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

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Version History and Disclaimer

Version number	Date	Revision
RD18-001538-1	26 April 2018	First issue
RD18-001538-2	21 June 2018	Updated following meeting on 30 April 2018
RD18-001538-3	24 July 2018	Updated following feedback received 11 July 2018 • Slide 57 added • EU Reference Scenario 2016 – reference added p24
RD18-001538-4	24 August 2018	Minor plot format modifications

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Mass EV adoption and Low Carbon Fuel scenarios both achieve similar reductions in total parc GHG emissions, at similar cost

Executive Summary

- The impacts of three scenarios in the European light duty vehicle market to 2050 have been analysed, versus a European Commission **Business As Usual (BAU) scenario,** as follows :
  - **High EV scenario** representing mass EV adoption to ~90% BEV parc by 2050
  - **Low Carbon Fuels scenario** representing use of significant proportions of biofuels and eFuels
  - **Alternative scenario** representing use of more PHEVs together with increased use of bio- and eFuels
- Total parc life cycle GHG emissions reduce to less than 13% of 2015 value by 2050 for all three scenarios, and the annual parc total costs to the end user are similar for the High EV and Low Carbon Fuels scenarios
- In the High EV scenario the cost of EV charging infrastructure alone could reach €30 Billion p.a. by 2040, and a cumulative cost of ~€630 Billion by 2050, versus ~€326 Billion for the Low Carbon Fuels scenario
- There are 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
- The modelling suggests an optimal solution from the perspective of cost-effective GHG reduction may lie somewhere in-between the scenarios evaluated
- Due to the rapid rate of change in this area, there are significant uncertainties on the future evolution of battery technology and costs and on the infrastructure requirements to support a wholesale shift to BEVs

Contents

Ricardo has conducted a study for CONCAWE on the implications of mass EV adoption w.r.t. GHG emissions, energy, and economics

Project Introduction

- CONCAWE requested Ricardo to conduct a study aiming to answer the following questions:
  - **What are the implications of a scenario of mass EV adoption compared to a Low Carbon Fuels scenario for light duty vehicles in Europe**
    - What are the implications for greenhouse gas (GHG) emissions?
    - What are the implications for energy supply and infrastructure?
    - What are the implications for materials and natural resources?
    - What are the implications for economics?
- This report combines the outputs of updated modelling of the mass EV adoption scenario, previously separately reported, with output from new analysis of a low carbon fuels scenario with a significant proportion of bio- and eFuels
  - The report is the output from Task 6 of project variation (P015713-001-5)

Source: Proposal B015713-002

Contents

Four scenarios are considered : High EV; Low Carbon Fuels; Alternative with more PHEVs; and Business as Usual

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Four Scenarios

- All the scenarios consider the European light duty vehicle fleet only. L-category vehicles, buses, and medium and heavy duty trucks have not been included in the analysis

High EV

- Represents “mass EV adoption”, with 100% BEV light duty vehicle new registrations by 2040, and c.90% BEV vehicle parc by 2050

Low Carbon Fuels

- Low Carbon Fuels scenario meeting similar GHG reduction targets, using a significant proportion of biofuels and eFuels

Alternative (Higher PHEV)

- Alternative scenario for meeting similar GHG reduction targets, using more hybrid vehicles with increased use of biofuels and eFuels

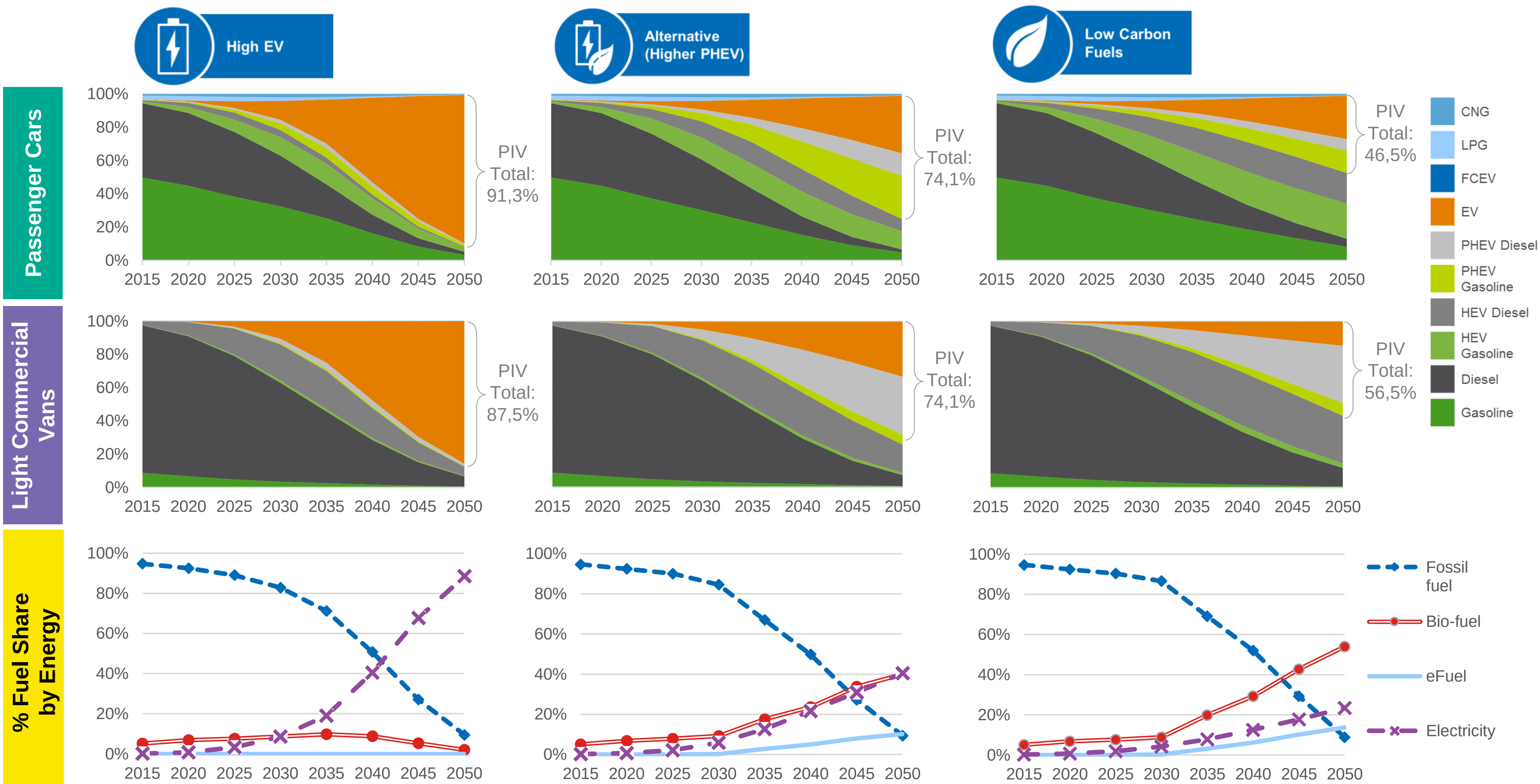
BAU

- “Business as usual” (BAU) scenario, used by European Commission as a baseline for quantifying the impact of future policy changes

The three new scenarios achieve similar WTW GHG reductions, through different powertrain and fuel combinations

- **WTW GHG outputs are shown in the results section**
- **Further scenario details, including new registration shares, are described in Appendix 2**

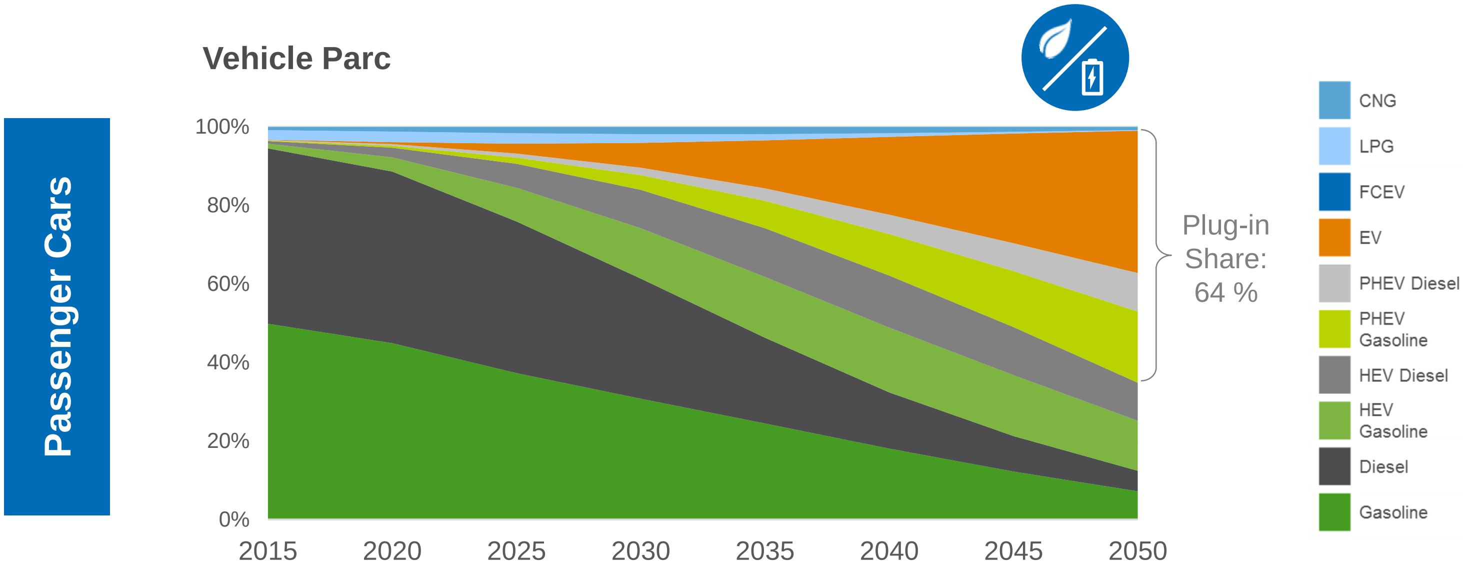
Change of Vehicle Parc is given below for three different scenarios



Notes: The Alternative scenario is similar (35%/39%/26% car fleet share for BEV/PHEV/ICE+Hybids by 2050) to the ERTRAC Mixed Fleet Scenario (36%/28%/36%), which has lower PHEV shares

A scenario was also created based on the "ERTRAC" mixed fleet scenario with combined xEV and Low Carbon Fuel powertrains at 2050

Mixed Fleet Scenario – Based on "ERTRAC" Mixed Fleet Share Scenario study to be published



- The Mixed Fleet scenario is most similar to the Alternative scenario
- The Mixed Fleet scenario assumes 64% Plug-In Vehicle (PIV) at 2050, compared to 91% and 47% for the High EV and Low Carbon Fuel scenarios respectively
- The improvement in efficiency of Internal Combustion Engine and Hybrid vehicles was considered greater than in the High EV scenario, due to likely further development of engines in this scenario
- The share of biofuels and eFuels, rapidly increases after 2030, reaching 100% and 75% share for diesel and gasoline respectively by 2050

Source: Ricardo Energy & Environment;
ERTRAC: European Road Transport Research Advisory study to be published

Contents

SULTAN is an adaptable transport policy analysis tool, developed for the European Commission and used on a variety of projects

Introduction to SULTAN

- Ricardo Energy & Environment developed the SULTAN (SUstainabLe TrANsport) policy impacts assessment tool for the European Commission as a transport policy modelling tool, 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 greenhouse gas emissions
  - Lifetime costs
  - Tailpipe NOx, SOx and PM
  - Energy security
- The SULTAN tool can also be used to evaluate demand-based policy measures and has been used on a number of projects for the European Commission to provide a rapid and cost-effective assessment of transport policy. For example, SULTAN was used as an input to the development of the 2011 EU Transport White Paper
- The tool is highly adaptable and has also been used for a variety of other public and private-sector clients, to assess European, national or even city-level impacts (e.g. in support of the development of a low emission vehicle roadmap for London)
- The EU-level version of the tool has been updated several times by Ricardo Energy & Environment across several European Commission projects, as well as through internally funded development activities
- The latest version of SULTAN was updated in 2016 and the baseline scenario has been calibrated to be consistent with the 2016 Reference scenario used in the modelling informing the 2030 Climate & Energy framework. The model is set at a European level, and does not split out individual countries

The process for using the tool involves preparing the input data, running SULTAN, and post-processing the results

Overview of the SULTAN modelling analysis

Input Data / Pre-processing

Activity by mode

Vehicle Energy Consumption [MJ/km]
- By mode, model year, powertrain type *

Vehicle stock
- Fleet # projection by mode
- Survival rates
- % share of new vehicles by powertrain *

GHG Emission Factors [CO_2e/MJ]
- By fuel / energy carrier **
- TTW and WTW

AQP Emission Factors
- By mode fuel / powertrain
- Direct emission factors for NOx, SOx, PM

Cost Data
- Fuel costs (excl./incl. tax) **
- Capital costs by powertrain
- O&M costs

Scenario Modelling Calculations

SULTAN Scenario Database and Calculation Engine

Results Database and SULTAN Results Viewer

Notes:
* Key input variable, set by the scenarios developed for this study
** Input variable to sensitivity scenarios for this study, e.g. electricity CO_2e/kWh, energy prices, etc.
*** Input data for calculations informed by Literature Review and Deep Dive analysis

Output Data / Post-processing

SULTAN Outputs
- Fleet numbers / mix by powertrain
- Energy consumption by fuel
- TTW, WTW, AQP emissions
- Energy Security metrics
- Economic outputs (social, end-user)
  - TCO: Capital, Fuel and O&M costs
  - Net fiscal revenue impact
  - External costs of emissions
  - Cumulative costs

Vehicle numbers by powertrain

Additional Post-Processing ***
- GHG emissions from vehicle production and disposal
- Alternative fuel infrastructure requirements (# by type, share of energy cons., costs)
- Resource requirements

Additional Final Results, e.g.
- Total life cycle GHG emissions
- Total costs including infrastructure

Source: Ricardo Energy & Environment

The SULTAN model includes built-in calculation of fleet-level costs. Input datasets are based on analysis for the European Commission

Methodology: Cost Analysis (1/2)

- The SULTAN model can use a range of cost datasets to calculate total annualised costs from a social perspective (excluding tax) and end-user/consumer perspective (including taxes). The model also calculates the impacts on net fiscal revenue (= total in-year costs with tax – costs without tax)
- *Key assumptions*: the annualised capital cost calculations assume a discount rate of 4% for social perspective (as recommended for Commission impact assessment), and 10% for the consumer perspective
- *Baseline vehicle capital costs:* The baseline capital cost / price of an average car and LCV for 2015 is based on data from ICCT's European vehicle market statistics: Pocketbook 2016/2017*
- *Marginal vehicle capital costs*: The marginal additional capital costs of different powertrains are calculated using a pre-calculation process using technology cost and CO_2 / energy reduction cost curves
- *Fuel costs, taxes*: this dataset comes directly 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 are linked to the GHG intensity scenarios and have been developed based on previous SULTAN analysis
- *Other taxes*: average EU vehicle purchase tax and VAT rate are also from the EC's 2016 Reference scenario
- No additional tax changes (e.g. for electricity) have been assumed for the two scenarios, compared to the baseline (BAU) scenario
- 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

* Source: http://www.theicct.org/sites/default/files/publications/ICCT_Pocketbook_2016.pdf

Average marginal capital costs and energy consumption are calculated based on new vehicle gCO_2/km and powertrain shares

Methodology: Cost Analysis (2/2)

xEV Baseline Marginal Capital Costs

- Marginal capital costs for a range of xEV powertrains (i.e. BEV, PHEV, REEV, FCEV) were developed as part of previous analysis for the European Commission. These were based upon assumptions on the costs of different components (i.e. batteries, motors, etc.), and other assumptions (e.g. sizing of components, reserved battery state of charge (SOC), electric range, etc.) which were tested in consultation with stakeholders during the project
- Future cost reductions were estimated using a learning-based methodology, cross-checked with a range of forecasts from the literature
- The assumptions on electric range (increased) and future battery cost projections (decreased) were updated at the start of the project, based on more recent evidence on how these are now forecast to change in the future

Cost-Optimised SULTAN Marginal Capital Cost inputs:

- Before running SULTAN, a capital cost analysis is performed as a pre-processing step using a proprietary model. This 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 CO_2 target and for the user defined share of powertrains
- The relationship between vehicle capital cost and CO_2 performance (/energy consumption for BEVs and FCEVs) 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 (also available from the Commission’s website), 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 implication for network infrastructure, Ricardo has considered a series of recharging scenarios for plug-in vehicles

Based on total electrical energy requirements calculated by SULTAN

Recharging Scenarios

Home Unmanaged

Home charging is where users charge mainly using off-street home or on-street residential recharging infrastructure

Home Managed

Same charging type split as "Home Unmanaged", but with longer time periods to simulate managed charging

Grazing Unmanaged

Grazing is where users charge little and often, mainly using charging points away from the home

Grazing Managed

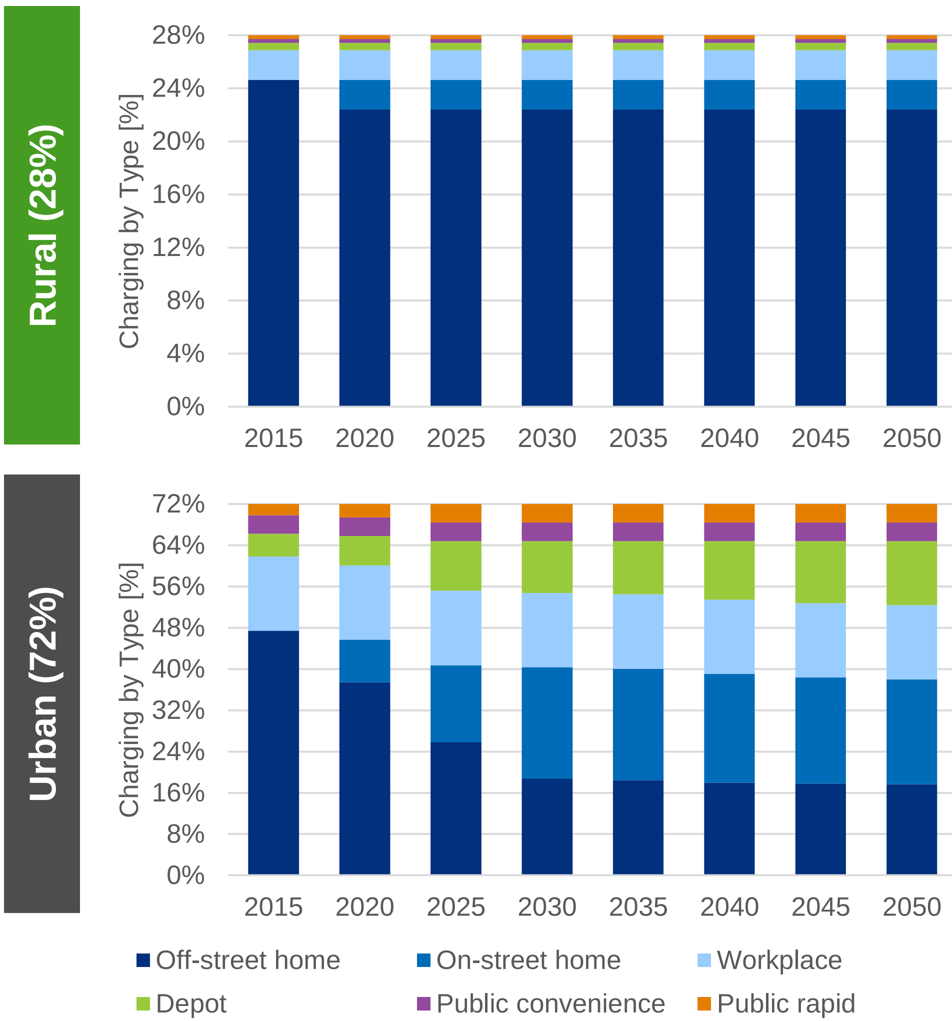
Same charging type split as "Grazing Unmanaged", but with longer time periods to simulate managed charging

Current EU housing data shows 28% of households are located in rural environments, and 72% are located in urban and sub-urban environments. Therefore, Ricardo has assumed an EV electricity demand split of 28% for rural charging and 72% for urban charging, applied to all four scenarios. Urban includes both urban and sub-urban properties

Source: Eurostat (online data code: ilc_lvho01)

The “home” recharging scenario assumes most EV users charge their EV at home

Recharging Scenario – “Home”

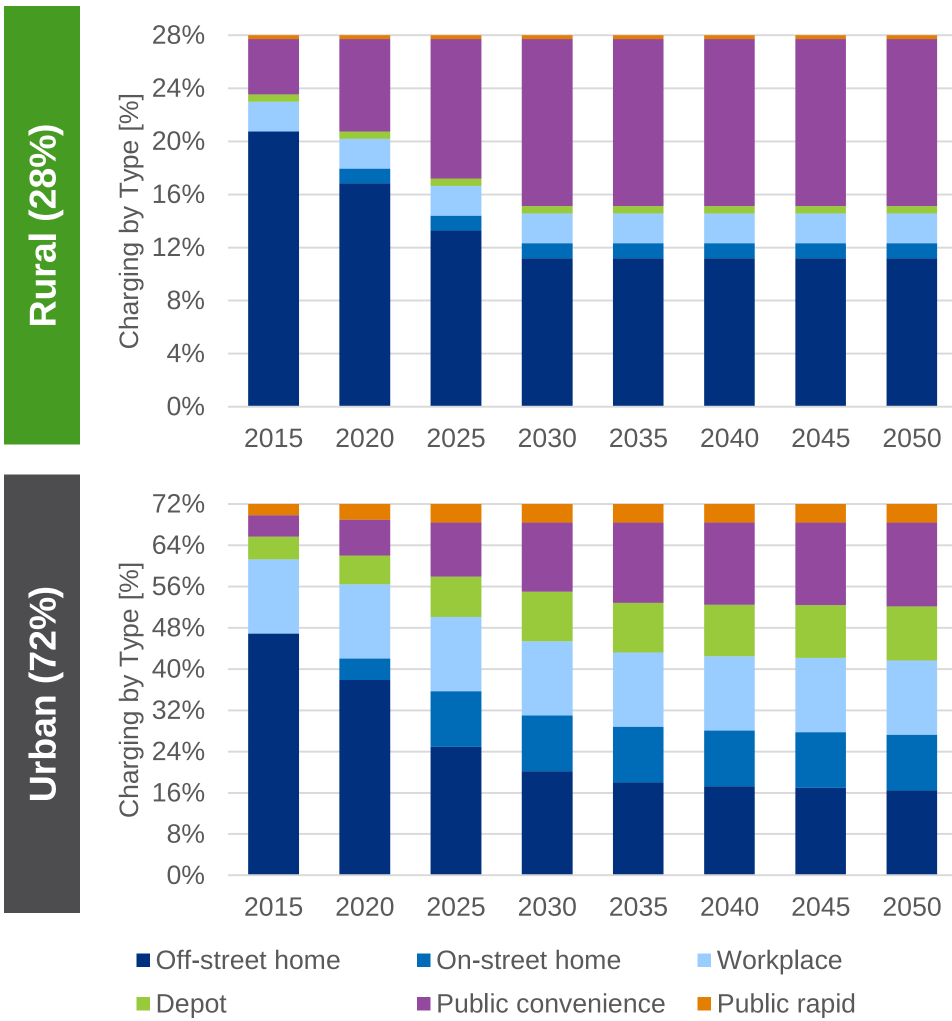


- In the “home” recharging scenario EV users charge mainly using off-street home or on-street residential recharging infrastructure
- The majority of rural charging is undertaken at home where EV users have access to private off-street parking facilities
- However in urban environments, it is assumed that most cars are parked on the street (e.g. terraced housing and flats). There is also greater workplace and commercial depot charging infrastructure
- The proportion of off-street home charging decreases from 2015 until 2050 for the urban users
  - It is assumed that people who are able to charge at home are more likely to be early adopters of EVs. While those living in inner city environments will wait until there is sufficient access to on-street residential charging

Source: Ricardo Energy & Environment scenario

While the "grazing" recharging scenario assumes EV users make greater use of public charging to keep their EVs topped up

Recharging Scenario – "Grazing"



- In the "grazing" recharging scenario, it is assumed that EV users charge little and often, mainly using charging points away from the home
- This is reflected in both rural and urban split where public convenience has a high proportion of EV charging compared to the "home" scenario
- Total energy for recharging has been calculated by SULTAN

Source: Ricardo Energy & Environment scenario

Ricardo has used SULTAN Model outputs with the recharging scenarios to estimate costs for upgrading the network infrastructure

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Estimating Infrastructure Network Costs – calculation approach

Recharging Scenarios

SULTAN Model Outputs

- Number charging units by location type
- Number Electric Vehicles
- Energy Consumption [TWh], split by charging location type

Estimate Peak Power

Each of the different charging locations are assumed to be in operation for a certain number of days per year across a certain number of hours per day. This enables a **power requirement** to be derived from the energy output of SULTAN

Determine Required Infrastructure

Peak power is used to size the infrastructure required to supply that peak power

- A 1 kW load over 24 hours will consume 24 kWh of energy, which is greater than a 7 kW load used for 1 hour (7 kWh).
- The 7 kW load will require a larger conductor and hence more electrical infrastructure than the 1 kW load

- DNO: Charging distributor network operator.

Estimate Cost

An associated cost for each piece of infrastructure was estimated, based on publicly available literature from distribution network operators

A final cost was estimated by multiplying the average DNO cost with the electrical infrastructure required

Source: Ricardo Energy & Environment Analysis

Contents

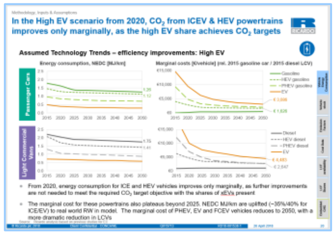
Key input data and assumptions are described in the following section

Further assumptions are described in the Appendices

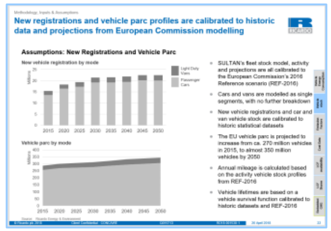
Input Data / Pre-processing

Additional Post-Processing

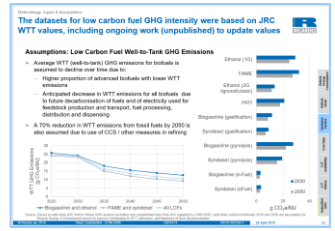
Vehicle Energy Consumption



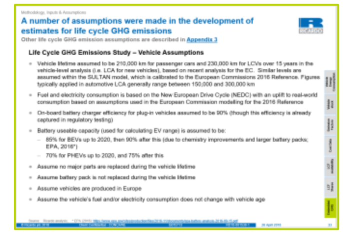
Vehicle stock



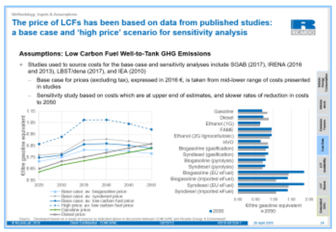
GHG Emission Factors



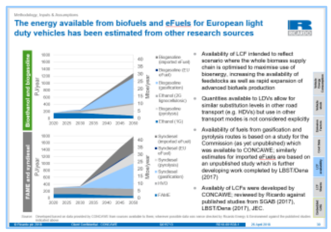
GHG-vehicle production & disposal



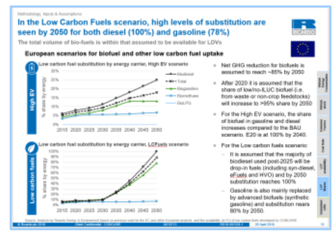
Cost Data



Low carbon fuel availability



Low carbon fuel shares



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- The key core assumptions, as well as the assumptions used in the sensitivity studies are described in this section
- 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

Source: Ricardo Energy & Environment

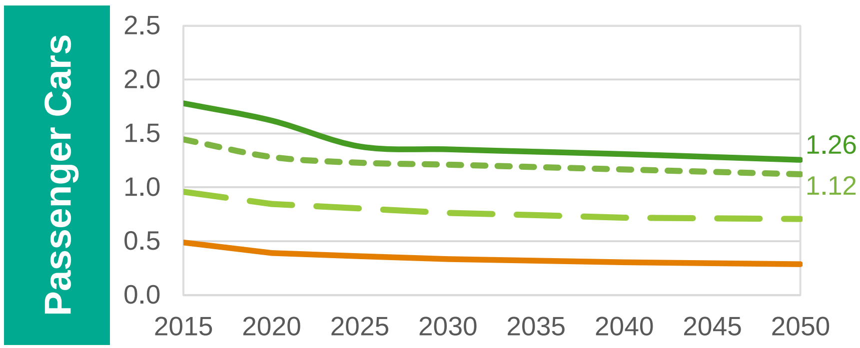
Vehicle Energy Consumption
Vehicle stock
Emission Factors
Cost Data
LCF availability
LCF Shares
Embedded GHG

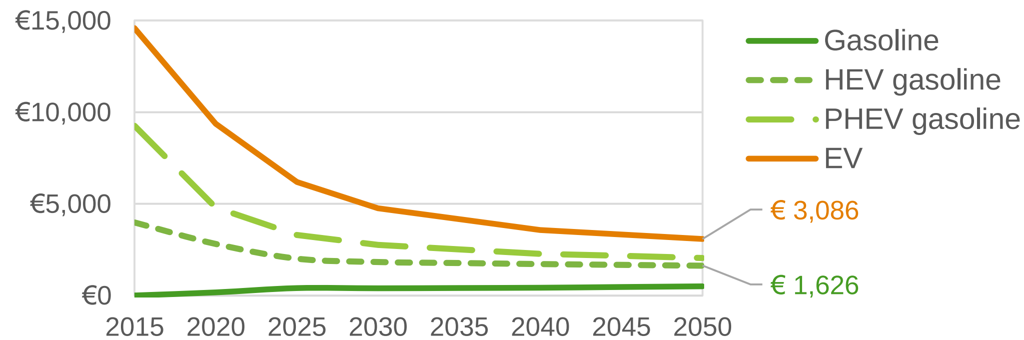
In the High EV scenario from 2020, CO_2 from ICEV & HEV powertrains improves only marginally, as the high EV share achieves CO_2 targets

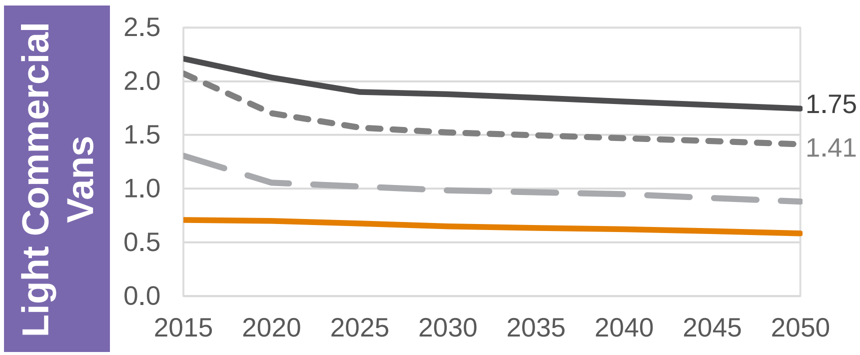
Assumed Technology Trends – efficiency improvements: High EV

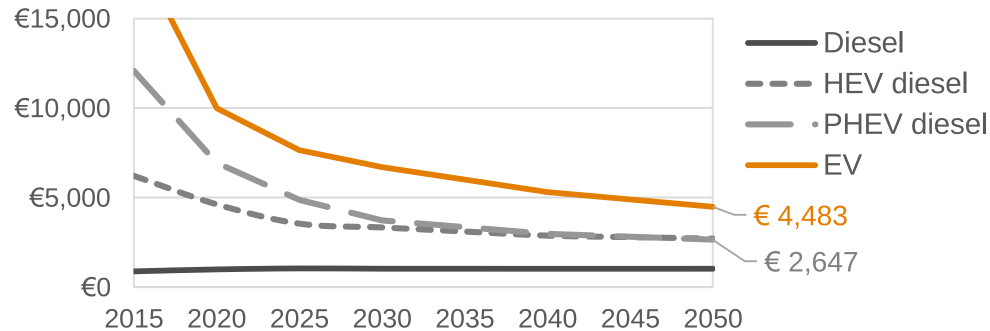
Energy consumption, NEDC [MJ/km]

Marginal costs [€/vehicle] (rel. 2015 gasoline car / 2015 diesel LCV)









- From 2020, energy consumption for ICE and HEV vehicles improves only marginally, as further improvements are not needed to meet the required CO_2 target objective with the shares of xEVs present
- The marginal cost for these powertrains also plateaus beyond 2025. NEDC MJ/km are uplifted (~35%/40% for ICE/EV) to real world RW in model. The marginal cost of PHEV, EV and FCEV vehicles reduces to 2050, with a more dramatic reduction in LCVs

Source: Ricardo analysis based on previous studies for EC

Vehicle Energy Consumption
Vehicle stock
Emission Factors
Cost Data
LCF availability
LCF Shares
Embedded GHG

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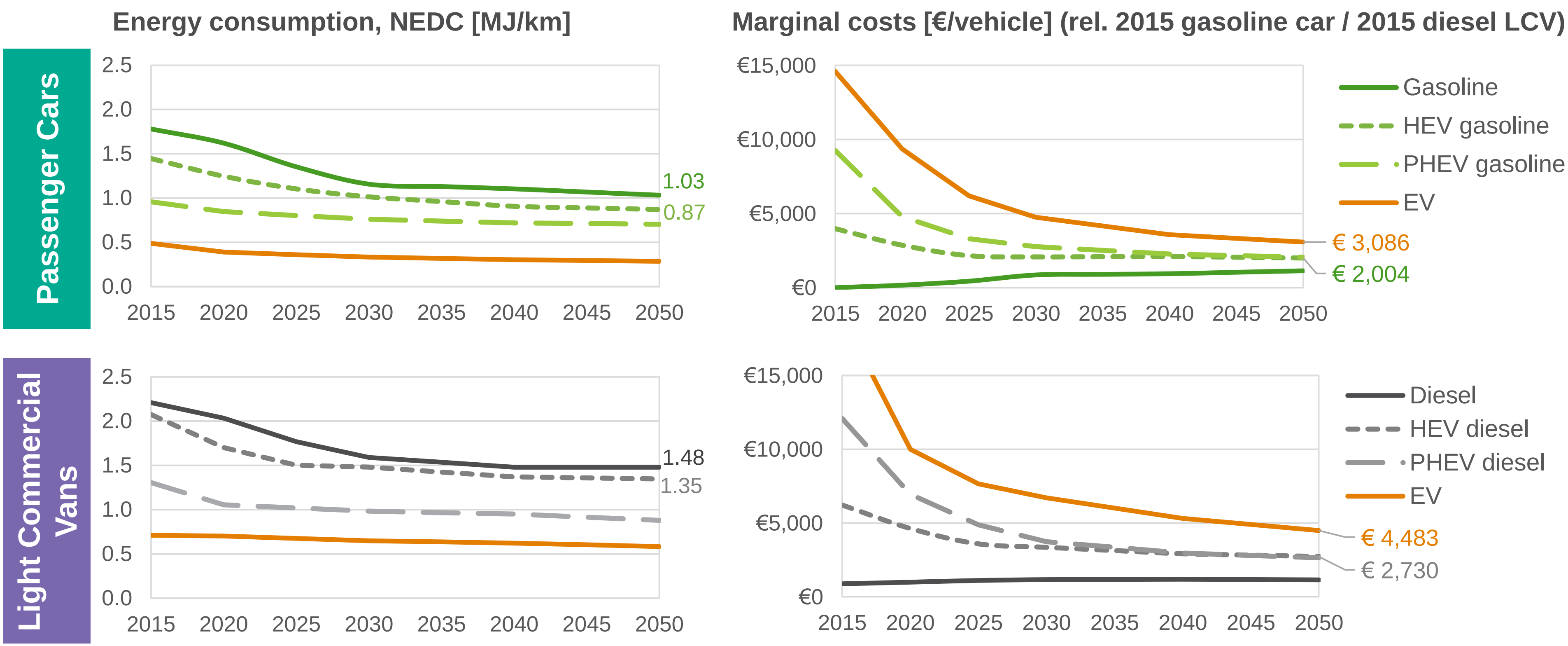
In the Low Carbon Fuels/Alternative scenario, the costs and rate of improvement in CO_2 from ICEV and HEV powertrains is higher

Assumed Technology Trends – efficiency improvements: Low Carbon Fuels/Alternative



- From 2020, energy consumption for ICE and HEV vehicles improves at a greater rate than for the High EV scenario; the marginal cost correspondingly increases more significantly to 2050
- Similar trends also for LCVs

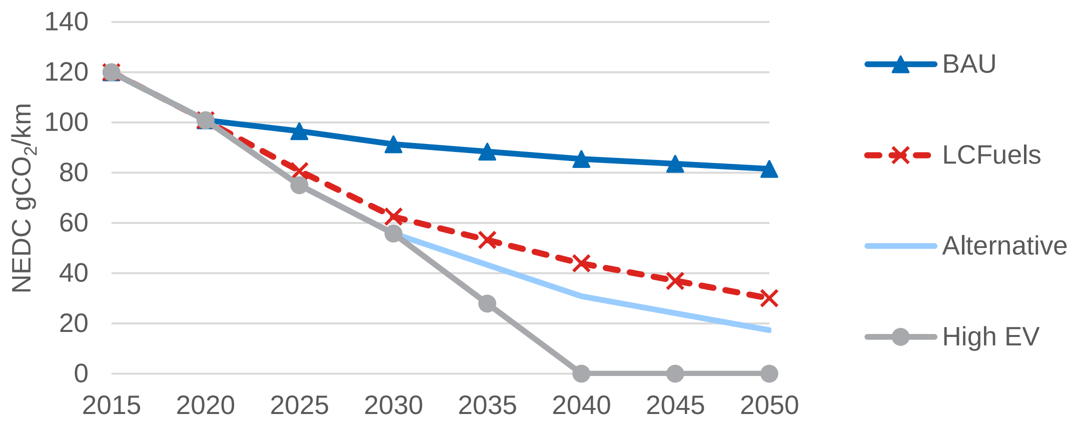
Source: Ricardo analysis based on previous studies for EC

The trajectories for CO_2 improvement have been set up consistent with the range proposed for exploration of post-2020 targets

Input assumptions on TTW NEDC gCO_2/km improvement trajectory for new vehicles

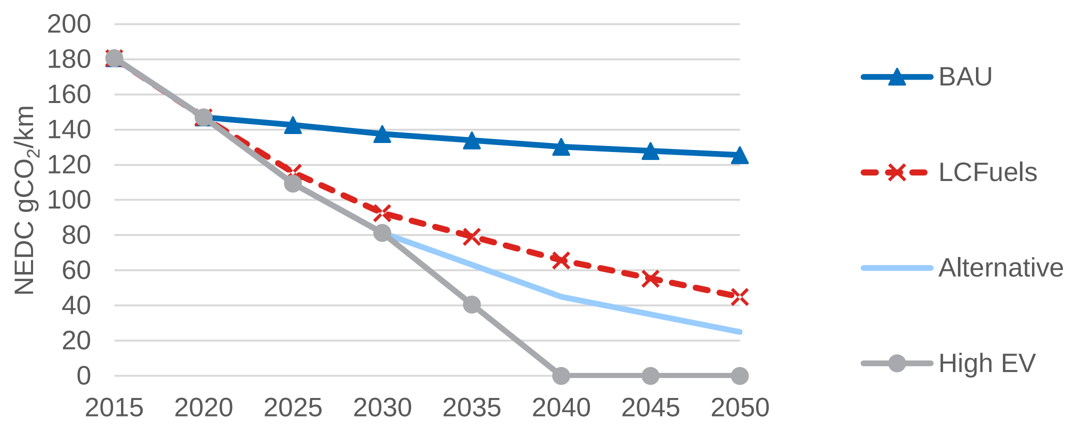
Passenger Cars

gCO_2/km improvement trajectories for passenger cars



Light Commercial Vans

gCO_2/km improvement trajectories for light commercial vans

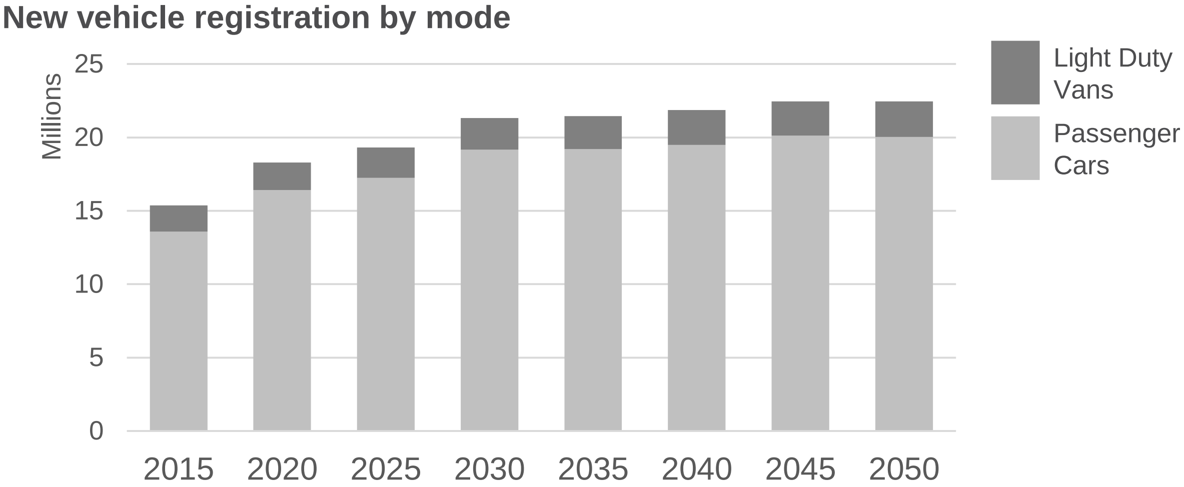


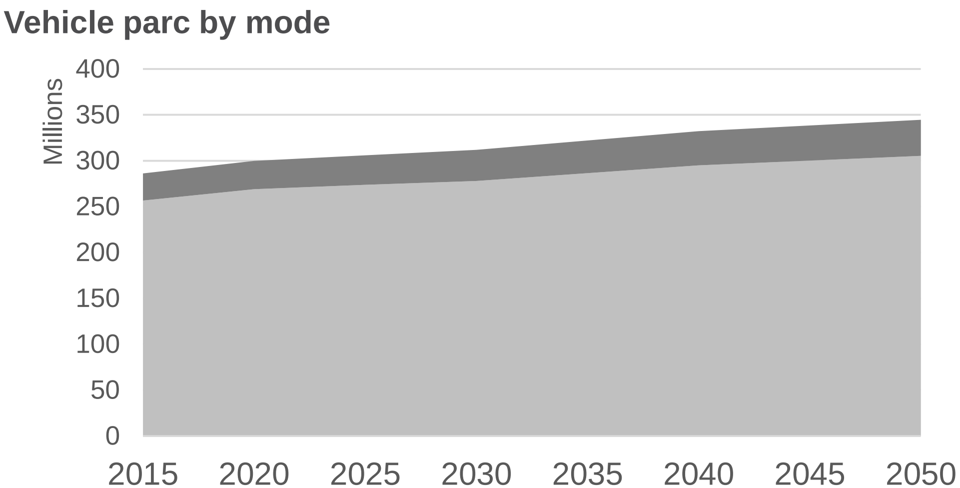
- The baseline (BAU) scenario is consistent with the Commission's 2016 Reference scenario
- The European Parliament indicated a range of improvement of gCO_2/km emissions that should be explored by the EC for potential post-2020 regulatory CO_2 targets for LDVs
- The post-2020 gCO_2/km reduction trajectories for the High EV and Alternative scenarios have been set up to be consistent with the upper end of these recommendations, and extrapolated to 2050. Targets can be closer to current proposals for LC Fuels scenario, for equivalent WTW
- 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

Source: Ricardo Energy & Environment

New registrations and vehicle parc profiles are calibrated to historic data and projections from European Commission modelling

Assumptions: New Registrations and Vehicle Parc





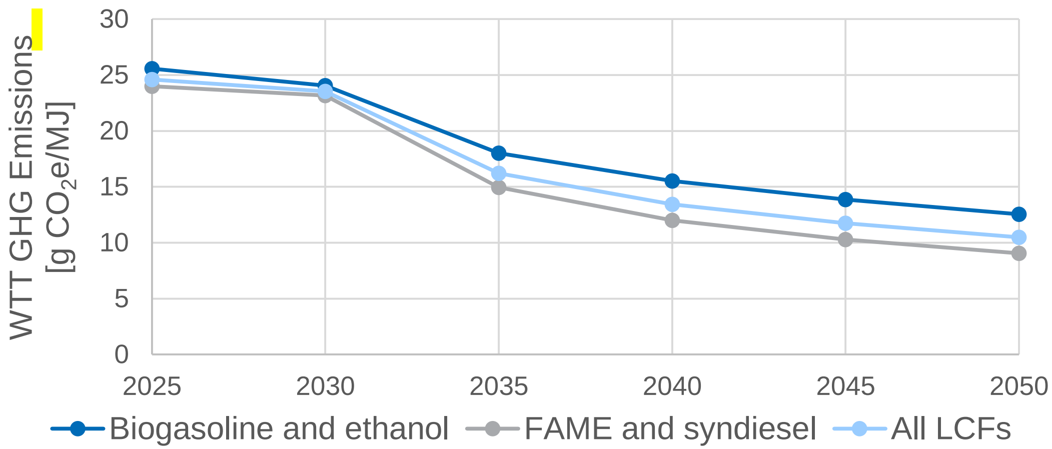
- SULTAN's fleet stock model, activity and projections are all calibrated to the European Commission's 2016 Reference scenario (REF-2016)
- Cars and vans are modelled as single segments, with no further breakdown
- New vehicle registrations and car and van vehicle stock are calibrated to historic statistical datasets
- The EU vehicle parc is projected to increase from ca. 270 million vehicles in 2015, to almost 350 million vehicles by 2050
- Annual mileage is calculated based on the activity vehicle stock profiles from REF-2016
- Vehicle lifetimes are based on a vehicle survival function calibrated to historic datasets and REF-2016

