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Impact Analysis of Mass EV Adoption and Low Carbon Intensity Fuels Scenarios

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Summary

Ricardo delivered a study for CONCAWE examining the impacts of alternative scenarios for achieving high decarbonisation of light-duty vehicles in Europe by 2050. Scenarios were assessed versus the European baseline using the SULTAN model, considering High EV uptake vs alternatives with higher uptake of Low Carbon Fuels. The project examined impacts on: lifecycle GHG emissions; costs; implications for energy supply and infrastructure, and on materials, natural resources. There are significant uncertainties on the future evolution of technology, costs and infrastructure requirements to support BEV uptake; the findings suggest a cost-optimal solution for GHG reduction may lie in-between the extremes evaluated.

Keywords: BEV (battery electric vehicle), fuel, modelling, emissions, cost.

1 Introduction

Road transport is a major source of greenhouse gas (GHG) emissions in Europe (accounting for over a quarter of all emissions) and the EU has set ambitious targets/policies to support the transition towards a low-carbon economy. In response, industry is developing a range of solutions that deliver the targeted reductions, with electrification of road vehicles anticipated to contribute significantly to meeting targets. However, there is need to consider their potential plus other implications for end users and society to find the right balance between different technical (and other) options.

In a major study for industry body CONCAWE[1], Ricardo[2] assessed two extreme scenarios (mass electric vehicle uptake, and significant increase in the use of low carbon intensity fuels) and one intermediate scenario representing the potential for different technologies to deliver EU-targets for light-duty vehicle parc GHG emissions reductions for 2050 [1]. The impacts of the three scenarios are compared to the European Commission's current reference scenario in order to understand the magnitude of GHG emission savings of each solution alongside the costs to users and society. The scenario analysis also contributes to highlighting any risks of overreliance upon any one technology.

[1] Organisation monitoring the environmental performance of the European refining industry. For more information: https://www.concawe.eu/
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The study drew upon expertise from across the strategic consulting, energy and environment, and technical consulting teams of the Ricardo group to provide a broad-ranging, quantitative and objective analysis of impacts in four key areas: lifecycle GHG emissions (from vehicle production, operation and disposal); cost implications; implications for energy supply and infrastructure, and implications on materials, and natural resources.

2 Methodology

2.1 SULTAN modelling analysis

The scenario impacts on the vehicle fleet were analysed using SULTAN (SUstainabLe TrANsport) policy impacts assessment tool which is an adaptable transport policy analysis tool previously developed by Ricardo for the European Commission (DG CLIMA), with the ability to evaluate the medium- and long-term (to 2050) impacts of new vehicle technologies on: total energy consumption by fuel carrier; well-to-wheel GHG emissions; lifetime costs; tailpipe NO_x, SO_x and PM; energy security. The latest version of SULTAN was updated in 2016 and the baseline scenario has been calibrated to be consistent with the 2016 European Commission (EC) Reference Scenario used in the modelling informing the EU's 2030 Climate & Energy framework.

The process for using the tool involved preparing the input data, running SULTAN and post-processing the results, and is presented in Fig. 1. A more detailed analysis was conducted of the impact on marginal capital cost for meeting future regulatory targets and the assessment of the costs of electrified light duty vehicle powertrains on the basis of a Ricardo proprietary model which uses a genetic algorithm to identify the most cost-effective CO_2 improvement strategy across the various vehicle powertrains, whilst still meeting the desired fleet TTW (Tank-to-Wheel / tailpipe) CO_2 target and for the user-defined share of powertrains. The relationship between vehicle capital cost and CO_2 performance (/energy consumption for battery and fuel cell electric vehicles) is governed by a series of 'cost curves' produced by Ricardo Energy & Environment using our cost-curve optimisation model, and technology cost and performance dataset developed for the European Commission in consultation with stakeholders [2], and updated by review with Ricardo Technical Specialists. The calculated gCO_2/km performance of each powertrain is converted to MJ/km and added to the SULTAN policy scenario input database.

To investigate the implications for network infrastructure, we have also considered a series of alternative recharging cases for plug-in vehicles. The "home" recharging case assumes most electric vehicle (EV) users charge their EV at home, while the "grazing" recharging case assumes EV users make greater use of public charging to keep their EVs topped up. In addition, managed vs unmanaged charging were consider for each recharging case, where the managed version considers longer time periods for charging. The SULTAN Model outputs were combined with the alternative recharging cases to estimate costs for upgrading the network infrastructure.

2.2 Literature review and Deep Dive analysis

An extensive literature review was carried out as input for some of the post-processing calculations including several deep-dives into a number of areas of interest including life cycle assessment (LCA), battery resources and materials, and infrastructure. In total, we reviewed 175 papers with data on vehicle LCA and associated environmental impacts. Further information is available in Ricardo's full report for CONCAWE [1].

