inter-related, a series of fragmented linearized modelling frameworks as well as an extended non-linear optimization model were developed. A broad range of possible cases was defined based on the sensitivity analysis around the key parameters, including battery size, 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 and the impact of other barriers that could hinder the penetration of xEVs (e.g. the availability of recharging points in Europe) were not considered in this analysis which focused 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 optimizing the whole sales mix, given the amount of limited battery supply resources, leads to different conclusions. The key takeaway points from the modelling analysis—which will be especially relevant in the 2030 time frame— are summarised as follows, reflecting clear messages for an open debate with automotive manufacturers and regulatory authorities:

- In case of a low battery production capacity (e.g. below about 0.20 TWh/year) and assuming the average battery ranges of 60 km for PHEVs and 400 km for BEVs, a combination of **HEV+PHEV** sales would be the most effective strategy for reducing WTW GHG emissions if PHEVs are utilised with their moderate/high levels of utility factors (above 30%). The acceleration of low-carbon fuels would lead to further WTW GHG reductions, playing a key role especially in this powertrain combination.

- In the modelling framework and the scenarios considered for minimising WTW GHG emissions, PHEVs would be the key component of the optimal sales mix in a battery-constrained future. Increasing the utility factor of PHEVs is the most immediate and accessible way to decrease GHG emissions in the short term. The preliminary analysis on the potential impact of incorporating life-cycle GHG emissions indicated that the main conclusions on the role of PHEVs in the sales mix would even be more important.

- Increasing the contribution of low-carbon fuels in the fuel mix and decreasing the carbon intensity of the electricity mix would not change the optimal sales mix significantly. However, they will offer significant additional WTW GHG emissions savings. The findings showed that the use of low-carbon fuels (i.e. HVO) would lead to lower WTW GHG emissions, compared to the baseline analysis, regardless of the vehicle sales mix, battery supply cap level, and the assumed range for BEVs.

- Under optimistic WLTP-based utility factors, the higher energy consumptions for vehicles would not influence the optimal sales mix significantly. Under real-world utility factors, the higher energy consumption scenario could disadvantage the share of PHEVs, especially when they compete with shorter-range BEVs (as the option not likely to be attractive in the future market) in utilising limited battery resources.