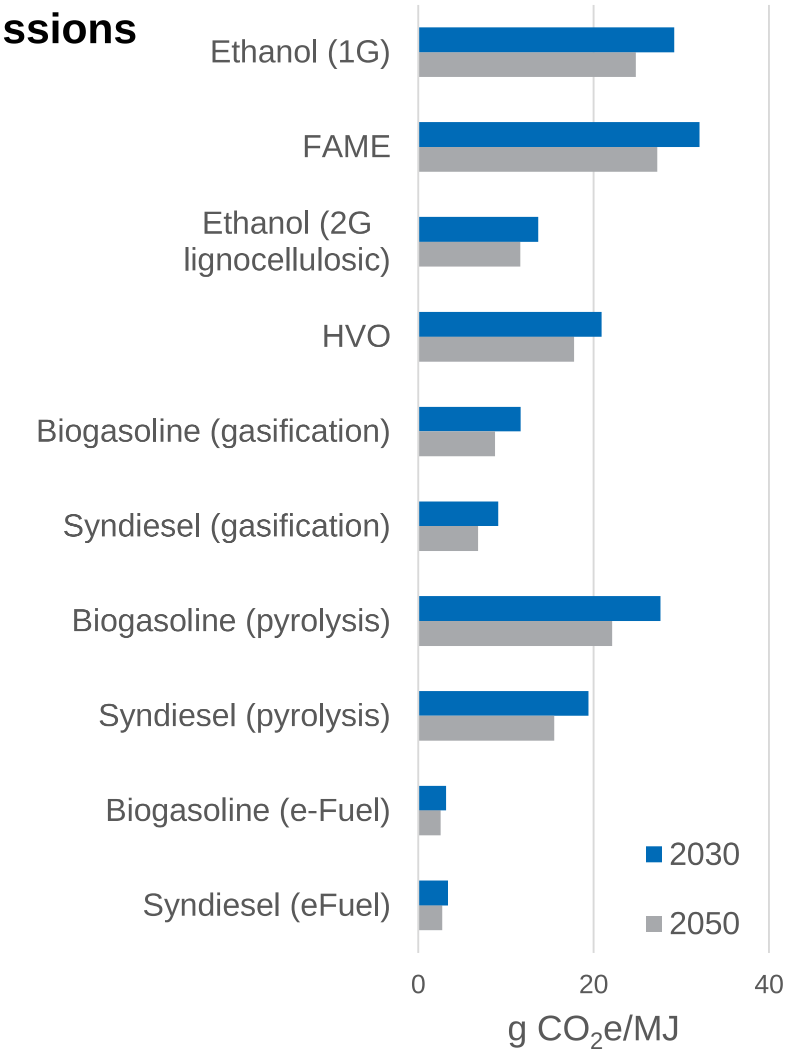
Source: Ricardo Energy & Environment EU Reference Scenario 2016 - Energy, transport and GHG emissions Trends to 2050, European Commission, 2016. https://ec.europa.eu/energy/sites/ener/files/documents/20160713%20draft_publication_REF2016_v13.pdf

The datasets for low carbon fuel GHG intensity were based on JRC WTT values, and EC study on the availability of Advanced Biofuels

Assumptions: Low Carbon Fuel Well-to-Tank GHG Emissions

- Average WTT (well-to-tank) GHG emissions for biofuels is assumed to decline over time due to:
  - Higher proportion of advanced biofuels with lower WTT emissions
  - Anticipated decrease in WTT emissions for all biofuels due to future decarbonisation of fuels and of electricity used for feedstock production and transport, fuel processing, distribution and dispensing
- A 70% reduction in WTT emissions from fossil fuels by 2050 is also assumed due to use of CCS / other measures in refining



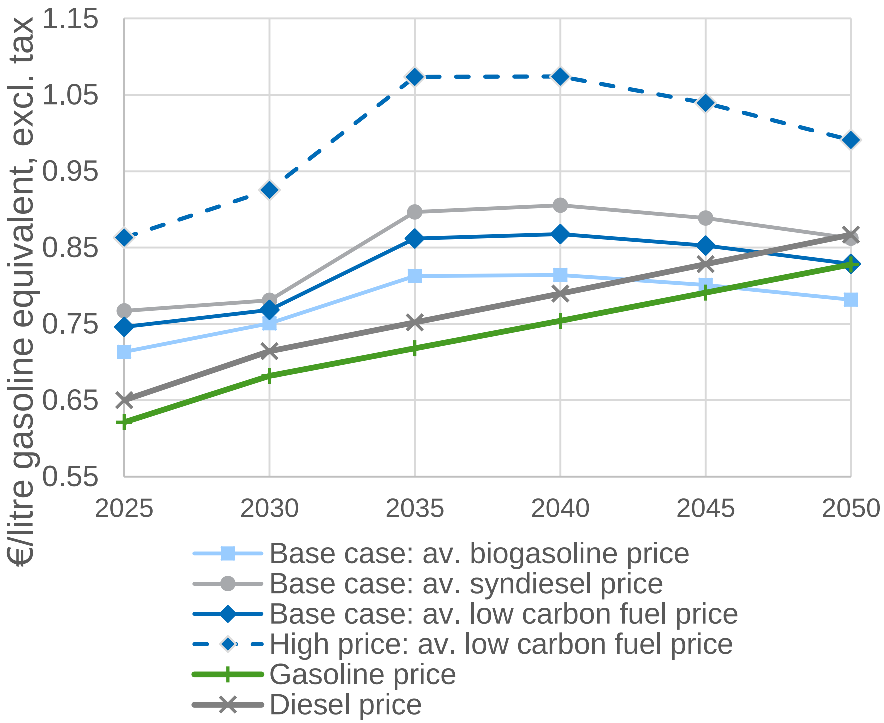


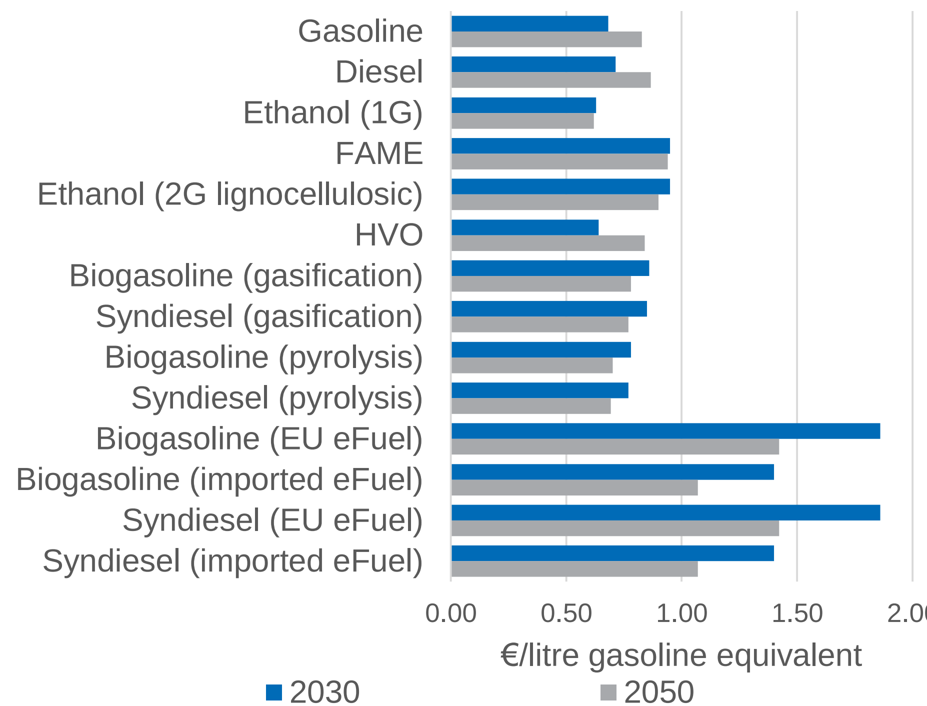
Source: Based on data from JRC Well to Wheel GHG analysis including new unpublished data from JRC supplied by CONCAWE; reductions achieved between 2030 and 2050 are assumption by Ricardo Energy & Environment based on sources contributing to WTT emissions and likelihood of their decarbonisation
European Commission D-G for Research & Innovation, Research and Innovation perspective of the mid - and long-term Potential for Advanced Biofuels in Europe, January 2018

The price of LCFs has been based on data from published studies: a base case and ‘high price’ scenario for sensitivity analysis

Assumptions: Low Carbon Fuel Costs

- Studies used to source costs for the base case and sensitivity analyses include SGAB (2017), IRENA (2016 and 2013), LBST/dena (2017), and IEA (2010)
  - Base case for prices (excluding tax), expressed in 2016 €, is taken from mid-lower range of costs presented in studies
  - Sensitivity study based on costs which are at upper end of estimates, and slower rates of reduction in costs to 2050



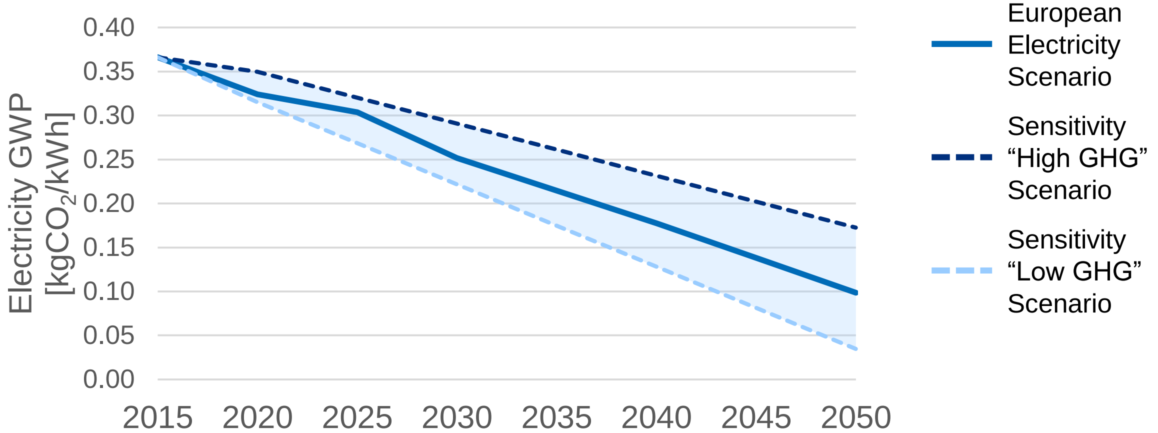


Source: Developed based on a range of sources as indicated above in discussion between CONCAWE and Ricardo Energy & Environment

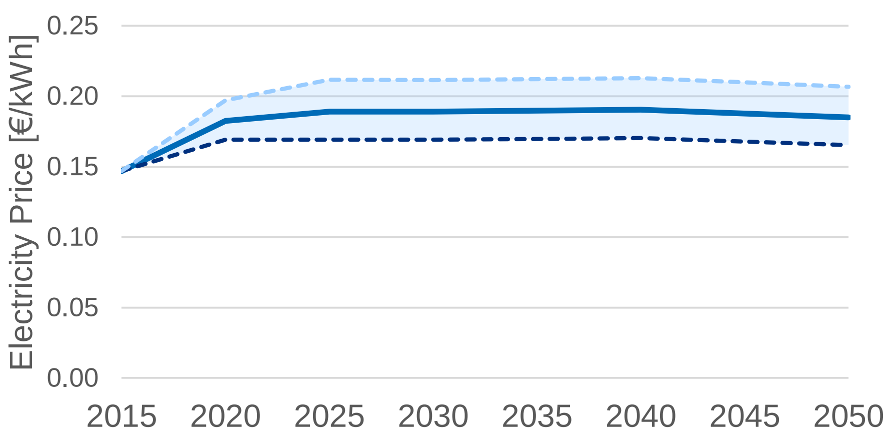
The datasets for electricity GHG intensity and prices were based on European Commission assumptions and other previous analysis

European Electricity Scenario

Electricity Global Warming Potential (GWP) [kgCO$_2$/kWh]



Electricity Price [€/kWh, excl. tax]

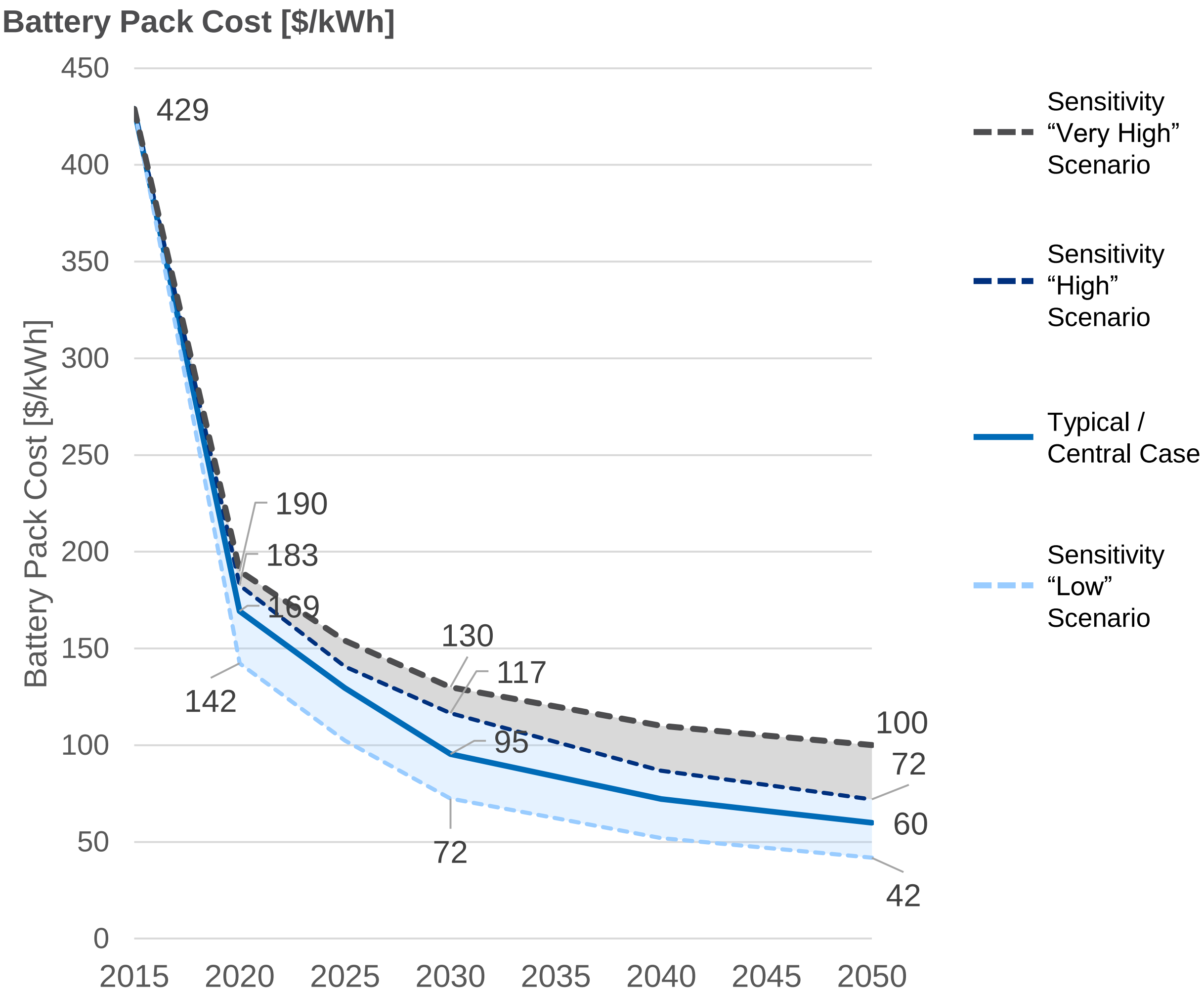


- The baseline trajectory for electricity GHG intensity and costs is based on the European Commission’s 2016 Reference scenario dataset
- Alternative scenarios for GHG intensity were based on previous analysis for the Commission from the EU Transport GHG: Routes to 2050 (R2050) projects
  - Low GHG intensity (93% reduction on 1990) is consistent with the low end of the range for high decarbonisation scenarios from the Commissions *“Roadmap for moving to a competitive low carbon economy in 2050”*
  - High GHG intensity (65% reduction on 1990) is a sensitivity from R2050 projects

Source: European Commission (2016) and previous analysis by Ricardo Energy & Environment for the EC and other European projects

Battery costs are a key component of EV costs and per kWh are expected to decline by over 70% by 2030 compared to prices in 2015

Assumed Technology Cost Trends – Battery Pack



Source: Ricardo Energy & Environment analysis

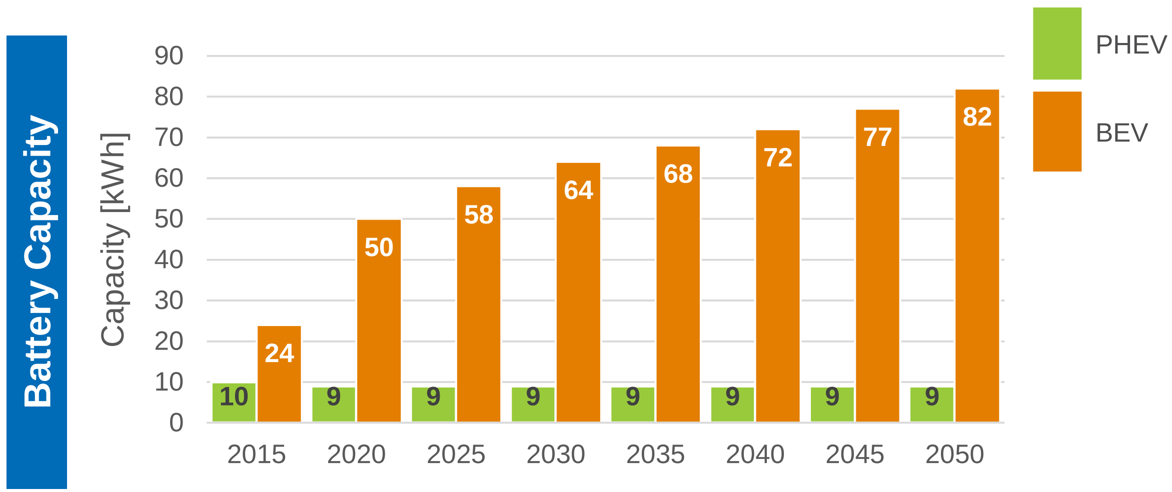
- Estimates for future battery costs (including assembly) are based on learning-based cost analysis developed as part of work for the European Commission
- These have been further cross-checked against evidence on recent historical trends and forecasts, such as from Bloomberg New Energy Finance (2017)*
- An additional 'Very High' sensitivity has been added to simulate a case where supply/demand considerations push up battery *prices* for OEMs
- Battery costs are used together with electric range and SOC assumptions to calculate the costs of baseline xEV powertrain vehicles relative to conventional equivalents
- Assembly of the battery pack into the vehicle is considered in vehicle costs

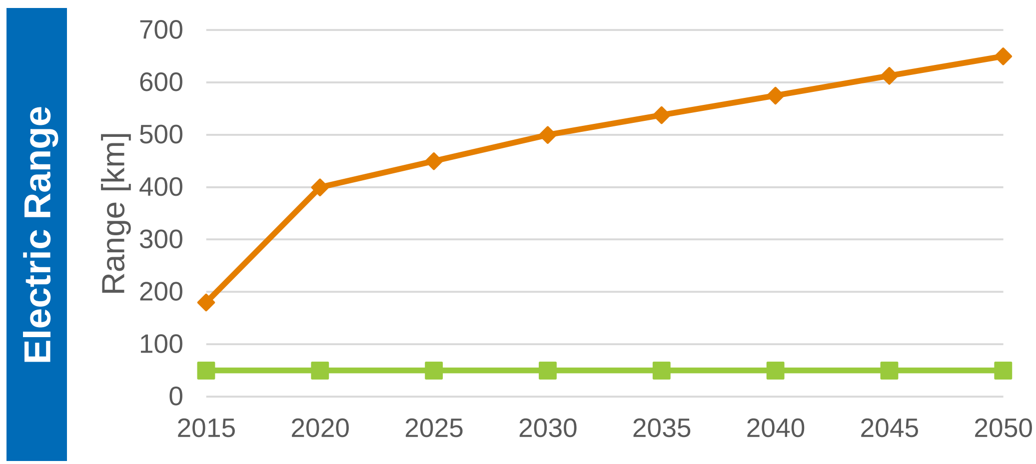
* Source: https://data.bloomberglp.com/bnef/sites/14/2017/04/2017-04-25-Michael-Liebreich-BNEFSummit-Keynote.pdf

Average battery pack size in 2020 is expected to be more than double that in 2015 driven by increased range and lower costs

RICARDO

Assumed Technology Trends – Battery Pack, Passenger Cars (All Scenarios)





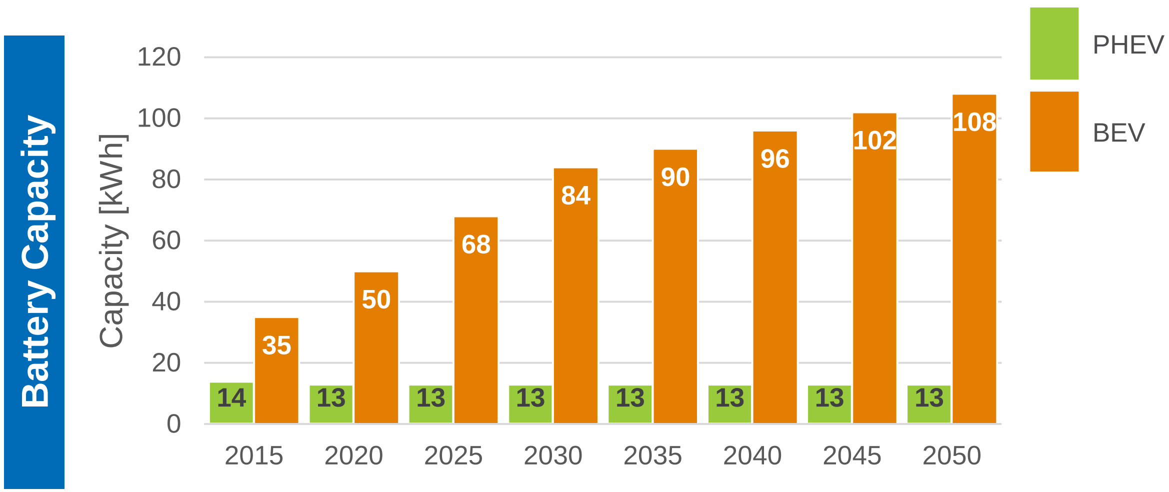
- Average electric range and battery sizes have been rapidly increasing over the last few years, as costs have declined faster than anticipated and manufacturers seek to provide a more compelling offering to customers
- 200+ mile real-world range BEVs (~450 km NEDC) are anticipated to become the norm in the next 5-10 years, with further increases in electric range likely in the future
- In contrast, in the absence of strong regulatory incentives, increasing PHEV battery size beyond 50 km electric range is likely to lead to very quickly diminishing benefits vs costs, so we have assumed these will remain broadly constant going forwards

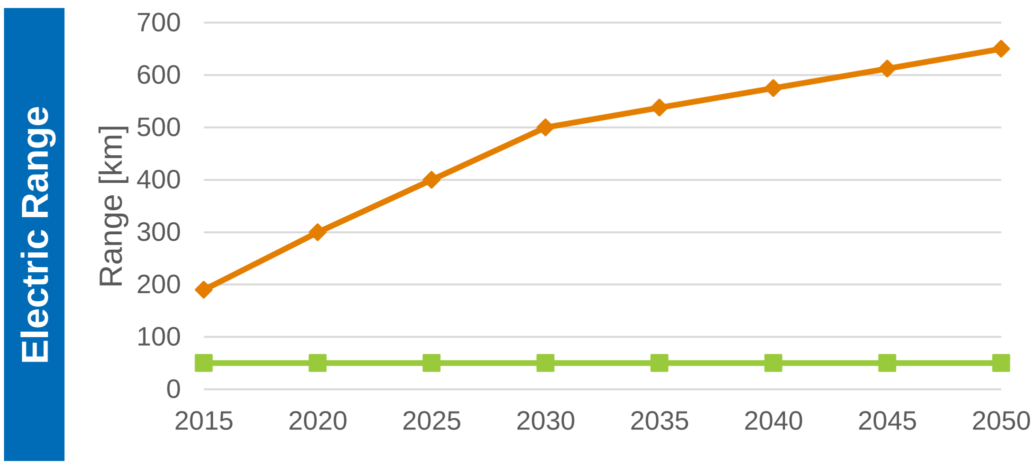
Note: Battery packs are assumed to last the lifetime of the vehicle

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The LCV market is lagging behind passenger cars in offering longer ranges as costs are particularly sensitive but will catch up in future

Assumed Technology Trends – Battery Pack, Light Commercial Vans (All Scenarios)





- The electric LCV market is currently well-behind passenger cars
- Based on current market trends, operational profiles and the particular cost-sensitivity of the van market, it is assumed that average van electric ranges will not reach parity with average cars until 2030
- There are currently few commercial options and the more conservative sector has been slow to take up EVs despite potentially higher TCO benefits than passenger cars
- In the medium term (2030) it is anticipated that range and equivalent battery size will catch up with passenger cars

Note: Battery packs are assumed to last the lifetime of the vehicle

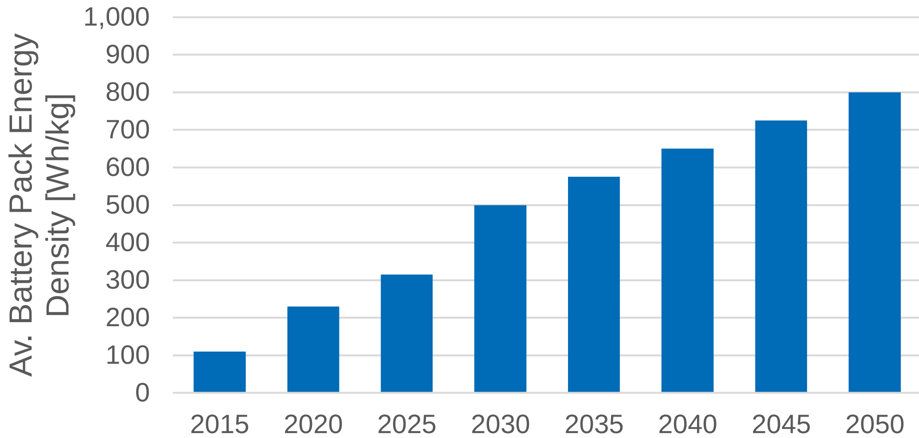
Vehicle Energy Consumption
Vehicle stock
Emission Factors
Cost Data
LCF availability
LCF Shares
Embedded GHG

Source: Ricardo Energy & Environment SULTAN modelling and analysis

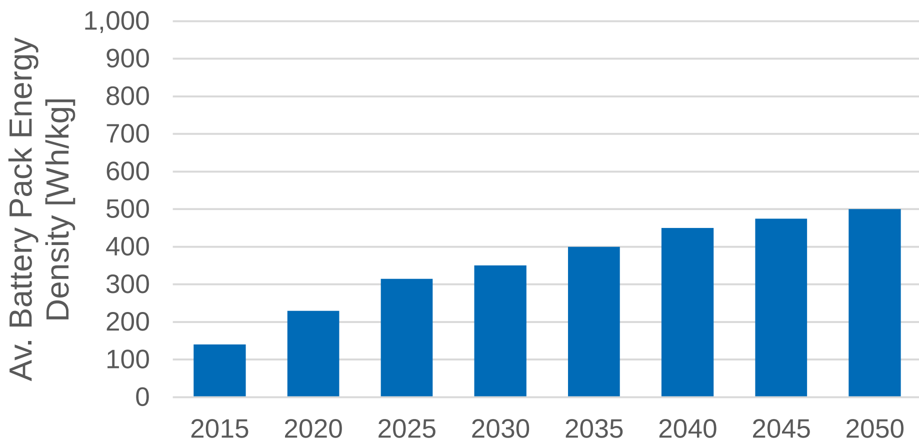
Battery pack energy density is projected to double between 2015 and 2020, with similar further improvements to 2030 and to 2050

Assumptions on average battery pack gravimetric energy density assumptions, Wh/kg

Battery Energy Density



Sensitivity

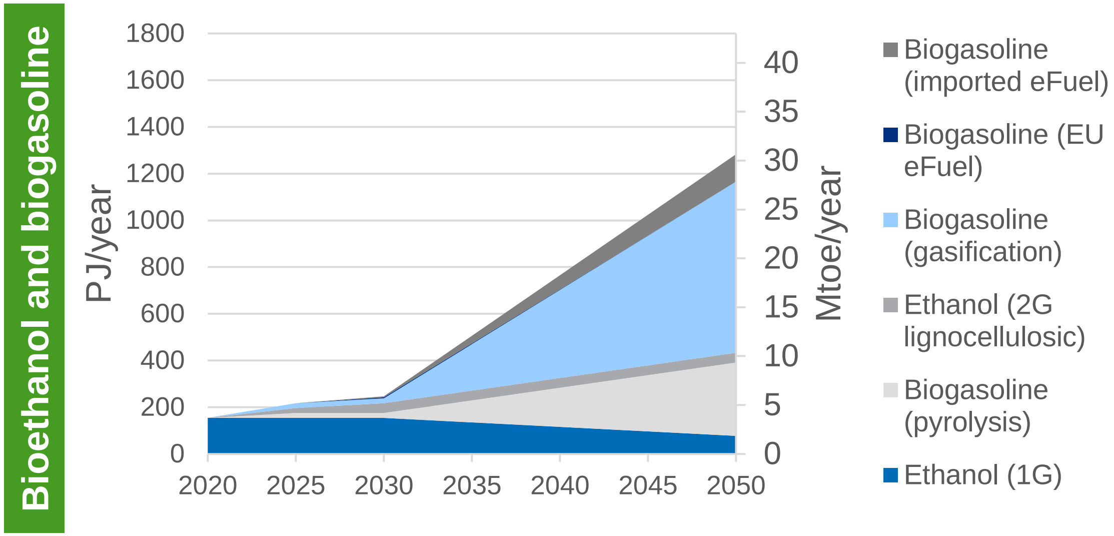


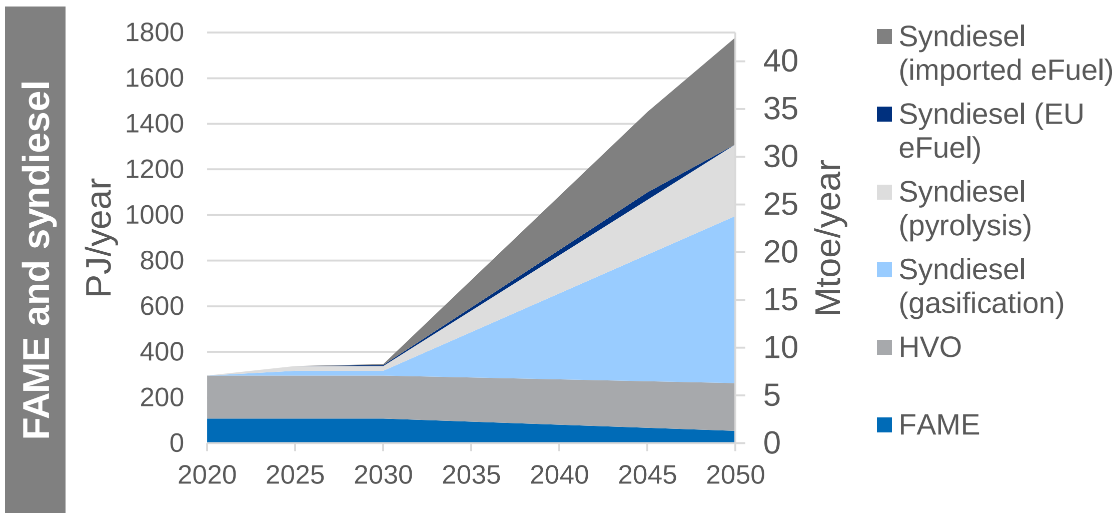
- The average battery pack energy density for 2015 is based on a report by ACEA and Eurobat
- Volumetric and gravimetric energy densities have been rapidly improving in recent years with existing BEV platforms achieving battery kWh upgrades within the same space/mass
- Projected improvements to 2030 are driven by a combination of improved pack design and a shift to advanced chemistries (such as Li-S and solid-state batteries)
- In the longer term options being researched, such as Li-Air, offer potentially much more radical increases in energy density up to ~1400-1700 Wh/kg at a battery cell level

Vehicle Energy Consumption
Vehicle stock
Emission Factors
Cost Data
LCF availability
LCF Shares
Embedded GHG

Source: Ricardo Energy & Environment analysis; ACEA/EUROBAT (2015): http://eurobat.org/sites/default/files/rev_of_battery_executive_web_1.pdf

The energy available from biofuels and eFuels for European light duty vehicles has been estimated from other research sources





- Availability of LCF intended to reflect scenario where the whole biomass supply chain is optimised to maximise use of bioenergy, increasing the availability of feedstocks as well as rapid expansion of advanced biofuels production
- Quantities available to LDVs allow for similar substitution levels in other road transport (e.g. HDVs) but use in other transport modes is not considered explicitly
- Availability of fuels from gasification and pyrolysis routes is based on a study for the Commission; similarly estimates for imported eFuels are based on an unpublished study which is further developing work completed by LBST/Dena (2017)
- Availably of LCFs were developed by CONCAWE; reviewed by Ricardo against published studies from SGAB (2017), LBST/Dena (2017), JEC.

Source: Directorate-General for Research and Innovation (European Commission), "Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe," 2018;
K. Sub Group on Advanced Biofuels Sustainable Transport Forum, Maniatis, I. Landälv, L. Waldheim, E. Van Den Heuvel, and S. Kalligeros, "Final Report, Building Up the Future," 2017;
dena (German Energy Agency), "«E-FUELS» STUDY - The potential of electricity-based fuels for low-emission transport in the EU - VDA," 2017;
H. D. C. Hamje et al., "EU renewable energy targets in 2020: Revised analysis of scenarios for transport fuels."

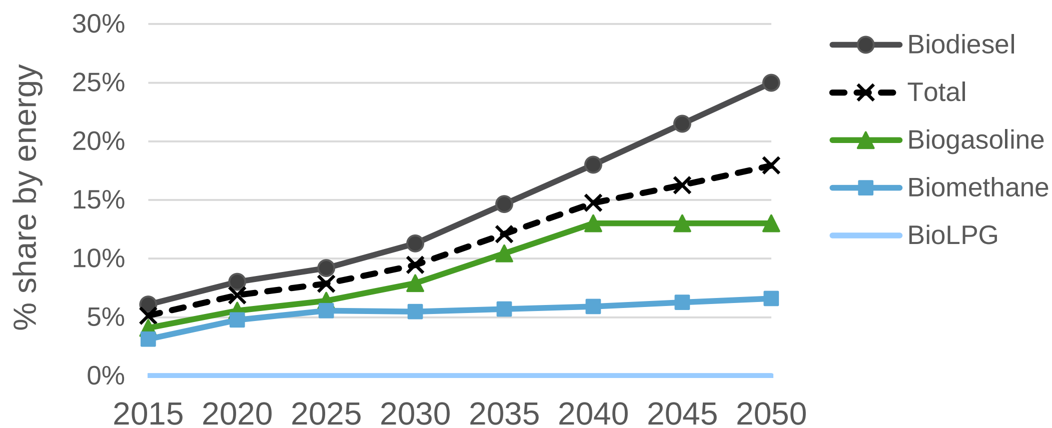
In the Low Carbon Fuels scenario, high levels of substitution are seen by 2050 for both diesel (100%) and gasoline (78%)

The total volume of bio-fuels is within that assumed to be available for LDVs

European scenarios for biofuel and other low carbon fuel uptake

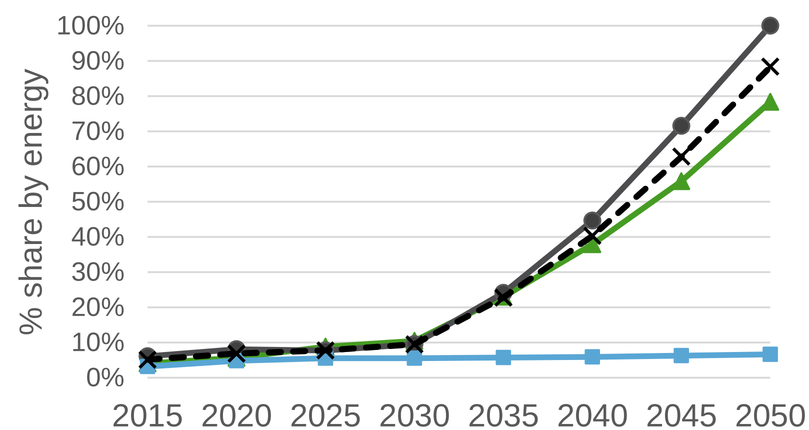
High EV

Low carbon fuel substitution by energy carrier, High EV scenario



Low carbon fuels

Low carbon fuel substitution by energy carrier, LCFuels scenario



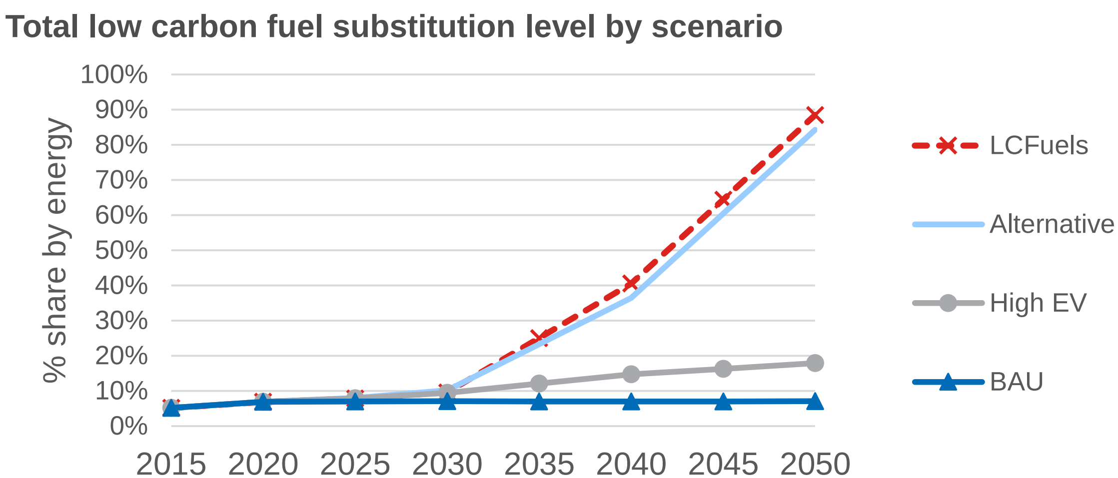
- Net GHG reduction for biofuels is assumed to reach ~85% by 2050
- After 2020 it is assumed that the share of low/no-ILUC biofuel (i.e. from waste or non-crop feedstocks) will increase to >95% share by 2050
- For the High EV scenario, the share of biofuel in gasoline and diesel increases compared to the BAU scenario. E20 is at 100% by 2040.
- For the Low carbon fuels scenario:
  - It is assumed that the majority of biodiesel used post-2025 will be drop-in fuels (including syn-diesel, eFuels and HVO) and by 2050 substitution reaches 100%
  - Gasoline is also mainly replaced by advanced biofuels (synthetic gasoline) and substitution nears 80% by 2050.

Source: Analysis by Ricardo Energy & Environment based on previous work for the EC and other European projects, and the availability (in PJ) of low carbon fuels developed by CONCAWE

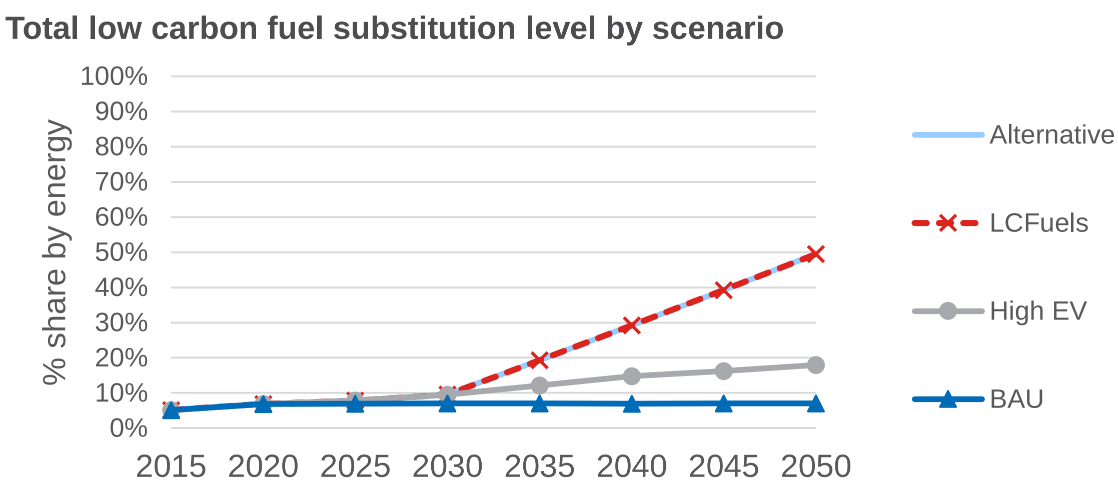
A base case and sensitivity case for biofuel / low carbon fuel uptake was developed for each of the four scenarios

European scenarios for biofuel and other low carbon fuel uptake, and sensitivity

Base Case Scenarios



Sensitivity



- In the base case scenarios, the low carbon fuel substitution levels for the Low Carbon Fuel and alternative scenarios are at similar proportions from 2030 onwards
  - This level is required for the Alternative scenario to achieve a similar WTW profile
  - Total PJ low carbon fuel supplied is significantly lower for the Alternative scenario
- A sensitivity case was also defined where total substitution was limited to 50% by 2050

Source: Analysis by Ricardo Energy & Environment based on previous work for the EC and other European projects, and the availability (in PJ) of low carbon fuels developed by CONCAWE

A number of assumptions were made in the development of estimates for life cycle GHG emissions

Other life cycle GHG emission assumptions are described in Appendix 3

Life Cycle GHG Emissions Study – Vehicle Assumptions

- Vehicle lifetime assumed to be 210,000 km for passenger cars and 230,000 km for LCVs over 15 years in the vehicle-level analysis (i.e. LCA for new vehicles), based on recent analysis for the EC. Similar levels are assumed within the SULTAN model, which is calibrated to the European Commissions 2016 Reference. Figures typically applied in automotive LCA generally range between 150,000 and 300,000 km
- Fuel and electricity consumption is based on the New European Drive Cycle (NEDC) with an uplift to real-world consumption based on assumptions used in the European Commission modelling for the 2016 Reference
- On-board battery charger efficiency for plug-in vehicles assumed to be 90% (though this efficiency is already captured in regulatory testing)
- Battery useable capacity (used for calculating EV range) is assumed to be:
  - 85% for BEVs up to 2020, then 90% after this (due to chemistry improvements and larger battery packs; EPA, 2016*)
  - 70% for PHEVs up to 2020, and 75% after this
- Assume no major parts are replaced during the vehicle lifetime
- Assume battery pack is not replaced during the vehicle lifetime
- Assume vehicles are produced in Europe
- Assume the vehicle's fuel and/or electricity consumption does not change with vehicle age

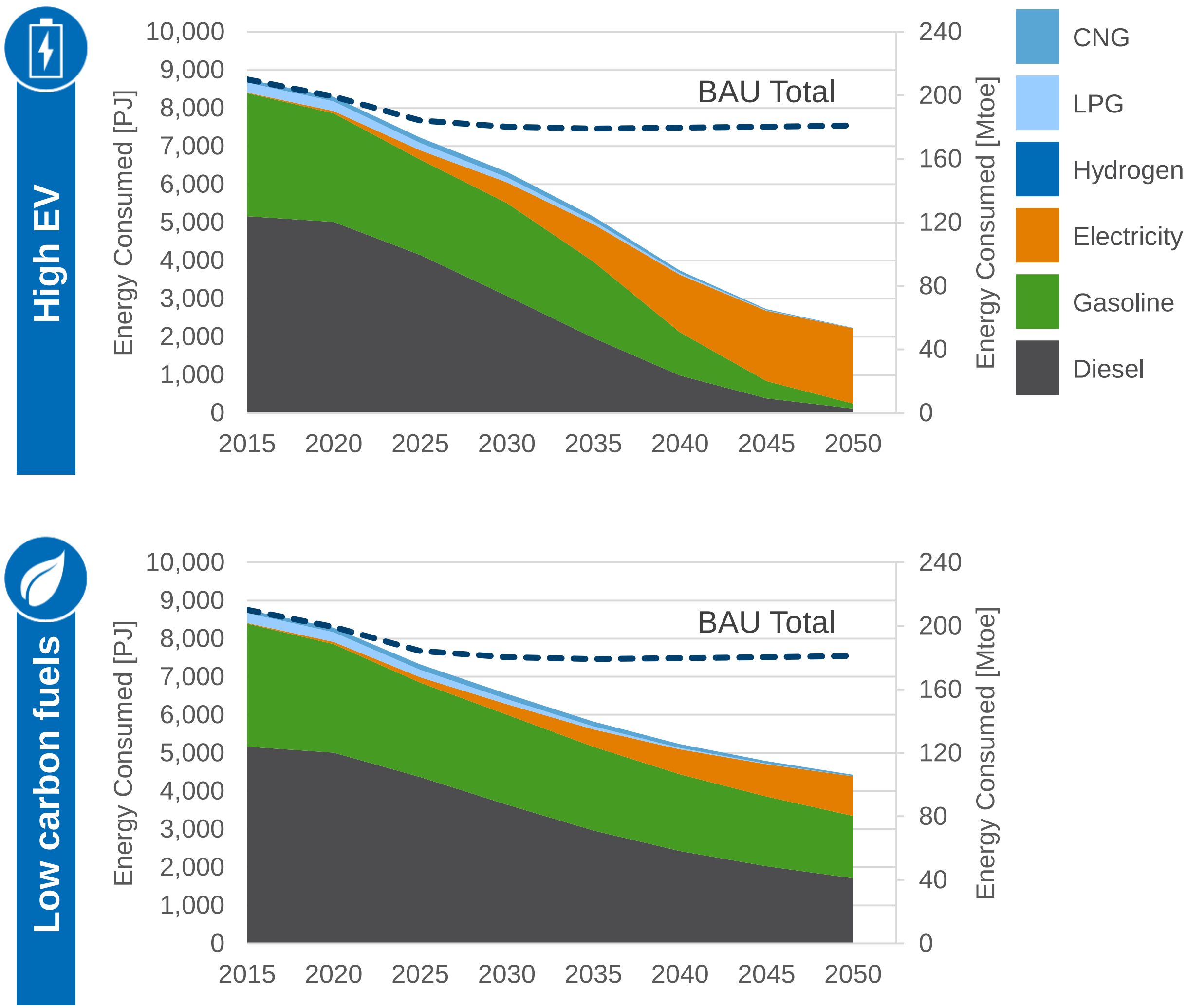
Vehicle Energy Consumption
Vehicle stock
Emission Factors
Cost Data
LCF availability
LCF Shares
Embedded GHG

Source: Ricardo analysis; * EPA (2016): https://www.epa.gov/sites/production/files/2016-11/documents/epa-battery-analysis-2016-09-15.pdf

Contents

Significant reduction in overall energy consumption resulting from both scenarios, with 550 TWh of electricity consumption for High EV