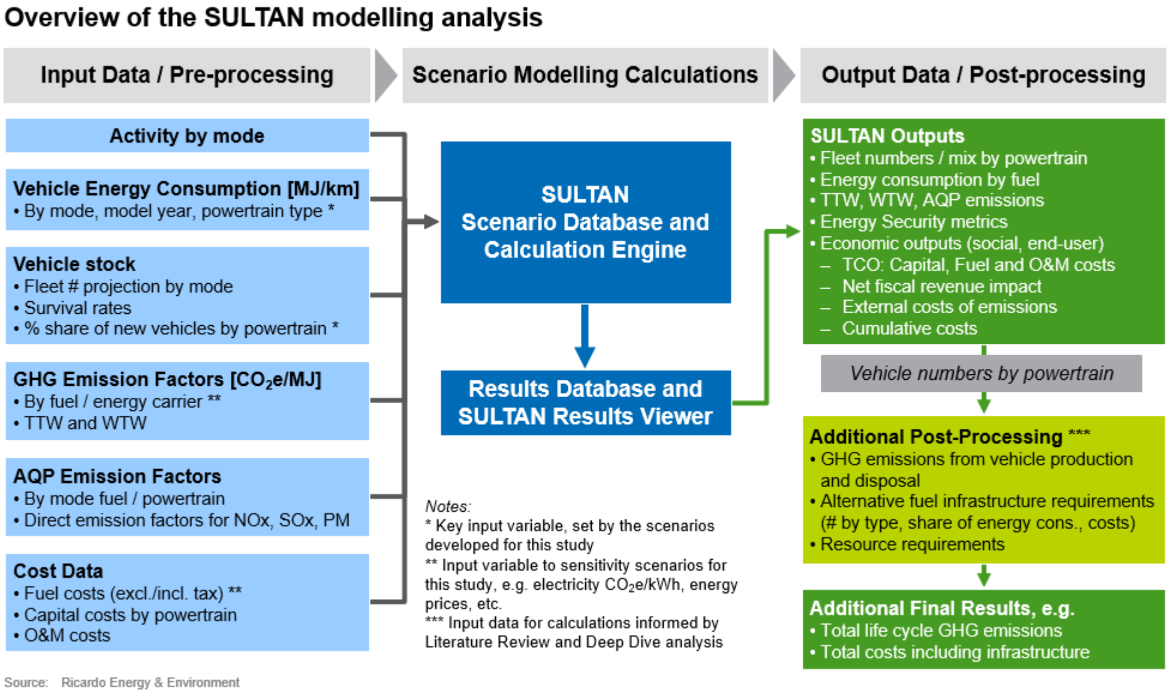

Figure 1: Overview of the SULTAN model

2.3 Assumptions and inputs

The study focussed on the European light duty vehicle fleet only and modelled its evolution for the time period between 2015 and 2050. New registrations and vehicle parc profiles were calibrated to historic data and projections from the European Commission (EC) modelling. It was assumed vehicles are produced in Europe.

The analysis includes a range of powertrain technologies: internal combustion engine vehicle (ICEV), hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), and battery electric vehicle (BEV). Total vehicle costs were calculated for each powertrain type based on a number of cost components (i.e. baseline cost, energy-related costs, taxes). The marginal additional capital costs of different powertrains were calculated using a pre-calculation process based on technology cost and TTW CO_2 / energy reduction cost curves as explained above. Fuel costs and taxes are based on a dataset from the EC's 2016 Reference scenario for the different fuels, which is included in the SULTAN baseline (BAU) scenario. Additional sensitivities for electricity price have been developed based on previous SULTAN analysis. The analysis also considers additional taxes, including average EU vehicle purchase tax and VAT rate from the EC's 2016 Reference scenario. No additional tax changes (e.g. for electricity) have been assumed for the scenarios, compared to the BAU scenario. For the annualised capital cost calculations, it is assumed a discount rate of 4% for social perspective (as recommended for Commission impact assessment), and 10% for the consumer perspective.

The analysis considers a range of fuel/energy sources (Diesel, Gasoline, Hydrogen, Liquified Petroleum Gas (LPG), Compressed Natural Gas (CNG), Electricity). The datasets for electricity GHG intensity and prices were based on European Commission's 2016 Reference scenario dataset and on previous analysis for the Commission from the EU Transport GHG: Routes to 2050 projects. The datasets for low carbon fuel GHG intensity were based on JRC WTT values, and EC studies on the availability of Advanced Biofuels. The energy available from biofuels and eFuels for European light duty vehicles has been estimated from other research sources. See [1] for further details.

Fuel and electricity consumption is based on the New European Drive Cycle (NEDC) with an uplift to real-world consumption based on assumptions from [3]. For calculating EV range, battery useable capacity is assumed to be 85% for BEVs up to 2020, then 90% after this (due to chemistry improvements and larger battery packs), and 70% for PHEVs up to 2020, and 75% after this. It was assumed the vehicle's fuel and/or electricity consumption does not change with vehicle age.

As a key component of EVs, battery technology and costs have been assessed in more detail. It was assumed that costs would decline by over 70% by 2030 compared to prices in 2015. In addition, average battery pack size in 2020 is expected to be more than double that in 2015 driven by increased range and lower costs, and battery pack energy density is projected to double between 2015 and 2020, with similar further improvements to 2030 and to 2050.

In order to model life cycle GHG emissions, vehicle lifetime was assumed to be 210,000 km for passenger cars and 230,000 km for LCVs (light commercial vehicles) over 15 years in the vehicle-level analysis (i.e. life cycle assessment (LCA) for new vehicles), based on recent analysis for the EC [4]. Similar levels are assumed within the SULTAN model, which is calibrated to the European Commission's 2016 Reference scenario. It was also assumed that no major parts nor the battery pack are replaced during the vehicle lifetime. The default LCA approach adopted for the analysis is an Avoided Burden approach (a.k.a. End-of-Life recycling, 0/100), with credits provided based on the average automotive recycling rate by material/component.

The study did not consider the potential implications of Connected and Autonomous Vehicles (CAV) and Mobility as a Service (MaaS), or model consumer purchase preferences.

3 Scenarios definition

In November 2017, the European Commission made proposals for improvements in the post-2020 gCO_2/km emissions for light duty vehicles (30% improvement on 2021 emission levels by 2030), and somewhat higher reduction levels were subsequently proposed by the European Parliament (40%) and European Council (35%) in 2018. All the scenarios model trajectories for TTW CO_2 improvement broadly consistent with these 2030 objectives, and extrapolated to 2050 (see Fig. 2 for new passenger cars).