- Comparing the results of the sole optimization of the sales mix with the results of the optimisation of both sales mix and battery sizes shows that the lower-range PHEVs with smaller batteries would be the preferable options over HEVs in reducing WTW GHG emissions when battery production capacity is low. This strategy can ensure the best utilisation of the limited battery resources, while taking the advantage of more efficient powertrains.
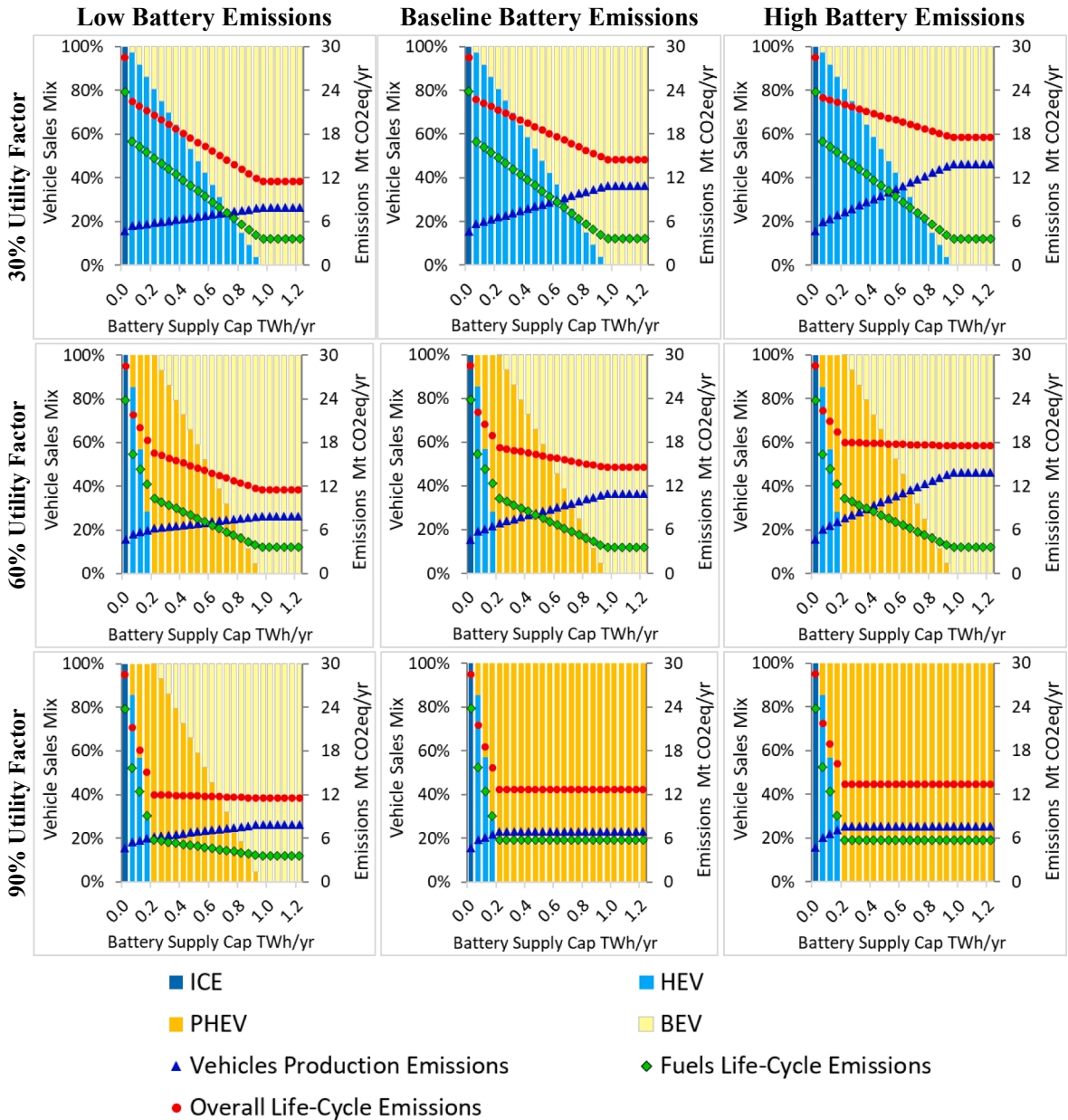
Fig. 16. Optimal vehicle sales mix minimizing life-cycle GHG emissions subject to battery supply cap — Baseline results assuming the battery sizes of 1.54 kWh (HEV), 12.5 kWh (PHEV-60), and 58.4 kWh (BEV-400).

- Comparing the TTW emissions of the optimal sales mix with the EU emissions targets revealed that the cases in which higher energy consumptions are combined with low utility factors could be at risk of not meeting the targets—especially when the ambition level is high and the battery supply is restricted. Utilising smaller battery sizes for both PHEVs and BEVs and enhancing the utility factor of PHEVs (in accordance with their battery sizes) are deemed as two important measures that could significantly support the fulfilment of the targets, especially with a deeper ambition level.
- Comparing the optimal break-even utility factors with the average utility factors of PHEVs observed in real-life, provides important insights into the potential role of PHEVs in decarbonising the road transport sector. One important insight from the results under short to medium range of BEVs (i.e. 200–400 km) is that the minimum required utility factor to maintain the role of the PHEVs with longer electric range must be above the average estimated/observed real-life utility factors. While it is generally recommended that vehicle manufacturers should increase the electric range of PHEVs in future, the current analysis reflects that, at least, a caveat must be made under a battery-constrained future: ***the longer-range PHEVs could contribute to WTW emissions reduction efficiently***

only if they can be utilised with higher (than average) utility factor. Hence, directing the usage of long-range PHEVs to proper applications, adapting consumers' driving behaviours, and incentivising more frequent recharging are necessary.