Vehicle Energy Consumption (Tank-to-Wheels) of the EU LDV Fleet

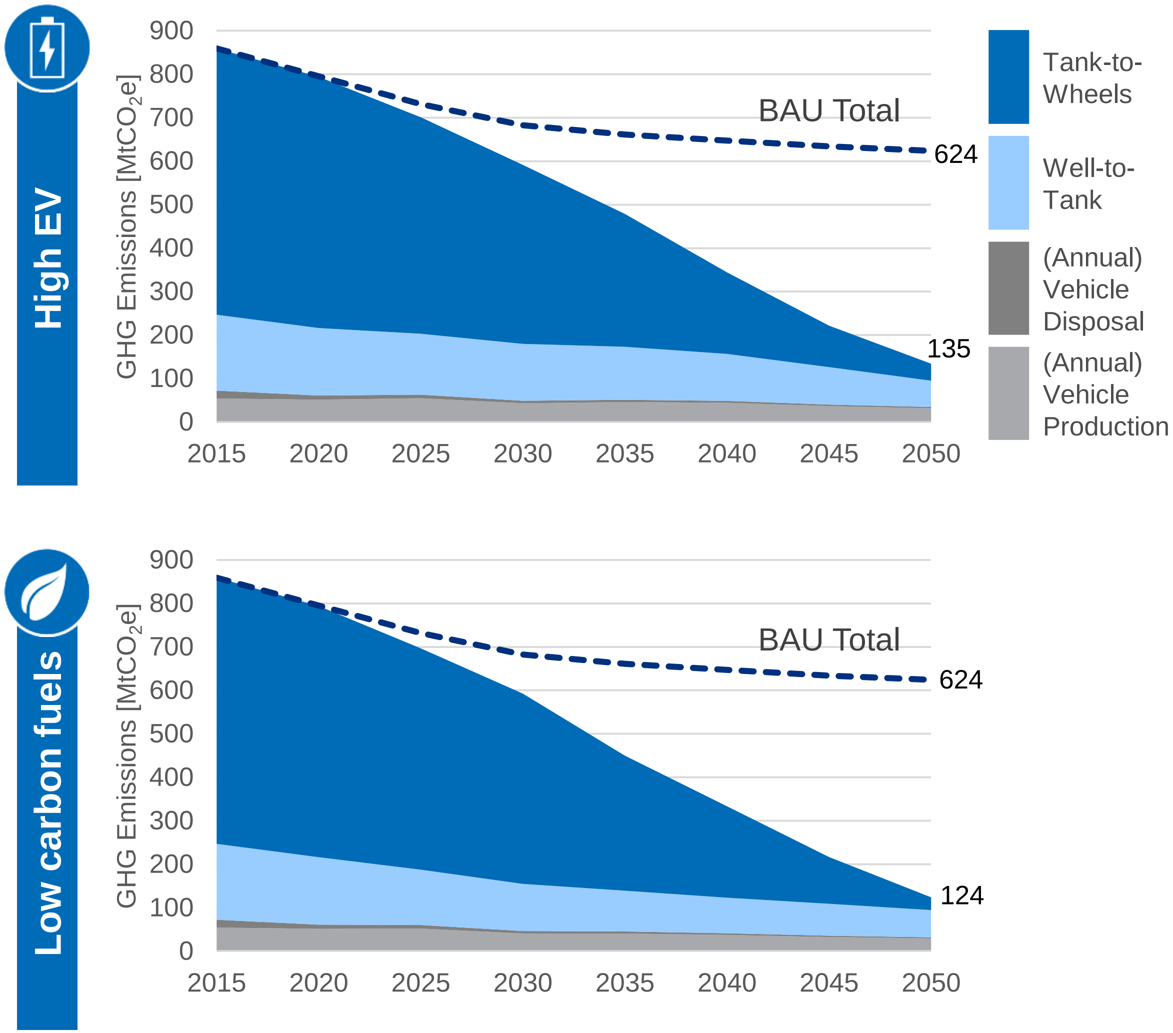


- **High EV scenario** over 74% reduction in overall energy consumption by 2050 versus 2015
- 97% reduction in liquid fuel use in the same period
- Electricity consumption is almost 90% of total energy use by 2050 at ~550 TWh (1980 PJ)
- **Low carbon fuel scenario** has 49% reduction in overall energy consumption
- 60% reduction in liquid fuel use. 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
- Production of EU eFuels will add +17% to the electricity use shown
- **Alternative scenario** is in-between

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Total life cycle GHG emissions reduce to less than 13% of 2015 value by 2050, for all scenarios; a TTW reduction of ~90% vs 1990

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



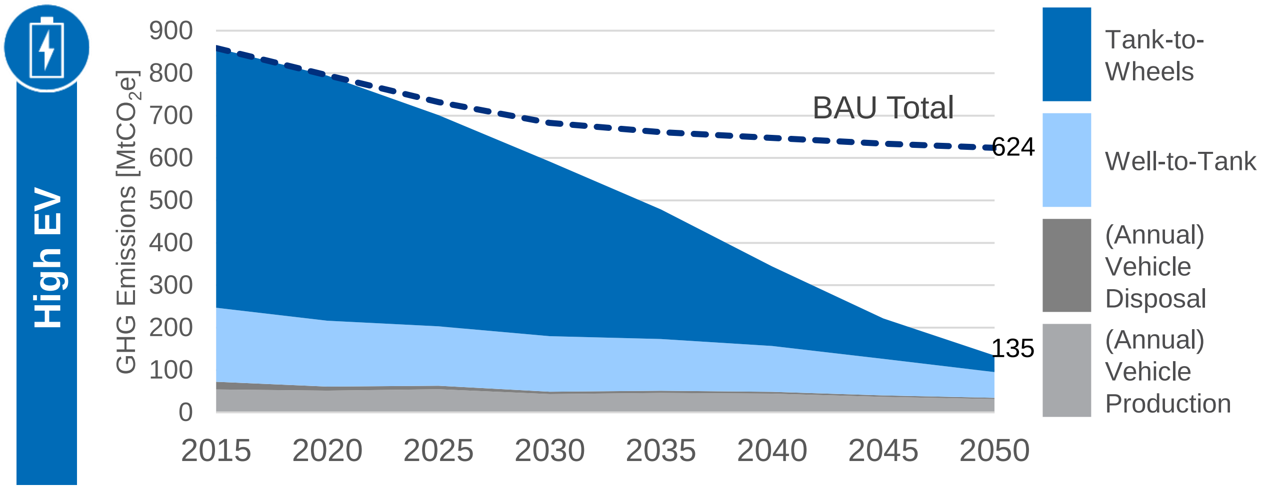
- All scenarios demonstrate broadly similar reductions in total GHG at 2050
- Embedded emissions from production and disposal of vehicles account for around 8% of total emissions in 2015 (including accounting/reduction for end-of-life vehicle recycling)
- This share rises to ~25% by 2050 for both the Low carbon fuels and the High-EV scenario
- All scenarios result in 2050 TTW GHG savings ~90% vs 1990*
  - WTW GHG savings vs 1990 range between 91.4-92.0%
- Alternative scenario falls in-between the other two scenarios

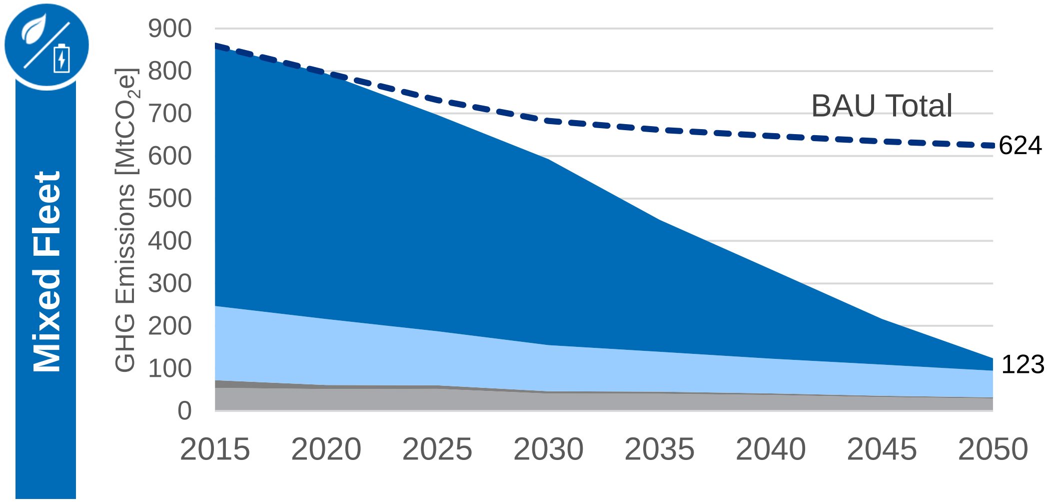
* The EU objective for TTW GHG from all transport is a 60% reduction vs 1990 by 2050

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The Mixed Fleet scenario also shows a significant and similar reduction in GHG emissions to the other scenarios

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



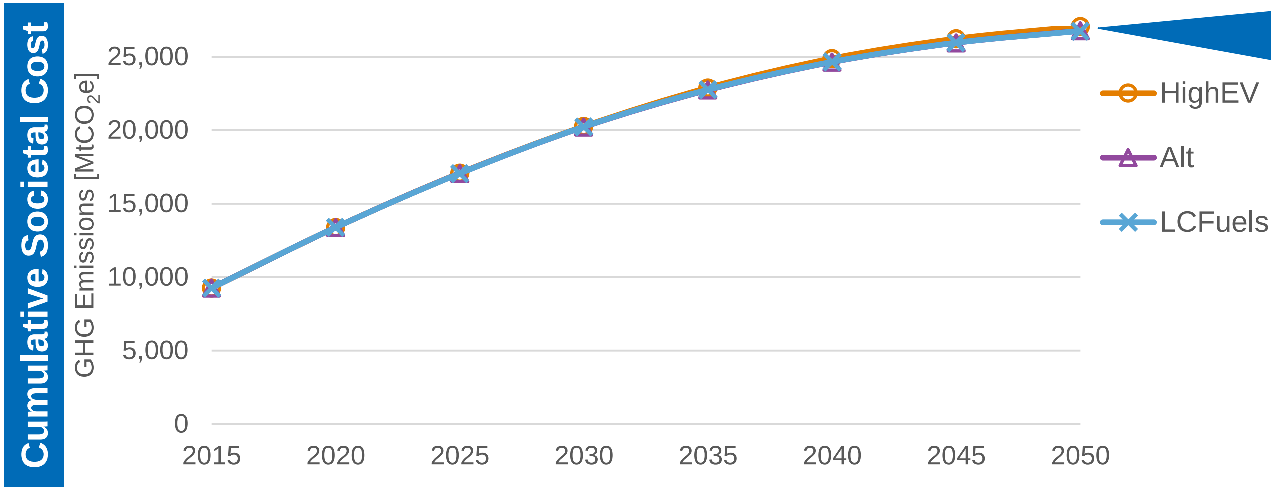


- All scenarios demonstrate broadly similar reductions in total GHG at 2050

Source: Ricardo Energy & Environment SULTAN modelling and analysis

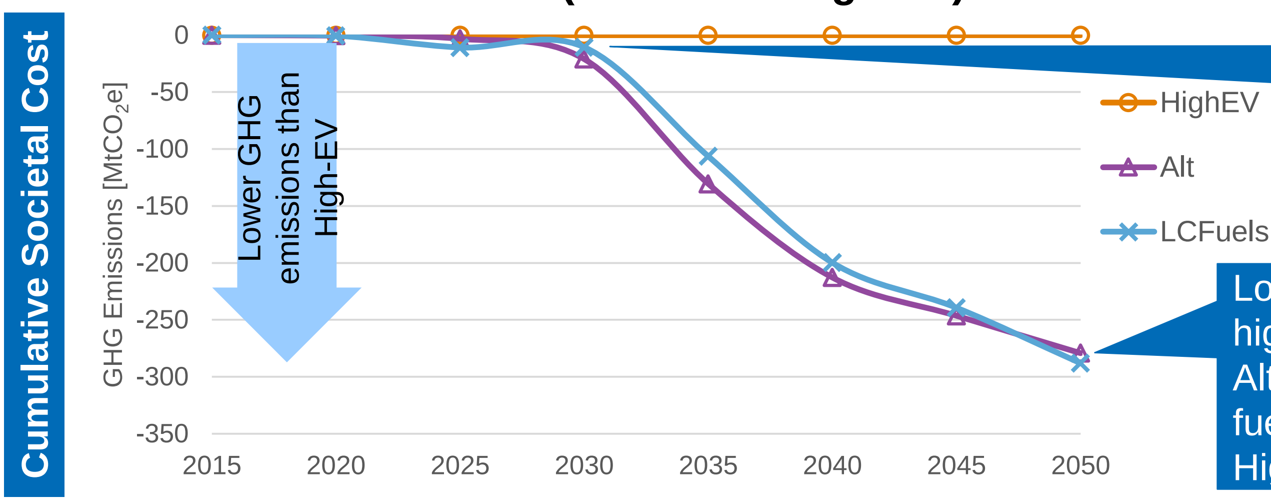
The High EV scenario has higher cumulative GHG emissions than Alternative and Low Carbon fuels scenarios

Cumulative GHG emissions



Cumulative life cycle GHG emissions from LDVs reach ~26,750-27,050 $MtCO_2e$ by 2050 (versus ~33,600 $MtCO_2e$ for BAU)

Cumulative GHG emissions (relative to High EV)



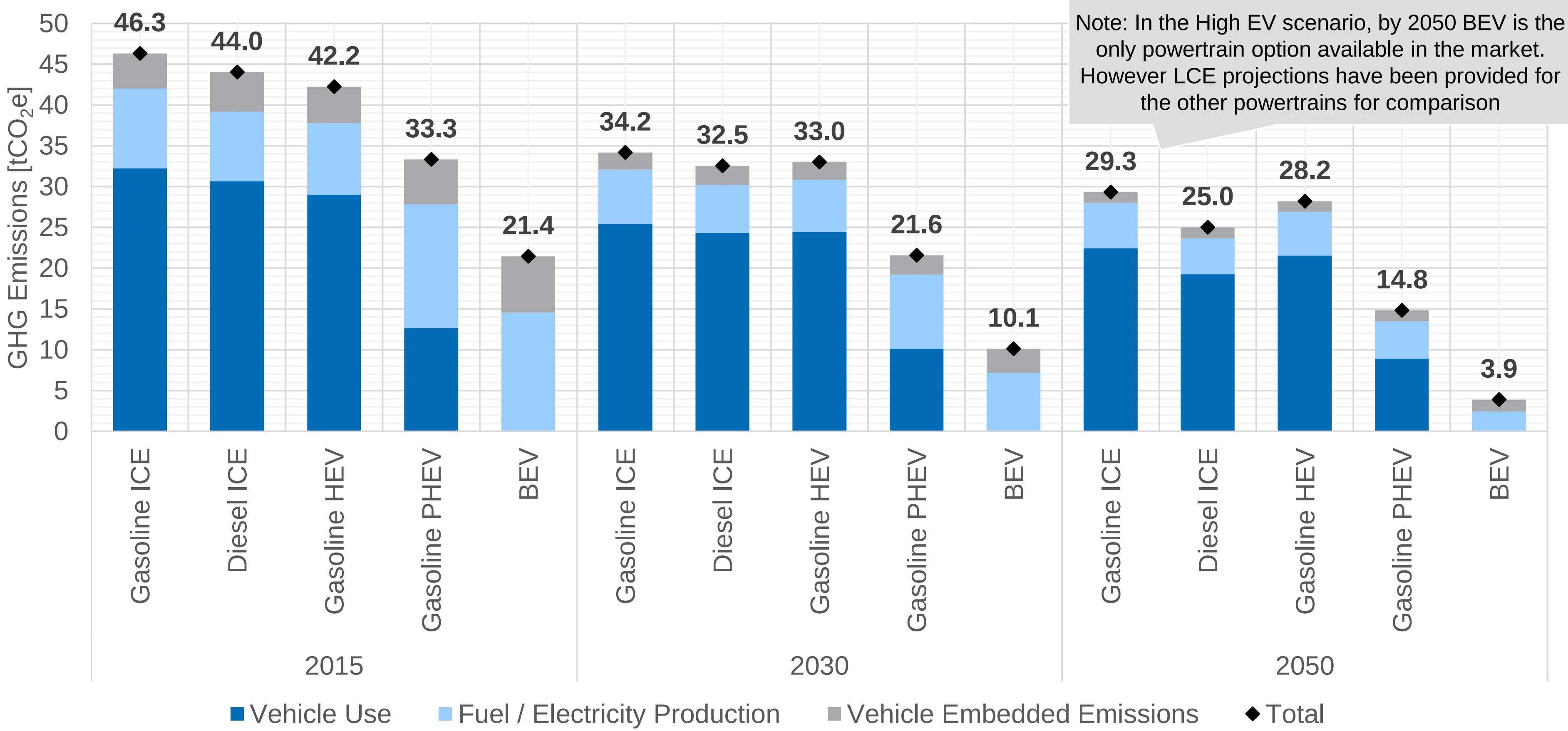
Cumulative life cycle GHG emissions from LDVs are similar for all scenarios up to c.2030

Longer term emissions savings are higher from the Low Carbon Fuels and Alternative scenarios; a greater level of fuel substitution by low carbon fuels in High EV would compensate for this

Source: Ricardo Energy & Environment SULTAN modelling and analysis

In the High EV scenario, improvements vs 2015 necessary to meet gCO_2/km targets are modest for ICEV and HEVs in 2030 and 2050

European Passenger Car Life Cycle GHG Emissions – "High EV" Scenario

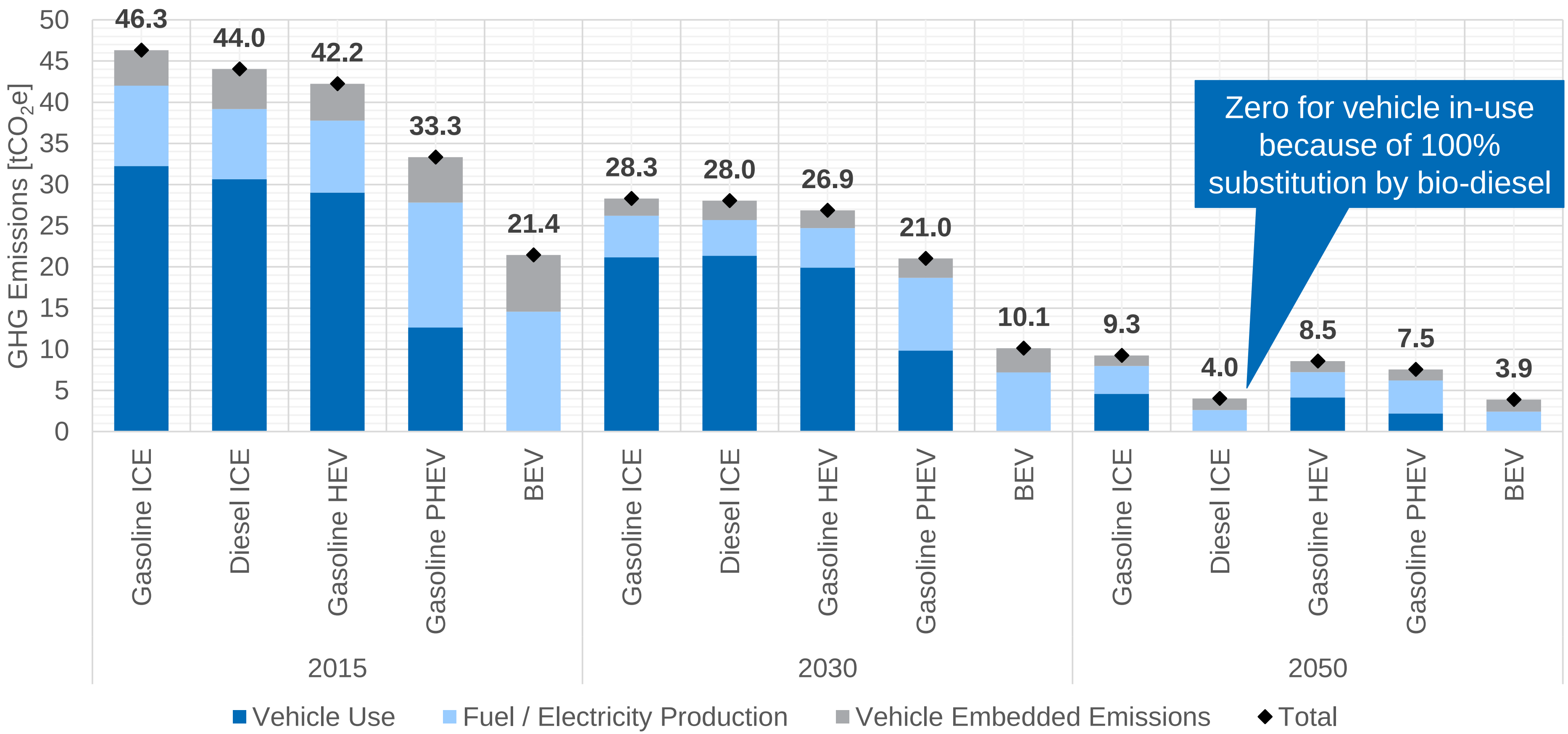


- Assumes lifetime 210,000 km, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV)
- GHG from fuel/electricity consumption is based on the average fuel/grid electricity factor over 15 yr. vehicle life

Source: Ricardo analysis

In the Low Carbon Fuels scenario, high levels of GHG emissions reductions are also possible by 2050

European Passenger Car Life Cycle GHG Emissions – "LowC Fuels" Scenario



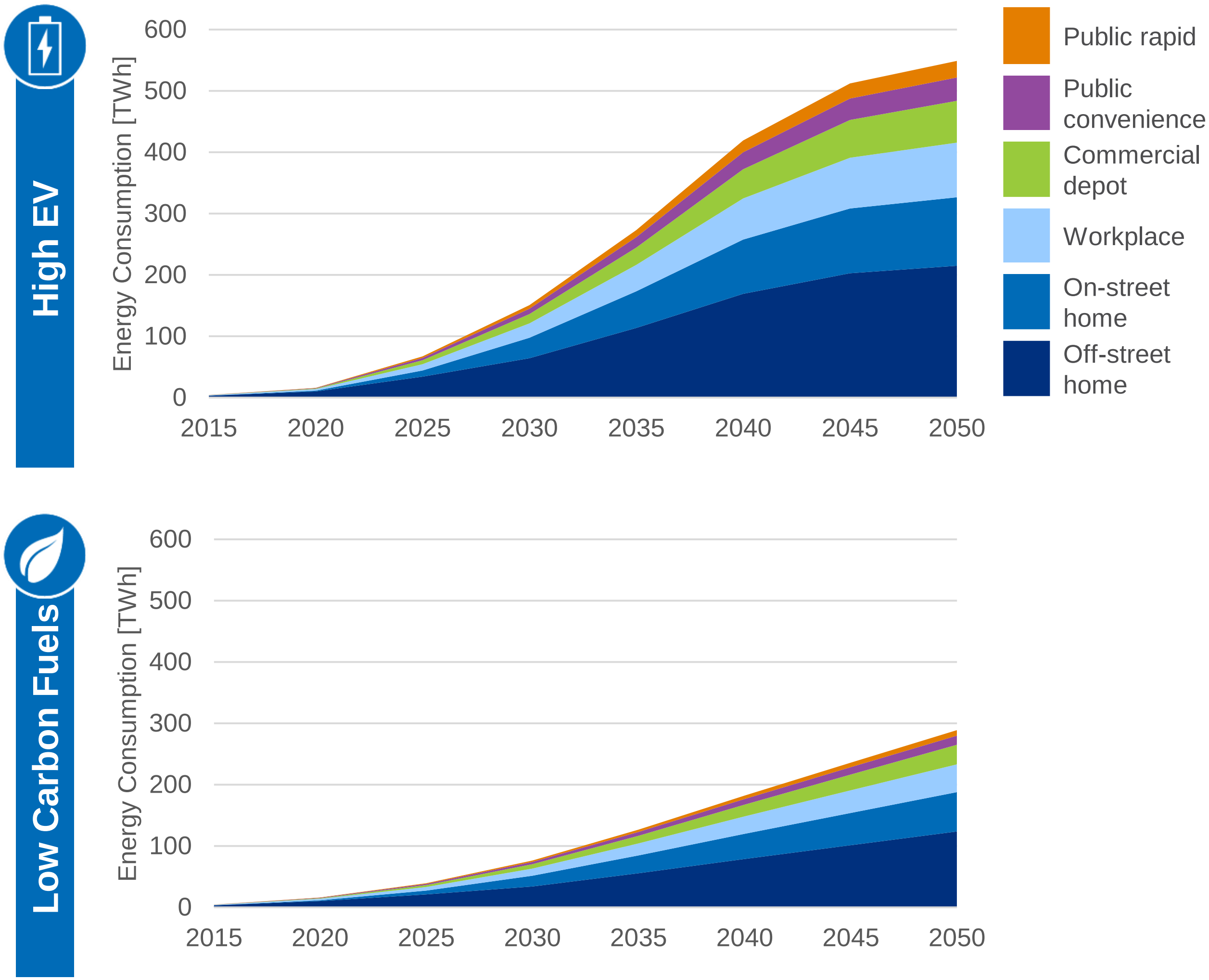
- Assumes lifetime 210,000 km, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV)
- GHG from fuel/electricity consumption is based on the average fuel/grid electricity factor over 15 yr. vehicle life

Source: Ricardo analysis

Contents

The majority of the 550 TWh of electricity required for EVs in 2050 from the High EV scenario is expected to come from home charging

Electricity consumption from recharging by location



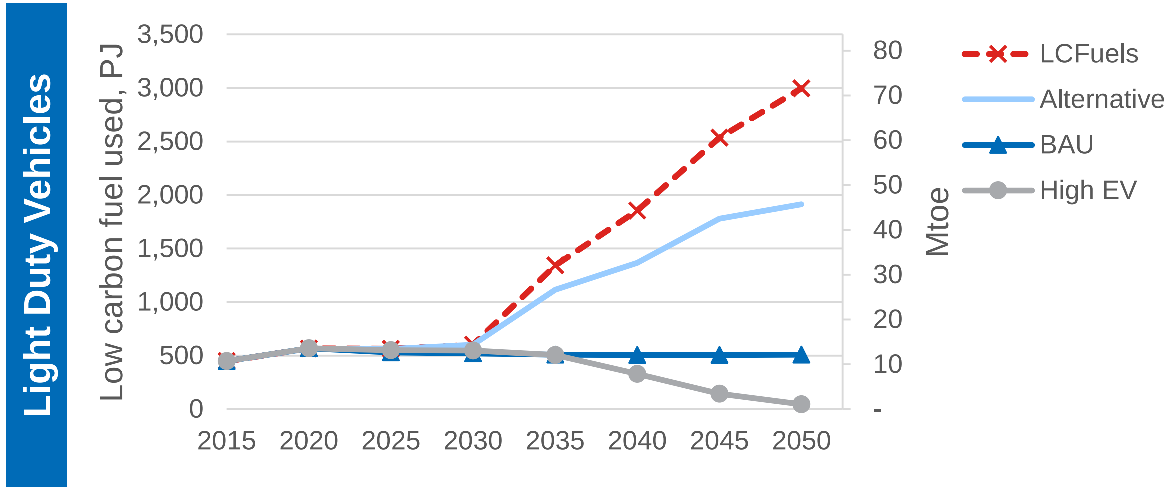
- 550 TWh of electricity demand from EV charging in 2050 represents around 17.5% of the EU's 2015 electricity generation
- In the default 'Home' scenario, most of this energy (~60%) is expected to come from charging overnight in residential areas (see also Appendix 4c for details)
- However, a significant amount of energy could also be provided at the workplace or from a range of fast and rapid public charging infrastructure
- Charging requirements are ~47%* (/ 28%) lower in the Low Carbon Fuels (/ Alternative) scenario, with a higher share of charging from residential/home
- *Note:* These are relatively conservative estimates, based on an extrapolation of currently observed charging patterns

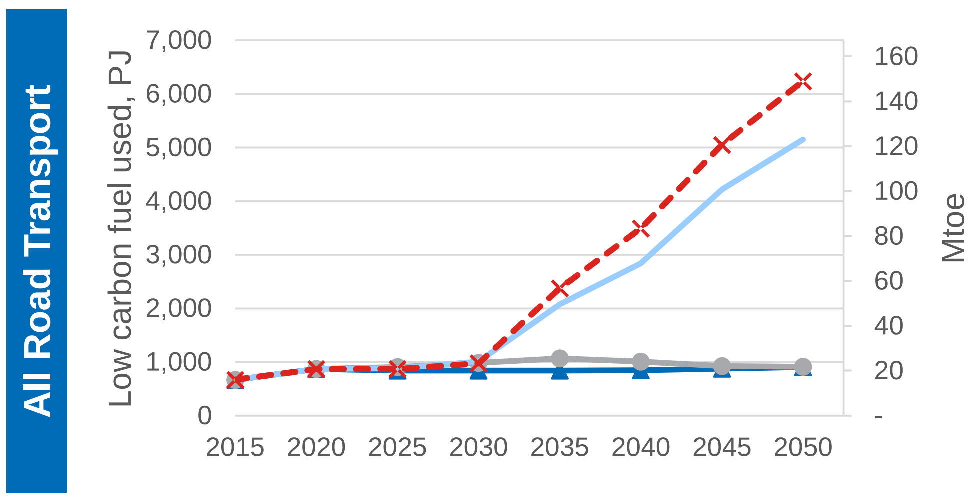
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Additional Note: * Including EU electricity used to produce EU eFuels decreases the difference to 39% for LCF vs High EV.

Absolute biofuel consumption varies by scenario, but is within the range of potential availability

Comparison of low carbon fuel consumption for LDVs and for all Road Transport [PJ]





- For LDVs, biofuels/ eFuel consumption increases to almost 3,000 PJ in the Low carbon fuel scenario by 2050, compared to around 50 PJ biofuel for the High EV scenario
- Biofuel/eFuel consumption in the Alternative scenario is 1,900 PJ
- Assuming similar substitution rates, this would mean total biofuel consumption of around 6,000 PJ for the whole of road transport* in the Low carbon fuel scenario, and around 5,000 PJ for the Alternative scenario**
- This compares to around 1,000 PJ in the High EV

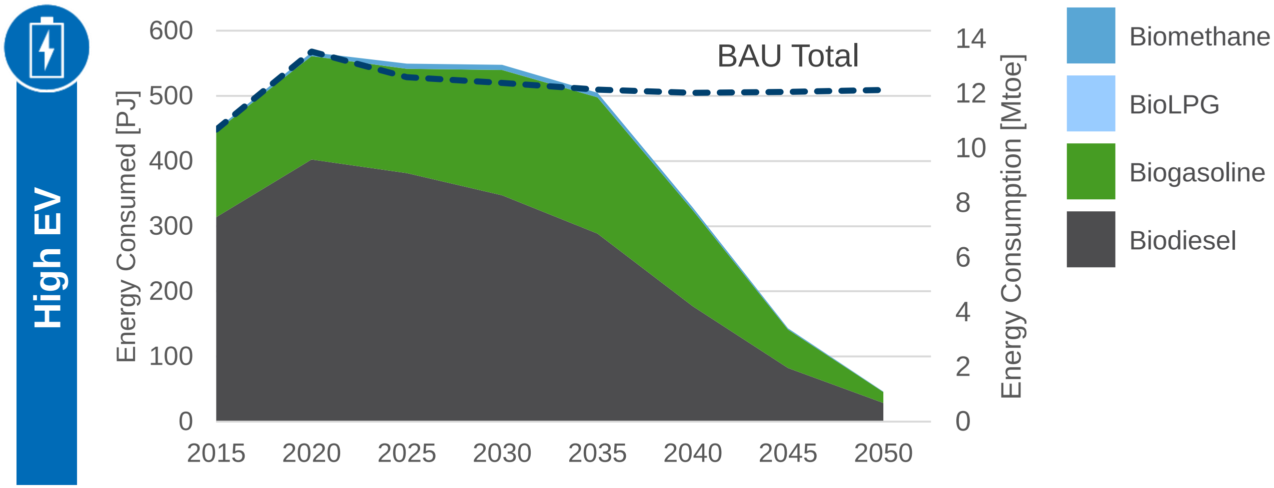
* Based on SULTAN model scenario data for all road transport modes

** These figures have been validated as reasonable based on the earlier referenced sources.

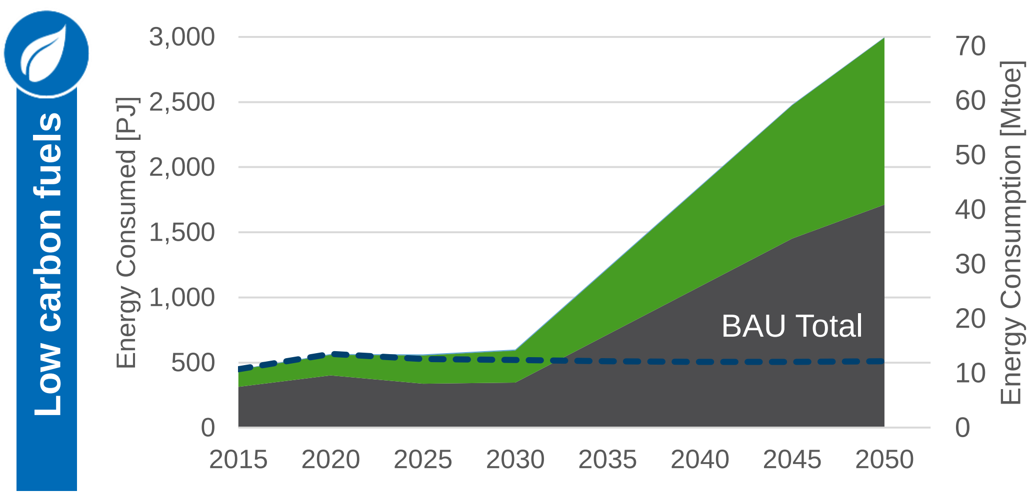
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Increasing bioenergy share in the Low Carbon Fuels scenario is seen post-2030 while biofuel use in the High-EV follows BAU to 2035

Vehicle BioEnergy Consumption (Tank-to-Wheels) of the EU LDV Fleet



- Biofuel consumption drops significantly after 2035 for the High EV scenario
- Total biofuel in PJ for road transport is assumed to remain ~constant after 2020, with the share (%) in light duty vehicles gradually increasing to ~18% in 2050. Even so overall PJ use in LDVs declines rapidly after 2035



- Biofuel (and eFuel) share increases rapidly after 2030 for the Low Carbon Fuels scenario
- Overall biofuel/eFuel consumption increases ~6x, from ~500 PJ in 2025 to 3,000 PJ in 2050 (with ~20% eFuel)
- Biofuel energy consumption in the BAU scenario is relatively constant over time

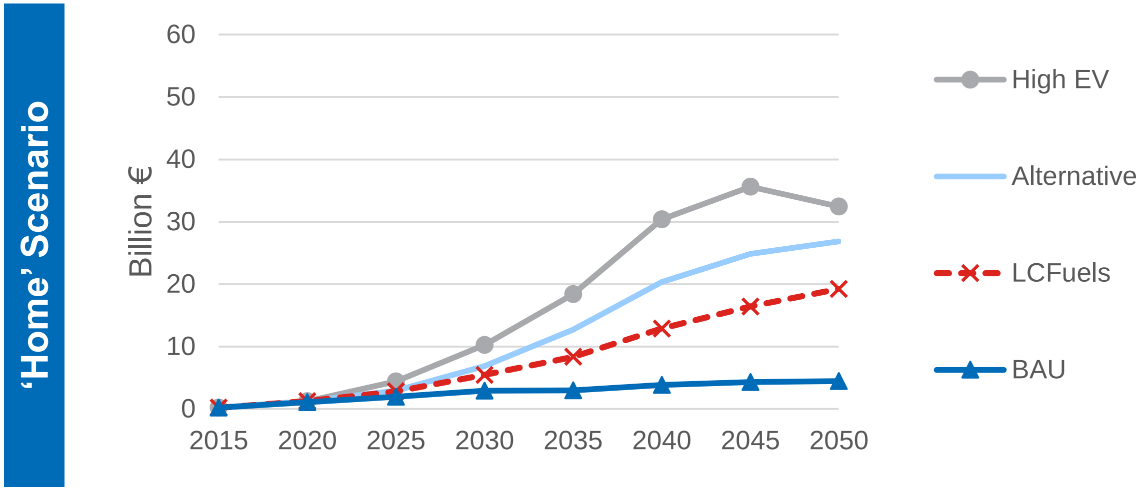
Source: Ricardo Energy & Environment SULTAN modelling and analysis

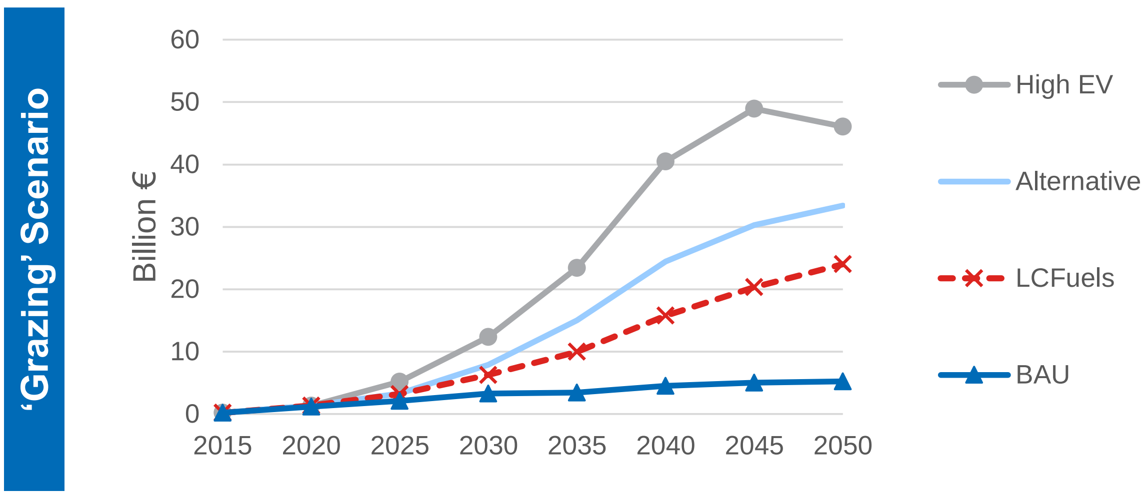
Contents

The cost of EV charging infrastructure alone could reach 36 €Billion p.a. by 2040 under the High EV, 'Home' charging scenario

Details of the electricity infrastructure analysis are given in Appendix 4

Comparison of annualised electric charging (Managed) and network infrastructure costs





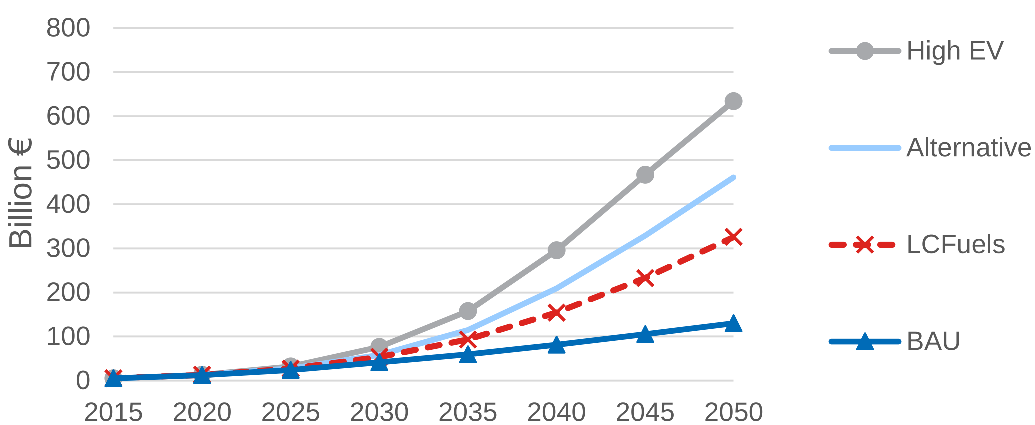
- Under the default 'Home' charging infrastructure scenario charging infrastructure results in infrastructure costs peaking at ~35.9 €Billion p.a. for the **High EV** scenario, reducing to ~32.6 €Billion p.a. by 2050
- In comparison, the Low Carbon Fuels /Alternative scenario annual costs reach 19.4/~27.0 €Billion p.a. by 2050

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The cumulative cost of EV charging and network infrastructure costs for the High EV, "Home" charging scenario are over €630bn

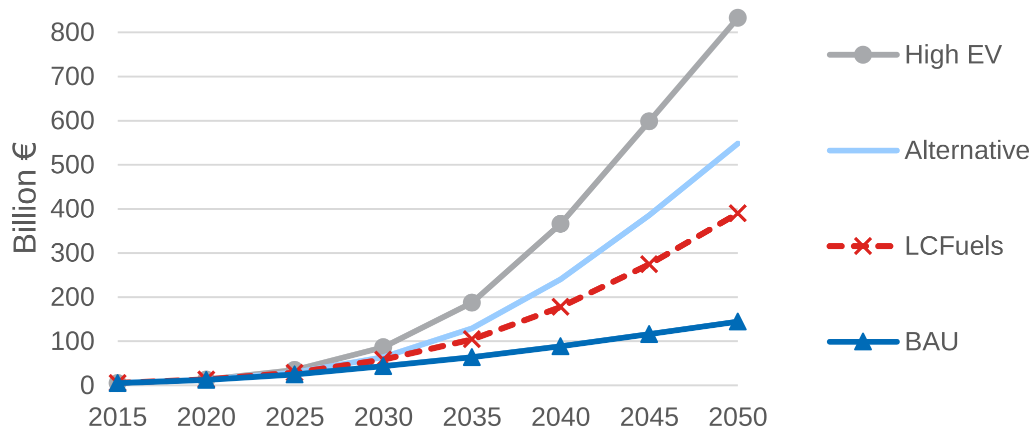
Comparison of cumulative electric charging (Managed) and network infrastructure costs

'Home' Scenario



- For the **High EV** scenario, the cumulative charging and network infrastructure costs for the 'Home' charging scenario are ~630 €Billion by 2050
- For the **Low Carbon Fuel** scenario the cumulative costs, and around half of this (~326 €billion)

'Grazing' Scenario



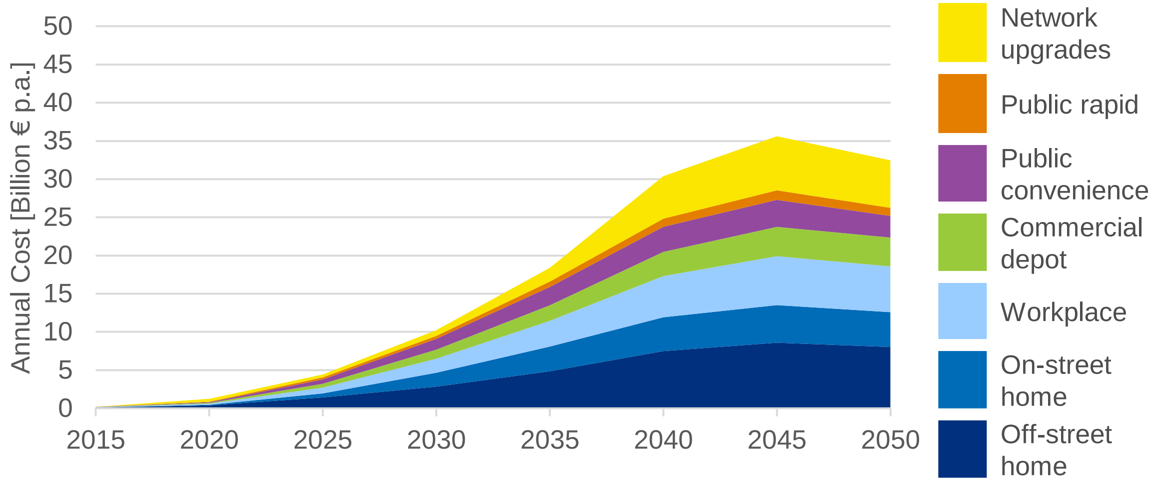
- For the 'Grazing' charging scenario sensitivity, High EV costs increase by 31% to ~830 €Billion, for High EV

Source: Ricardo Energy & Environment SULTAN modelling and analysis

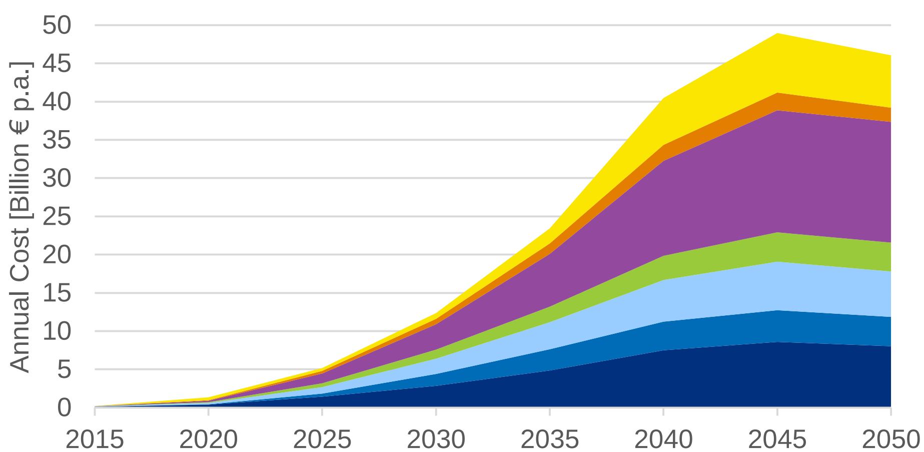
The calculated EV infrastructure costs consist of charging infrastructure and network upgrades

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

‘Home’ Scenario



‘Grazing’ Scenario

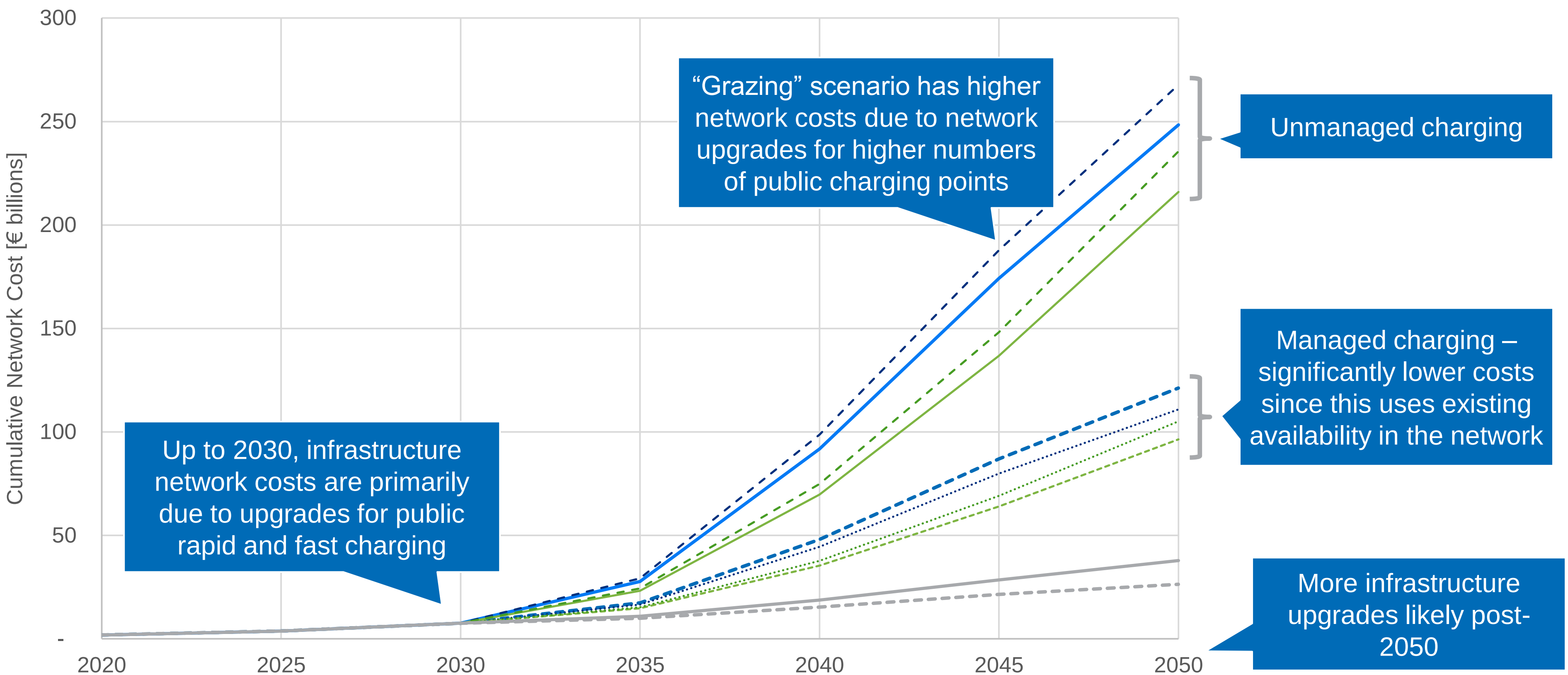


- The infrastructure costs include electricity network upgrades, as well as charging infrastructure for:
  - Public rapid charging
  - Public convenience charging
  - Commercial depot charging
  - Workplace charging
  - On-street home charging
  - Off-street charging
- Since EV charging infrastructure requirements are particularly uncertain, the alternative ‘Grazing’ case provides a higher cost alternative sensitivity