The post-2020 gCO_2/km reduction trajectory for the High EV scenario is set up in line with the higher end of these recommendations. The trajectory of the Low Carbon Fuels scenario, however, is set at a slightly lower percentage improvement versus the High EV scenario up to 2030: the Tank-to-Wheels (TTW) trajectory for the Low Carbon Fuels scenario achieves an equivalent Well-to-Wheels (WTW) CO_2 emissions to the High EV scenario. These assumptions on gCO_2/km trajectories are used together with the new vehicle powertrain shares to define the MJ/km improvement by powertrain needed to meet targets.

For comparison purposes, the baseline (BAU) scenario is consistent with the EC's 2016 Reference scenario.

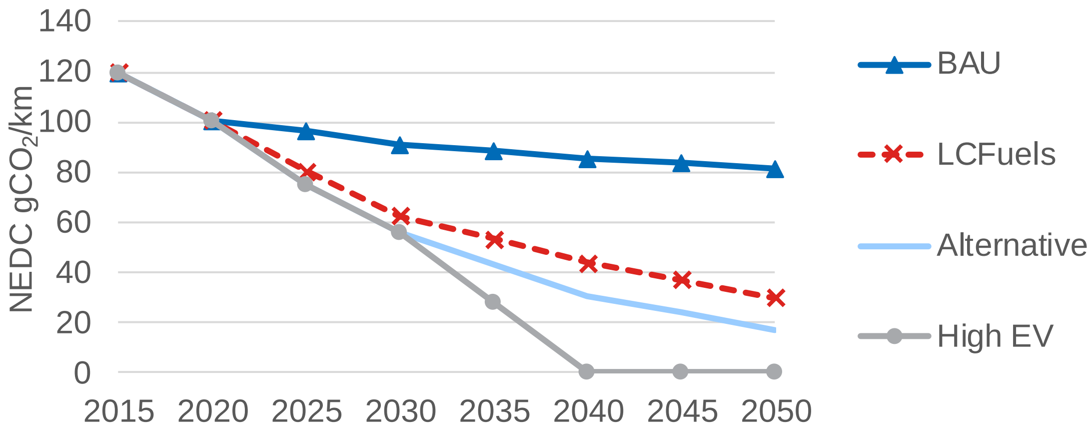

Figure 2: Input assumptions on TTW NEDC gCO_2/km improvement trajectory for new passenger cars

3.1 The High EV scenario

The High EV scenario assumes that full electrification of transport for passenger cars and LCVs in 2050 will reach 90% of the vehicle parc on the basis of 100% registration of BEVs from 2040 onward. The full breakdown of registrations and vehicle parc is shown in Fig. 3. The energy mix in this scenario (Fig. 4) shows a rapid decline in fossil fuel from 2030, a rapid rise in electricity use by 2050.

In addition, energy consumption for ICEV and HEV vehicles is assumed to improve only marginally from 2020, as further improvements are not needed to meet the required tailpipe CO_2 target objective with the shares of EVs (PHEV, BEV and FCEV) present. The marginal cost for these powertrains also plateaus beyond 2025, whereas the marginal cost of EVs reduces to 2050, with a more dramatic reduction in LCVs.