- Even though the longer-range BEVs are envisaged for the near future to meet consumers preferences, however they cannot be deemed as the optimal choice in terms of a systemic GHG emissions reduction. Assuming the larger battery sizes for BEVs (greater than400 km) under a battery-constrained condition would lead to the higher contribution of PHEVs in the optimal sales mix. PHEVs even with real-world utility factors can enhance the efficient utilization of battery resources to minimize GHG emissions, compared to BEV-400+ .

8.1. Limitations and prospects for future research

The scope of the presented analyses was limited to the optimized passenger car sales under simplified but meaningful assumptions on vehicle technical attributes and battery production cap. The analysis can be further extended from different perspectives at a system level to provide additional insights into low-carbon transport system. For example, defining the resource constraints as the required raw materials for each kWh of battery capacity per vehicle type, and including the battery demand for HDVs could improve the analysis.

Within the scope defined in the present study, an additional battery demand for HDVs would not influence the robustness of the main conclusions because a broad range of resource supply cap has been investigated and any additional demand outside the scope of the current analysis could only shift the centre of attention onto the presented results under lower battery supply capacities. In other words, the potential impact of additional battery demand elsewhere has been implicitly addressed in the analysis. The only concern in this context could be ignoring a possible competition between transport modes in utilising battery resources. However, if other transport modes (or even other stationary demands for batteries) are included in the model, it would be required to deal with an additional dimension of resource allocation among different transport modes as well as different HDV categories. In this framework, additional criteria such as the maximum feasible replacement of ICEVs with BEVs (due to payload loss for heavier vehicles) as well as the role of electrified roads must be considered. This requires more detailed data and would lead to a complicated modelling framework. A future study could be proposed to expand the scope of the analysis to show the implications of an expected battery-constrained environment on decarbonizing strategies in the whole transport sector.

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. Although the cost factor would be an important aspect for consideration, however, minimizing the costs from a car manufacturer perspective needs extensive data on, e.g. battery production costs, efficiency improvement costs, different taxes, etc. From a consumer perspective, it involves upfront purchase costs, operation and maintenance costs, fuel costs, and different taxes on both vehicles and fuels. The cost analysis can be conducted in the context of an advanced energy-transport system modelling framework.

In the presented study, different xEV configurations treated the same in using the same battery resources. According to the related literature, this assumption can be justified to provide insights at an aggregated systemic analysis. Nevertheless, further analysis on the impact of technology improvement to deal with the resource constraint would be worthwhile. For instance, as an initial idea, the battery production capacity (in TWh/year) can be converted to battery material requirement (in kg/year) using an average "battery energy density" (in kWh/kg). As a result, the battery size of xEVs can be related to their corresponding energy densities and driving range. Implementing this approach could improve the resource allocation problem by defining different battery densities for different powertrains (i.e. HEV, PHEV, and BEV).

The presented modelling framework intends to deal with the resource limitation problem and it provides systemic insights towards a low-carbon passenger car fleet. The optimisation of new sales mix using the aggregated average profile of vehicles and consumers may not be equivalent to an aggregation of the optimization of individual cases — i.e. consumers with certain driving/charging patterns and individual vehicle types with certain technical attributes. In reality, the battery size, driving range, and energy consumption vary according to vehicle size and segment. Moreover, the expected annual distance travelled and the utility factor of PHEVs vary with different vehicle sizes. The incorporation of these heterogeneities in vehicle types and individual behaviours needs a complex modelling framework with a higher level of granularities for both consumer choice behaviours and vehicle market development.

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CRediT authorship contribution statement

Ehsan Shafiei: Conceptualization, Methodology, Software, Validation, Formal analysis, Data curation, Writing – original draft, Writing – review & editing, Visualization. **Roland Dauphin:** Conceptualization, Validation, Writing – original draft, Writing – review & editing, Supervision. **Marta Yugo:** Conceptualization, Validation, Data curation, Writing – review & editing, Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary material

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