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Cumulative costs for network upgrades alone could reach €270bn for unmanaged charging or €120bn for managed charging

Cumulative Network Cost (shown as yellow shaded on previous annualised plot)

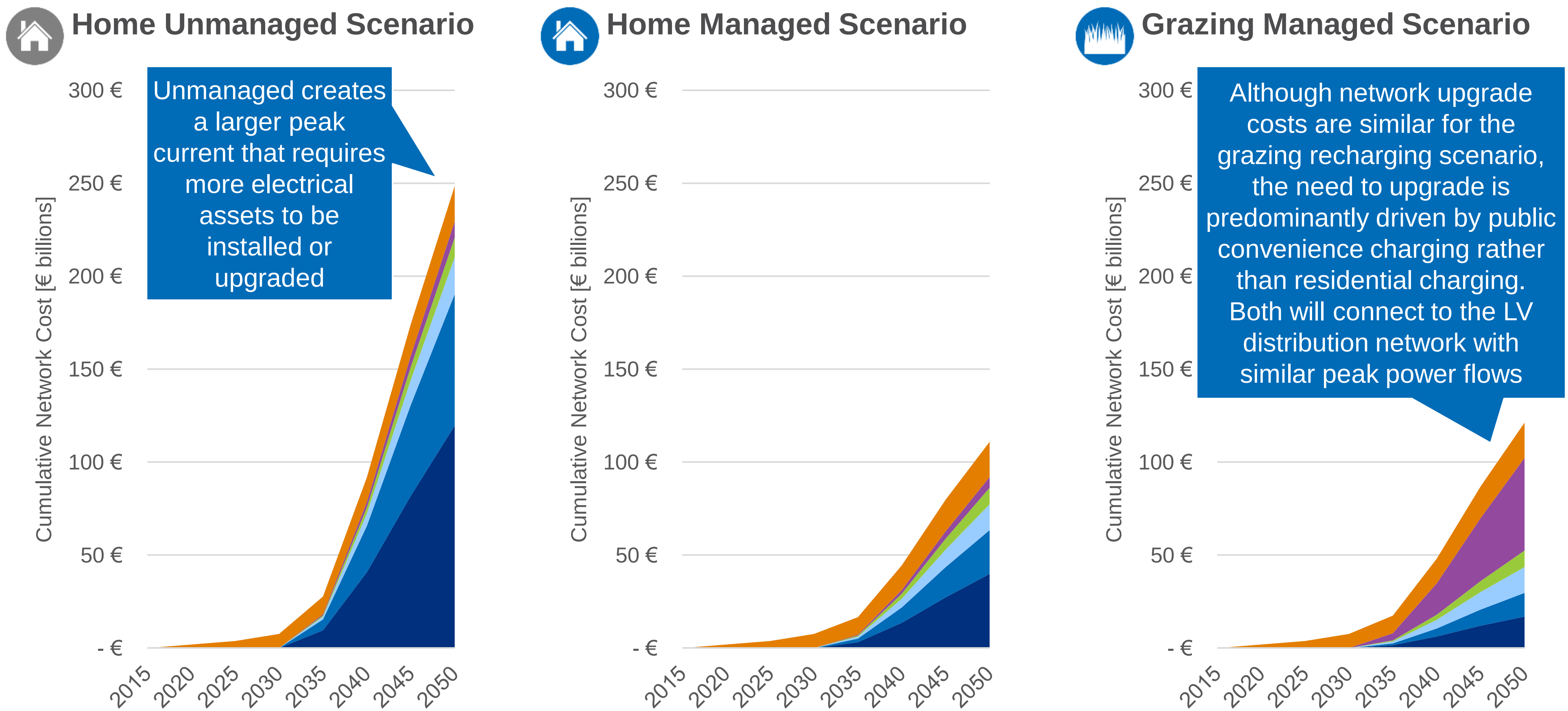


The results displayed are estimates of the likely network upgrade costs associated with market uptake of plug-in vehicles. This analysis does not include infrastructure upgrades to support electrification in other sectors such as heat

Source: Ricardo Energy & Environment Analysis

Unmanaged charging is likely to require significantly more upgrades to LV networks to support off-street and on-street charging

Cumulative Network Cost Breakdown by charging type – "High EV" Scenario



- Off-street home
- On-street home
- Workplace
- Depot
- Public convenience
- Public rapid

The residential networks are particularly affected by unmanaged charging. When EV users return home they connect the EVs to the charger, so charging starts during the peak period for domestic properties

Source: Ricardo Energy & Environment Analysis

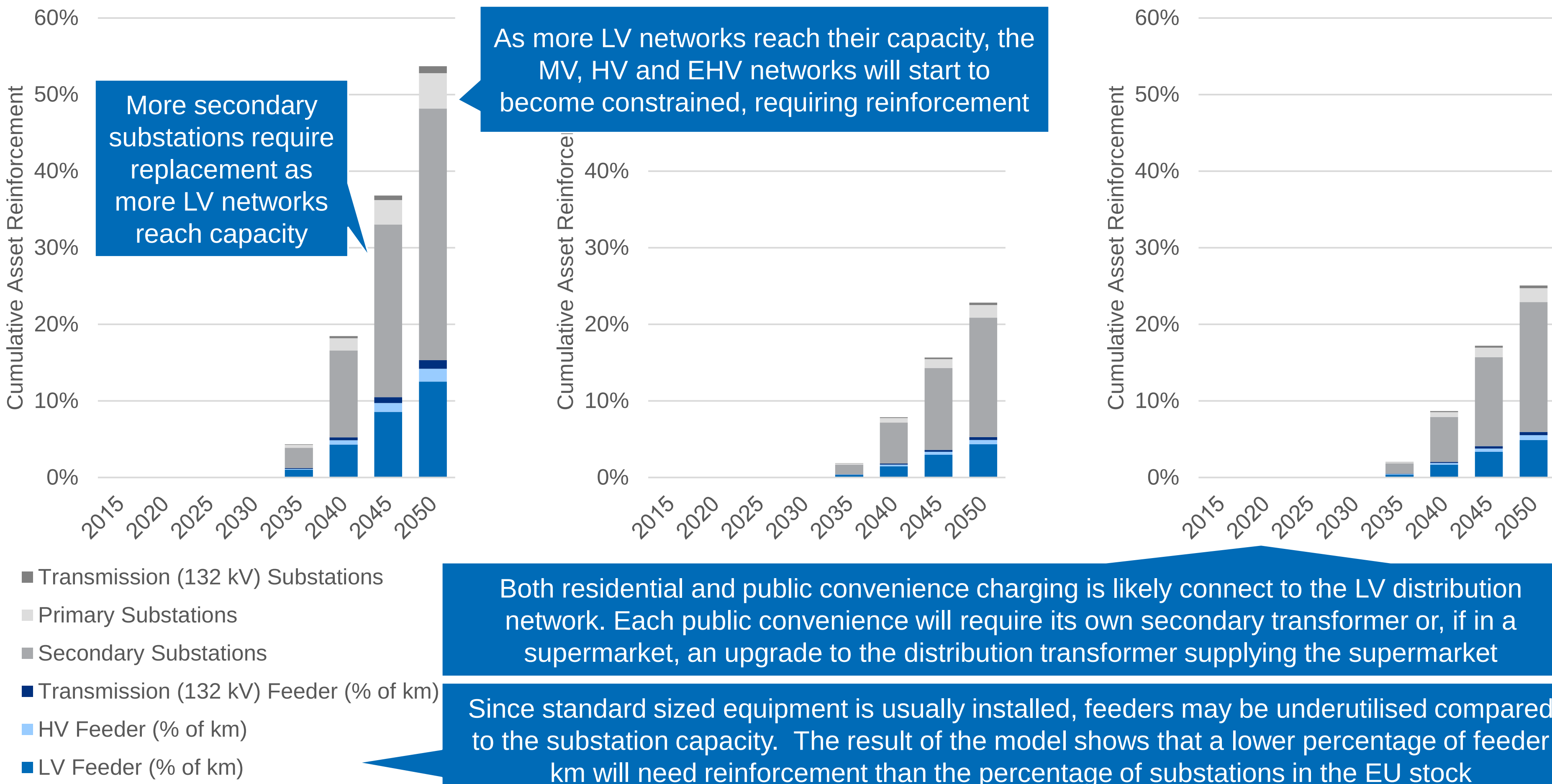
For all recharging scenarios, the need to replace secondary substations contributes most to infrastructure upgrade costs

Cumulative Network Equipment requiring upgrade – "High EV" Scenario

Home Unmanaged Scenario

Home Managed Scenario

Grazing Managed Scenario



More secondary substations require replacement as more LV networks reach capacity

As more LV networks reach their capacity, the MV, HV and EHV networks will start to become constrained, requiring reinforcement

Both residential and public convenience charging is likely connect to the LV distribution network. Each public convenience will require its own secondary transformer or, if in a supermarket, an upgrade to the distribution transformer supplying the supermarket

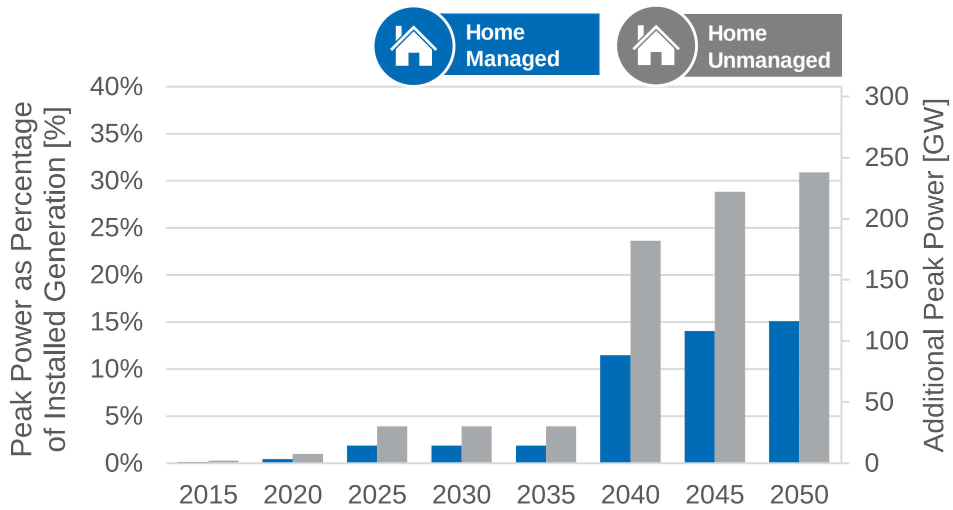
Since standard sized equipment is usually installed, feeders may be underutilised compared to the substation capacity. The result of the model shows that a lower percentage of feeder km will need reinforcement than the percentage of substations in the EU stock

Source: Ricardo Energy & Environment Analysis

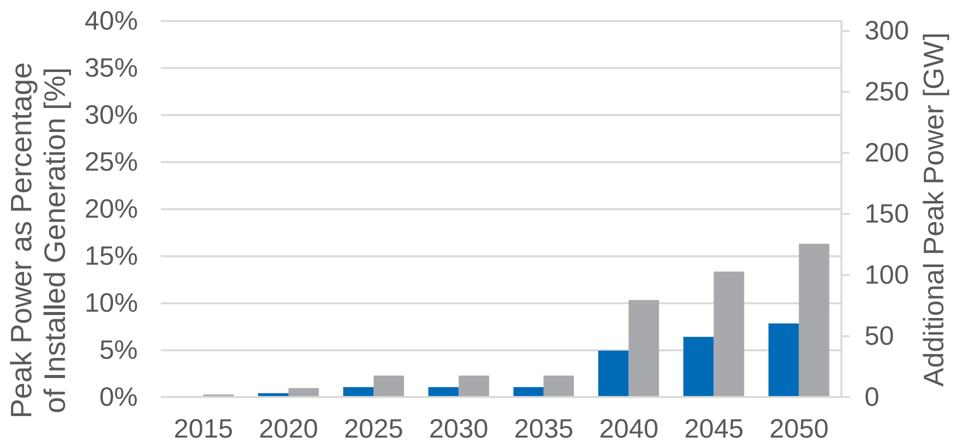
Increased peak power for managed home charging is 115GW (15% of currently installed peak power generation) for the High EV scenario

Additional peak power as a percentage of existing installed generation capacity

High EV



Low carbon fuels



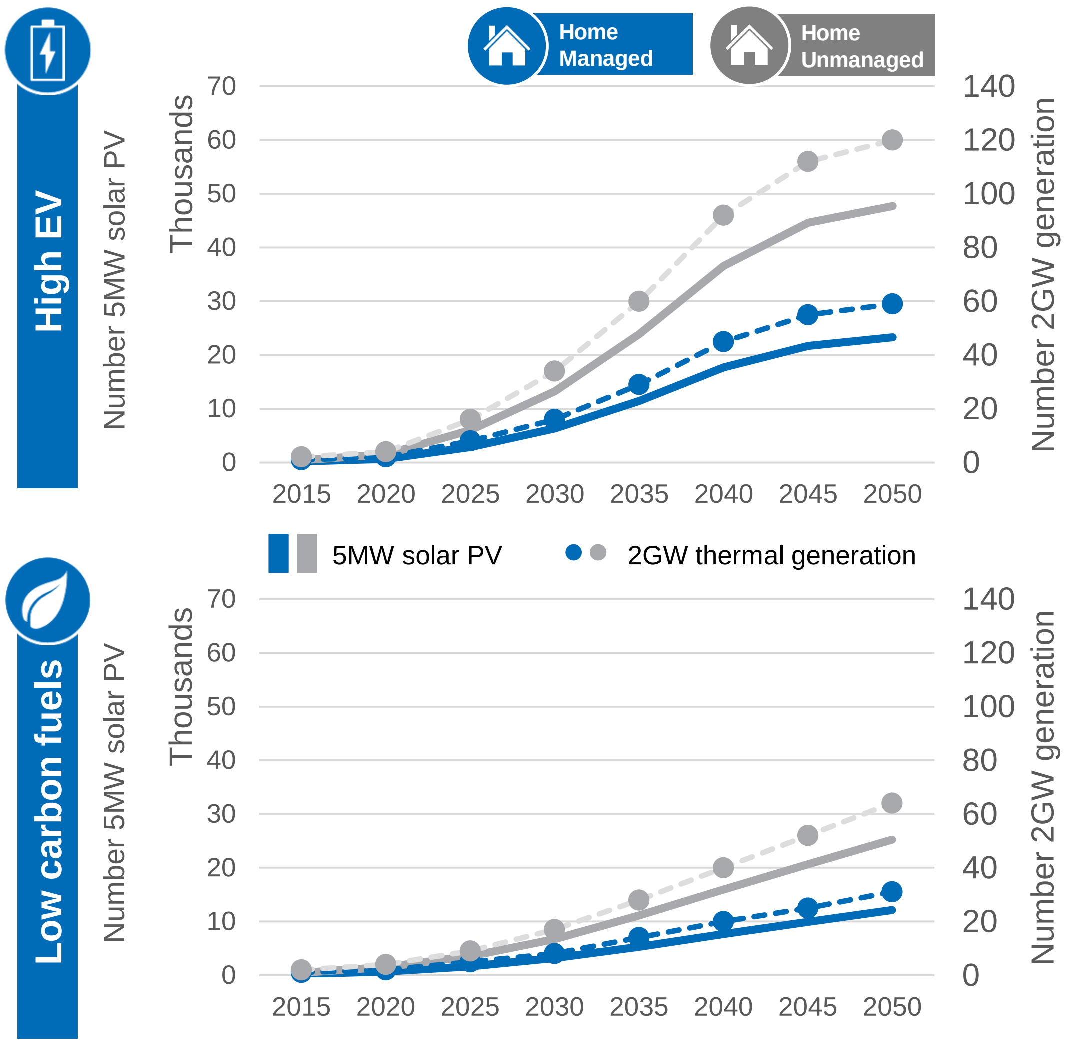
- In 2015 the EU28 had **770GW** of installed peak power generation and the peak load was **528GW**
  - In the**, managed charging at home case**, by 2050 the estimated increase in peak power as a percentage of currently installed peak power generation is
    - **~15% (115GW**) for High EV scenario
    - **~8% (63GW)** for Low Carbon Fuels
  - Unmanaged charging doubles the peak power requirement
  - Both grazing and home charging will have similar peak power flows requiring a similar quantity of generation assets
    - Adding additional storage to the network could reduce the peak power required

In 2015, 39% of EU28 installed peak power generation was from renewable sources and 53% was from traditional generation (fossil & nuclear)

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The number of new generation assets required depends on when EV charging occurs and will have greatest impact when unmanaged

Additional peak power represented as generation assets

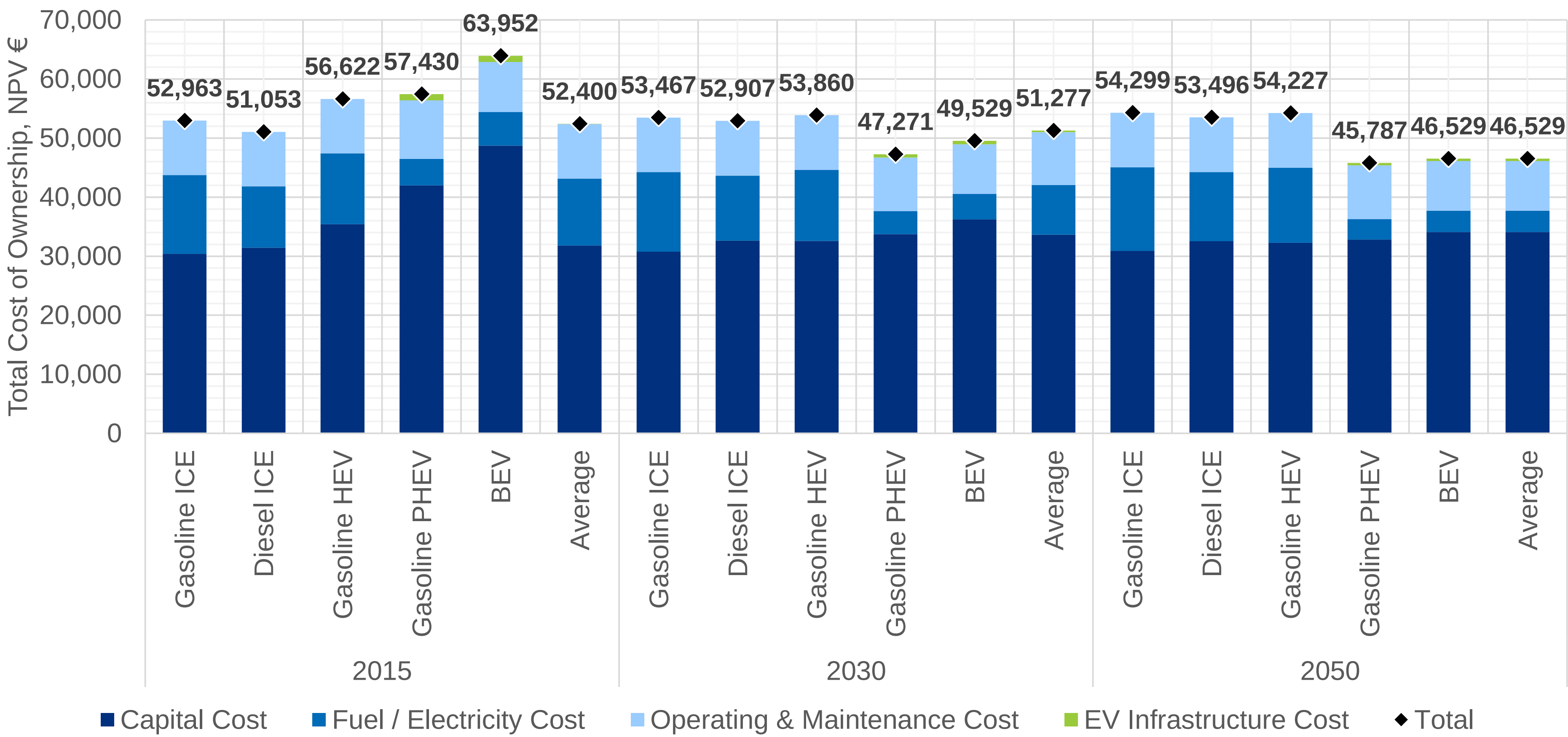


- If the unmanaged charging peak for High EV (238GW) coincided with the network peak (528GW) the total demand would be 766GW (99.5% of installed capacity)
  - The time of day for charging will impact the total generation assets required. If the charging peak occurs during the evening when the network is already at peak, more generation assets will be required than if the charging peak occurs when the other loads in the network are low
  - Generation assets required to support EV charging for the High EV scenario equates to **120 traditional 2GW** power stations or **48,000 5MW PV** farms or **29,800 8MW** Wind Turbines
  - Managing the charging reduces the requirement for new generation assets

Source: Ricardo Energy & Environment SULTAN modelling and analysis.

In the High EV scenario, the NPV Total Cost of Ownership for end-users is lower for BEV and PHEV vs ICEV/HEV powertrains by 2030

New European Passenger Car Total Cost of Ownership – "High EV" Scenario

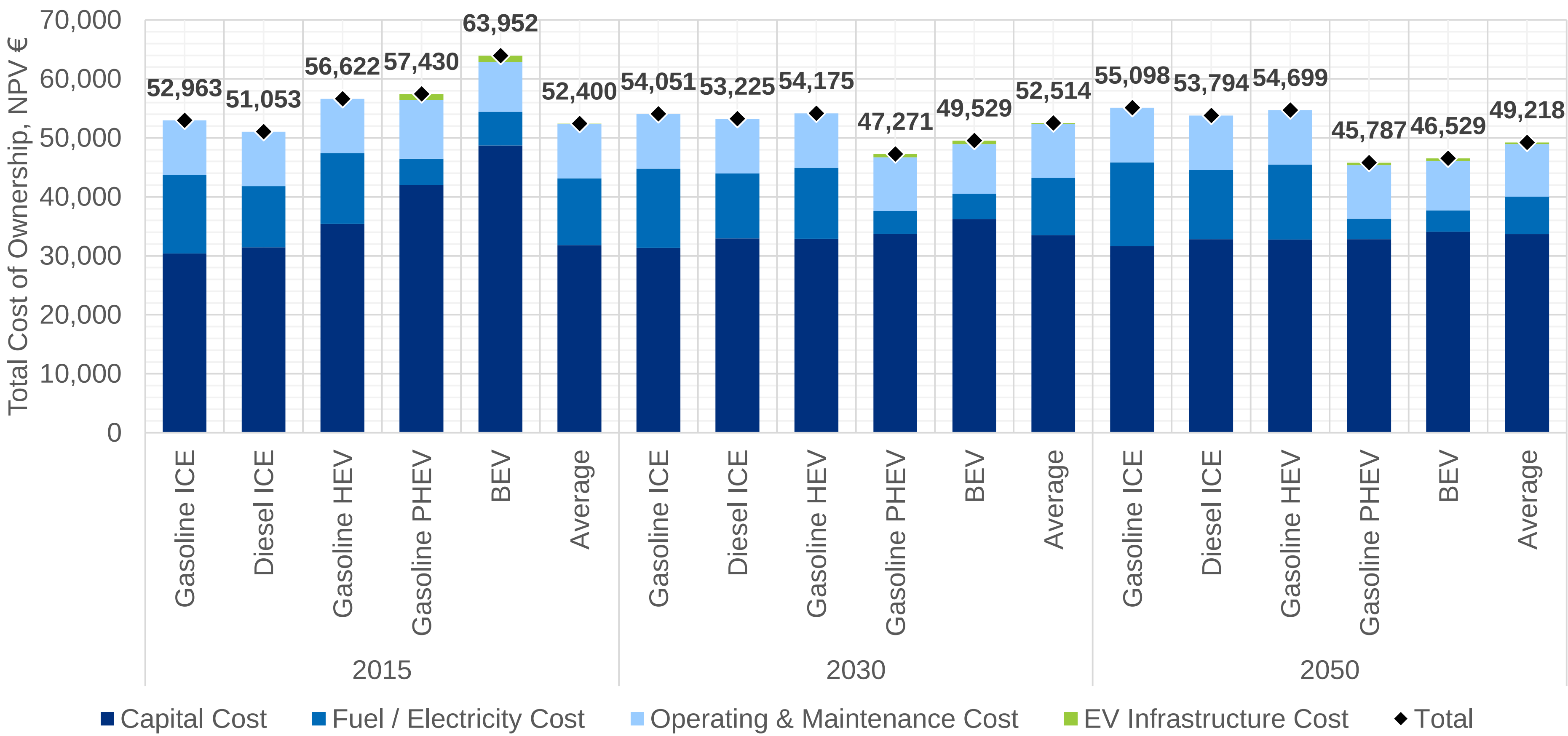


- Assumes lifetime 210,000 km over 15 yrs, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV)
- End-user perspective (including all taxes) with future costs discounted to Net Present Value (with DR = 10%)

Source: Ricardo analysis. EV Infrastructure costs include only cost end-users are assumed to directly pay for – i.e. provision of on-/off-street charging units. DR = Discount Rate

In the LowC Fuel scenario, the NPV Total Cost of Ownership for end-users is higher for ICEV, HEVs and on Average for 2030-2050

New European Passenger Car Total Cost of Ownership – "Low C Fuel" Scenario



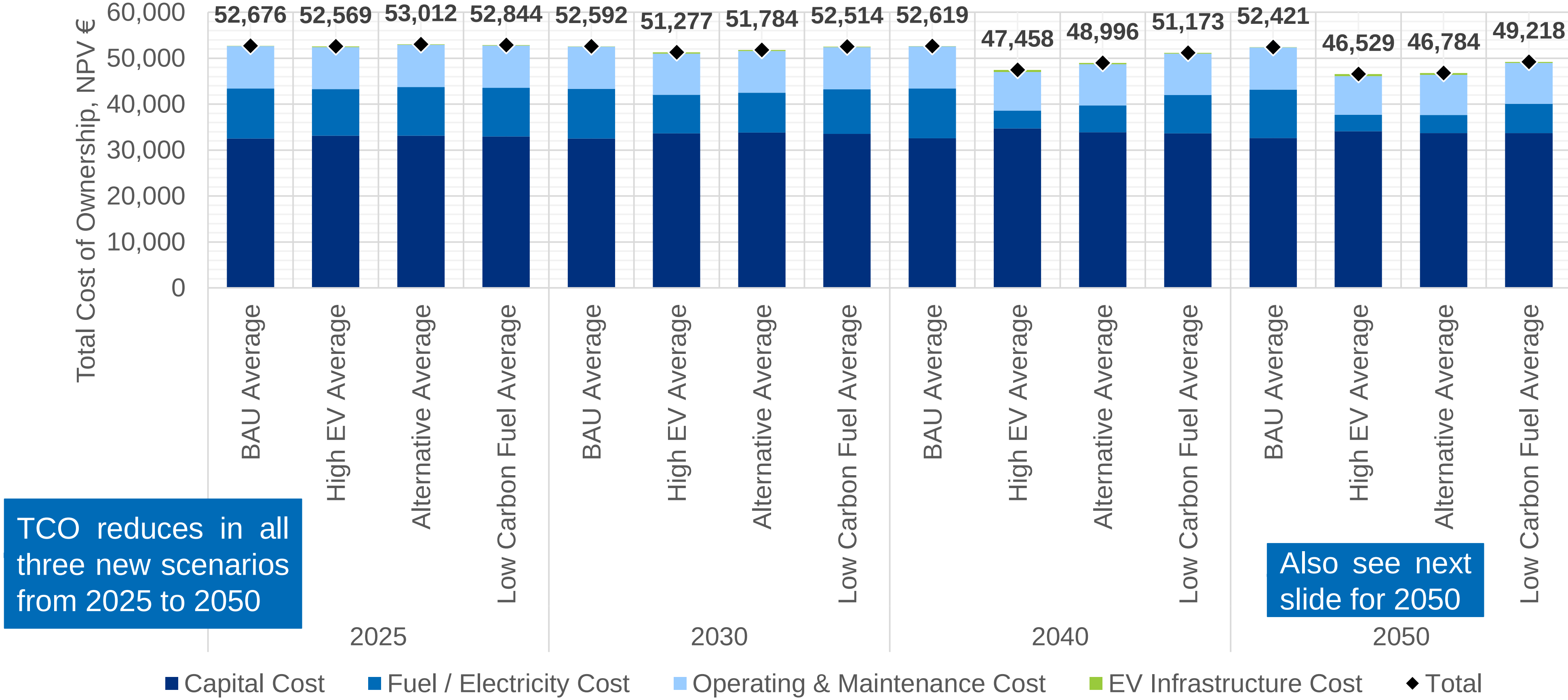
- Assumes lifetime 210,000 km over 15 yrs, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV)
- End-user perspective (including all taxes) with future costs discounted to Net Present Value (with DR = 10%)

Source: Ricardo analysis. EV Infrastructure costs include only cost end-users are assumed to directly pay for – i.e. provision of on-/off-street charging units. DR = Discount Rate

In the LowC Fuels/Alternative scenarios, average NPV TCO for end-users is greater than the High EV scenario in the 2025-2050 period

Excludes consideration of possible recovery of lost fuel tax revenue from consumer (see later slides)
Taxes are applied for all energy carriers at their current and projected (BAU) levels

New European Passenger Car Total Cost of Ownership (TCO) – Scenario Comparison



- Assumes lifetime 210,000 km over 15 yrs, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV)
- End-user perspective (including all taxes) with future costs discounted to Net Present Value (with DR = 10%)

Source: Ricardo analysis . EV Infrastructure costs include only cost end-users are assumed to directly pay for – i.e. provision of on-/off-street charging units.

Overall Total Cost of Ownership (TCO) to end-users, for the average vehicle, reduces in both scenarios compared to BAU

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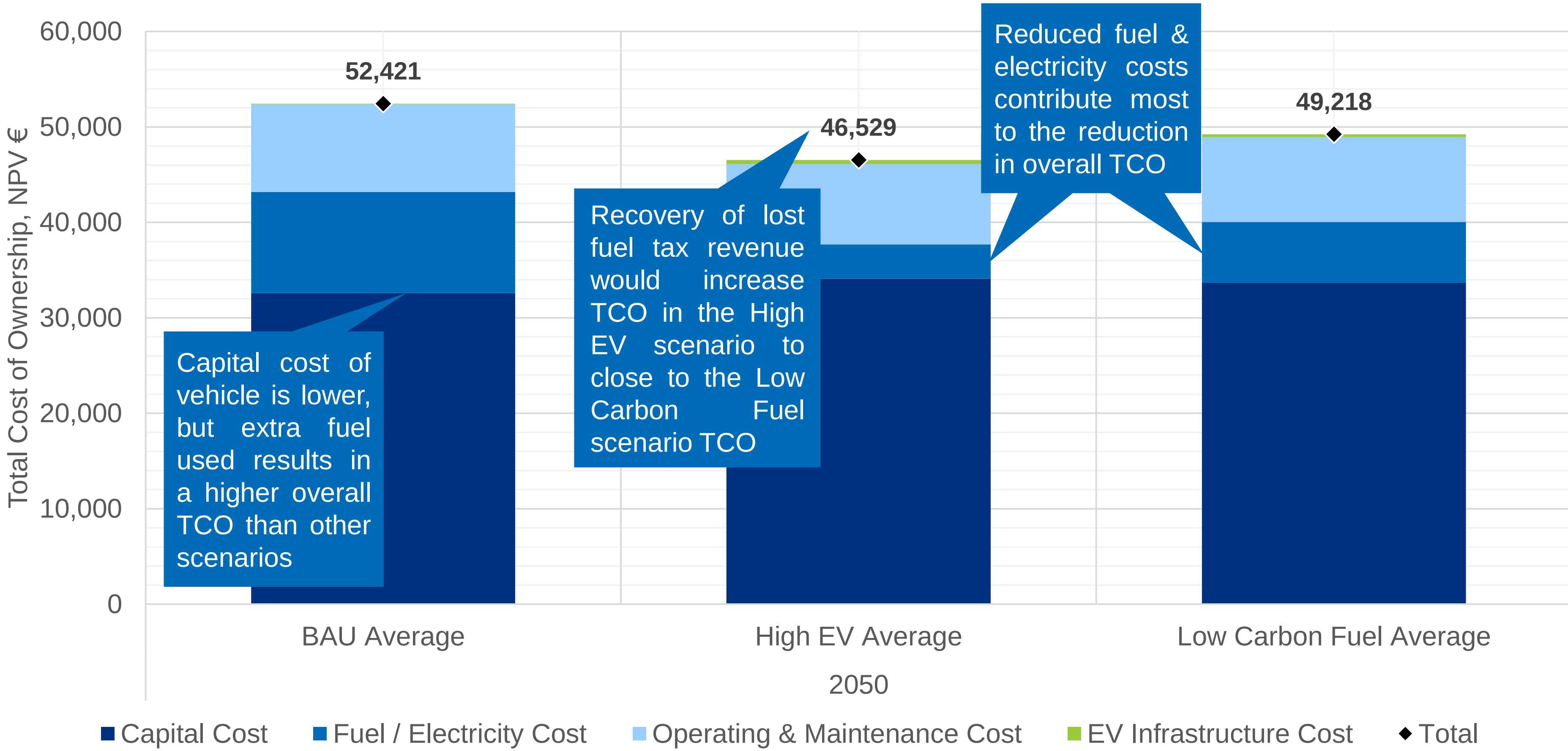
Taxes are applied for all energy carriers at their current and projected (BAU) levels

New European Passenger Car Total Cost of Ownership (TCO) – Scenario Comparison



- Assumes lifetime 210,000 km over 15 years
- End-user perspective (including all taxes) with future costs discounted to Net Present Value (NPV)*

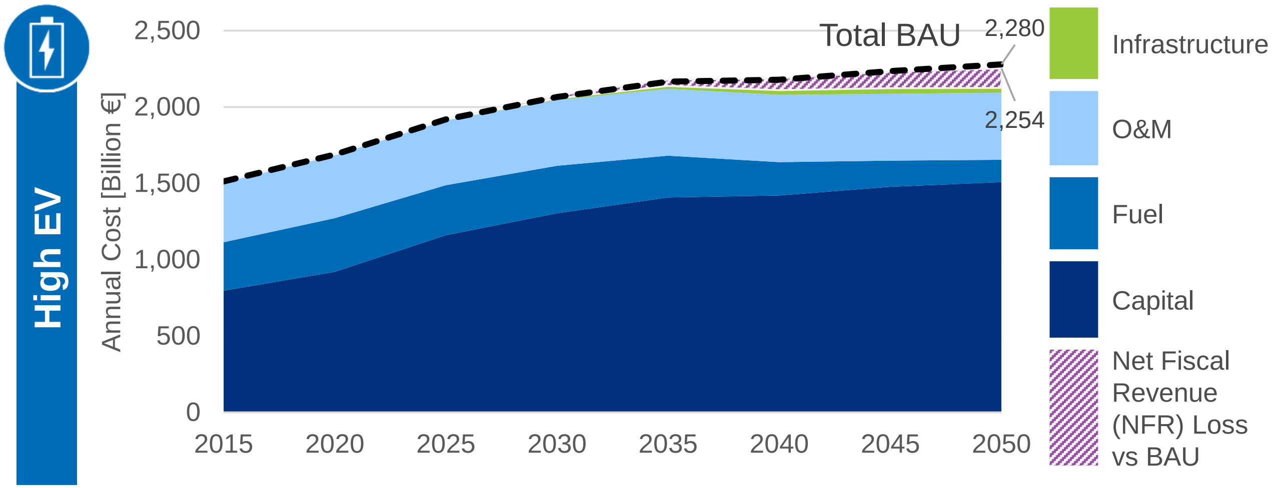
Source: Ricardo Analysis   BAU : Scenario as used by European Commission as a baseline for quantifying the impact of future policy changes

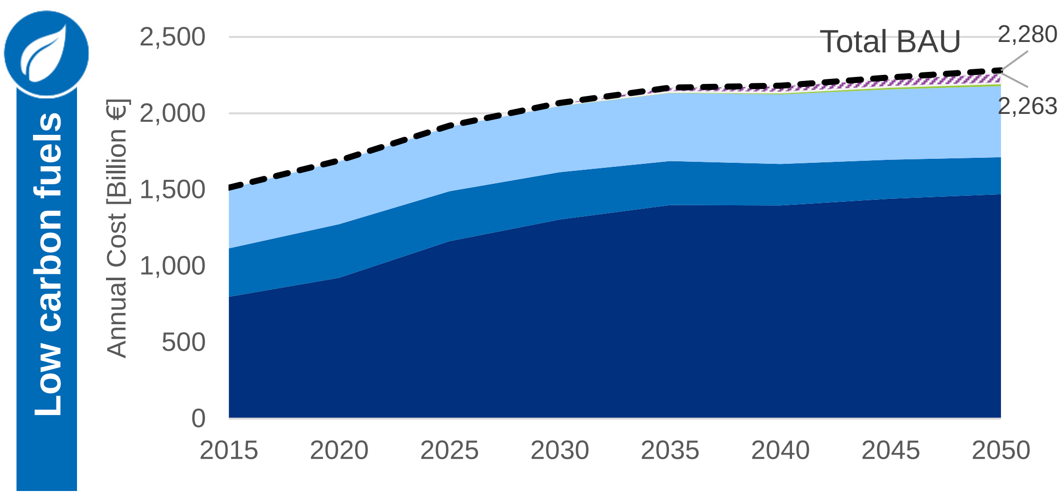
Note: EV Infrastructure costs include only cost end-users are assumed to directly pay for – i.e. Provision of on-/off-street charging units. - NPV assumes 10% Discount Rate

The annual parc total costs to the end user (incl. recovery of lower tax receipts) are similar for the High EV and Low Carbon Fuels scenarios

Taxes are applied for all energy carriers at their current and projected (BAU) levels

Total Parc Annual Costs to End-user, including AFV Infrastructure and Network upgrades





Net fiscal revenue loss is greater for the High EV scenario because liquid fuels have a larger proportion of tax & because the energy requirement for EVs is less due to their higher efficiency

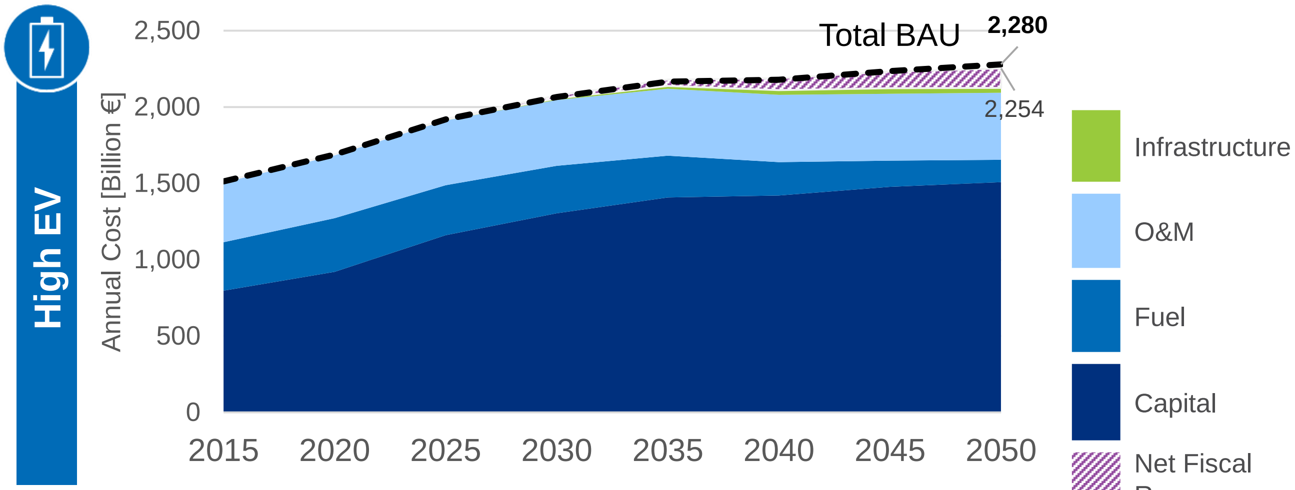
- Including AFV infrastructure and electricity network upgrades into the accounting for total end-user costs narrows the gap between the scenarios to a degree
- Whilst costs are higher in the period to 2035 for the High EV scenario, the net costs are ~70 €Billion p.a. lower by 2050
- This gap would reduce further to ~61 €Billion p.a. in the high EV infrastructure (Grazing) case
- Including NFR loss (vs BAU) closes the gap to 9 €Billion p.a.
- Costs for the Alternative scenario are in-between the other two scenarios
- All scenarios reduce GHG emission/meet reduction objectives at lower overall cost than BAU, which does not meet GHG reduction objectives

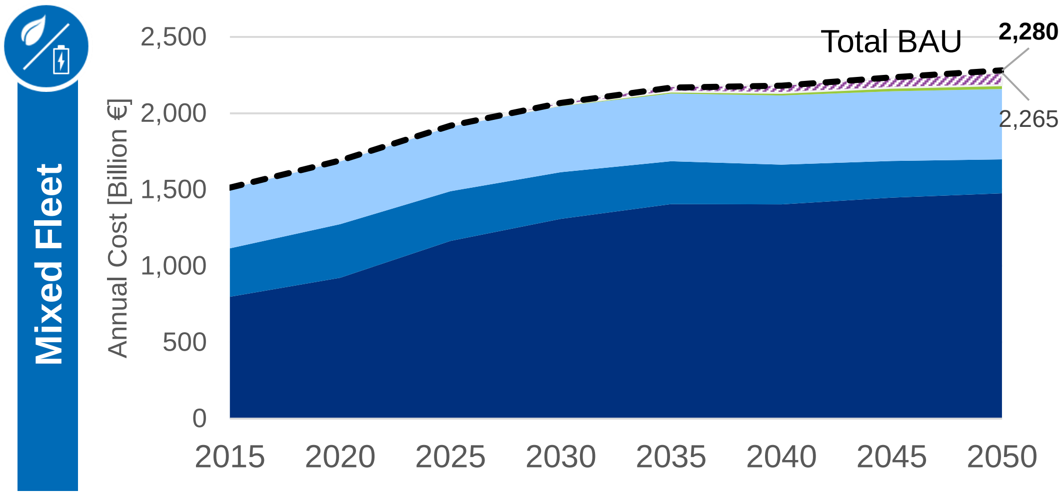
Source: Ricardo Energy & Environment SULTAN modelling and analysis.