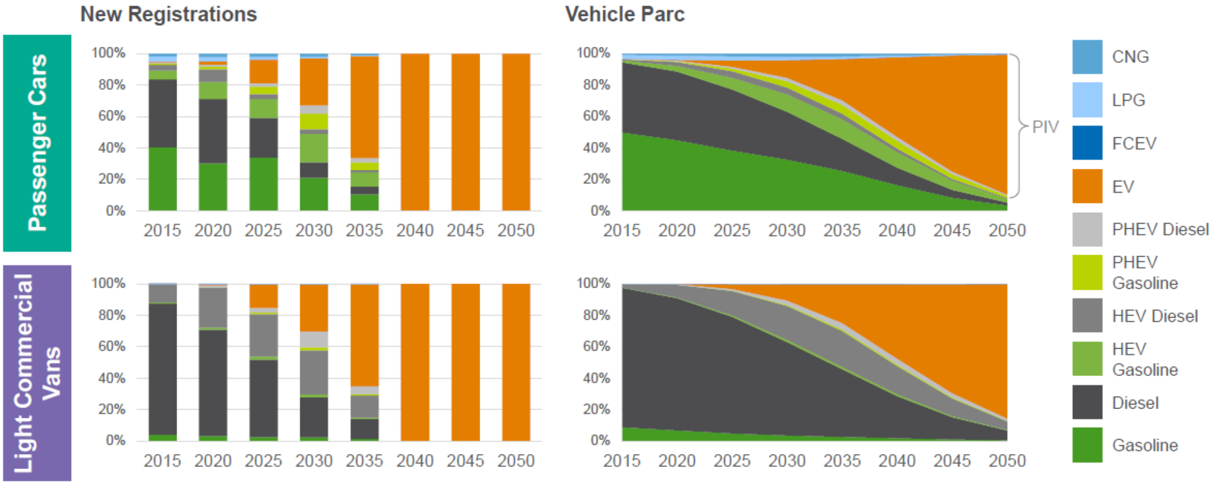

Figure 3: High EV scenario vehicle parc

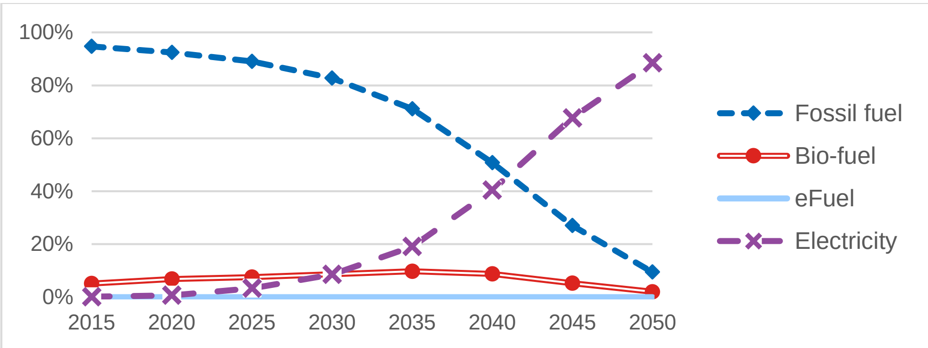

Figure 4: Fuel share for the High EV scenario

3.2 The Low Carbon Fuels scenario

The Low Carbon Fuels scenario is defined to meet similar GHG reduction targets as the High EV scenario, using a significant proportion of biofuels and eFuels. It assumes that in 2050 the vehicle parc will consist of very efficient ICEV, with a high penetration of low-carbon fuels (68% fuel share by energy) complemented by 23% electricity and a minor quota of fossil fuels in 2050 (Fig. 5). The biofuel/ e-Fuel share is higher in 2020-2030 compared with the High EV scenario, increasing rapidly post-2025 with 100% substitution for diesel in 2050 as shown in Fig. 6. There is also increased efficiency improvement in ICEV and HEV passenger cars from 2020 compared to the High EV scenario. Correspondingly, the marginal cost increases more significantly to 2050.

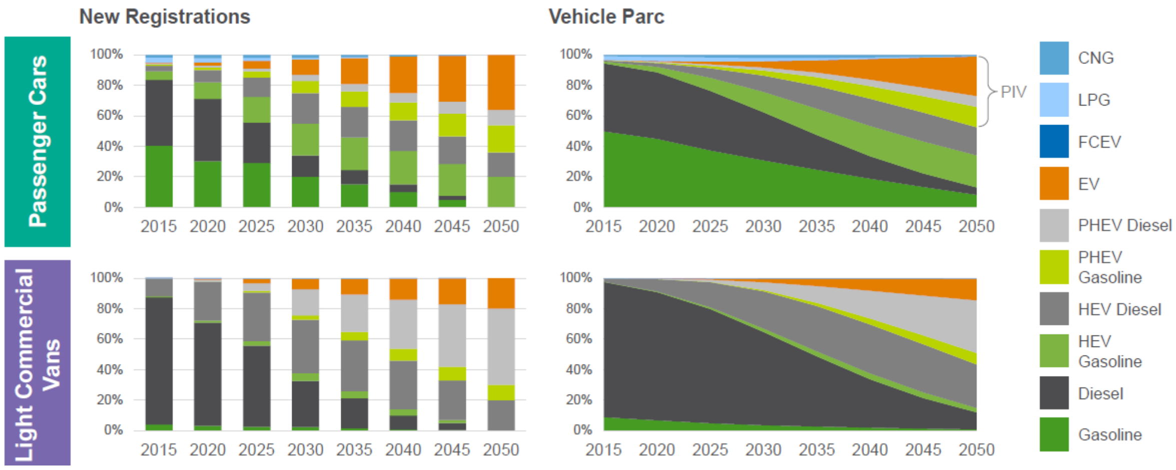

Figure 5: Low Carbon Fuels scenario vehicle parc

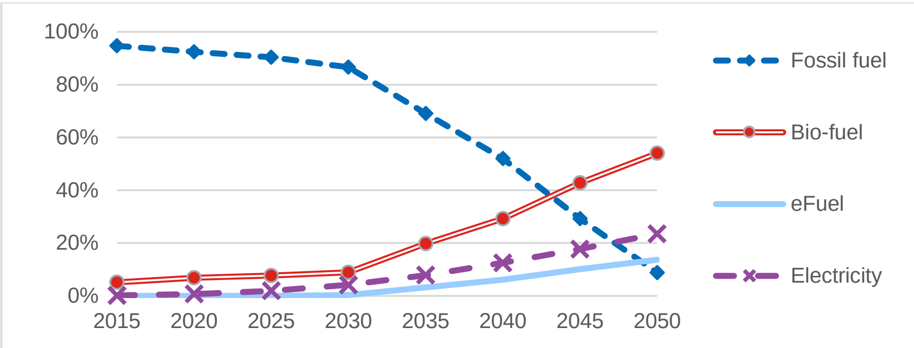

Figure 6: Low carbon scenario fuel share by energy

3.3 Alternative scenario

An alternative scenario for meeting similar GHG reduction targets, using more hybrid vehicles with increased use of biofuels and eFuels (compared to High EV) was also developed.

4 Results

The project examined impacts across four key areas: life cycle GHG emissions (from vehicle production, operation and disposal); cost implications; implications for energy supply and infrastructure and implications on materials and natural resources.

4.1 Life cycle GHG emissions

The analysis found both the High EV and Low Carbon Fuels scenarios to result in a similar and significant reduction in total life cycle GHG emissions (84-86% from 2015 to 2050, and by >90% vs 1990), as displayed in Fig. 7. Embedded emissions from production and disposal of vehicles account for around 8% of total emissions in 2015 (including accounting/reduction for end-of-life vehicle recycling), which rise to ~25% by 2050. The alternative scenario falls in-between the other two scenarios.

Life cycle GHG emissions are lowest for new BEVs (~3.9 tCO_2e) and half that of new low carbon fuels vehicles at 2050, but overall fleet GHG emissions are lowest for the Low Carbon Fuels scenario in 2050.

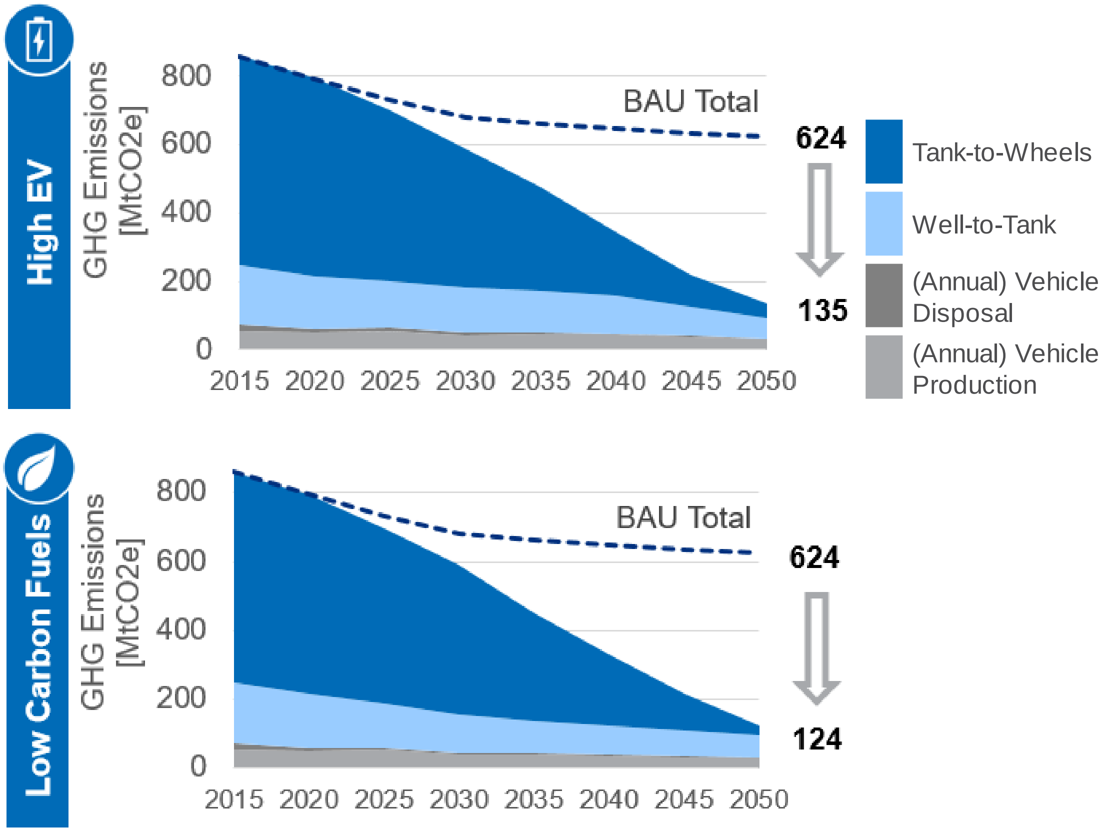

Figure 7: Well-to-Wheel GHG Emissions + Vehicle Embedded GHG Emissions from the EU LDV Fleet

4.2 Cost implications

Total direct annual parc costs to the end user were similar for the High EV and Low Carbon Fuels scenarios in 2050 (and lower than the reference case). Fig. 8 shows that, whilst costs are higher in the period to 2035 for the High EV scenario, the net costs are ~€70billion p.a. lower by 2050 compared to the Low Carbon Fuels scenario. Including Net Fiscal Revenue loss (vs BAU) closes the gap to €9bn p.a.

All scenarios therefore reduce GHG emissions and meet reduction objectives at lower overall cost to the end user, primarily due to lower fuel and energy costs than the BAU reference, which does not meet GHG reduction objectives.

However, the reduction in Net Fiscal Revenue versus the BAU scenario could reach €127 Billion p.a. for the High EV scenario (a 29% reduction) by 2050 if no changes were made to existing taxation approaches. The shortfall is however 44 / 61 €Billion p.a. less for the Alternative/ Low carbon fuels scenarios respectively (with a 19% / 15% reduction versus BAU).

This study also assessed the cost of each scenario from the societal perspective after inclusion of externalities for GHG and air pollutant emissions. Fig. 9 shows that the net cumulative societal costs (i.e. excluding taxes) are significant lower for the High EV scenario (33.5 €Billion p.a. lower compared to the Low carbon fuels) by 2050.