NFR = Net Fiscal Revenue

The annual parc total costs to the end user are similar for the High EV and Mixed Fleet Scenarios

Total Parc Annual Costs to End-user, including AFV Infrastructure and Network upgrades



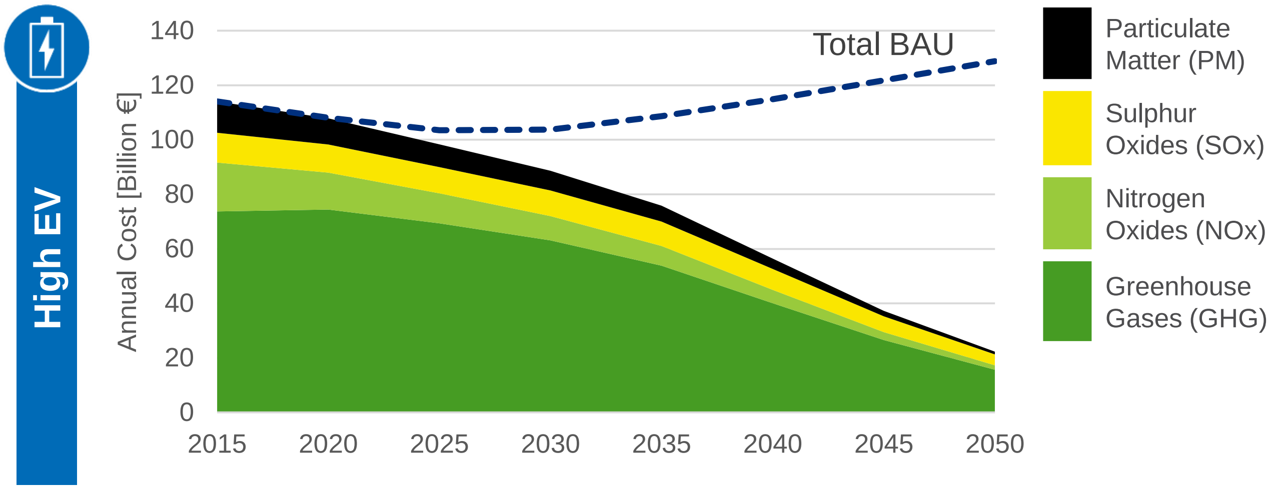


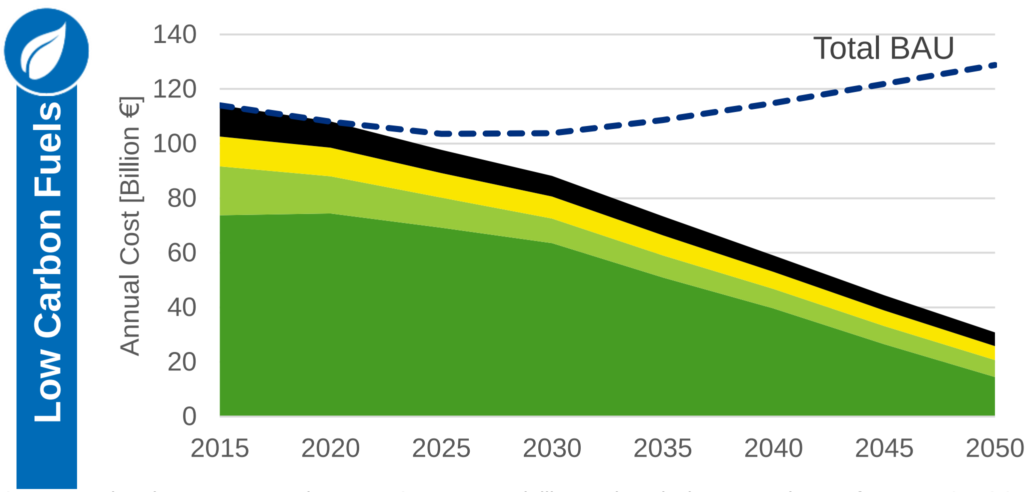
- Whilst costs are higher in the period to 2035 for the High EV scenario, the net costs are ~€58bn p.a. lower than Mixed Fleet scenario by 2050
- Including Net Fiscal Revenue (NFR) loss (vs BAU) closes the gap to €11bn p.a.
- All scenarios reduce GHG emission/meet reduction objectives at lower overall cost to the end user, primarily due to lower fuel and energy costs than the Business as Usual (BAU) reference, which does not meet GHG reduction objectives

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Externalities from emissions of GHG and air quality pollutants decrease significantly in both scenarios, but more under High EV

Externalities for WTW emissions of GHG, and also WTW emissions of NOx, PM and SOx



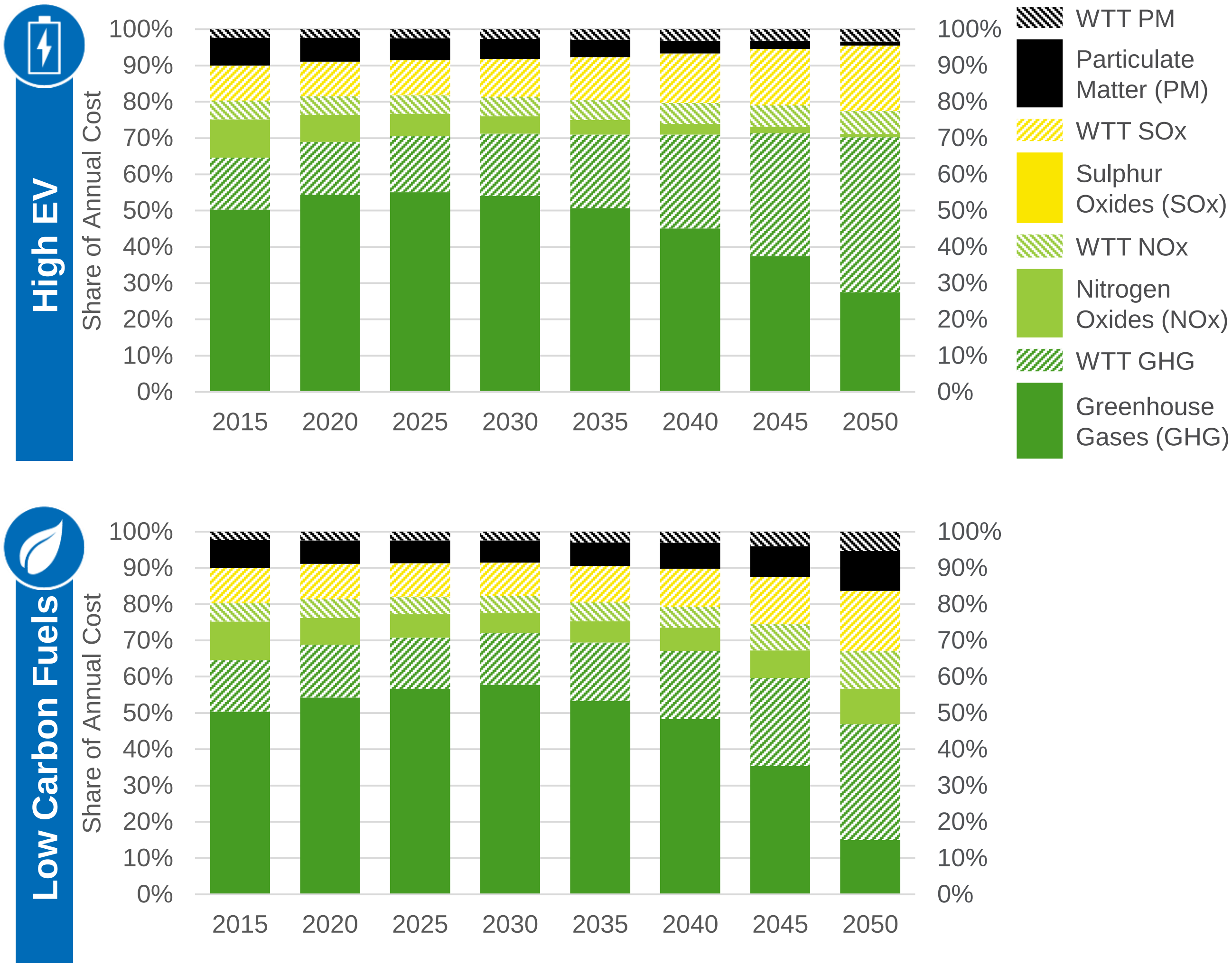


- The impacts of greenhouse gas, air quality pollutant emissions and other impacts such as noise and congestion do not have directly attributable costs
- External costs (or 'externalities') are the monetary value attached to these impacts due to indirect effects, for example on public health and other elements
- These costs are commonly used in cost-benefit analysis (CBA), for example for policy impact assessments, to assess the wider net impacts of policies on the overall costs to society
- The externalities associated with GHG now dominate, and hence are reduced to the greatest degree in the High EV scenario by 2050

Source: Ricardo Energy & Environment SULTAN modelling and analysis; External costs for PM, NOx, SOx, GHG are extrapolated from 2010 base values through to 2050 using EU GDP projections. 2010 base values are from "Update of the Handbook on External Costs of Transport": https://ec.europa.eu/transport/sites/transport/files/handbook_on_external_costs_of_transport_2014_0.pdf

GHG externalities remain the greatest share of emissions under High EV, but NOx and PM externalities increase for other scenarios

Relative share of WTT and TTW annual costs for emissions of GHG, NOx, PM and SOx



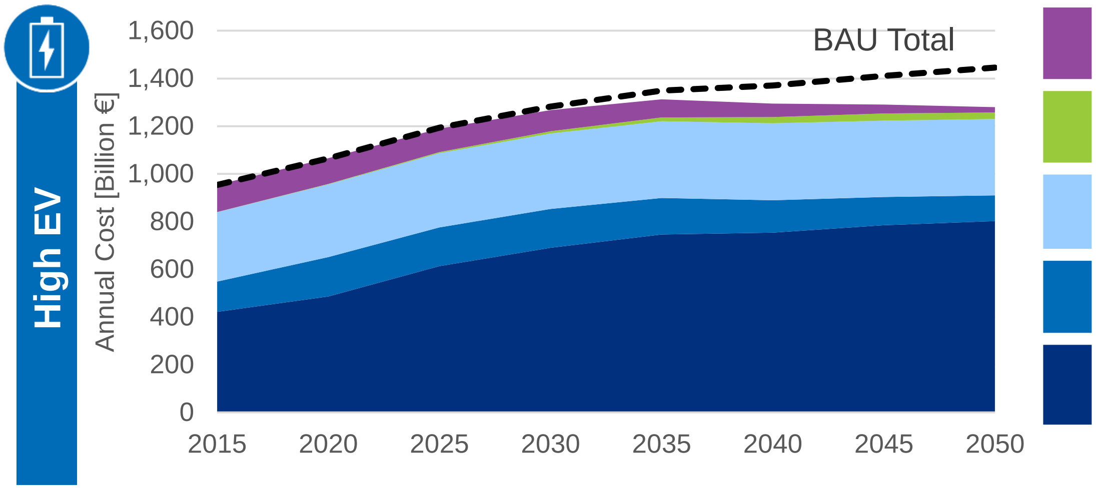
- For the High EV scenario, GHG emissions (WTT and TTW) comprise the majority share of externalities from 2015-2050
- For the Low Carbon Fuels scenario, emissions of NOx and PM form a larger share of overall externalities in later periods
- Externalities from tailpipe (TTW) emissions of SOx are negligible compared to other components
- Technologies will continue to develop to deliver “zero impact” on air quality from tailpipe but this was not considered in this analysis

Note: WTT emission factors are based on life cycle data from EC modelling (2011-2012) (most fuels) and the Ecoinvent database (for biofuels). They have been extrapolated forwards from 2015 to 2050 largely based on the relative reduction in GHG intensity.

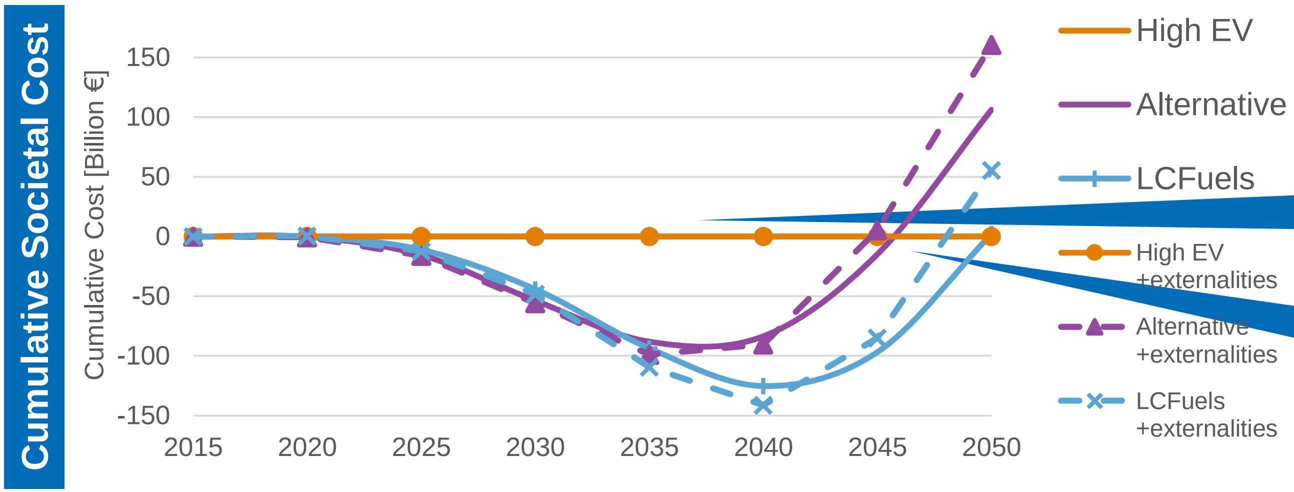
Source: Ricardo Energy & Environment SULTAN modelling and analysis

The net societal cumulative costs are lower for High EV scenario only in later periods

Total Parc Annual Societal Costs (excl. tax), including Externalities



Cumulative Net Societal Costs (relative to High EV)



- Calculating the net societal costs for both scenarios including all cost components as well as externalities results in a significant lowering of High EV costs in the period after 2035
- Up to 2035, the total annual societal costs are slightly higher under the High EV scenario
- By 2050, the total societal costs are 33.5 €Billion p.a. lower for the High EV scenario than for the Low carbon fuels scenario

Cumulative net societal costs are significantly higher for the High EV scenario in earlier periods

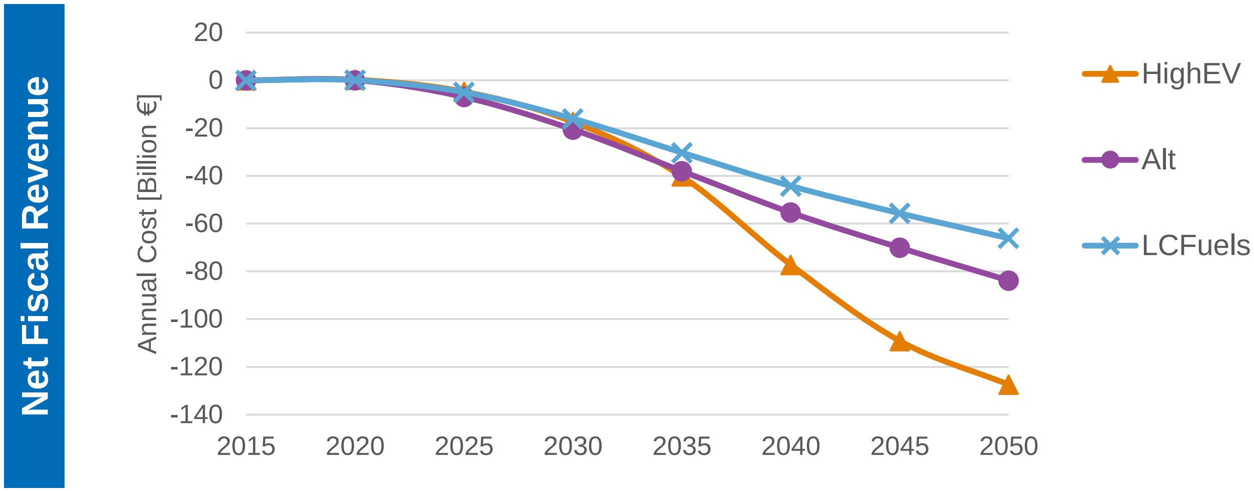
Overall cumulative cost-effectiveness is best for the other scenarios up to 2045-2050

- *Note*: Societal costs exclude all taxes

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The reduction in Net Fiscal Revenue could be 44-61 €Billion p.a. greater by 2050 for the High EV scenario without taxation changes

Net Fiscal Revenue (vs BAU baseline)



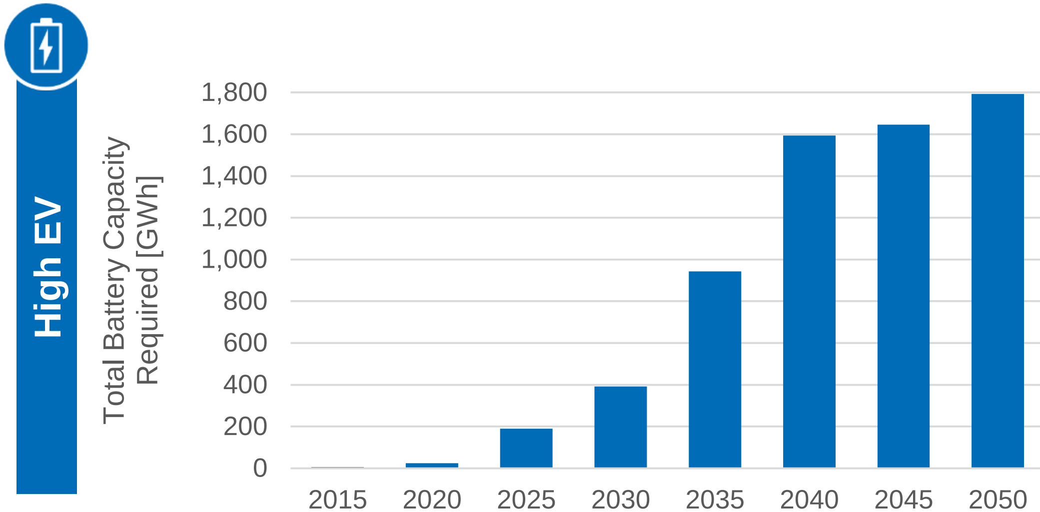
- By 2050, the reduction in net fiscal revenue versus the BAU scenario could reach €127 Billion p.a. for the High EV scenario (a 29% reduction) if no changes were made to existing taxation approaches
- The shortfall is 44 / 61 €Billion p.a. less for the Alternative/ Low carbon fuels scenarios respectively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

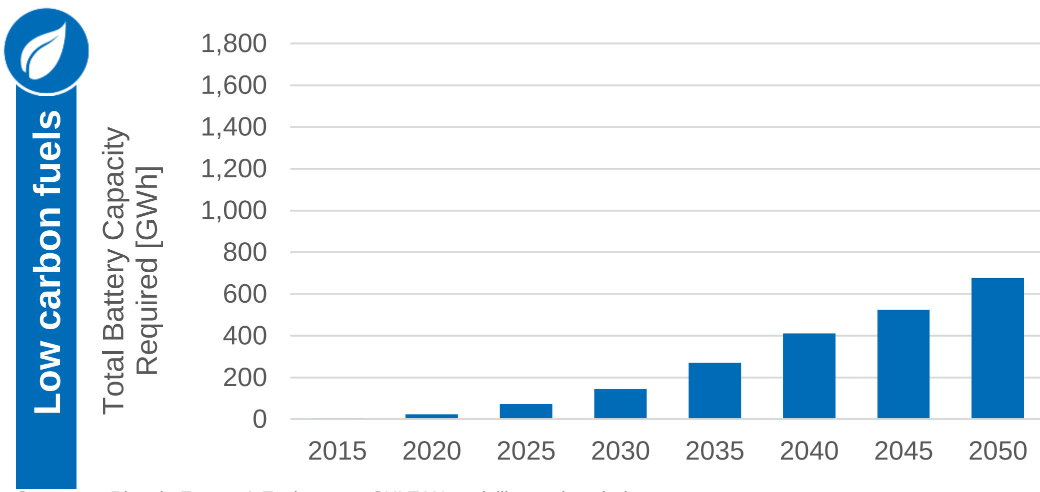
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Contents

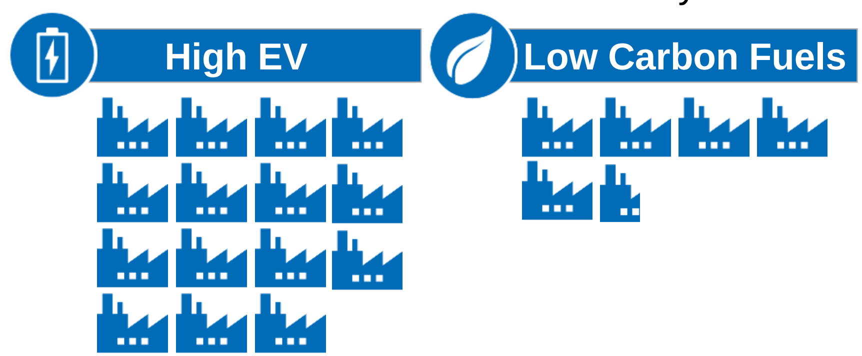
Under the High EV scenario, ~15 Gigafactories would be needed to supply batteries to the European EV market by 2050

Resources & Materials – Annual Battery Capacity [GWh]





- The High EV scenario requires almost **three times the total battery capacity** compared to the Low Carbon Fuels scenario
  - The Tesla Gigafactory is projected to produce ~35 GWh per annum*
  - Europe will need ~15 giga-factories under the High EV Scenario, while ~5.5 such factories will be needed under the Low Carbon Fuels Scenario by 2050



Note: Tesla Giga Factory estimates factor in anticipated battery energy density improvements per unit from 2025-2050 This output should be expected to scale with increased battery kg/Wh*

Source: Ricardo Energy & Environment SULTAN modelling and analysis;
* Tesla (https://www.tesla.com/en_CA/gigafactory)

The Lithium resource requirements for the Low Carbon Fuels scenario are less than half of those for the High EV scenario

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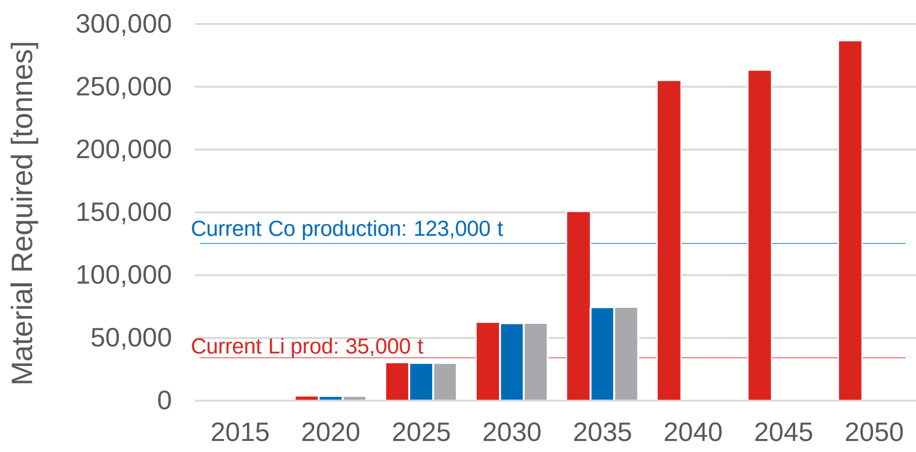
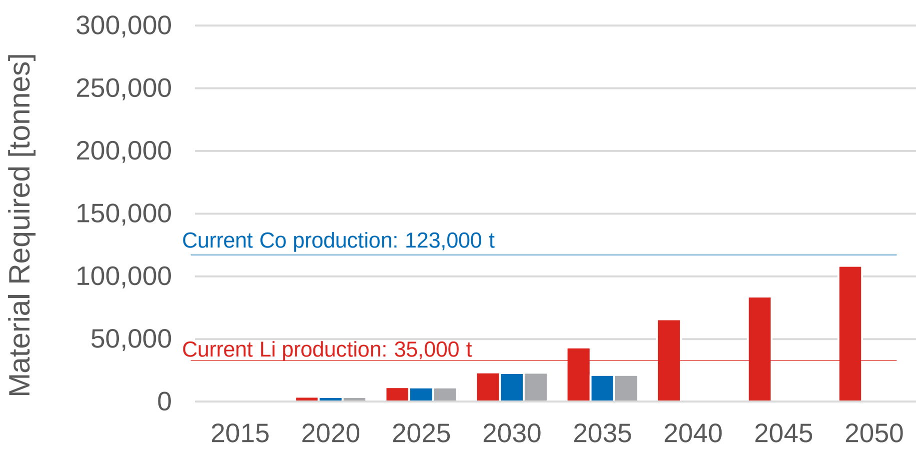
Resources & Materials – Key Battery Materials [tonnes], annual demand

High EV



Low carbon fuels



Source: U.S Geological Survey (Mineral Commodity Summaries 2017); Ricardo Energy & Environment Sultan Modelling And Analysis

3 **Li** Lithium

27 **Co** Cobalt

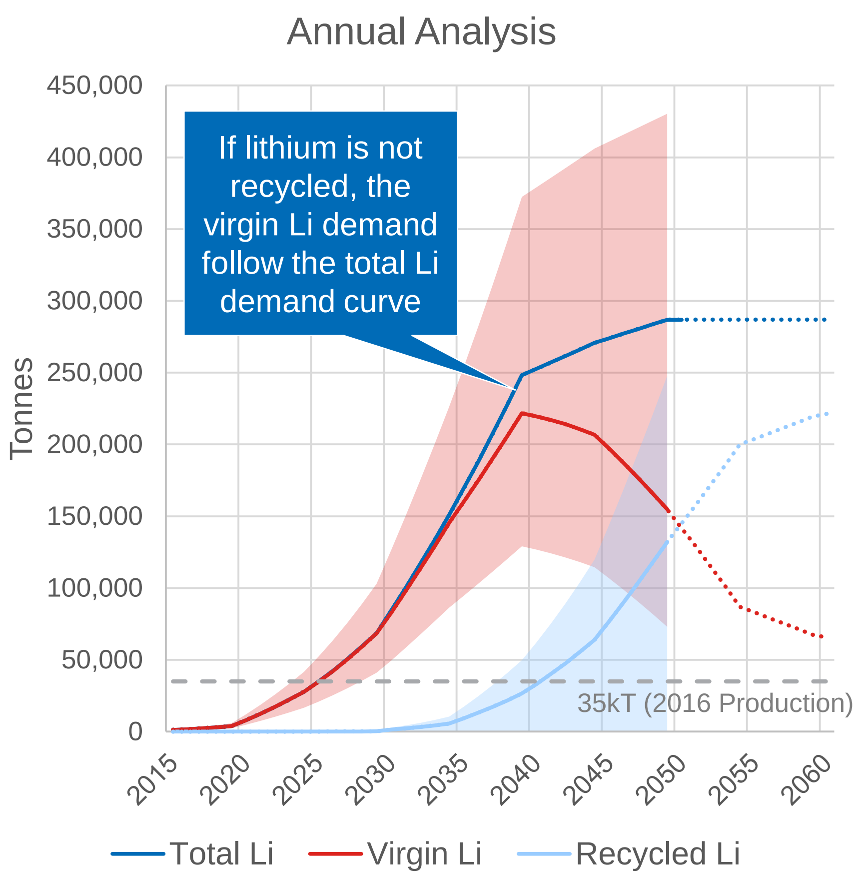
28 **Ni** Nickel

- Assuming current chemistry mixes the resource requirements for Lithium, Cobalt and Nickel would increase very substantially over the period to 2050, which would pose a potential availability risk
- Current global total production p.a.:
  - Li : 35 kt (with 14 Mt reserves)
  - Co : 123 kt (with 7 Mt reserves)
  - Ni : 2.25 Mt (78 Mt reserves)
- Overall resource requirements for the High EV scenario would more than double those for the Low Carbon Fuels scenario under these assumptions

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

Lithium production would need to increase significantly to meet European EV demand in the High EV scenario

Lithium Material Analysis



Analysis to calculate annual lithium demand for European light duty car sales in a mass EV adoption scenario (100% light duty sales are BEV by 2040). Results and sources can be found in RD17-003175-1 Q015713 - Task 3 - Materials and Recycling – Workbook.xlsx. Shaded areas refer to sensitivities studied.

Source: Lebedeva et al. (2016) (#A275); Kushnir and Sanden (2012) (#A381); Foss et al. (2016) (#A256)

- For the High-EV scenario, annual virgin lithium demand increases rapidly until a peak is reached in 2040, when EV recycling becomes significant
- Peak virgin lithium demand is 6 times higher than global lithium production in 2016 (35kt)
  - Currently, ~6% of lithium production is used for automotive batteries
  - Non-automotive lithium demand is forecast to increase by 4% annually until 2025 (not included in this analysis)
- By 2050, the production of lithium from recycled sources almost meets the virgin lithium extraction
  - Currently less than 1% of lithium is recovered at the end of the product life, indicating that battery recycling to recover lithium is an industry that does not yet exist
  - It is unclear what economic or market factors will be required to encourage the growth of the recycling industry

There may be enough lithium for European mass EV adoption, however the rate of lithium production could be the limiting factor

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Further impacts on resources and materials are discussed in Appendix 5 and summarised below

Lithium Resources and Reserves

- 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
- 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 – additional very few countries have lithium reserves
- Lithium from recycled batteries has a limited impact on the total virgin lithium required by 2050

Lithium Production

- Virgin lithium extraction capacity must be increased significantly in order to reach peak demand in 2040
- Battery recycling to recover lithium could become a large industry by 2050, however it may not be economically feasible for all battery types (e.g. LFP batteries have little recyclable material of value)

Cobalt Production

- Congo (Kinshasa) has half of the global cobalt reserves and production, however there are concerns over the economical impacts and the security of supply results in large price fluctuations

Environmental Impacts

- Environmental impacts from material extraction are being reduced in some regions, however there is a risk that large scale exploitation of lithium and cobalt resources could lead to significant environmental impacts

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Energy Security metrics were developed as part of the EU Transport GHG: Routes to 2050 project for the European Commission

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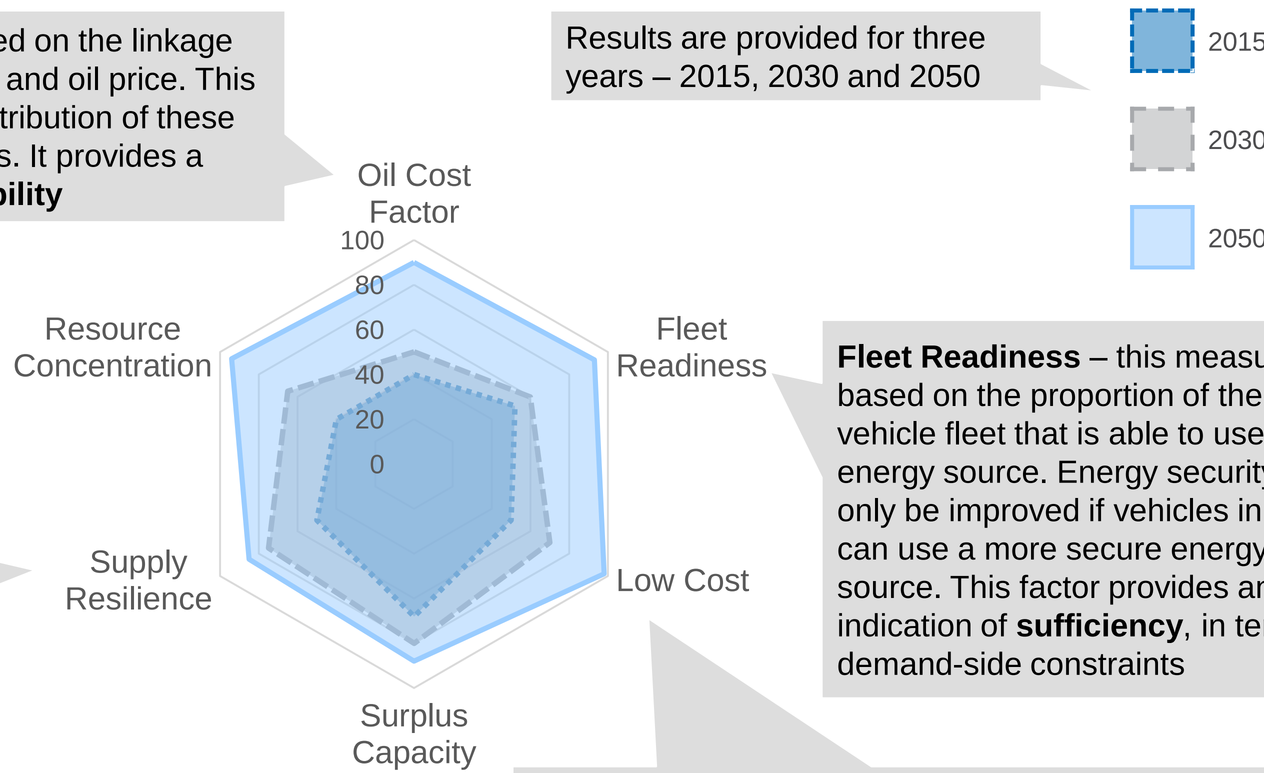
Energy Security – Explanation of Criteria

Oil Cost Factor – this is defined based on the linkage between price of new energy sources and oil price. This can occur when production and/or distribution of these fuels relies on conventional fossil fuels. It provides a measure of **sufficiency and affordability**

Results are provided for three years – 2015, 2030 and 2050



Resource Concentration – this metric factors in the uneven geographical concentration of resources as a pertinent cause of energy insecurity affecting **affordability** and **sufficiency**

Fleet Readiness – this measure is based on the proportion of the vehicle fleet that is able to use a new energy source. Energy security can only be improved if vehicles in a fleet can use a more secure energy source. This factor provides an indication of **sufficiency**, in terms demand-side constraints

Supply Resilience – this metric provides an indicator of the susceptibility of an energy source to supply disruption is an indicator of **sufficiency**

Supply Capacity – this indicator is expressed in terms of annual consumption as a percentage of total global fuel reserves. It provides an assessment of **sufficiency**. Surplus of supply capacity over demand is highly relevant for finite resources. Renewables are not limited by supply, but by production capacity, so are not relevant here

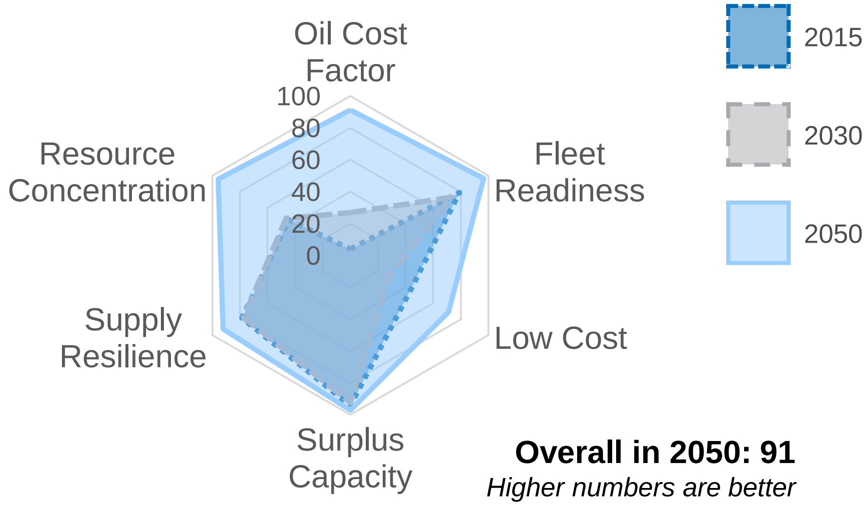
Low Cost – this metric provides an assessment of the relative cost of energy, taking into account both the price of the energy and relative efficiency of different vehicle powertrain types using different energy carriers. It assesses the key **affordability** element of energy security

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Both scenarios improve Energy Security in the long-term across a number of metrics included in the SULTAN model

Energy Security

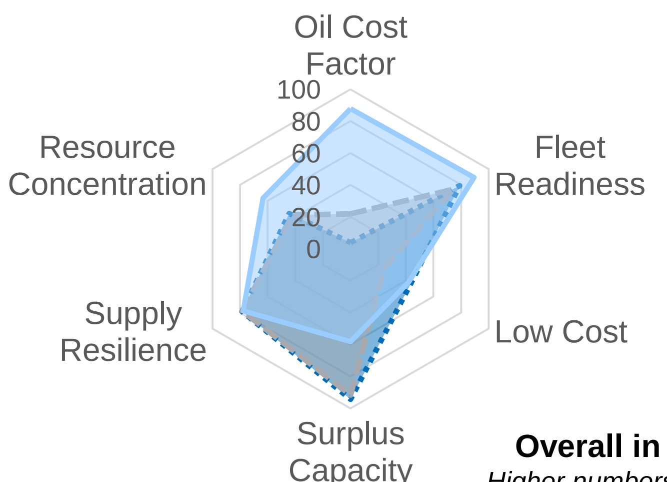
High EV



Overall in 2050: 91

Higher numbers are better

Low Carbon Fuels



Overall in 2050: 70

Higher numbers are better

- The SULTAN model has an in-built analysis of a range of Energy Security metrics in the Results Viewer developed for the European Commission*
- Both scenarios improve the overall level of Energy Security in the medium and longer-term
- The High EV scenario shows greater longer-term improvement across all six of the Energy Security metrics calculated by SULTAN
- *Note*: Analysis is based on methodology developed in 2012 for the EU Transport GHG: Routes to 2050 II project, and does not include infrastructure cost elements.

  Resource security is only assessed for energy sources. **No measure is included for potentially scarce materials for EVs**

Source: Ricardo Energy & Environment SULTAN modelling and analysis

*EU Transport GHG: Routes to 2050 II Task 1 report 2012

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Contents

A range of sensitivity scenarios were developed to explore the potential implications of uncertainties around key assumptions

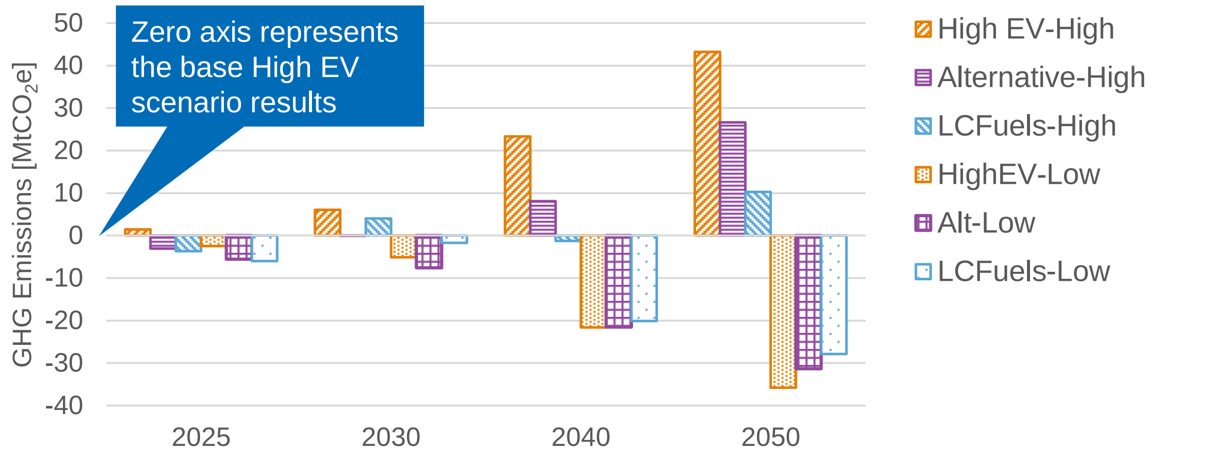
Scenario Sensitivities

- In addition to the main four scenarios (BAU, High EV, Low Carbon Fuels, Alternative) a number of scenario sensitivities were also explored to better understand the importance of key assumptions in areas of particular uncertainty. These are mainly grouped into two categories: those mainly affecting GHG emissions, and those impacting cost
- *Sensitivities impacting on GHG emissions:*
  1. The GHG intensity of electricity generation is a key assumption
  2. Sensitivities on embedded emissions from vehicle production and disposal
  3. Sensitivity on the degree of improvement in battery energy density by 2050 (reduced from 800 Wh/kg to 500 Wh/kg)
  4. Sensitivity on the availability of low carbon fuels – cap of 50% substitution in gasoline and diesel by 2050
- *Sensitivities impacting on costs:*
  5. Low/high cost sensitivities on future battery costs
  6. Building on the existing sensitivity, a high battery costs scenario where 2050 costs reach $100/kWh
  7. Recharging infrastructure requirements (and costs) for EVs (home vs grazing; managed vs unmanaged network)
  8. A high cost sensitivity on low carbon fuel prices (equivalent to ~20% increase on the base prices)

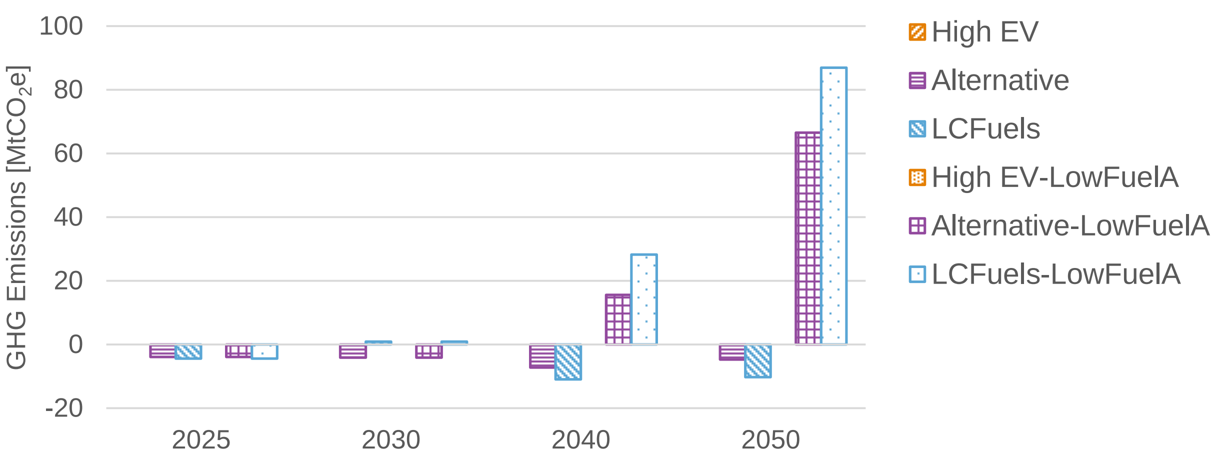
Sensitivities on electricity GHG intensity and the availability of low carbon fuel significantly change the comparison between scenarios

Sensitivities on Electricity GHG intensity & LowC Fuel availability vs base High EV scenario

Electricity GHG



Low C Fuel Availability



- GHG emissions by 2050 in the base scenarios range from 124-132 $MtCO_2$ p.a. (vs 624 $MtCO_2$ p.a. in BAU)
- Sensitivities on electricity GHG intensity show approximately up to +/-30% impacts on the total for the High EV scenario. Impacts are somewhat lower for the other scenarios
- The impact of the sensitivity on low carbon fuel availability (total substitution limited to 50% by 2050) for light duty vehicles results in a 55% increase in emission for the Alternative scenario for 2050 , and 78% for the low carbon fuel scenario

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Sensitivities on long-term battery energy density and embedded GHG worsen the emissions for High EV versus other scenarios

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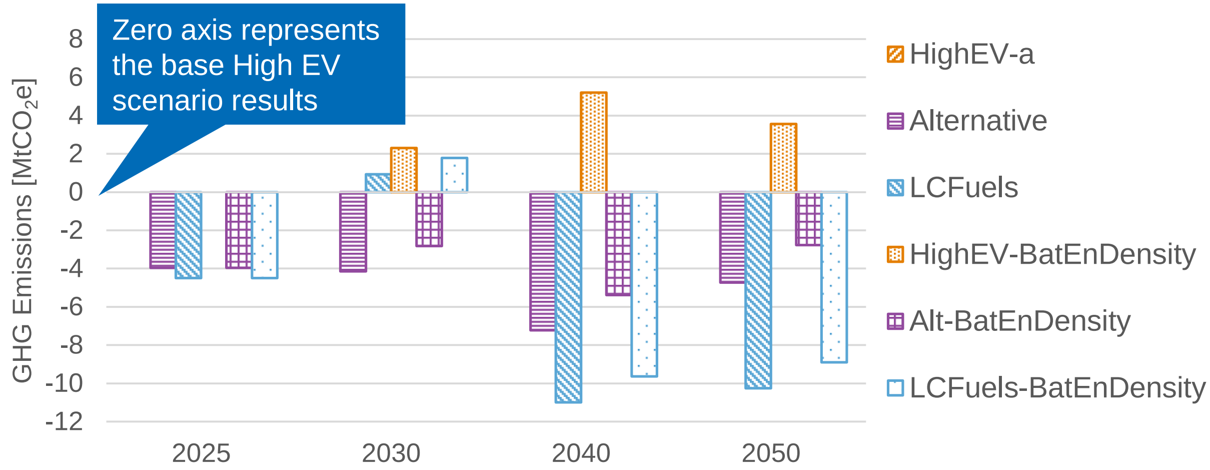
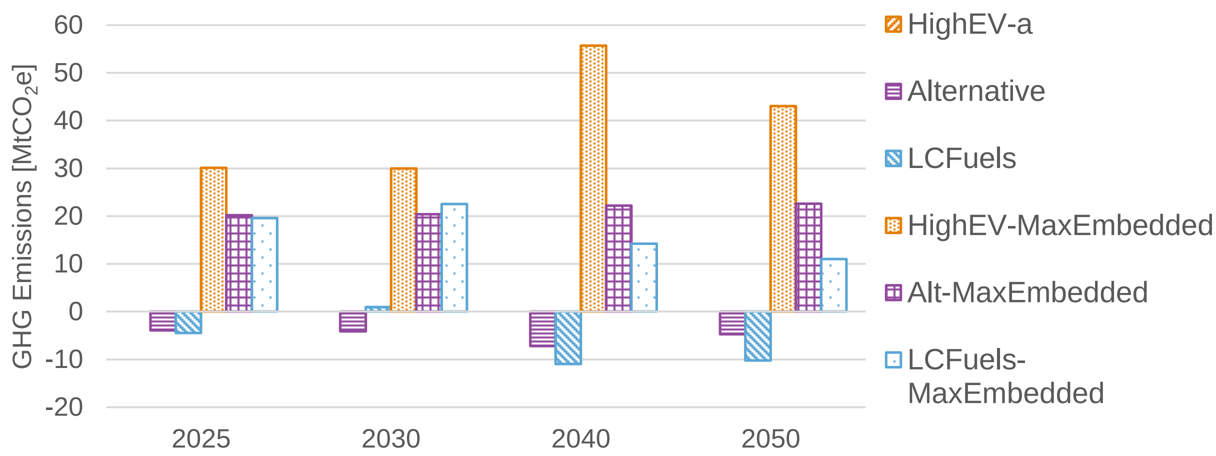
Sensitivities on Vehicle Embedded Emissions, compared to the base High EV scenario

Low Battery En Density



- Reducing the battery energy density improvement to 2050 (from 800 Wh/kg to 500 Wh/kg) has only a small impact on total emissions – increasing emissions by up to 5 MtCO2 p.a.