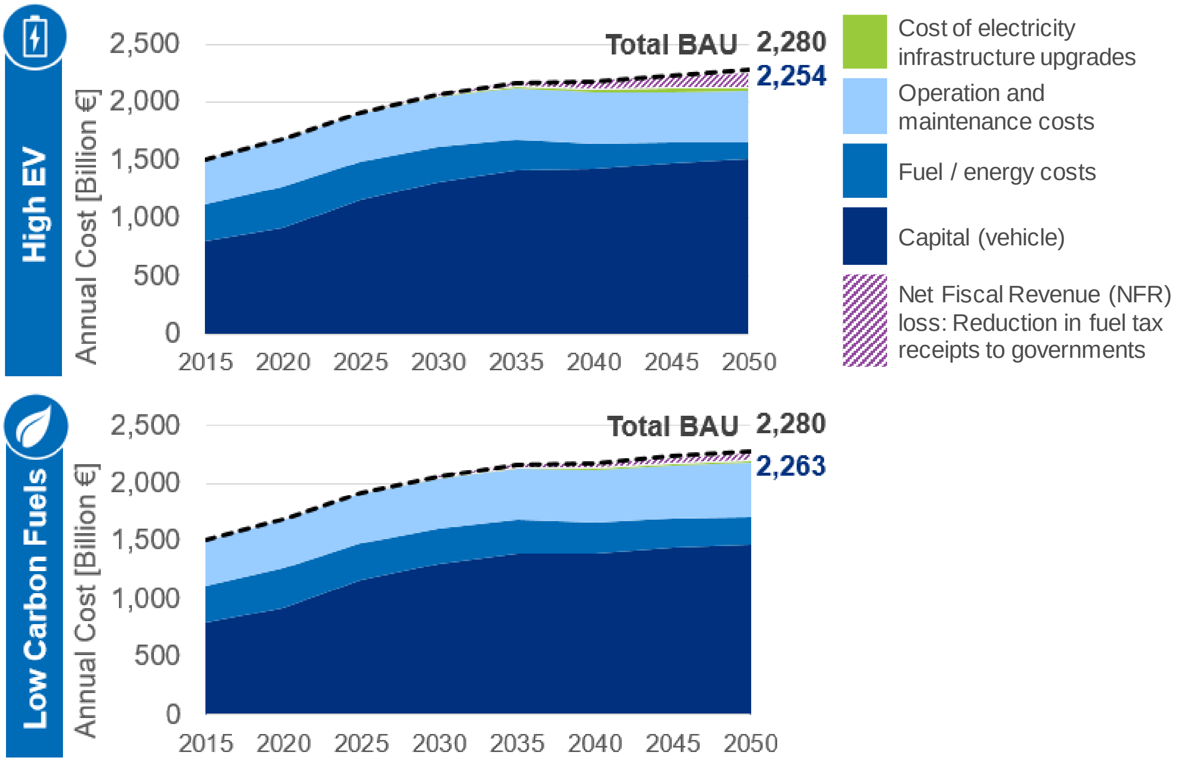

Figure 8: Total Parc Annual Costs to End-user, including charging infrastructure and network upgrades

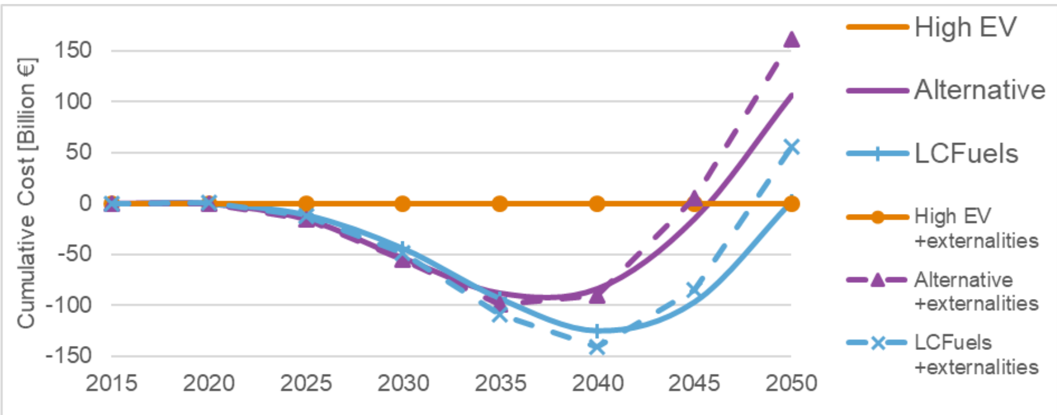

Figure 9: Cumulative Net Societal Costs (relative to High EV)

4.3 Implications for energy supply and electricity infrastructure

There is also a significant reduction in overall energy consumption resulting from both scenarios. The High EV scenario resulted in a 74% reduction in overall energy consumption by 2050 versus 2015, and 97% reduction in liquid fuel use in the same period. Electricity consumption is almost 90% of total energy use by 2050 at ~550 TWh (1980 PJ/year), and twice that of the Low Carbon Fuels scenario. This demand, excluding additional potential requirements across other sectors such as industry or buildings, represents ≈17,5% of EUs' electricity generation in 2015.

The Low Carbon Fuels scenario delivers a 49% reduction in overall energy consumption by 2050, comprising of 60% reduction in liquid fuel use which would be equivalent to 96% reduction in oil-based liquid fuels (excl. low carbon fuels). Low carbon fuel accounts for 88% share of liquid fuel use in 2050, equivalent to almost 3,000 PJ/year or 70 Mtoe for the whole Light Duty segment. It should be noted that production of EU e-Fuels will add +17% to the electricity use shown (and overseas electricity consumption would add a further +108%).

The study also assessed impacts on energy networks for alternative EV infrastructure cases and the effect of managed/unmanaged charging. Fig. 10 and Fig. 11 show results on electricity consumption and infrastructure and network costs from recharging for High EV in the 'home' charging scenario.

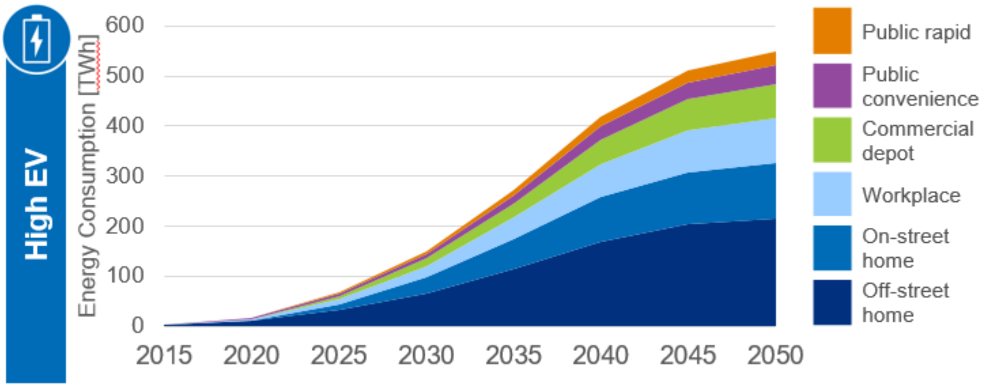

Figure 10: Electricity consumption from recharging by location (home charging scenario)

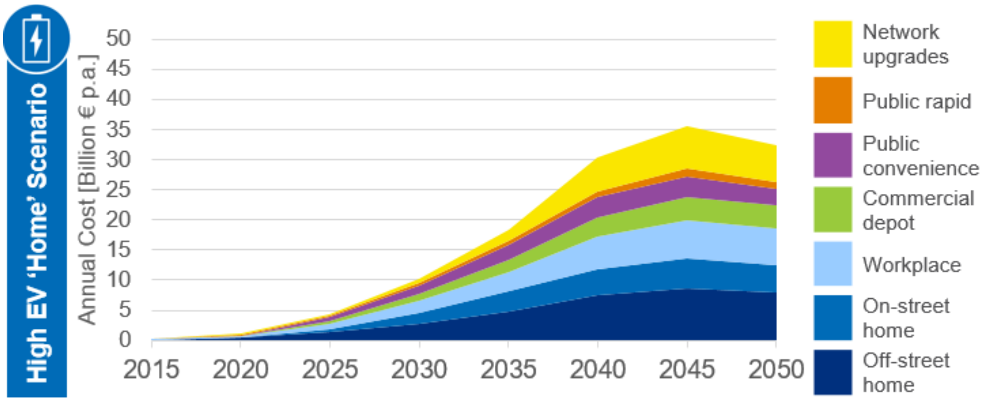

Figure 11: Annualised capital costs from charging infrastructure (Managed) by type – High EV scenario

Unmanaged charging was found to require significantly more upgrades for ~double the cost by 2050, as well as ~double the peak power requirements.

In the High EV scenario, the cumulative cost of a managed EV charging and network infrastructure reinforcement is estimated between €630bn and €830bn to 2050 (home and grazing recharging cases, respectively), compared to overall cumulative savings to the end-user between €1,100 & €1,600bn (1.3% - 1.8% of total end-user costs) vs EC's Reference scenario to 2050. In the Low Carbon Fuels scenario, the network infrastructure reinforcement cost is estimated to be €326bn – €389bn (home and grazing recharging cases, respectively).

4.4 Implications on resources and materials

In all the scenarios, the availability of raw materials for battery production was explored in detail. The High EV scenario was found to require almost three times the total battery capacity versus the Low Carbon Fuels scenario by 2050 which represents an estimated 15 Tesla Gigafactory (35 GWh p.a. [5]) equivalents for High EV, versus 5.5 Gigafactories for the Low Carbon Fuels scenario.

As a result, it is expected that the resource requirements for Lithium, Cobalt and Nickel (assuming current chemistry mixes) in the High EV scenario would increase very substantially over the period to 2050 (Fig. 12), which would pose a potential availability risk. We note that the use of Cobalt and Nickel in battery chemistries is expected to be phased out between 2030 and 2040; the share after this is uncertain.

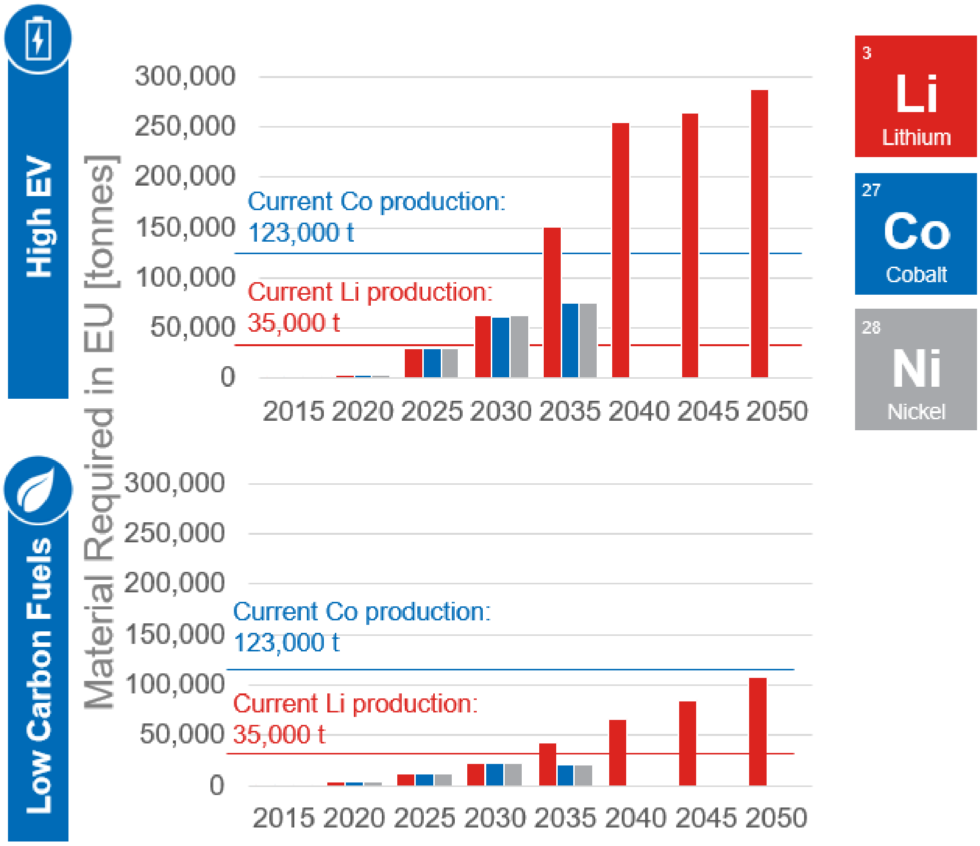

Figure 12: Material required in EU (Lithium, Cobalt and Nickel)