Maximum Embedded GHG

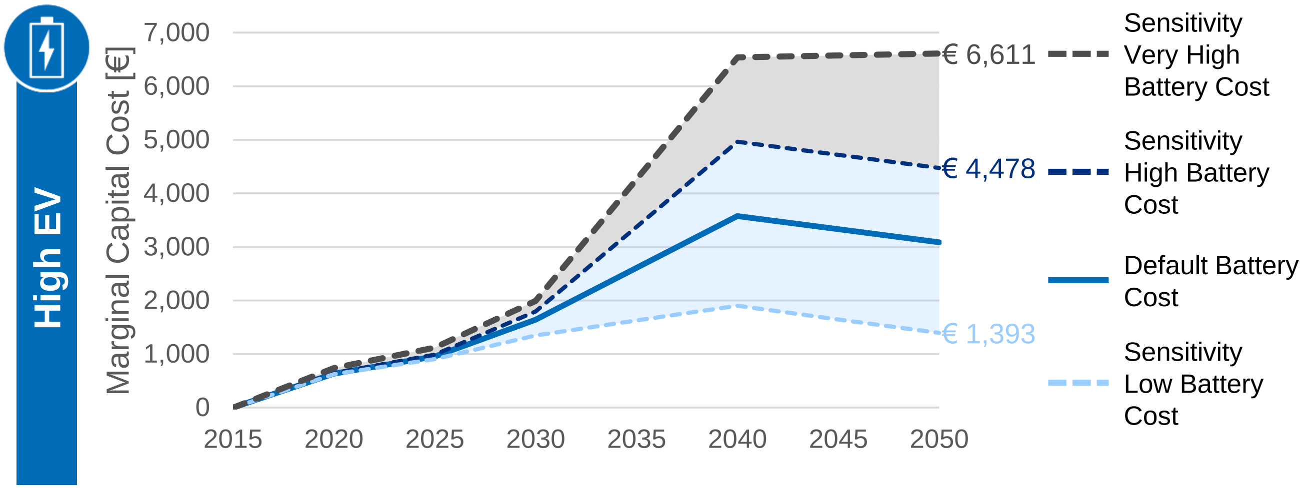


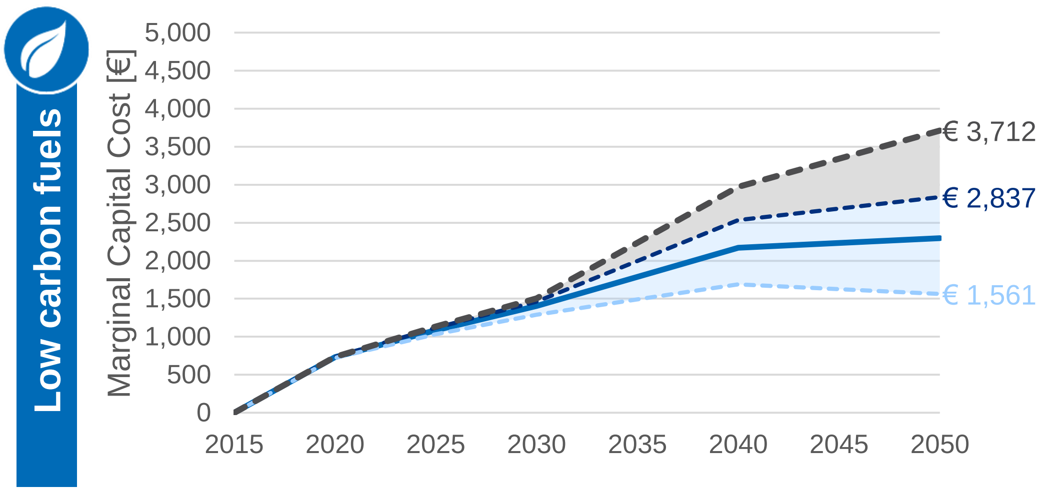
- In the worst / maximum embedded GHG case increases the GHG emissions gap between the High EV and Low carbon fuels scenario from ~8 $MtCO_2$ p.a. to ~32 $MtCO_2$ p.a. at 2050
- *Note*: Max case assumes no recycling, low improvement in material GHG intensity, recycled content method, high battery production emissions and lower battery energy density

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The estimated marginal capital costs for the High EV scenario are particularly strongly influenced by assumptions on battery prices

Average marginal additional capital costs per vehicle for passenger cars





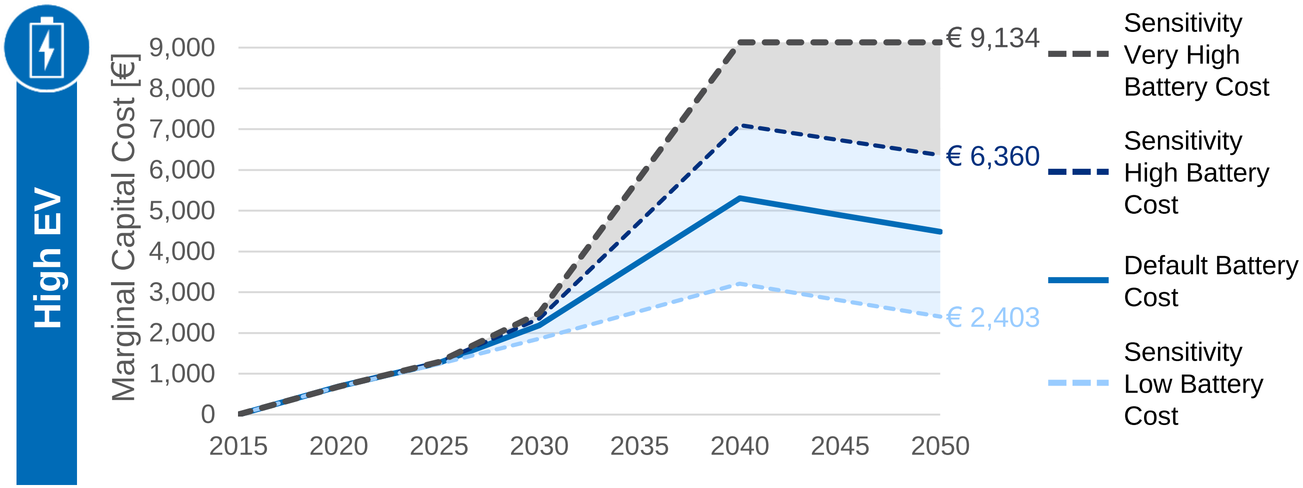
- The average marginal cost increases calculated for new cars under the High EV scenario are significantly higher than those under the Low carbon fuels (and Alternative) scenario
- Sensitivity scenarios were develop based on high and low cost battery projections, plus an additional very high cost case based on the price of batteries being higher due to supply constraints / very high demand

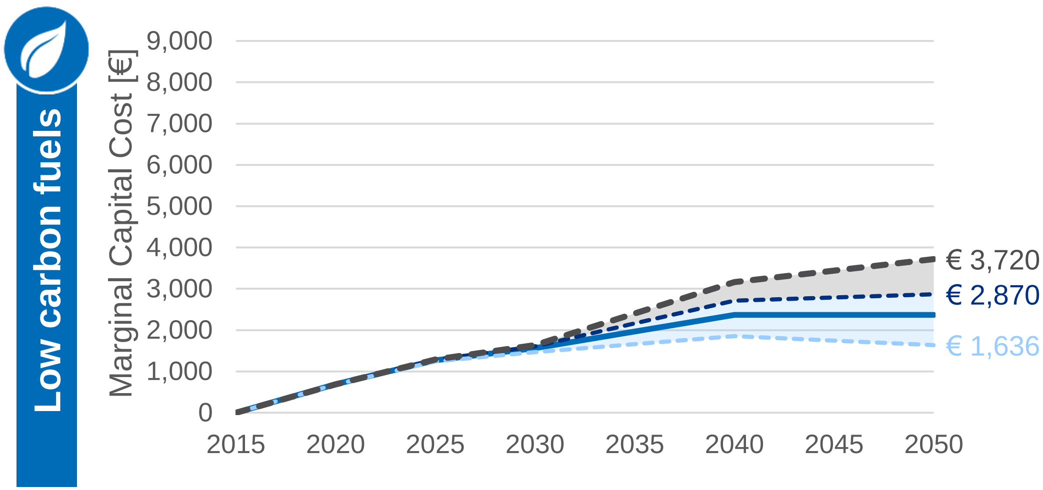
- *Note:* the estimation of future cost reduction for batteries is based on a deployment-based learning approach, so is not able to account for the potential for future disruptive changes in this area

Source: Ricardo Energy & Environment SULTAN modelling and analysis

The estimated marginal capital cost increase for vans is larger than for cars, particularly for the High EV scenario

Average marginal additional capital costs per vehicle for light commercial vehicles



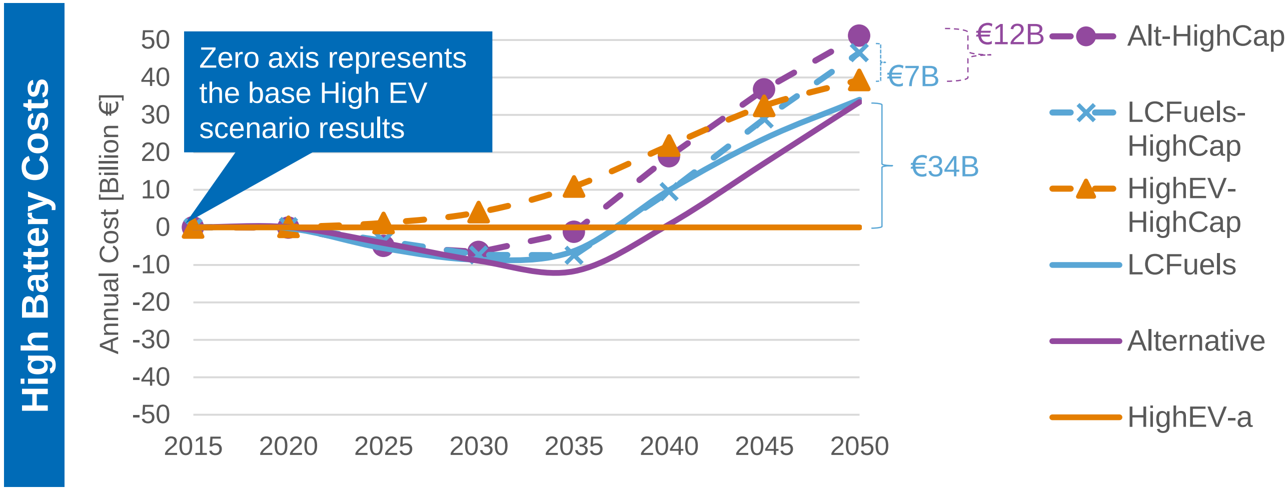


- The increase in marginal capital costs for vans is even greater than for cars for the High EV scenario in comparison to the Low Carbon Fuels scenario
- The calculated marginal capital costs for vans also shows significant deviations for high/low battery costs in particular for the High EV scenario
  - The difference between the high and low battery cost scenario is ~€3,950 in 2050, and very high ~€2,775 more
- The Alternative scenario is much less affected by the assumptions on future battery cost reductions
  - The variation in costs between high and low battery cost case is ~€1,235 in 2050, and very high ~€850 more

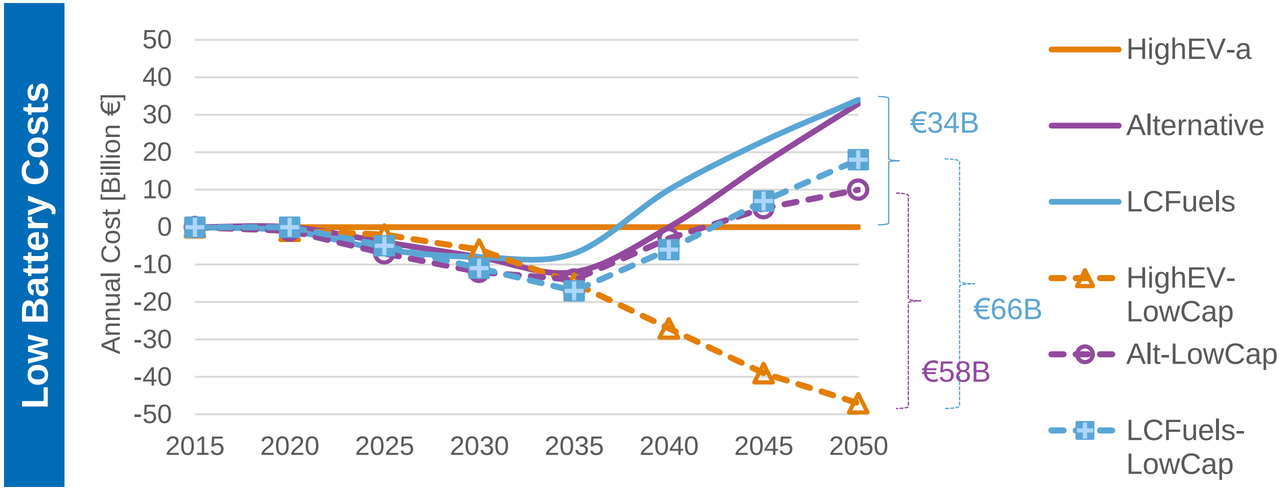
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Alternative battery cost assumptions can significantly change the differential between scenarios for long-term net societal costs

Sensitivity on Battery Cost Assumptions (relative to High EV)



- 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.



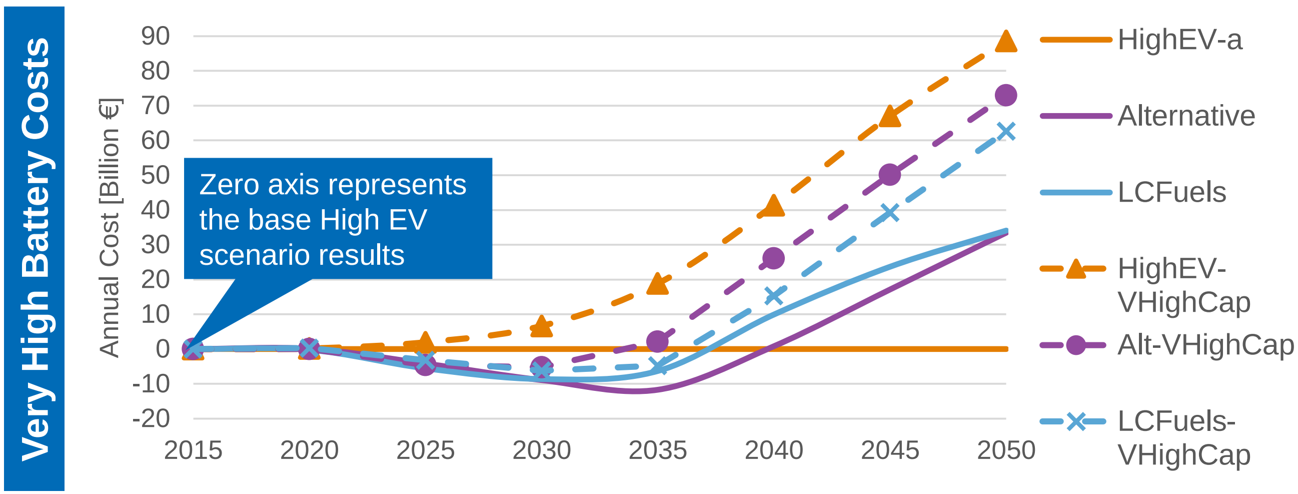
- Under low battery cost assumptions the reduction in net costs for the High EV scenario in 2050, relative to the Low carbon fuels and Alternative scenarios, increases from ~34 €Billion p.a. to 58-66 €Billion p.a.

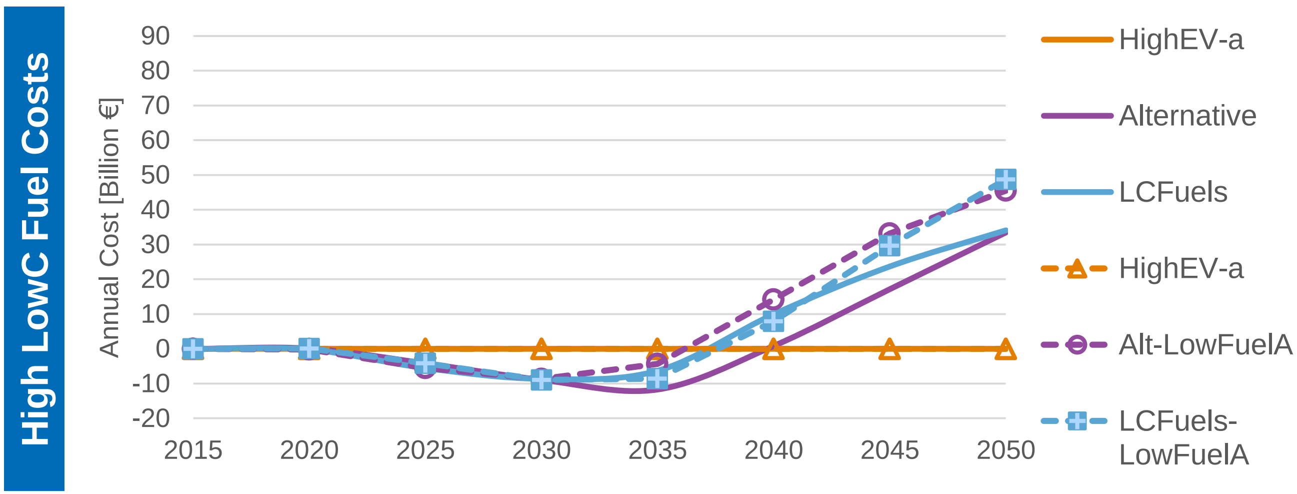
Note: These are all societal costs, excluding taxes and including externalities

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Very high battery cost and high fuel cost assumptions significantly change the differential between scenarios for long-term costs

Sensitivity on Battery Cost Assumptions (relative to High EV)





- 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
- However, in this situation it is very likely that manufacturers would simply not extend the average future electric range of BEVs to the same degree, reducing cost down again
- The sensitivity on low carbon fuel costs increases the differential between these scenarios

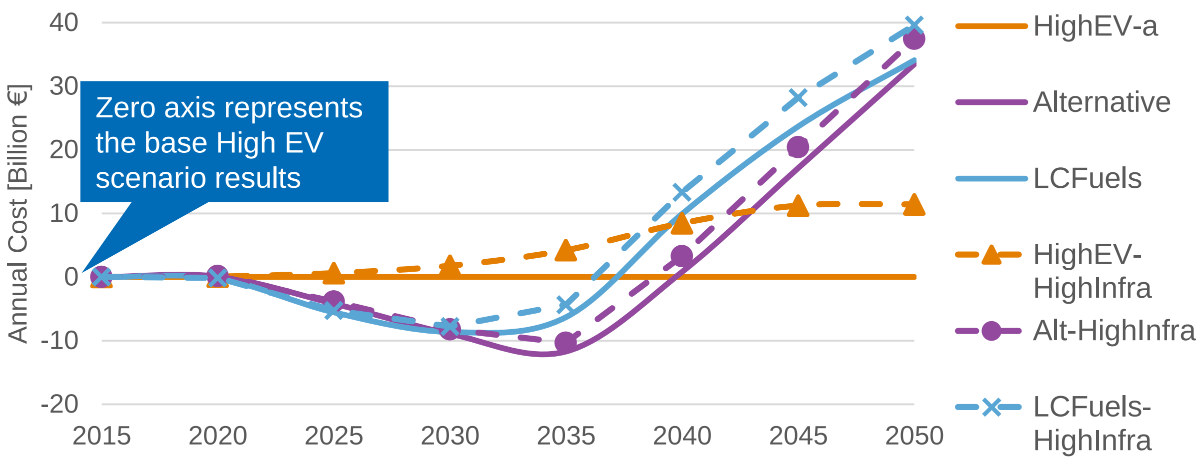
Note: These are all societal costs, excluding taxes and including externalities

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Sensitivities on infrastructure costs have relatively low impact on the overall comparison

EV Charging Infrastructure Sensitivity (vs to High EV)

High Infrastructure Costs



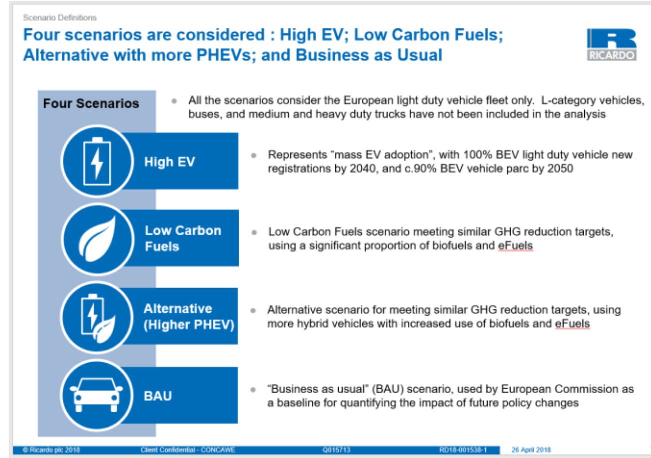
- Sensitivities on infrastructure costs have relatively low impact on the overall comparison
- Sensitivities on electricity cost are even more marginal in effect

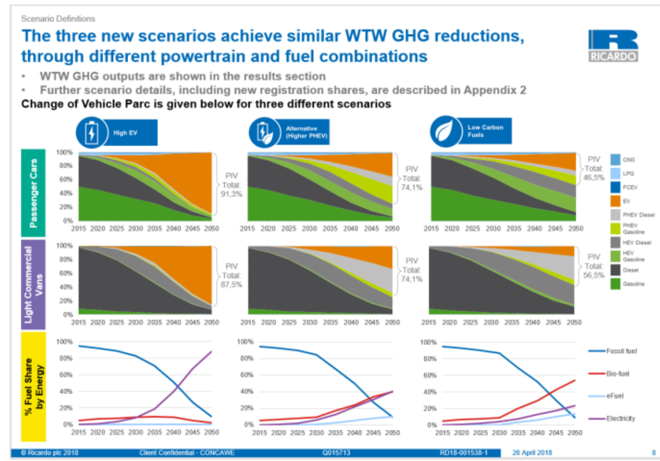
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Contents

Scenario analysis has examined the impacts of four scenarios: High EV, Low Carbon Fuels, an Alternative (Higher PHEV) and BAU

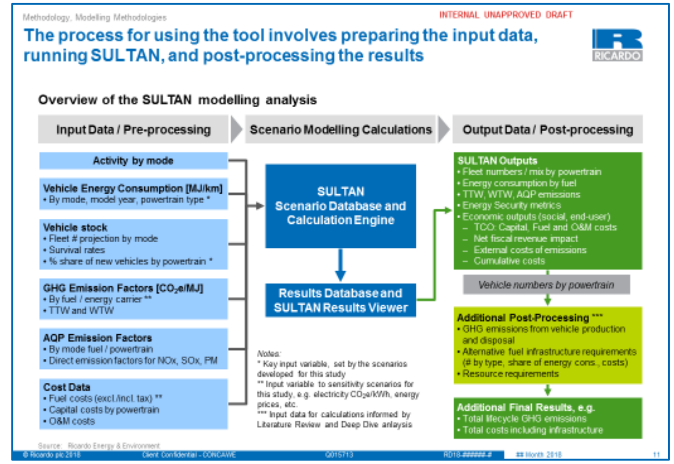
- Scenario modelling has been conducted to investigate the impacts of four scenarios in the European light duty vehicle market to 2050:
  - **High EV** represents mass EV adoption and c90% BEV vehicle parc
  - **Low Carbon Fuels** using significant proportion of biofuels and eFuels
  - **Alternative** using more hybrid vehicles together with increased use of bio- and eFuels
  - **Business As Usual (BAU)** used by European Commission as a baseline for quantifying the impact of future policy changes
- This report describes the impact of each scenario on the following:
  - Energy consumption & GHG emissions (well-to-wheel, life cycle)
  - Electricity and bio-energy requirements
  - Costs including electricity network infrastructure and charging network
  - Resources and materials
  - Externality costs, representing well-to-wheel NOx, SOx and PM
  - Energy security

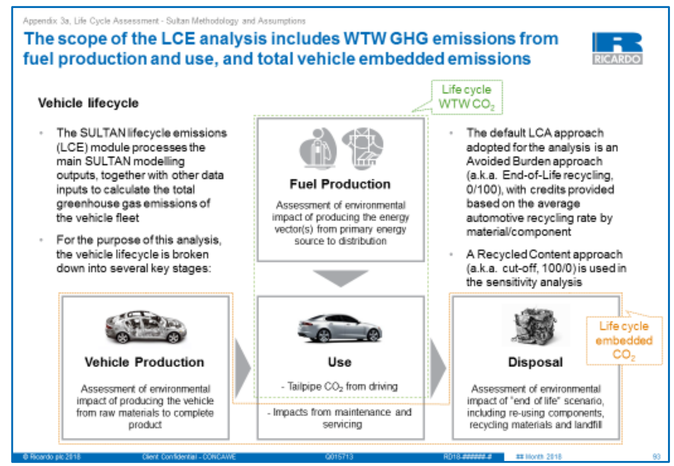




The study uses the SULTAN tool, with post-processing of electricity infrastructure & life cycle GHG emissions and a literature review

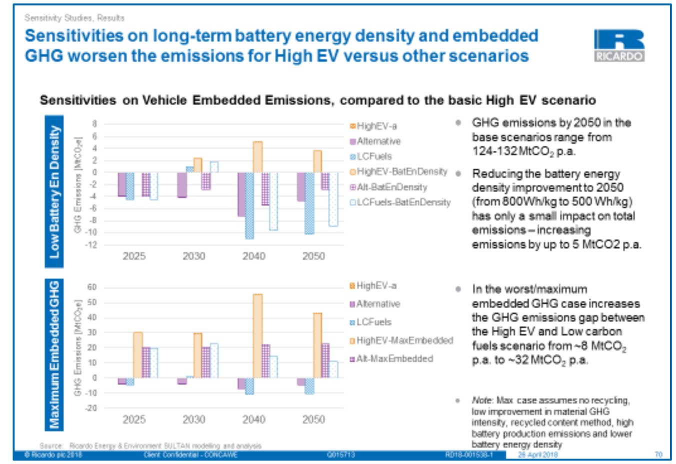
- The scenario modelling has been carried out using the SULTAN (SUstainabLe TrANsport) policy impact assessment tool
  - Key input assumptions including vehicle energy consumption, GHG emission factors, cost data, low carbon fuel avialability are described
  - The potential availability of biofuel and eFuel has been validated as reasonable by reference to other studies
- The SULTAN model outputs have been used with the following recharging scenarios to estimate costs for upgrading the network infrastructure
  - Managed (smart) vs. unmanaged charging
  - Home charging vs. 'grazing' where users charge little and often, using charging points away from the home to a greater degree
- Life cycle GHG emissions have been calculated including contributions from vehicle and fuel production, in-use and disposal
- The study is supported by an extensive literature search and analysis into the following:
  - Life Cycle Assessment
  - Electricity infrastructure and EV charging
  - Resources and materials





The sensitivity of impacts to key variables has also been studied

- Scenario sensitivities are also explored to better understand the importance of key assumptions in areas of particular uncertainty:
  - Sensitivities impacting on GHG emissions:
    - GHG intensity of electricity generation
    - Embedded emissions from vehicle production and disposal
    - Battery energy density
    - Availability of low carbon fuels
  - Sensitivities impacting on costs:
    - Future battery costs
    - Home vs grazing, and managed vs unmanaged charging
    - Low carbon fuel prices



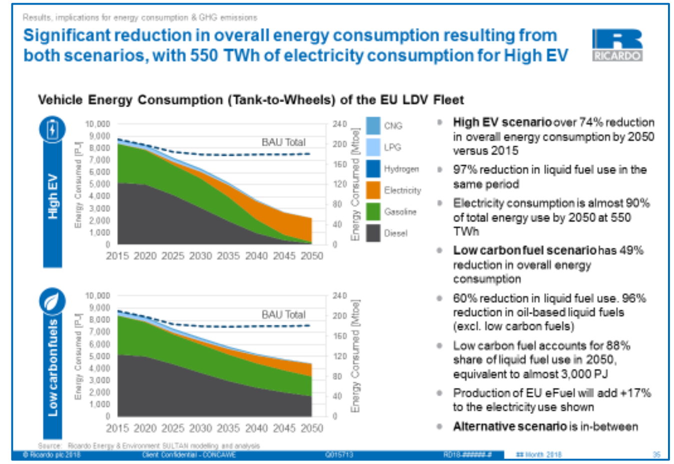
Lowest overall GHG emissions are in Low Carbon Fuels Scenario, while the largest reduction in total energy is in High EV

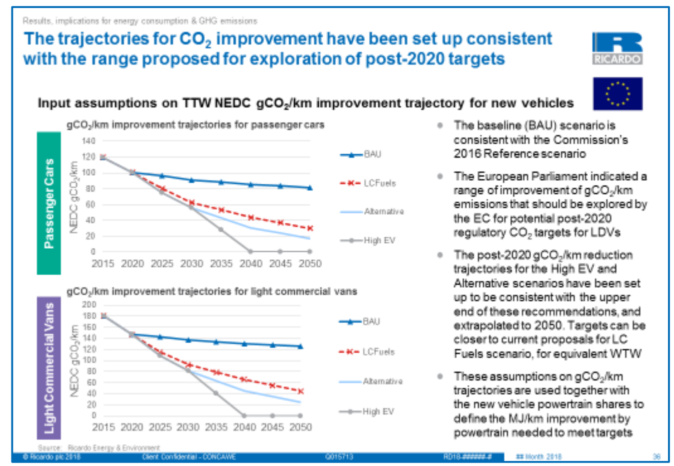
Energy

- All scenarios show at least 50% reduction in total energy use from 2015
- The High EV scenario shows the largest reduction in total energy, due to the relatively high efficiency of EVs, reducing by 74% from 8,775 PJ in 2015 to 2,234 PJ in 2050

GHG

- The three new scenarios achieve similar total GHG reduction targets
- The trajectories for fleet average tailpipe CO_2 improvement are greater (i.e. lower CO_2) than current EC proposals for all scenarios
- Total life cycle GHG emissions reduce by 84-86% from 2015 to 2050, and by >90% vs 1990, for all scenarios
- Life cycle CO_2 emissions are lowest for BEVs and half that of low carbon fuels vehicles at 2050, but overall fleet GHG emissions are lowest for the Low Carbon Fuels scenario in 2050

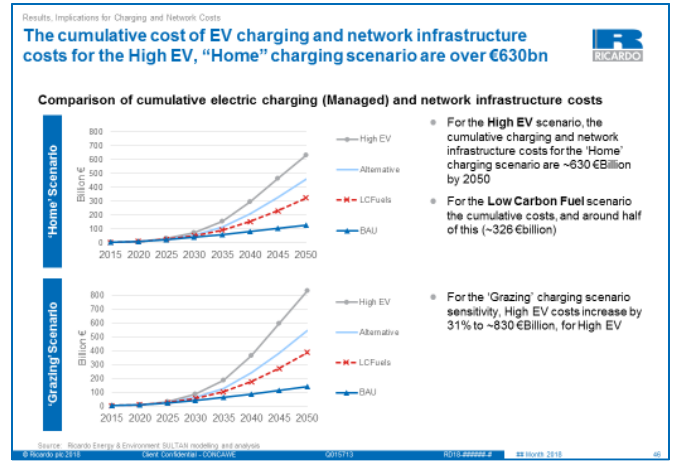




The largest reduction in total energy is in the High EV scenario, but the cumulative cost of EV charging infrastructure could reach €630bn

Electricity Consumption and Infrastructure

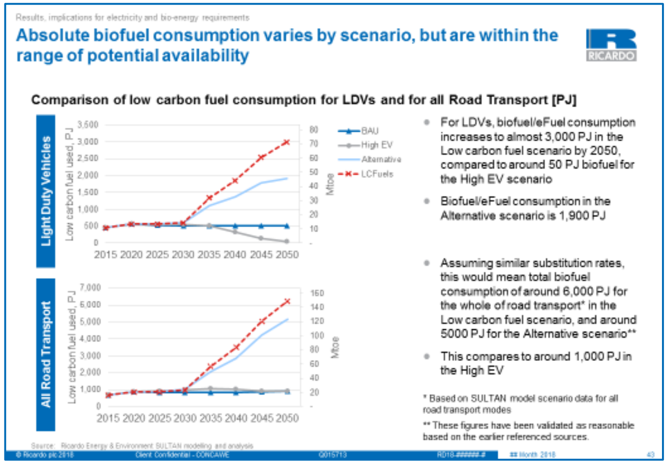
- The majority (~60%) of the 550 TWh of electricity required for EVs in 2050 from the High EV scenario is expected to come from home charging
- The 'Home' charging scenario would see lower costs compared to a 'Grazing' scenario – which has higher levels of public charging infrastructure
- The cost of EV charging infrastructure alone could reach €30 Billion p.a. by 2040 under the High EV scenario, and a cumulative cost of ~€630 Billion (~€326 Billion for Low Carbon Fuels scenario)
- Unmanaged charging would likely require significantly more upgrades to Low Voltage (LV) networks to support off-street and on-street charging (and therefore much higher cost – more than double the cost cumulatively to 2050)
- For all recharging scenarios, the need to replace secondary substations contributes most to infrastructure upgrade costs



Average TCO is lowest in High EV Scenario, but the annual parc total costs to the end user are similar for the High EV and LCF scenarios

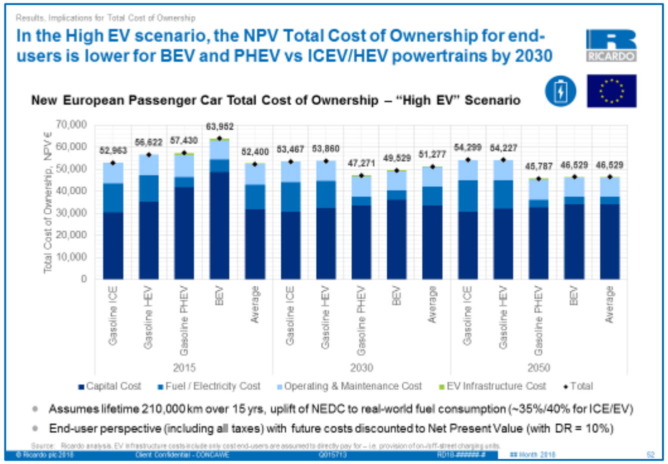
Low Carbon Fuels

- Absolute biofuel consumption varies by scenario, but all are within the range of potential availability identified



Total Cost of Ownership

- In the High EV scenario, the NPV Total Cost of Ownership (TCO) for end-users is lower for BEV and PHEV vs ICEV/HEV powertrains by 2030
- The High EV scenario provides the lowest average new vehicle TCO of all scenarios for end-users and society, but all scenarios reduce the TCO over time
- A gasoline PHEV provides the lowest TCO for end-users in 2050; BEVs provide the lowest cost for society
- The annual parc total costs to the end user are similar for the High EV and Low Carbon Fuels scenarios



The Low Carbon Fuels scenario requires less than half the Lithium resources of High EV

Resources and Materials

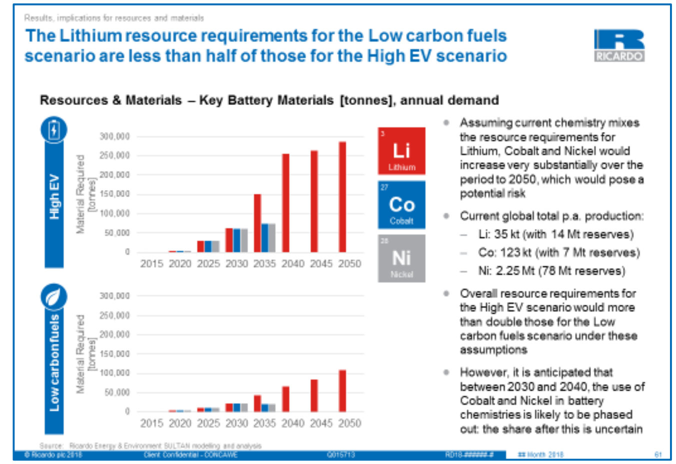
- Under the High EV scenario, ~15 Gigafactories (~1800 GWh) would be needed to supply batteries to the European EV market by 2050, compared to ~5.5 Gigafactories (~650 GWh) in the Low Carbon Fuels scenario by 2050
- The Lithium resource requirements for the Low Carbon Fuels scenario are less than half of those for the High EV scenario
- In the High EV scenario, peak virgin lithium demand (~220kt) is 6 times higher than global lithium production in 2016 (35kt)

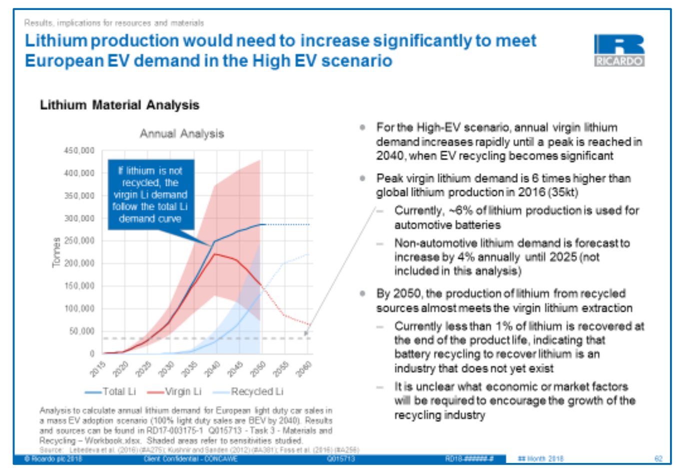
Externalities (Monetary values attached to the impacts of WTW emissions of GHG, NOx, PM and SOx)

- Externalities from emissions of GHG and air quality pollutants decrease significantly in both High EV and Low Carbon Fuels scenarios, but more under High EV

Energy security metrics

- Both the High EV and Low Carbon Fuel scenarios improve Energy Security in the long-term across a number of metrics included in the SULTAN model

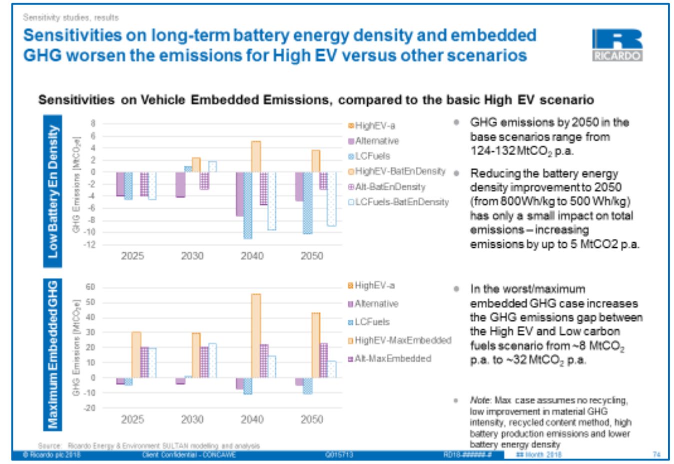


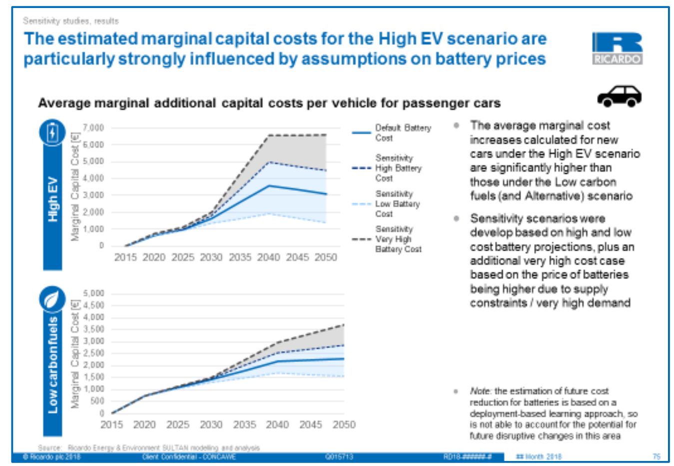


In the worst case GHG assumptions, High EV emissions are 32MtCO_2 p.a. higher than the Low Carbon Fuels scenario

Sensitivities

- Sensitivities on electricity GHG intensity show approximately up to +/-30% impacts on the total for the High EV scenario. Impacts are somewhat lower for the other scenarios
- The impact of the sensitivity on low carbon fuel availability (total substitution limited to 50% by 2050) for light duty vehicles results in a 55% increase in GHG emissions for the Alternative scenario for 2050, and 78% for the Low Carbon Fuel scenario
- 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.
- The worst/maximum embedded GHG case increases the GHG emissions gap between the High EV and Low Carbon Fuels scenario from ~8 MtCO_2 p.a. to ~32 MtCO_2 p.a.
- The estimated marginal capital costs for the High EV scenario are particularly strongly influenced by assumptions on battery prices





High battery cost assumptions lead to consistently higher costs for the High EV scenario. Net fiscal revenue could be reduced by up to €66bn

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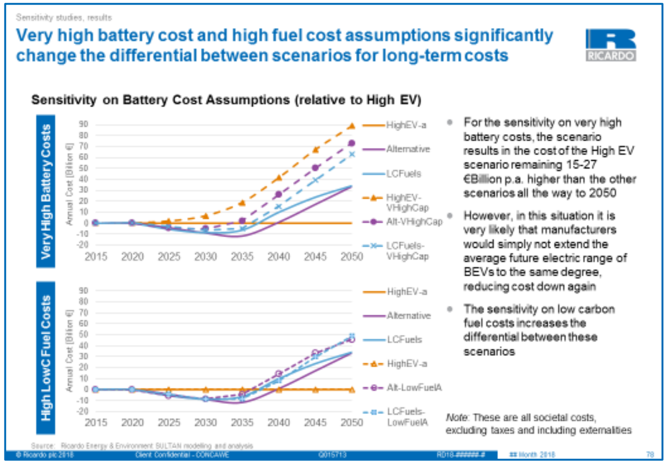
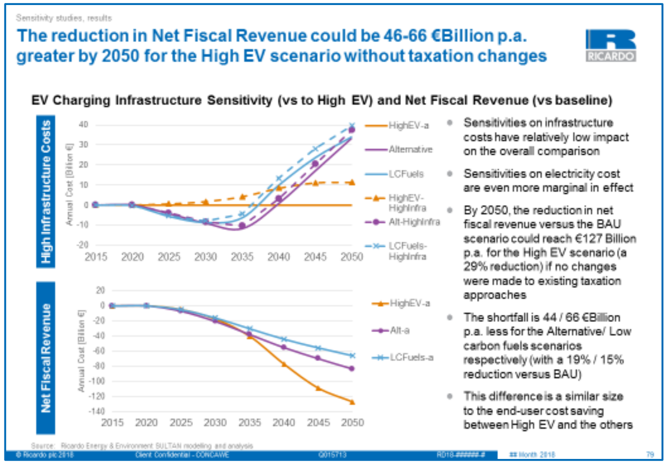
Sensitivities

- 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
- The reduction in Net Fiscal Revenue could be 46-66 €Billion p.a. greater by 2050 for the High EV scenario without taxation changes





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Abbreviations

Abbr.	Explanation	Abbr.	Explanation	Abbr.	Explanation
c.	Circa	DC	Direct Current	FSI	Fragile States Index
AC	Alternating Current	DER	Distributed Energy Resources	GB	Great Britain
ACEA	European Automobile Manufacturers' Association	DNO	Distribution Network Operator	GHG	Greenhouse Gas
ADMD	After Diversity Maximum Demand	DR	Discount Rate	Gpkm	Giga-passenger kilometres
AFV	Alternative Fuel Vehicle	DSO	Distribution System Operator	GWP	Global Warming Potential
ANM	Active Network Management	EC	European Commission	HDV	Heavy Duty Vehiclce
AQP	Air Quality Pollutant	EHV	Extra High Voltage	HEV	Hybrid Electric Vehicle
BAU	Business As Usual	ENA	Energy Networks Association	HV	High Voltage
BEV	Battery Electric Vehicle	EOL	End of Life	HVO	Hydrotreated Vegetable Oil
CAPEX	Capital cost (expenditure)	EU	Europe/European Union	ICCT	International Council on Clean Transportation
CBA	Cost-benefit analysis	EU28	EU 28 member states	ICE	Internal Combustion Engine
CCC	Committee on Climate Change	EV	Electric Vehicle	ICEV	ICE Vehicle
CCS	Carbon Capture System	FCEV	Fuel Cell Electric Vehicle	IEA	International Energy Agency
CNG	Compressed Natural Gas	FP7	Framework Programme 7	ILUC	Indirect Land Use Change

Abbreviations

Abbr.	Explanation	Abbr.	Explanation	Abbr.	Explanation
JEC	JEC Consortium (JRC, CONCAWE AND EUCAR)	**MV**	Medium Voltage	**SGAB**	Sub Group on Advanced Biofuels - European Commission
kVA	Kilo Volt Ampere (power)	**MVA**	Mega Volt Ampere (power)	**SOC**	State of Charge
LBST	Ludwig-Bölkow-Systemtechnik	**NEDC**	New European Driving Cycle	**SOx**	Sulphur Oxides
LCA	Life Cycle Assessment	**NFR**	Net Fiscal Revenue	**TCO**	Total Cost of Ownership
LCE	Life Cycle Emissions	**NOx**	Nitrogen Oxides	**ToU**	Time of Use
LCF	Low Carbon Fuel	**O&M**	Operation & Maintenance	**TTW**	Tank-to-Wheel
LCI	Life Cycle Inventory	**OEM**	Original Equipment Manufacturer	**TWh**	Tera Watt-hours
LCV	Light Commercial Vehicle/Van	**OHL**	Overhead Line	**UTC**	Coordinated Universal Time (Greenwich Meridian Time)
LDV	Light Duty Vehicle	**PHEV**	Plug-in Hybrid Electric Vehicle	**VAT**	Value Added Tax
LFP	Lithium Iron Posphate	**PIV**	Plug-in Vehicles	**WTT**	Well-to-Tank
LPG	Liquefied petroleum gas	**pkm**	Passenger kilometres	**WTW**	Well-to-Wheel
LV	Low Voltage	**PM**	Particulate Matter	**xEV**	X Electric Vehicle
MJ	Mega Joule	**PV**	Photovoltaic		
Mtoe	Million Tonnes of Oil Equivalent	**REEV**	Range Extended Electric Vehicle		

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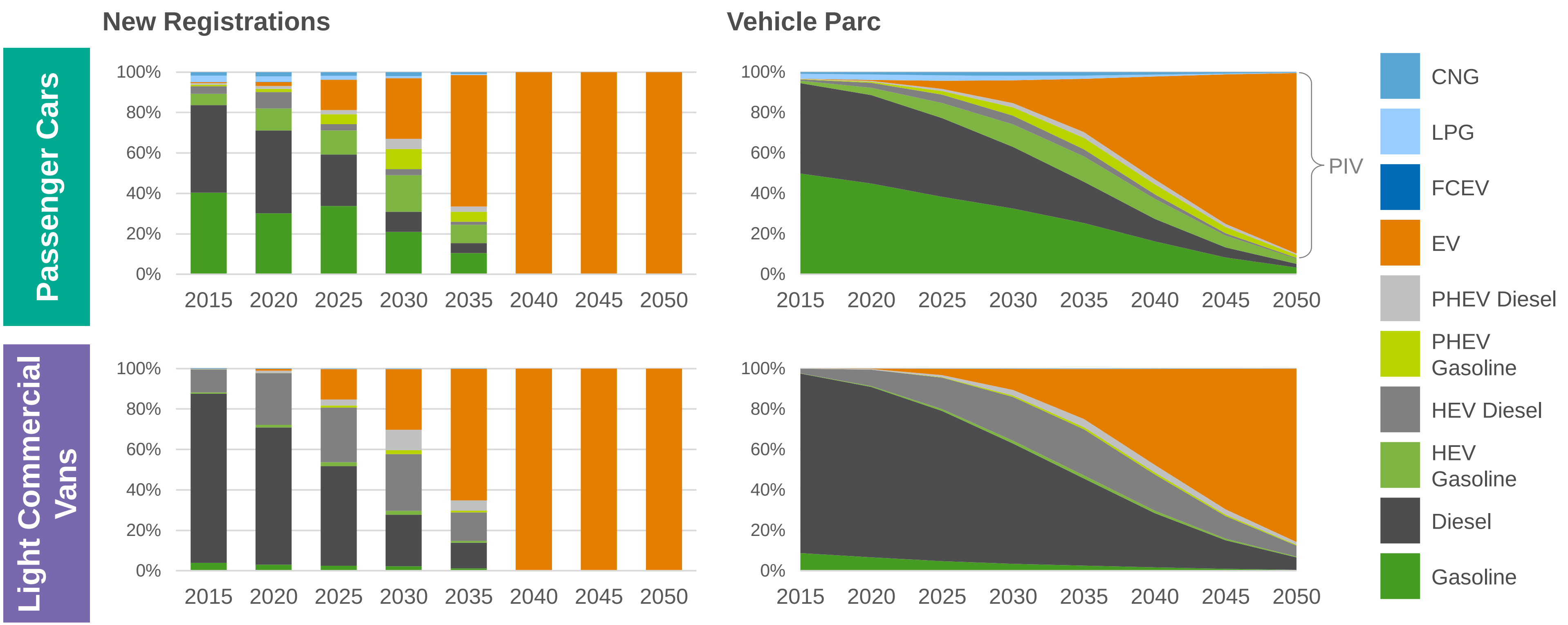
The High EV scenario has 100% BEV sales by 2040 and c.100% BEV parc by 2050

SULTAN “High EV” Scenario

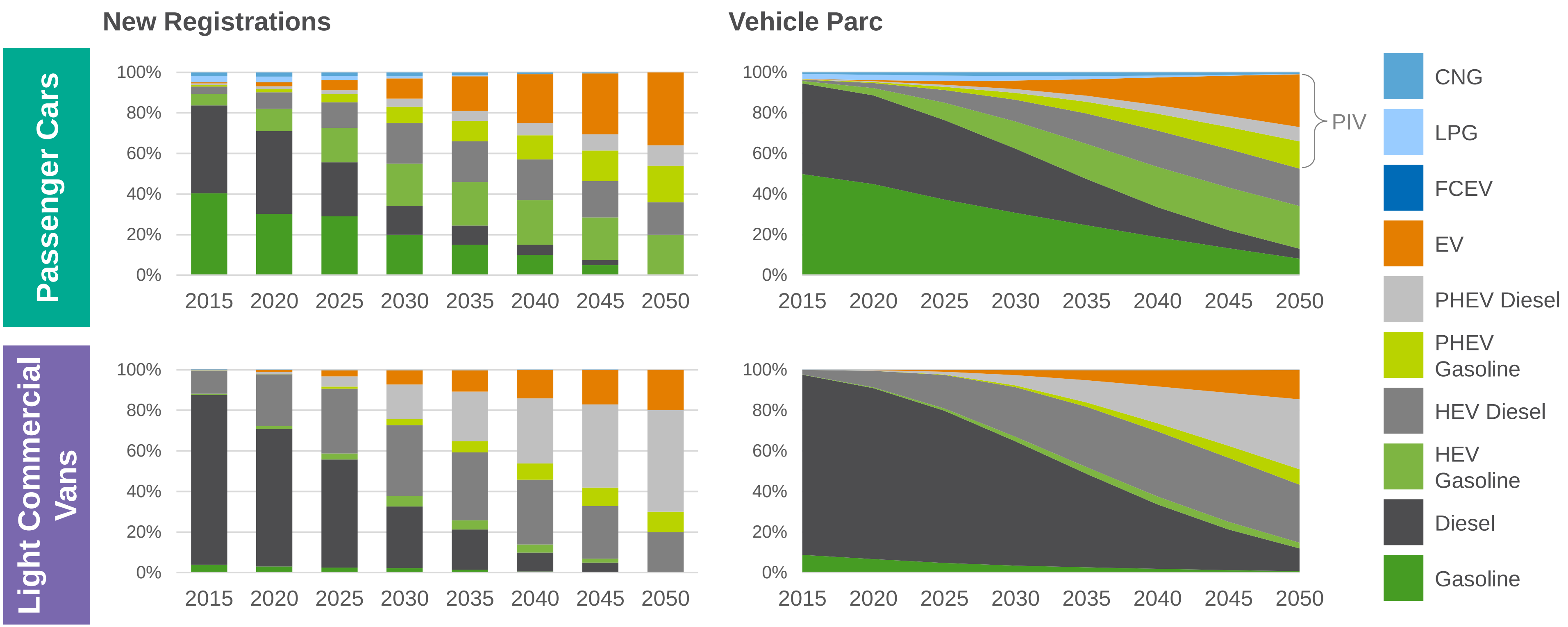


- Carbon reduction trajectory (tailpipe gCO_2/km) is consistent with the upper limit of %p.a. improvement indicated for exploration of post-2020 targets by the European Commission to 2030
- The trajectory increases, exceeding this post-2030 with the transition to 100% BEVs in 2040
- An assumed lower level of efficiency improvement in ICEV and Hybrids is required for higher EV uptake
- No change to biofuel share compared to BAU scenario