Lithium production, in particular, would need to increase significantly to meet European EV demand in the High EV scenario. In this scenario, annual virgin lithium demand is expected to increase rapidly until a peak is reached in 2040 (i.e. 6 times higher than global lithium production in 2016 (35kt)), when EV recycling becomes significant.

It is expected that European mass EV adoption will consume a larger share of global lithium reserves than the European share of global vehicle sales, potentially causing a shortage of lithium if other regions also undergo mass EV adoption. Therefore, new lithium resources will likely need to be accessed to meet the required demand, although these vary in terms of feasibility, production capacity and local impacts. Additionally, very few countries have lithium reserves. Battery recycling technologies to recover lithium could help reduce the total virgin demand but are expected to have a limited impact: only by 2050, does the production of lithium from recycled sources almost meet the virgin lithium extraction according to our analysis for the High EV scenario. It is unclear what economic or market factors will be required to encourage the growth of the recycling industry. Research is also currently underway into non-lithium battery chemistries, but it is unclear to what extent these might contribute in the future.

4.5 Sensitivity analysis

A number of sensitivity cases were also included to test the robustness of the results against key parameters. It was found that GHG intensity of electricity is a particularly important factor, especially for the High EV scenario where sensitivities on this parameter show approximately up to +/-30% change on the total GHG emissions for the scenario. The impact of the sensitivity on low carbon fuel availability (total substitution limited to 50% by 2050) for light duty vehicles also results in a 55% increase in GHG emissions for the Alternative scenario for 2050, and 78% for the Low Carbon Fuel scenario.

It was also found that the estimated marginal capital costs for the High EV scenario are particularly strongly influenced by assumptions on battery prices, and alternative battery cost assumptions can significantly change the differential between scenarios for long-term net societal costs. For the sensitivity on battery costs, the high battery cost scenario results in a narrowing of the gap in 2050 between the High EV and other scenarios, from ~34 €Billion p.a. to 7-12 €Billion p.a. For the sensitivity on very high battery costs, the scenario results in the cost of the High EV scenario remaining 15-27 €Billion p.a. higher than the other scenarios all the way to 2050. On the other hand, reducing the battery energy density improvement to 2050 (from 800Wh/kg to 500 Wh/kg) has only a small impact on total emissions – increasing emissions by up to 5 $MtCO_2$ p.a.

5 Discussion and conclusions

The results show that both the High EV scenario and the Low Carbon Fuels scenario offer the potential to significantly reduce GHG emissions at a similar cost (when adjusted to maintain Net Fiscal Revenue), but require large increases in battery production and infrastructure, or low carbon fuel supply respectively. A summary of the key points from their assessment is provided in Table 1 below.

In the High EV scenario, the cost of EV charging infrastructure alone could reach a cumulative cost of €630 - 830 Billion by 2050. There are also potential risks associated with the availability of key resources and increased battery production rates required to serve a complete transition to BEVs by 2040. In addition, major shifts to electrified transport in the High EV scenario would certainly require alternative approaches to tax revenue generation, due to substantial (up to 66 €Billion p.a.) reductions in net fiscal revenue. There are however significant uncertainties on the future evolution of battery technology and costs, and on the infrastructure requirements to support a wholesale shift to BEVs due to the rapid rate of change in this area.

On the other hand, the Low Carbon Fuels scenario assumes a high availability of low carbon fuels (allowing 100% substitution for diesel by 2050) – if supply of these fuels is limited (either by resource or production capacity), the potential for reducing GHG emissions reduces drastically: our analysis shows that if total substitution is restricted to 50% by 2050, GHG emissions would be almost 80% higher in 2050 (reducing lifecycle GHG savings vs 2015 emissions from ~87% to ~77%). Similarly to battery production, there will be significant challenges in ramping up the production capacity for these fuels.

Table 1: Summary of the positives and uncertainties of the High EV and Low Carbon Fuels scenarios

	Positives	**Uncertainties**
High EV	● Most efficient use of renewable electricity ● Free up low carbon fuel supplies for other transport applications	● Battery costs and improvements in energy density ● Investment in charging infrastructure and electricity distribution network ● Availability of resources for batteries (e.g. Lithium & Cobalt)
Low Carbon Fuels	● No behaviour change in refuelling ● Allows greater use of our existing manufacturing skills and assets	● Low carbon fuel supply chain and processes scale up / building sufficient production capacity ● Development to deliver zero impact on air quality from vehicle tailpipe

The analysis therefore suggests that an optimal solution from the perspective of cost-effective GHG reduction may lie somewhere in-between the scenarios evaluated.

More details on the project/methodology and the results of the analysis are available in the final reports, written by Powell, N. and Hill, N. et al. [1].

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Dr Nick Powell is a Principal in Technology Strategy at Ricardo Strategic Consulting with over 27 years experience in automotive engineering consultancy. He has led numerous engine development, NVH and advanced technology projects. Nick has a particular passion for understanding the technical, economic and strategic drivers for innovative technology development. Nick is a Fellow of the Institution of Mechanical Engineers.