Source: Ricardo Energy & Environment

Ricardo has prepared a “Low Carbon Fuels” scenario with high use of low carbon fuels, lower xEV uptake and similar WTW CO_2

SULTAN “Low Carbon Fuels” Scenario



- Biofuel/eFuel share higher in 2020-2030, increasing rapidly post-2025, with 100% substitution for diesel in 2050
- Carbon reduction trajectory (tailpipe gCO_2/km) is set at a slightly lower %p.a. improvement versus High EV
- Tailpipe CO_2 [gCO_2/km] trajectory is further extrapolated using the same %p.a. improvement to 2050
- Increased efficiency improvement to ICEV and Hybrids compared to High EV scenario

Source: Ricardo Energy & Environment

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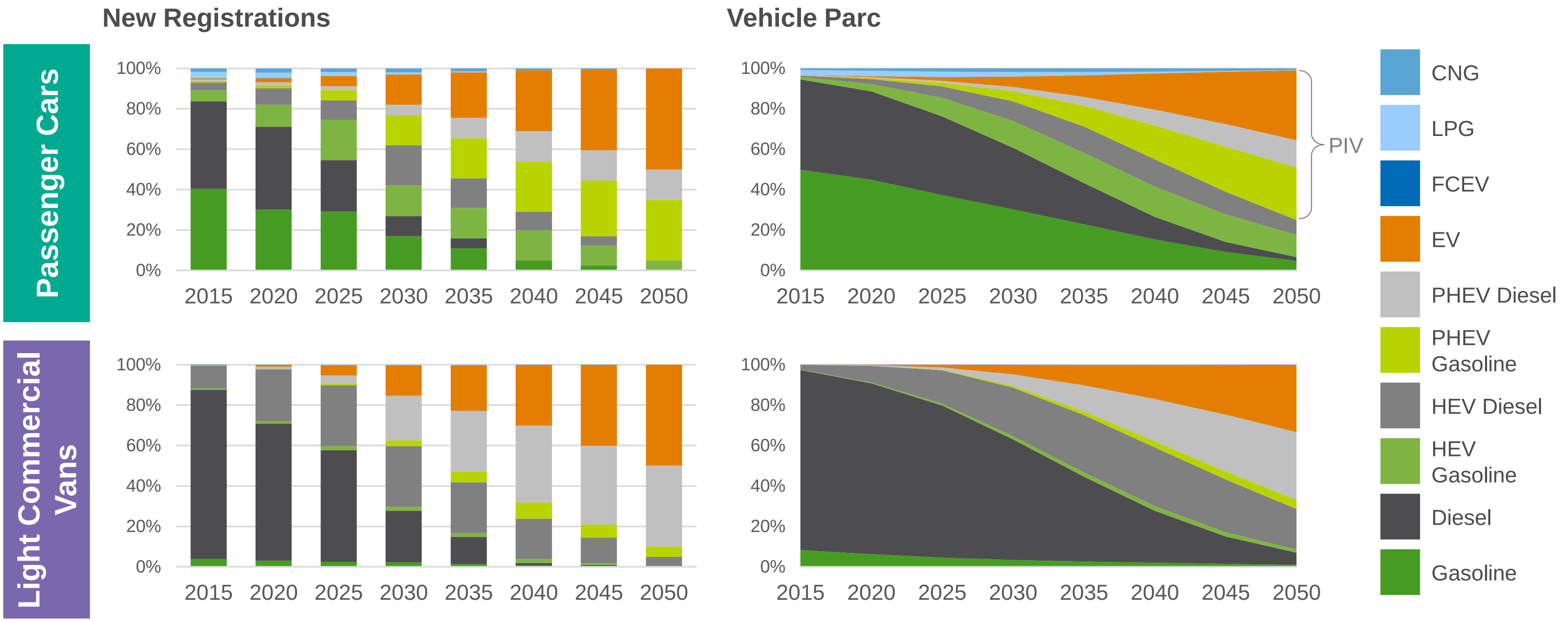
Ricardo has also prepared an "Alternative" scenario with lower BEV uptake, a moderate level of low carbon fuels, and similar WTW CO_2

SULTAN "Alternative" Scenario



- Carbon reduction trajectory (tailpipe gCO_2/km) is consistent with upper limit of %p.a. improvement indicated for exploration of post-2020 targets by the European Commission to 2030
- Tailpipe CO_2 [gCO_2/km] trajectory is further extrapolated using the same %p.a. improvement to 2050
- Increased efficiency improvement to ICEV and Hybrids compared to High EV scenario
- Increased share of biofuel / eFuel, rapidly increasing after 2030, reaching 100% /75% for diesel /gasoline by 2050

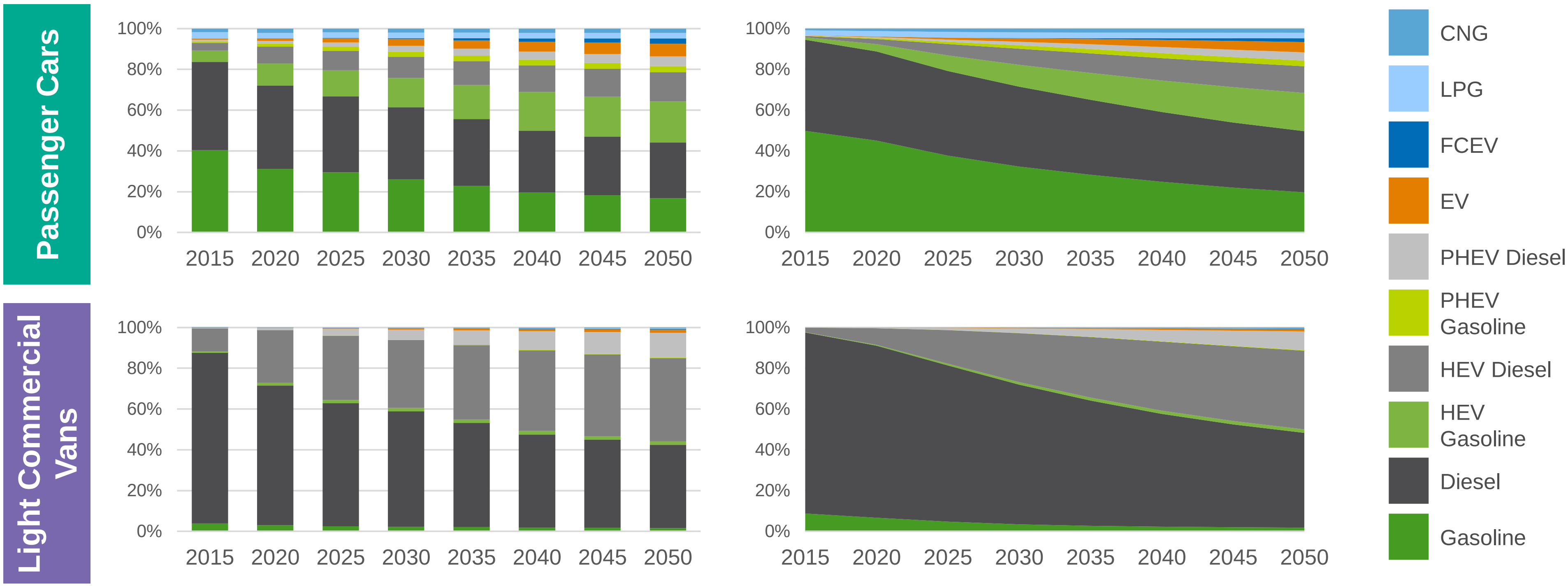
Source: Ricardo Energy & Environment

SULTAN has built-in scenarios, which have been used as a baseline for understanding the implications of mass EV adoption

SULTAN "BAU" Scenario

New Registrations

Vehicle Parc



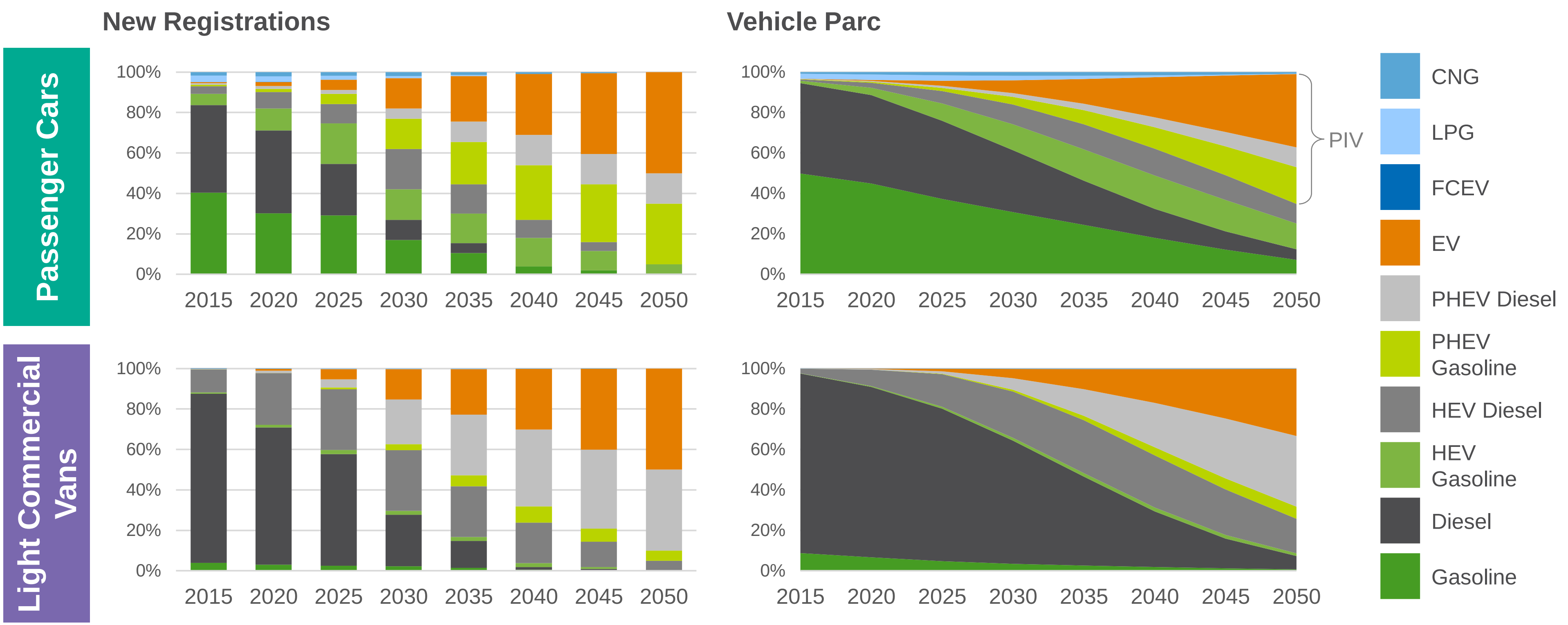
- The "business as usual" (BAU) scenario is a built-in scenario within SULTAN. It is used to provide a baseline for quantifying the impact of future policy changes
- The BAU scenario has been previously agreed with the European Commission, and is consistent with their official 2016 Reference scenario. It represents the default position if no changes are made to policy or legislation from those already in place/pending implementation today

Source: Ricardo Energy & Environment

Ricardo developed a Mixed Fleet scenario based on the “ERTRAC” scenario with xEV uptake, and significant levels of low carbon fuels,

WTW emissions approximately equivalent to other scenarios

SULTAN Mixed Fleet scenario based on “ERTRAC” Mixed Fleet Share Scenario

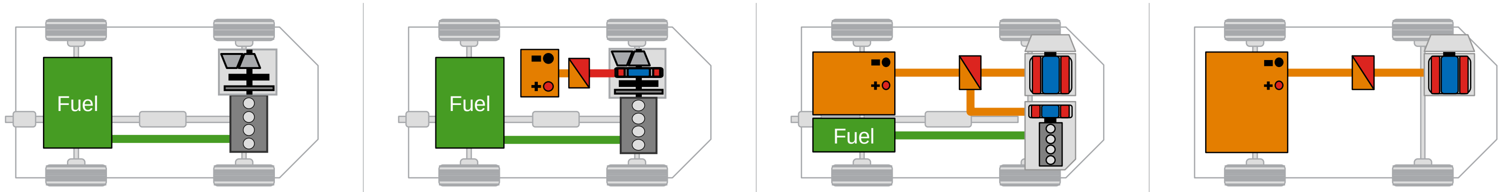


- Carbon reduction trajectory (tailpipe gCO_2/km) is consistent with upper limit of %p.a. improvement indicated for exploration of post-2020 targets by the European Commission to 2030
- Tailpipe CO_2 [gCO_2/km] trajectory is further extrapolated using the same %p.a. improvement to 2050
- Increased efficiency improvement to ICEV and Hybrids compared to High EV scenario
- Increased share of biofuels/eFuels, rapidly increasing after, reaching 100% / 75% for diesel /gasoline by 2050

Source: Ricardo Energy & Environment ERTRAC: European Road Transport Research Advisory study to be published

The specifications for 2015 powertrains are calibrated relative to the SULTAN baseline scenario for equivalent vehicles

European Passenger Car Vehicle Specifications 2015



	Gasoline	Gasoline HEV	Gasoline PHEV	Electric Vehicle
Engine	Gasoline	Gasoline	Gasoline	-
Battery Pack *	-	0.8 kWh NiMH	10 kWh Li-ion	24 kWh Li-ion
Electric Motor	-	39 kW	39 kW	72 kW
EV Range	-	-	50 km	180 km
Vehicle Mass	1,225 kg	1,275 kg	1,430 kg	1,560 kg
Fuel / Electricity Consumption (combined)**	5.5 L/100km	4.5 L/100km	1.9 L/100km 9.8 kWh/100km	13.5 kWh/100km

Notes: * Selection of battery capacity based on compromise between EV range, cost and mass

**Within the SULTAN modelling and LCE analysis, NEDC-based consumption is uplifted to real-world (~35%/40% for ICE/EV)

Source: Ricardo Energy & Environment SULTAN Modelling

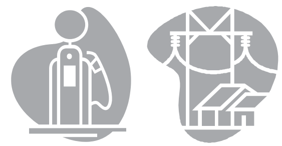
Contents

The scope of the LCA analysis includes WTW GHG emissions from fuel production and use, and total vehicle embedded emissions

Vehicle life cycle

- The SULTAN life cycle emissions (LCE) module processes the main SULTAN modelling outputs, together with other data inputs to calculate the total greenhouse gas emissions of the vehicle fleet
- For the purpose of this analysis, the vehicle life cycle is broken down into several key stages:

Life cycle WTW CO_2



Fuel Production

Assessment of environmental impact of producing the energy vector(s) from primary energy source to distribution

Vehicle Production

Assessment of environmental impact of producing the vehicle from raw materials to complete product

Use

- Tailpipe CO_2 from driving

- Impacts from maintenance and servicing

Disposal

Assessment of environmental impact of "end of life" scenario, including re-using components, recycling materials and landfill

Life cycle embedded CO_2

- 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
- A Recycled Content approach (a.k.a. cut-off, 100/0) is used in the sensitivity analysis

GHG emissions originating from each stage of the vehicle life cycle were analysed to determine total life cycle emissions

Methodology: Top-down LCA estimation (1/2)

- The SULTAN life cycle emissions (LCE) module calculates the GHG emissions associated with each phase of the vehicle life cycle. The following slides provide an overview of the LCA methodology, the elements considered in each life cycle stage and the data used for calculating the results
- Production is assumed to be primarily located in the EU for both vehicles and batteries. More detailed information concerning data sources and key assumptions are provided later in this Appendix
- **Vehicle production**
  - The environmental impact associated with producing vehicles from raw materials through to the complete product was assessed. For each transport mode and powertrain, data relating to the following elements was collected:
    - *Average vehicle composition by material* was obtained from the GREET model (https://greet.es.anl.gov/) and cross-checked with European datasets and recently published life cycle analyses of vehicles sold in the EU market. Expected developments in vehicle lightweighting are taken into consideration to develop projections for vehicle composition in the future. Note, lithium ion batteries were separated out from the rest of the vehicle as the impacts associated with Li-ion batteries are of specific interest to this study
    - *Emissions factors and automotive recycling rates* for each material were obtained from previous work performed by Ricardo Energy & Environment and updated during the project. These were complemented with data from the LCA ‘deep dive’, which allowed for sensitivities to be developed for materials emission factors and Li-ion battery production
    - *Energy (natural gas and electricity)* required to manufacture vehicles
    - *Vehicle transport* through the production process to the point of sale

GHG emissions originating from each stage of the vehicle life cycle were analysed to determine total life cycle emissions

Methodology: Top-down LCA estimation (2/2)

- **Fuel production**
  - The environmental impact of producing the energy vector(s) from primary energy source to distribution is calculated by the SULTAN model and processed within the LCE module. These emissions are also referred to as the indirect, or well-to-tank (WTT) emissions. Emissions from fuel production are dependent on the production pathway – trends in future years (for example, the decarbonisation of electricity) are therefore taken into consideration and are based on the EU Reference Scenario
- **Vehicle use**
  - The environmental impact of driving a vehicle can be divided into two main categories, as follows:
    - Fuel use: these are the CO_2 emissions produced while driving the vehicle. These emissions are also referred to as the direct, or tank-to-wheel (TTW) emissions. These are a direct output from the SULTAN model.
    - Operation and maintenance: these are the greenhouse gas emissions associated with maintenance and servicing of the vehicle during its lifetime. Other items such as refrigerant leakage are also taken into consideration. Data on these impacts was collected from previous work by Ricardo Energy & Environment
- **Vehicle disposal**
  - The environmental impact of vehicle disposal at the end of its life is taken into consideration during this phase. This includes the emissions from shipping the vehicle for disposal/recycling, energy requirements and the emissions from sending materials to landfill
  - Note, automotive recycling rates are taken into consideration in the vehicle production section and are therefore not accounted for in this stage to avoid double counting

A number of assumptions were made in the development of estimates for life cycle GHG emissions [1/5]

Assumed Trends – Vehicle Material Composition

- **Baseline material composition**
  - Data on 2015 vehicle composition (vehicle mass by material) was collected from the GREET model and scaled to be consistent with average EU vehicles (based on average mass). The data was cross-checked with a number of other databases and recently published LCAs and found to be comparable.
- **Future years**
  - Vehicle lightweighting projections (from Oeko Institute, et al, 2016*) were then used to estimate future vehicle material composition. These projections assume that the amount of steel, iron and several other materials will decrease, while the amount of aluminium and composites will substantially increase
  - In the absence of further data, it is assumed that an intermediate level of lightweighting (~20%) is achieved on average by 2030 and the full potential is reached only by 2050

2015 average gasoline car

Material	Mass%
Steel	62.21%
Plastics	11.28%
Cast iron	10.17%
Aluminium	6.29%
Glass	2.96%
Other	2.22%
Rubber	2.16%
Copper	1.86%
Lead	0.81%
Glass FRP	0.02%
Magnesium	0.02%
Zinc	0.00%
Carbon FRP	0.00%
Nickel	0.00%

Source: Ricardo analysis; * Oeko Institute, et al (2016): https://www.oeko.de/fileadmin/oekodoc/RenewbilityIII_Endbericht.pdf

A number of assumptions were made in the development of estimates for life cycle GHG emissions [2/5]

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Assumed Trends – Material Carbon Intensity Factors kgCO_2e/kg material

- **Baseline emissions factors**
  - Materials emissions factors were gathered from previous work carried out by Ricardo Energy & Environment for the CCC
  - To calculate the emissions from vehicle production, the amount of material in the vehicle is multiplied by the emissions factor for that material
  - In the SULTAN LCE module, recycling is accounted for during vehicle production (rather than during vehicle disposal). Recycling rates are therefore defined for each material and the overall emissions associated with that material are calculated as a weighted average of the virgin material and recycled material emissions factors
  - The values used in 2015 are shown in the table on the right in kgCO_2e/kg material
  - A sensitivity was also conducted using instead average recycled content

Material	Recycling rate	Recycled content	2015: Virgin materials EF	2015: Recycled materials EF
Steel	95%	39%	2.09	0.76
Cast iron	95%	39%	1.81	0.48
Aluminium	91%	33%	8.65	0.45
Copper	80%	37%	3.44	0.76
Zinc	90%	30%	3.78	0.47
Magnesium	100%	50%	55.85	27.38
Glass	60%	0%	1.22	0.53
Plastics	93%	24%	3.49	2.15
Rubber	85%	0%	2.74	0.80
Carbon FRP	0%	0%	19.07	0.00
Glass FRP	0%	0%	6.93	0.00
Nickel	0%	0%	11.94	0.00
Lead	100%	62%	3.05	0.52
Textiles	80%	0%	18.57	14.91
Electronics	0%	0%	25.00	0.00
Other	30%	0%	0.00	0.00
Lubricating oil	98%	0%	0.97	0.45
Refrigerant	0%	0%	0.00	0.00

Note: EFs include accounting for all upstream processes, including mining

Source: Ricardo Energy & Environment analysis

A number of assumptions were made in the development of estimates for life cycle GHG emissions [3/5]

Assumed Trends – Material Carbon Intensity Factors

- **Emissions factors in future years**
  - In future years, emissions from raw materials are expected to decrease, as processes are decarbonised.
  - Each material used in vehicles has been allocated a trajectory from the table below. Materials emissions factors trajectories are based on IEA (2017) analysis and analytical work carried out by Ricardo Energy & Environment for the UK Committee on Climate Change (2013)
  - Sensitivity analysis was also performed, giving results for higher emission trajectories based on IEA analysis

Trajectory	Sensitivity	Units	2010	2020	2030	2040	2050
Steel	Central	% of 2010 value	100%	81%	61%	42%	23%
Aluminium	Central	% of 2010 value	100%	79%	58%	37%	16%
Plastics	Central	% of 2010 value	100%	67%	38%	33%	28%
Composites	Central	% of 2010 value	100%	73%	37%	23%	15%
Other	Central	% of 2010 value	100%	93%	85%	78%	70%

Source: Ricardo Energy & Environment analysis; IEA (2017): IEA Global EV Outlook 2017

A number of assumptions were made in the development of estimates for life cycle GHG emissions [4/5]

Assumed Trends – Battery Pack Carbon Intensity Factors

- **Lithium-ion batteries**
  - Li-ion batteries account for a significant proportion of GHG emissions. This area is therefore of particular importance to this study, given that the aim is to investigate the potential impacts of mass EV deployment
  - The SULTAN LCE module has built-in functionality to consider three sensitivities (low, central and high) and also whether battery recycling takes place, or not. The sensitivities were developed based on the LCA deep dive and rapid evidence assessment
  - As for materials emission factors, trajectories were developed based on work Ricardo Energy & Environment carried out for the CCC (2013)
- **2010 emissions factors**

Sensitivity	$kgCO_2e/kg$ battery
Low	4.4
Central	15.3
High	30.0

- **Li-ion battery emission factor trajectory**
  - Projected improvement due to reduction in energy and industrial GHG intensity to 2050

Units	2010	2020	2030	2040	2050
Default % of 2010 value	100%	81%	61%	42%	23%
Sensitivity % of 2010 value	100%	90%	80%	70%	59%

Source: Ricardo Energy & Environment analysis

A number of assumptions were made in the development of estimates for life cycle GHG emissions [5/5]

Vehicle End-of-Life

- **Vehicle disposal**
  - Several factors are considered when calculating emissions associated with vehicle 'end of life'. Primarily, these are:
    - Shipping of vehicle for disposal/recycling – broken down into train, lorry and ship
    - Energy for recycling/disposal – broken down into electricity and natural gas
    - Disposal to landfill
  - Emissions credits from vehicle recycling are accounted for in the vehicle production section

- **Shipping of vehicle for disposal**
  - Prior to recycling/disposal, it is assumed that vehicles will be shipped approximately 550km by train, 400km by lorry and 2,000km by ship. These values are derived from Ricardo Energy & Environment work for the CCC

- **Energy for recycling/disposal**
  - Based on Ricardo Energy & Environment's work for the CCC, an energy required of 0.7kWh/kg material recycled is assumed in this analysis

Source: Ricardo analysis,

Contents

Ricardo reviewed >100 papers with data on vehicle LCA and associated environmental impacts, including finding new entries

Literature Review Status – 27 September 2017

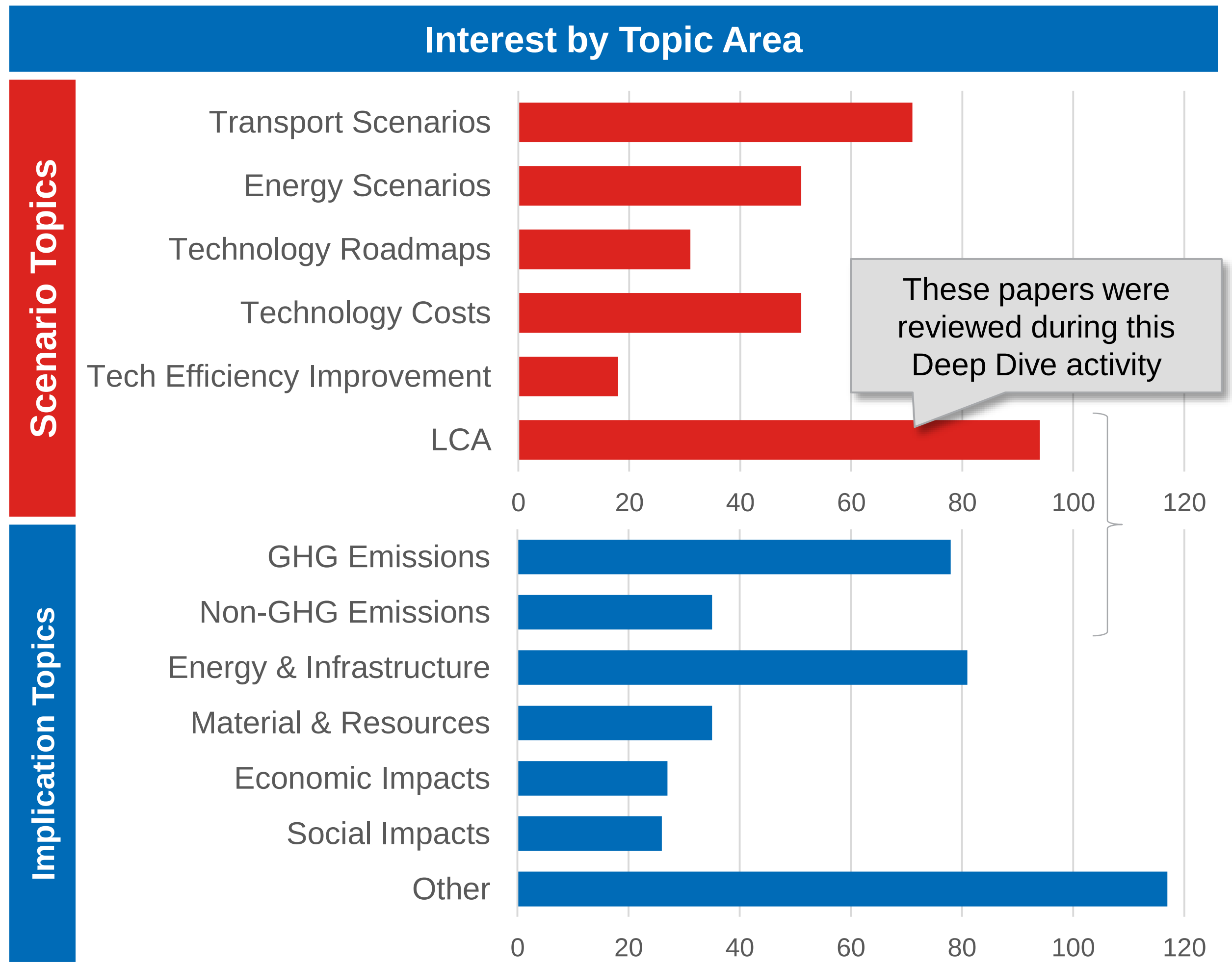
401 **abstracts identified**

10+ Literature Searches completed

175 papers scan read or reviewed

Priority Ranking	
High	65 papers
Medium	138 papers
Low	161 papers
Not Relevant (‘-’)	37 papers

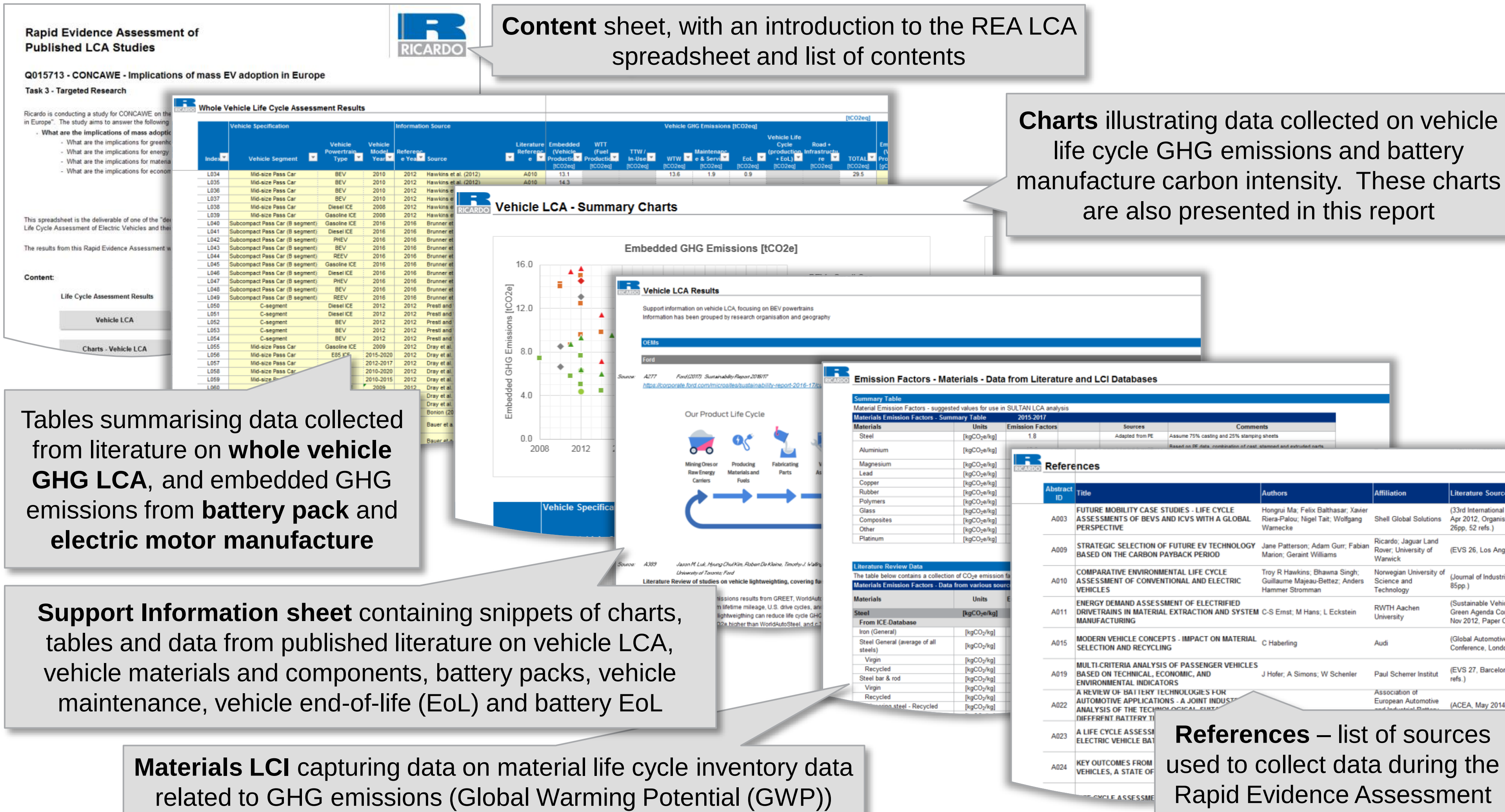
Geography	
Europe or European Country	215 papers
Global	93 papers
Other	54 papers



See the Literature Review Database (RD17-002577) for a full set of the results, including the list of literature searches (“Searches” tab) and Literature database (“Literature Scan”)

The main output from this Deep Dive is the "Rapid Evidence Assessment of Published LCA Studies" spreadsheet (RD17-002993)

Guide to "Rapid Evidence Assessment of Published LCA Studies" spreadsheet



Content sheet, with an introduction to the REA LCA spreadsheet and list of contents

Charts illustrating data collected on vehicle life cycle GHG emissions and battery manufacture carbon intensity. These charts are also presented in this report

Tables summarising data collected from literature on **whole vehicle GHG LCA**, and embedded GHG emissions from **battery pack** and **electric motor manufacture**

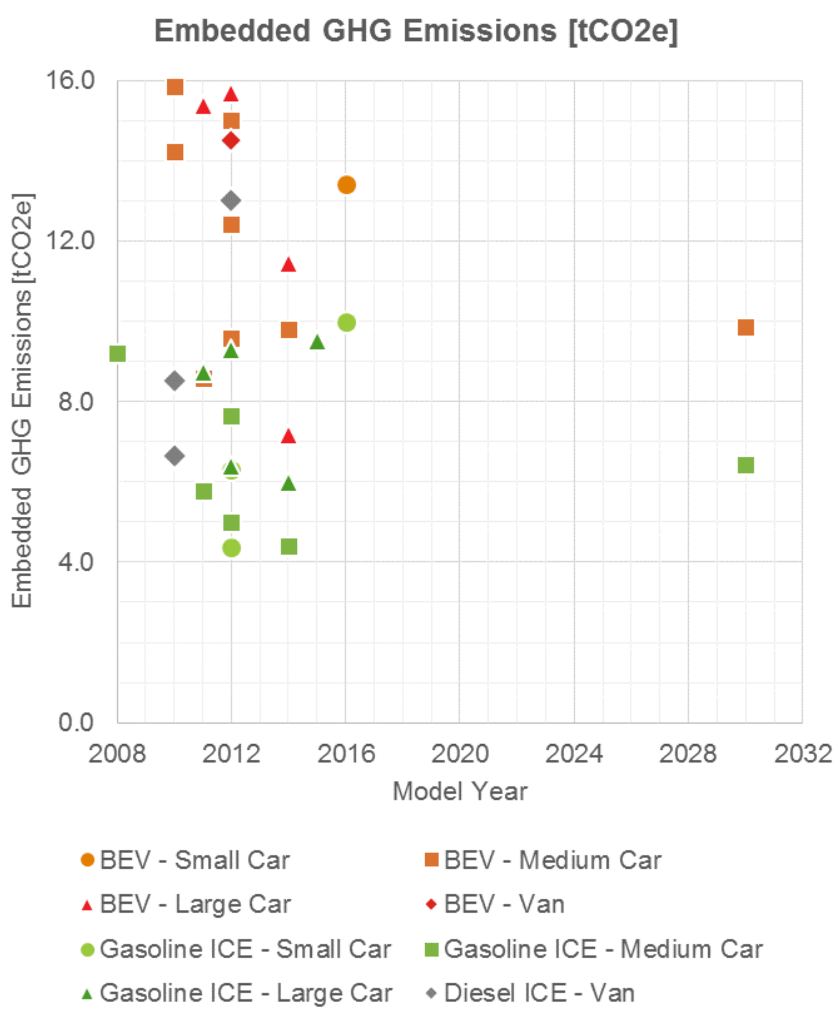
Support Information sheet containing snippets of charts, tables and data from published literature on vehicle LCA, vehicle materials and components, battery packs, vehicle maintenance, vehicle end-of-life (EoL) and battery EoL

Materials LCI capturing data on material life cycle inventory data related to GHG emissions (Global Warming Potential (GWP))

References – list of sources used to collect data during the Rapid Evidence Assessment

Published LCA studies concur that BEVs have higher embedded GHG emissions than their equivalent gasoline and diesel ICEs

Life Cycle Embedded GHG Emissions

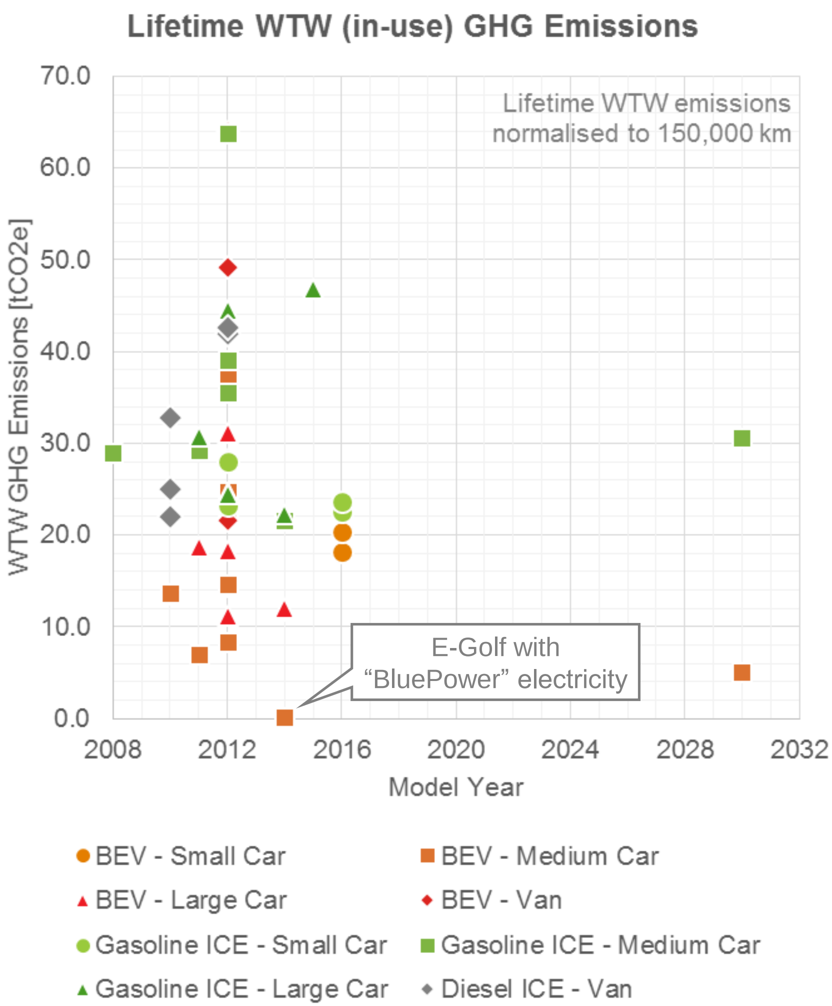


- In general, BEVs have higher embedded GHG emissions than their gasoline ICE equivalents (c.20-60% increase)
  - This is expected to continue until at least 2030, although the magnitude of the difference will decrease
  - The higher embedded GHG emissions is mostly due to the battery pack – its materials and energy required for manufacture and assembly
- There is a wide variability in published results. Reasons for the variability include:
  - Size of vehicle
  - Selection of underlying life cycle inventory (LCI) database and LCA modelling tool
  - Inclusion or exclusion of energy required during vehicle manufacture
  - Assumptions regarding vehicle material composition
  - Battery pack capacity, cell chemistry, and assumed carbon intensity factor

Source: Ricardo analysis of published LCA studies – see RD17-002993 for chart data

However, lifetime WTW GHG emissions are generally lower, unless electricity carbon intensity is high

Lifetime Well-to-Wheels GHG Emissions

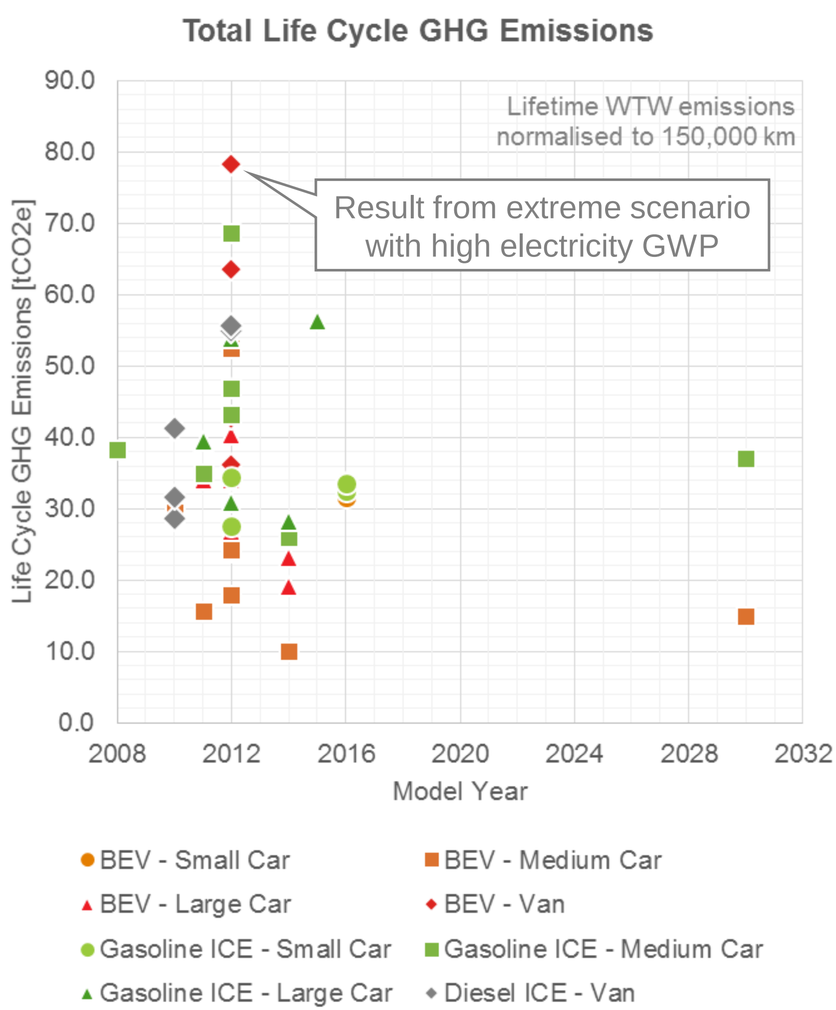


- In general, gasoline and diesel ICE vehicles have higher lifetime WTW GHG emissions than BEVs. Although this is dependent on assumptions regarding vehicle energy consumption, efficiencies, and electricity GWP
  - If electricity carbon intensity (GWP) is high (e.g. coal powered generation without CCS), then BEV lifetime WTW GHG emissions may be as high or higher than WTW GHG emissions from gasoline and diesel vehicles

Source: Ricardo analysis of published LCA studies – see RD17-002993 for chart data

So, overall life cycle GHG emissions for BEVs are generally lower than for gasoline and diesel ICEs

Total Life Cycle GHG Emissions



Source: Ricardo analysis of published LCA studies – see RD17-002993 for chart data

- For most LCA studies and sensitivity scenarios, BEV life cycle GHG emissions are lower than gasoline and diesel ICE equivalent vehicles
- There are a few exceptions, usually related to sensitivity scenarios with high electricity GWP
  - Since BEV have higher embedded GHG emissions, if the electricity GWP is as high as gasoline and diesel WTW emissions, then the BEV will have higher life cycle GHG emissions

However, some LCA studies suggest BEVs may have higher life cycle acidification environmental impacts

SELECTED EXAMPLES

Other life cycle environmental impacts

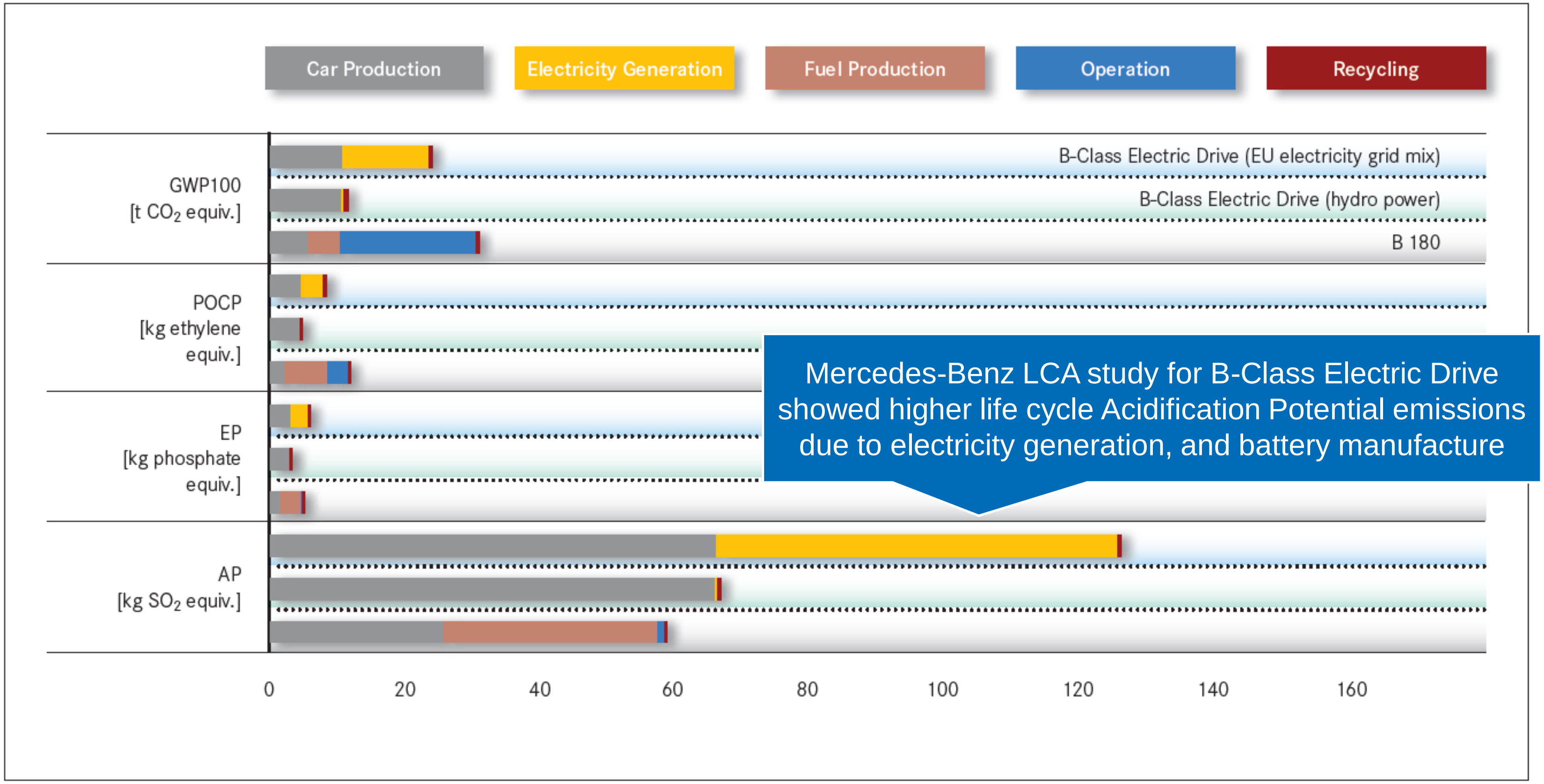
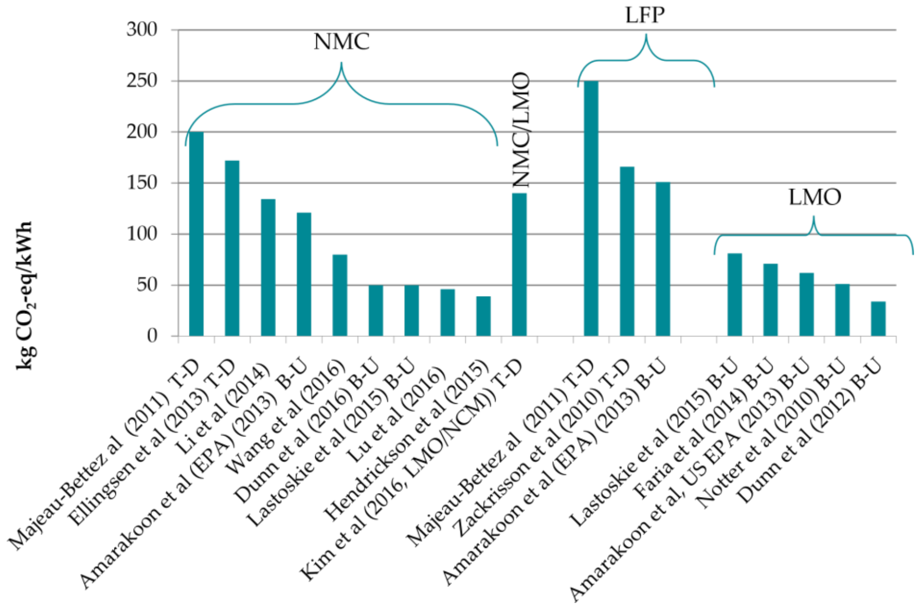


Figure 2-7: Selected LCA parameters for the new B-Class Electric Drive compared with the B 180 petrol-engine variant [unit/car]

A few recent LCA papers reveal deeper understanding of the environmental impact of battery production …

Li-ion Battery Pack Cradle-to-Gate GHG Emissions (1/3)

- There are a couple of key papers that add to our understanding of embedded GHG emissions due to battery pack manufacture, such as Kim et al. (2016) and Ellingsen et al. (2014)
  - Kim et al. (2016) claim to have conducted the first cradle-to-gate LCA study of a mass-production Li-ion battery pack, as used in Ford Focus BEV, with data from cell and pack suppliers
  - Ellingsen’s assessment includes actual factory energy consumption provided by a battery cell manufacturer
  - Hao et al. (2017) used the latest ANL GREET and BatPac models to compare the battery manufacture in China with USA
  - Romare and Dahllöf (2017) recently published a detailed comparison on published studied, commissioned by the Swedish Energy Agency and Swedish Transport Administration

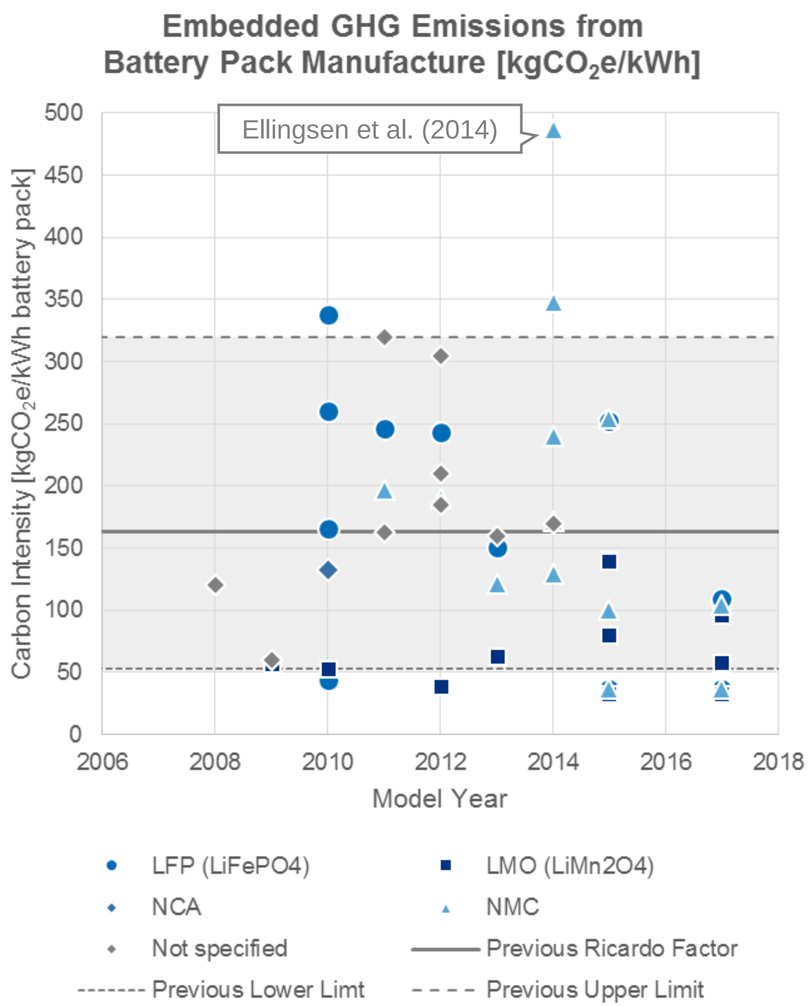


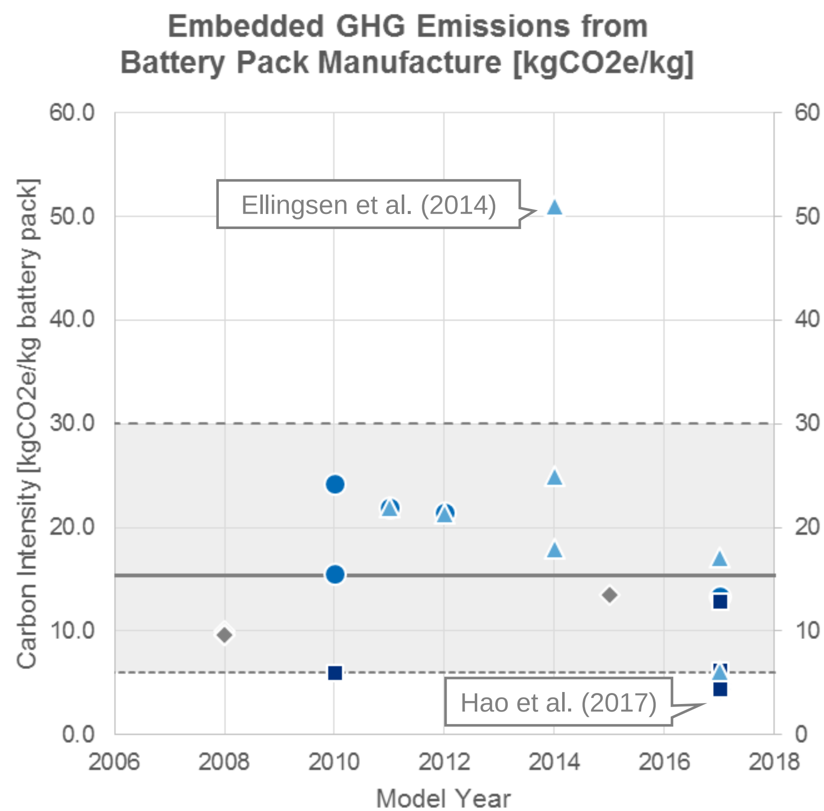
Picture: Romare and Dahllöf (2017) (Figure 3)
Calculated greenhouse gas emissions for different LCA studies of lithium-ion batteries for light vehicles for the chemistries NMC, NMC/LMO, LFP and LMO.
Top-Down (T-D) approach uses manufacturing data from a battery cell or pack assembler. Energy use is allocated to processes, based on information about the processes
Bottom-Up (B-U) approach using data collected for a single activity in a facility

Source: Kim et al. (2016) CRADLE-TO-GATE EMISSIONS FROM A COMMERCIAL ELECTRIC VEHICLE LI-ION BATTERY: A COMPARATIVE ANALYSIS. (Environmental Science & Technology, 19 Jul 2016, Vol. 50, Issue 14, pp7715-7722.) [A062]; Ellingsen et al. (2014). Life Cycle Assessment of a Lithium-Ion Battery Vehicle Pack. Journal of Industrial Ecology. Vol 18. Part 1. Pages 113-124 [A394]; Romare and Dahllöf (2017). The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries - A Study with Focus on Current Technology and Batteries for light-duty vehicles. Report commissioned by Swedish government [A271]; Hao et al. (2017). GHG Emissions from the Production of Lithium-Ion Batteries for Electric Vehicles in China. [A176]

… however, there is still a wide range of results, which could have significant implications for BEV life cycle environmental impact

Li-ion Battery Pack Cradle-to-Gate GHG Emissions (2/3)





Cradle-to-gate GHG emission from Li-ion battery production should be compared on per kWh and per kg basis, since studies have different assumptions regarding battery specific energy [kWh/kg]

Source: Ricardo analysis of published LCA studies – see RD17-002993 for chart data

Reasons for variation relate to input assumptions about battery chemistry, energy for manufacture, and material LCI data, etc.

Li-ion Battery Pack Cradle-to-Gate GHG Emissions (3/3)

- More information has been published on battery cell and pack materials, manufacture and assembly processes, and energy consumption
- Many researchers are now using the BatPac and GREET models provided by Argonne National Laboratory for LCA of xEVs
- However, older BEV LCA studies (pre-2012) are still frequently referred to in literature reviews
- And, results still vary widely. Reasons for this variation include:
  - Assumptions regarding battery chemistry, and component breakdown
  - Assumptions regarding battery density [kWh/kg] – many academic studies assume higher energy density values than OEMs
  - Assumptions regarding energy required for manufacture, energy GWP and region of production
  - Selected material life cycle inventory databases, and LCA modelling tools (GaBi, SimaPro, GREET or other)

A Review of Battery Technologies for Automotive Applications

Lithium-ion Electric Vehicle Battery, courtesy of Nissan

Picture: Eurobat et al. (2014)

Source: Ricardo analysis of published LCA studies – see RD17-002993 for chart data

To conclude, the life cycle GHG emission benefits of xEVs is highly dependent on electricity, and the battery pack is a major contributor

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BEV LCA – Key Messages from Deep Dive (1/2)

- The life cycle GHG emission benefits of BEVs is highly dependent on the carbon intensity of the electricity used
  - Therefore, transport decarbonisation policies involving plug-in vehicles must be in tandem with policies to decarbonise electricity
  - Across Europe, each member state already has plans and policies designed to decarbonise electricity (see "Energy Infrastructure and EV Recharging" deep dive)
- In general, BEVs already have lower life cycle GHG emissions than conventional ICE and HEV technologies
- The battery pack is a major contributor to the embedded and end-of-life emissions of a plug-in vehicle
  - According to recent literature, production processes for the battery cells and pack assembly are well understood
  - However, the carbon intensity factor for a Li-ion battery pack continues to vary widely study to study (results range from 4.4 – 24.3 kgCO_2e/kg battery pack). Factors influencing this variation include:
    - Battery chemistry
    - Assumptions regarding energy required, and energy source
    - Material life cycle inventory databases, and LCA modelling tools

But OEMs are actively seeking to mitigate the environmental impact through use of LCA tools and adopting life cycle philosophies

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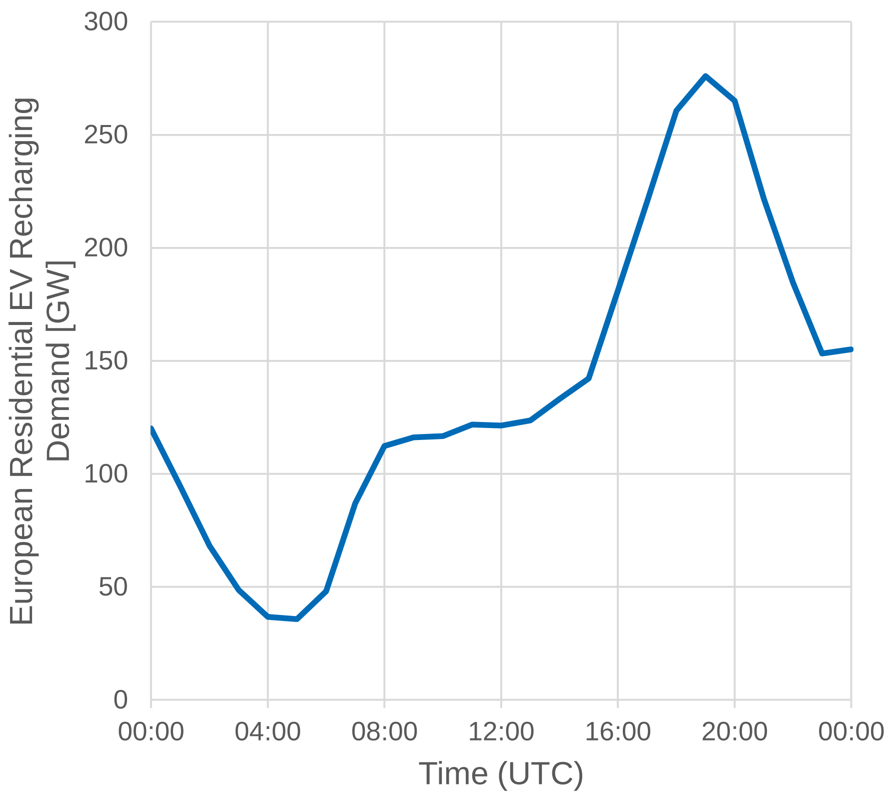
BEV LCA – Key Messages from Deep Dive (2/2)

- Most of the major automotive OEMs are already using LCA tools to measure the environmental impact of their products
  - There will be opportunities to reduce life cycle GHG emissions through further adoption of a life cycle philosophy
- Many academic researchers are now using GREET and BatPac models provided by Argonne National Laboratory in USA, and NREL's ADVISOR vehicle simulation tool to support their LCA studies of passenger cars

Contents

Unmanaged EV recharging will greatly increase the peak electricity demand. It is likely that managed (smart) charging will be required

The Potential Effect of Unmanaged EV Recharging on Electricity Demand



2050 scenario for European load profile for EV recharging developed using results from GB My Electric Avenue project (2012-2015). Chart shows potential peak demand from EV recharging at home across Europe for a typical weekday.

- The estimated **peak demand** from unmanaged EV recharging for the whole EU28 is **276 GW** at 19:00 UTC. This is likely to coincide with the non-EV peak electricity demand, which is traditionally highest on a weekday evening
  - For context, this peak demand is **22%** of the expected EU28 **electricity generation capacity** in 2050

GB Case Study

- A National Grid scenario estimated peak demand (excluding EV recharging) of **58.8 GW** in 2050
- From Ricardo analysis, the estimated peak demand from EV charging in UK is **37 GW**
  - After correcting for differences in EV parc share, the National Grid scenario containing uncontrolled recharging suggests a peak demand from EVs of 32 GW
- Although calculating the peak demand varies according to assumptions on consumer behaviour, this indicates that unmanaged recharging would require a very large increase in generation capacity

Source: My Electric Avenue (2015) (#A374); Cluzel and Hope-Morley (2015) (#A334); Capros et al. (2016) (#A396); National Grid (2017) (#A284); Ricardo analysis

Managed EV recharging could reduce the need to increase the generation capacity by avoiding times of peak electricity demand

The Potential Effect of Managed EV Recharging on Electricity Demand

- Current literature suggests that managed or smart EV recharging could avoid the increase in peak electricity demand, or result in small increases that could be catered for without increased generation capacity
  - Although managed charging is usually associated with networked smart charging, time of use tariffs have been found to have an effect in adjusting consumer behaviour towards recharging during off-peak periods
  - Public and work charging will also impact the time of charging, and help to avoid evening peak charging
- Aside from reducing the impact on peak demand (and therefore generation capacity), managed recharging can also be implemented at a local level to resolve thermal and voltage issues in the distribution network. Managed EV charging can delay network reinforcement
  - Managed charging could also work in parallel with Distributed Generation
- Trials have shown users of managed charging are in general not adversely effected by managed recharging
  - Studies in this area are currently ongoing

Source: Cluzel and Hope-Morley (2015) (#A334); My Electric Avenue (2015) (#A374); Skippon, S. (2016) (#A208); Eurelectric (2015) (#A365)

Contents

Introduction - Electricity Infrastructure and PIV Charging of High EV scenario

- This Appendix provides further details on the analysis of the impact of the High EV scenario on Electricity infrastructure and Plug-In vehicle (PIV) recharging
- The infrastructure and recharging analysis examined the following impact questions:
  - What will be the increase in peak electricity demand with and without managed (smart) EV recharging?
  - What are the options for recharging EVs?
  - How much will it cost to install a rapid charging station equivalent to a current fuel station?
  - What are the potential implications for the European electricity grid?
  - How much of the existing electricity grid will need to be upgraded? What will this cost?
  - What is the current variation in electricity generation carbon intensity across Europe?
  - How is this forecast to change by 2050?
  - How does this effect the Well-to-Tank emissions of EVs, and what is the variation across Europe?

The electricity grid uses a range of voltage levels and networks to distribute electricity from generators to end consumers

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SIMPLIFIED

Design of the Electricity Grid

This diagram is a simplified, generic representation of the European power network ignoring redundancy, and not showing regional differences

Generation

Transmission Network	400 kV / 275 kV	
	Grid Supply Point	500 – 2000 MVA
Extra High Voltage Network	EHV (132 kV)	
	Bulk Supply Point	100 – 500 MVA
High Voltage (HV) Network	HV (33 kV – 22 kV)	
	Primary Substation	20 – 100 MVA
Medium Voltage (MV) Network	MV (11 kV – 10 kV)	
	Secondary Substation	0.2 – 1 MVA
Low Voltage (LV) Distribution Network	LV (400 V three phase - 230 V single phase)	

Load

The electricity distribution network is sized to allow for load growth. Each asset is expected to last for 20 to 60 years

A 100 MVA bulk supply point will supply c.65,000 homes

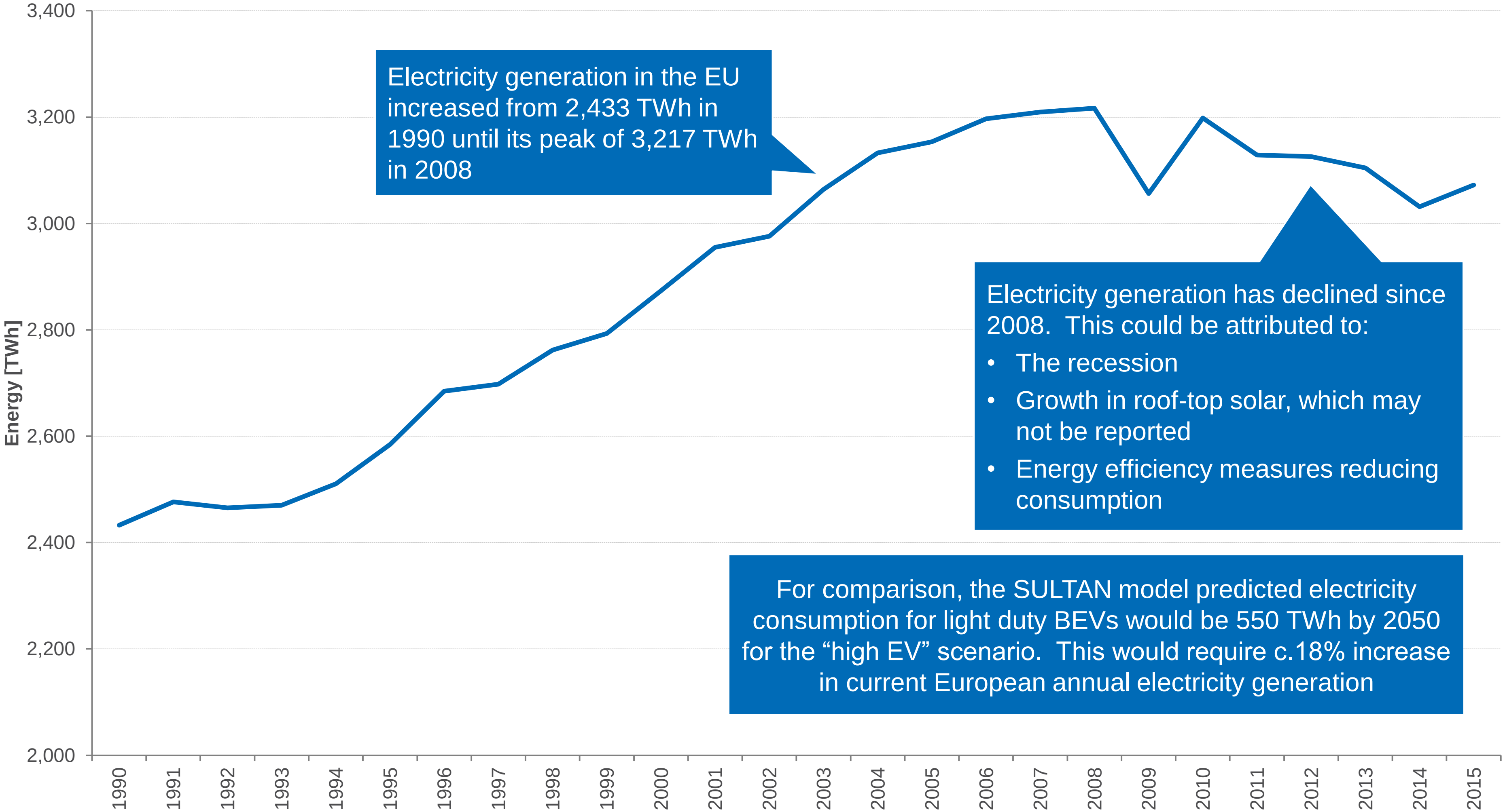
A 20 MVA primary substation will supply c.13,000 homes

A 1 MVA distribution transformer will supply c.600 homes

Each property connected to the LV network is assumed to use 1.5 kVA, or 10 kVA if electric space and water heating is used

European electricity generation increased from 1990 until a peak in 2008 – increased use of BEVs will create more demand for electricity

European Electricity Generation

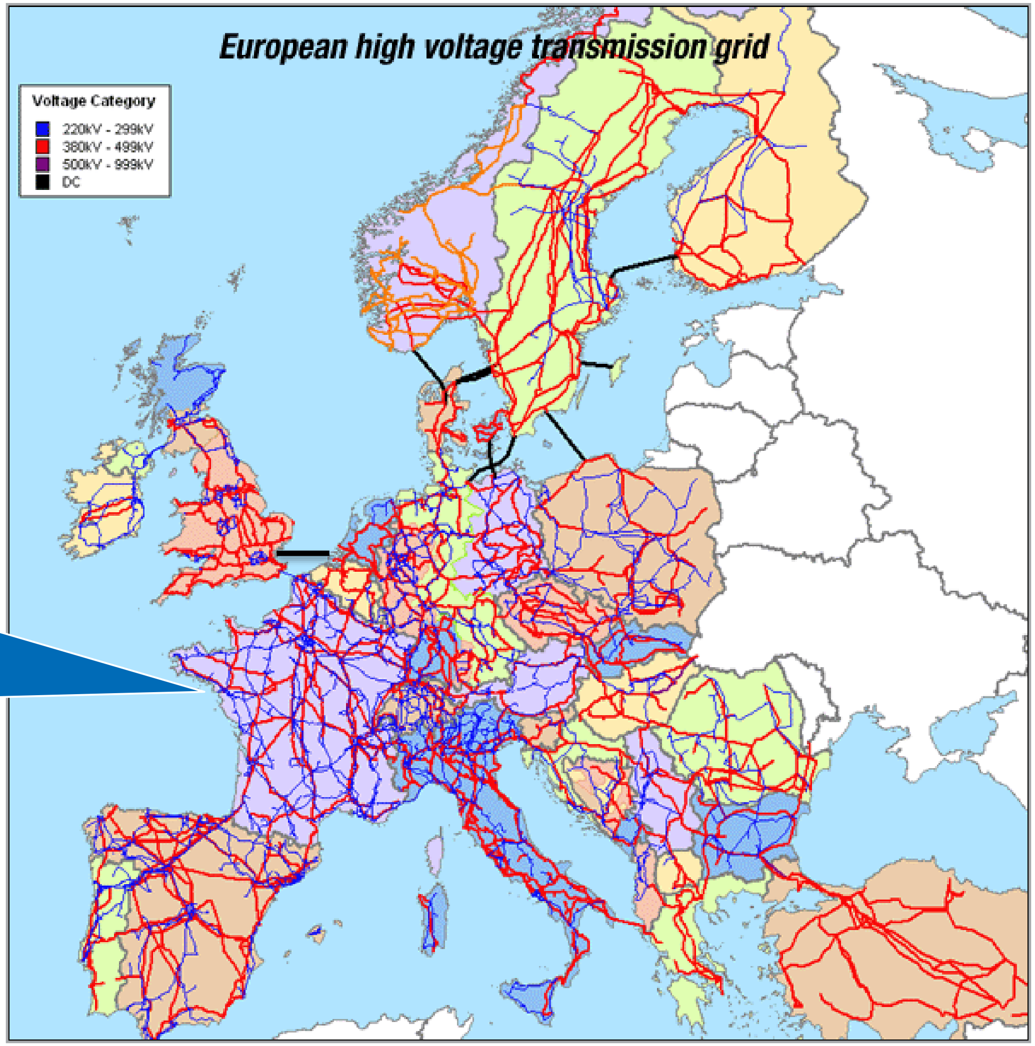


Source: Eurostat (online data code: nrg_105a)

Central Europe has a strong transmission network which will be able to facilitate load growth and connection of fast charging

European Transmission Map

The transmission network is not expected to require significant upgrades due to electric vehicle charging



Strongly interconnected meshed network that should provide many locations for rapid charging stations to connect to the transmission network

Historic Maximum peak load in the EU28 was 557 GW in February 2012 (due to cold weather)

Generation capacity in EU28 is approximately 1000 GW with 58% from nuclear and fossil fuel and 42% from renewable sources

Peak load is 50% of available generation capacity (86% of nuclear and fossil fuel capacity)

Source: Online, http://www.geni.org/globalenergy/library/national_energy_grid/europe/europeannationalelectricitygrid.shtml; (Accessed October 2017)

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There are >4 million substations across EU, with a rolling maintenance and replacement schedule of c.2.5% per year

Electrical Assets in Europe

Substations	Stock (approx.)	Transformer Size	Approximate Installed Capacity	Annual Replacement
EHV Substations	20,000	100 MVA	2 TW	3.3%
Primary Substations	60,000	40 MVA	2.4 TW	3.3%
Secondary Substations	4,459,000	500 kVA	2.2 TW	2.5%

Feeders	Stock (approx.)	Typical Sizes	Typical Current Rating *
LV Feeders	5,867,865 km	95 - 300 sq.. mm	200 – 600 A
HV Feeders	3,555,204 km	95 - 300 sq. mm	200 – 600 A
EHV Lines	307,200 km	200 - 400 sq. mm	500 – 900 A

* Ratings depend on installation

- All distribution and transmission network operators annually replace a proportion of their assets through their maintenance programmes
  - This is either due to asset failure, to replace ageing equipment or replace equipment being operated at maximum capacity due to network growth
- There are currently over 4 million secondary substations in the EU, of which 2.5% are replaced each year
  - Therefore, with the current maintenance schedule it would take c.40 years to replace the existing stock
- There are over 10,000 interconnection points between the distribution and transmission network

Source: Eco Transformer Report "LOT 2: Distribution and power transformers Tasks 1 – 7) and Eurelectric Report "Power Distribution in Europe : Facts and Figures"

Costs for upgrading assets typically vary by geographical location and complexity of reinforcement

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Typical Distribution Network Upgrade Costs

Part of Network	Typical Rating	Assumed Cost					
		Rural			Urban		
		Min	Average	Max	Min	Average	Max
Transformers							
EHV/HV transformation	500,000 kW	€ 1.1m	€ 4.2m	€ 9m	€ 1.1m	€ 4.2m	€ 9m
HV/MV transformation	60,000 kW	€ 1m	€ 3.4m	€8.4m	€ 1m	€ 3.4m	€8.4m
MV/LV transformation	500 – 1000 kW	€ 30k	€ 70k	€ 177k	€ 30k	€ 70k	€ 177k
Circuits							
HV (Rural **10 km** OHL, Urban **500 m** Cable)	114,000 kW	€ 11.3 m	€ 28 m	€ 86 m	€ 180k	€ 970k	€ 1.5m
MV (Rural **8 km** OHL, Urban **200 m** Cable)	6,700 kW	€ 118 k	€ 540 k	€ 1 m	€ 17k	€ 42k	€ 99k
LV (Rural **200 m** OHL, Urban **200 m** Cable)	240 kW	€ 5k	€ 15k	€ 41k	€ 19k	€ 38k	€ 100k

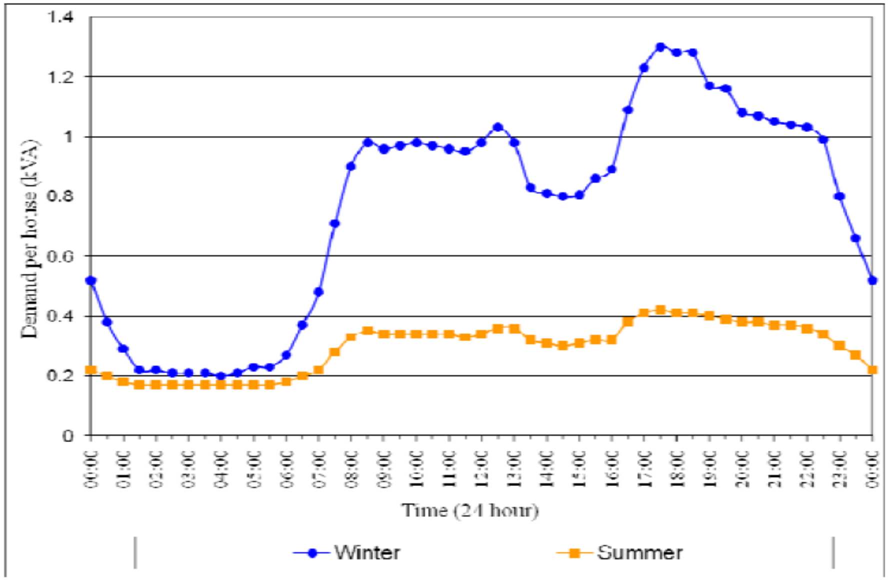
Upgrade costs for cables vary depending on geographic location and complexity of reinforcement. Minimum, average and maximum values are taken from published data on reinforcement costs, such as GB DNO charging statements, using assumed typical distances. Urban costs are typically greater due to the cost of excavating and relaying the pavement or road surface. And it is usually more expensive to excavate in large city than a small town. Rural networks are usually overhead, and are therefore cheaper to upgrade or repair

Source: Ricardo Energy & Environment Analysis

Customer demand will vary with application, time of day, season and country – European households are typically rated for 1-4 kW peak

Typical domestic property electrical loads

- Domestic households typically have a 50 - 80 A (12 kW - 19.2 kW) supply
- Properties do not always consume the maximum current. There is diversity for each connection
- Typical ADMD indexes for residential distribution networks vary by country. For example:
  - GB and Germany 1 – 1.5kW per household
  - Ireland 2.2 kW - 2.7 kW per household
  - Belgium 3kW per household
  - Spain and Norway 4kW per household
  - Where space heating and water heating is prevalent the ADMDs may be higher
- The time of peak demand will vary house to house. Therefore, an electrical network that connects 1000s of houses will have a lower ADMD index than the sum of the maximum demands of each property



Picture: Typical daily load profile for a domestic load (Putrus et al., 2009)

After Diversity Maximum Demand (ADMD) is an index used by the electricity networks industry to design electricity distribution networks. Demand is aggregated over a large number of customers

- ADMD represents the peak load a network is likely to experience over its lifetime. It is usually an overestimate of typical demand.
- ADMD determines the electrical infrastructure (number and size of transformers and cables) required for the network

Distribution assets need reinforcing when peak demand is exceeded – solutions depend on the issue and level of required upgrade

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Traditional Distribution Network Reinforcement

- Distribution assets need reinforcing when peak demand is exceeded
  - Peak demand occurs at different times of day by connection type (residential, commercial, industrial) and by country (heating and cooling, consumer behaviour)
- The method of reinforcement depends on the issue
  - For **LV feeder thermal or voltage problems** replace conductors for larger ones with higher rating and less voltage drop
  - For **11kV feeder thermal problems** overlay or replace conductors for larger ones
  - For **11kV (secondary) substation thermal problems**, add additional transformer and associated equipment, or add a new substation
  - For **MV (primary) substation thermal problems**, add additional transformer and associated equipment
- Reinforcement incurs additional costs, such as design and planning approval
  - Space constraints may make access and fitting of new equipment challenging
  - The building may need reinforcement to accommodate the distribution network changes
  - Additional land may have to be purchased

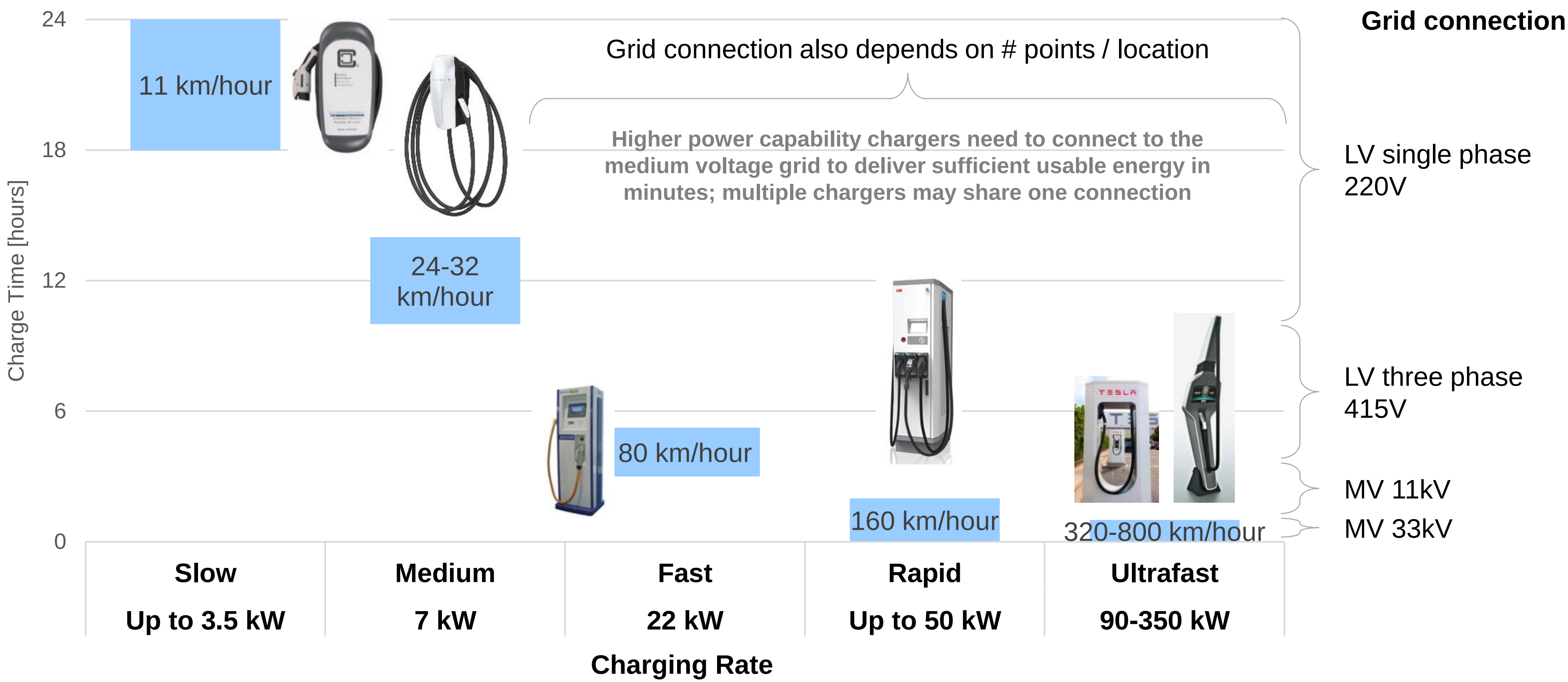
Thermal problems arise in power networks when high demands cause an overload, where too much current flows in the network, leading to overheating

Voltage problems arise in power networks when high demands or high output from generation cause either low voltages or high voltages, respectively

Contents

The charger power rating will determine the recharge time. Higher power rapid rechargers require direct connection to MV network

Typical Recharging Times for >400 km EV range with 85 kWh battery pack



Level 1 / Mode 1 Charging
13 A plug connection. Charger in the car

Mode 2 Charging
Up to 7 kW AC with communication between the car and charge point. Charger in the car

Level 2 / Mode 3 Charging
Up to 22 kW charge point pillar.
Charger in the car

Level 3 / Mode 4 Charging
Fast charging using an external charger

EV Charging infrastructure deployment assumptions are based on previous estimates developed with stakeholders

EV Charging Infrastructure Deployment Assumptions

- The infrastructure density/provision rates are the inverse of average numbers of vehicles per unit and are based on previous analysis by Ricardo Energy & Environment for a number of clients, updated with recent evidence from the IEA's 2017 Global EV Update, which was also used to estimate the share of electricity consumption
- Rapid charger rates reduced over time to account for changes in charger power rating, EV range, spacing, etc.
- **Average provision rates per vehicle for different EV charging type / location for BEV Cars:**

Default: "Home" infrastructure scenario

Type	2015	2020	2025	2030	2040	2050
Off-street home	0.85	0.75	0.65	0.55	0.55	0.55
On-street home		0.10	0.20	0.30	0.30	0.30
Workplace	0.20	0.20	0.20	0.20	0.20	0.20
Depot	0.05	0.05	0.05	0.05	0.05	0.05
Public convenience	0.067	0.067	0.063	0.060	0.040	0.030
Public rapid	0.0077	0.0077	0.0038	0.0019	0.0014	0.0010
Total	**1.17**	**1.17**	**1.17**	**1.17**	**1.14**	**1.13**

Sensitivity: "Grazing" scenario

Type	2015	2020	2025	2030	2040	2050
Off-street home	0.85	0.75	0.65	0.55	0.55	0.55
On-street home	0.00	0.05	0.15	0.25	0.25	0.25
Workplace	0.20	0.20	0.20	0.20	0.20	0.20
Depot	0.05	0.05	0.05	0.05	0.05	0.05
Public convenience	0.0667	0.150	0.150	0.150	0.150	0.150
Public rapid	0.0077	0.0077	0.0048	0.0038	0.0028	0.0018
Total	**1.17**	**1.21**	**1.21**	**1.21**	**1.21**	**1.20**

- **Average share of electricity total electricity consumption by EV charging type / location for BEV Cars:**

Default: "Home" infrastructure scenario

Type	2015	2020	2025	2030	2040	2050
Off-street home	62.0%	57.4%	52.0%	44.0%	44.0%	44.0%
On-street home	0.0%	7.6%	16.0%	24.0%	24.0%	24.0%
Workplace	21.0%	18.0%	15.0%	15.0%	15.0%	15.0%
Depot	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Public convenience	7.0%	7.0%	7.0%	7.0%	7.0%	7.0%
Public rapid	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

Sensitivity: "Grazing" scenario

Type	2015	2020	2025	2030	2040	2050
Off-street home	62.0%	54.4%	41.4%	30.3%	27.5%	26.8%
On-street home	0.0%	3.6%	9.6%	13.8%	12.5%	12.2%
Workplace	21.0%	21.0%	21.0%	21.0%	21.0%	21.0%
Depot	5.0%	5.0%	5.0%	5.0%	5.0%	5.0%
Public convenience	7.0%	10.0%	15.0%	20.0%	24.0%	25.0%
Public rapid	5.0%	6.0%	8.0%	10.0%	10.0%	10.0%
Total	**100%**	**100%**	**100%**	**100%**	**100%**	**100%**

The recharging scenarios use "time windows" to model the potential impact of unmanaged vs. managed for different types of charging

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Recharging Scenarios – Unmanaged vs. Managed "time windows"

Charging Type	Unmanaged home	Unmanaged grazing	Managed
Off-street parking	8 hours/day; 260 days/year		24 hours/day; 260 days/year
On-street home	8 hours/day; 360 days/year		24 hours/day; 360 days/year
Workplace	7 hours/day; 220 days/year		10 hours/day; 220 days/year
Depot	10 hours/day; 360 days/year		12 hours/day; 360 days/year
Public convenience	10 hours/day; 360 days/year	8 hours/day; 360 days/year	15 hours/day; 360 days/year
Public rapid	12 hours/day; 360 days/year		

- Unmanaged charging is when EVs are allowed to charge at any time of day without either direct control from the distribution or transmission network. Unmanaged charging is likely to lead to higher peak demands
- Managed charging is when charging is influenced either by ToU tariffs or Active Network Management (ANM). EVs are charged when there is availability in the network
- Ricardo has modelled "unmanaged" and "managed" charging by changing the assumptions regarding the available time windows for recharging by recharging type (see table above)
- By distributing the energy required over a longer period of time, the peak demand is reduced. This minimises the amount of reinforcement required to connect a mass uptake of EVs

Source: Ricardo Energy & Environment scenario

EV Charging infrastructure costs are based on previous estimates developed with stakeholders and updated with more recent evidence

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EV Charging Infrastructure Cost Assumptions

- Infrastructure costs are calculated by the infrastructure stock module based on SULTAN model scenario outputs
- Future capital and installation costs are estimated in the infrastructure module based on cumulative deployment from 2015 onwards – i.e. costs reduce by X% for every doubling of cumulative unit deployment. X% is defined by the learning factor (i.e. a factor of 0.9 reduces costs by 10% for each doubling of deployment)
- The 2015 assumptions used in the analysis are summarised below; costs exclude tax (which is added on separately for the end-user analysis). These assumption are based on previous estimates developed by Ricardo Energy Environment in consultation with stakeholder, updated with recent market estimates

2015	CAPEX cost	Installation cost	O&M cost	Learning rate CAPEX	Learning rate Installation	Lifetime	Payback period	Notes
Off-street home	€ 400	€ 500	1%	0.90	0.97	20	10	Up to 7kW
On-street home	€ 950	€ 500	1%	0.90	0.98	20	10	Lamp-post based charger or similar*
Workplace**	€ 1,100	€ 850	1%	0.90	0.98	20	10	Up to 7kW
Depot	€ 1,100	€ 850	5%	0.90	0.98	20	10	Up to 7kW
Public convenience	€ 2,300	€ 2,500	5%	0.90	0.98	20	10	7-22kW
Public rapid	€ 23,000	€ 21,000	5%	0.90	0.98	25	15	Capex and installation is assumed to be similar for 150kW+

- * Based on the current quoted costs for installing such systems in London, plus the cost for the charging cable
- ** Based on a range of quotations for the installation of workplace charging units

Contents

Many assumptions have been applied in this analysis, as documented below

Infrastructure Network Costs model assumptions

"Rules of thumb" for when reinforcement is required

- There is an existing programme of asset replacement that may increase the size of assets if necessary without much increase in cost to the network
- No network reinforcement required until EVs exceed 20% of vehicle parc (2030-2035)
- Some rural feeders will require upgrading as voltage drop will fall below minimum limits
- Rural secondary substations will have generally enough capacity and therefore not required an upgrade
- Some off-street home and on-street home charging will require upgrades on the Urban LV networks and the HV networks
- Communal charging locations will be developed where there is the most spare capacity for economic reasons. Cost of connection includes any required reinforcement and is less where no reinforcement is required
- Workplace charging may require upgrades at the local secondary substation and the HV networks
- Commercial depots have an opportunity to be flexible, and only require upgrades at the local secondary substations
  - Faced with high reinforcement costs they are likely to accept an agreement where they only charge when the network has capacity
- Convenience locations are likely to be connected to the network where there is capacity, but could require secondary substation and HV network upgrade
- Rapid chargers are likely to require new substations and direct HV circuits
- No rapid charge points will be installed in domestic properties
  - Due to the reinforcement costs, it is unlikely that existing properties have rapid chargers installed unless the owner pays for the reinforcement cost. (Some properties may have a larger three phase connection where rapid charging could be feasible)

- Allowance to be made for additional existing headroom in the networks
  - Some assets will be less lightly loaded in the present day
  - Not all the assets will need reinforcement after the 20% EV penetration level is reached
  - A profile of reinforcement is assumed from 20% in 2030 to 100% 2050
- The number of assets that will be reinforced must also be estimated
  - Splitting the required power [TW] between individual asset ratings will under estimate the assets required for reinforcement (once reinforced each asset will have regained headroom)
  - A profile of reinforcement is assumed for LV and HV assets (the reinforcement for HV being less to avoid over counting the need and impact of HV upgrade)
- The rapid charger reinforcement is considered separately as charging points at locations part way through long distance journey are expected to be fed with direct connections to HV networks

Items excluded from analysis

- Vehicle to Grid has not been considered – this can be considered as a mobile form of storage which could help alleviate local network constraints
- Impacts associated with intermittent renewable generation has not been considered
- Location and cost of generation has not been considered
- Decarbonising of heat – the move from gas to electric heating – has not be considered

Cost estimates for the recharging points have been included in the SULTAN report (RD-002976)

Source: Ricardo Energy & Environment Analysis

Different solutions exist to reduce the impact of EV charging on the distribution network which may require less reinforcement costs

Alternative solutions for reducing the impact of EV charging on the distribution network

Solar car port

- A single covered garage or roof-top typically provides 4 kW peak of generation
- A car requiring 10 kWh of electricity per day will require 2.5 hours of peak solar generation to charge the car
- The solar generation can be shifted by the use of a battery storage system, or sold to recharge a neighbour's car

"Time of Use" (ToU) tariff

- The peak demand can be minimised by the introduction of time of use tariffs (ToU). These tariffs offer high prices during the peak consumption times and low tariffs during the low consumption times
- Car charging could be shifted to a low cost period to minimise the impact on the network

Active network management

- If there are a significant number of outages due to EV charging, the distribution network operators may choose to manage the network by curtailing the amount of car charging to prevent the electricity network from being overloaded

Battery storage

- Battery storage could be used where there is a constraint. The battery would charge during the low demand periods and discharge during peak times. This would add extra capacity to the network without requiring new infrastructure to be installed
- Depending on where the constraint is, battery storage could be placed at the Primary substation, distribution substation or inside the home
- Battery storage has not been considered in this report

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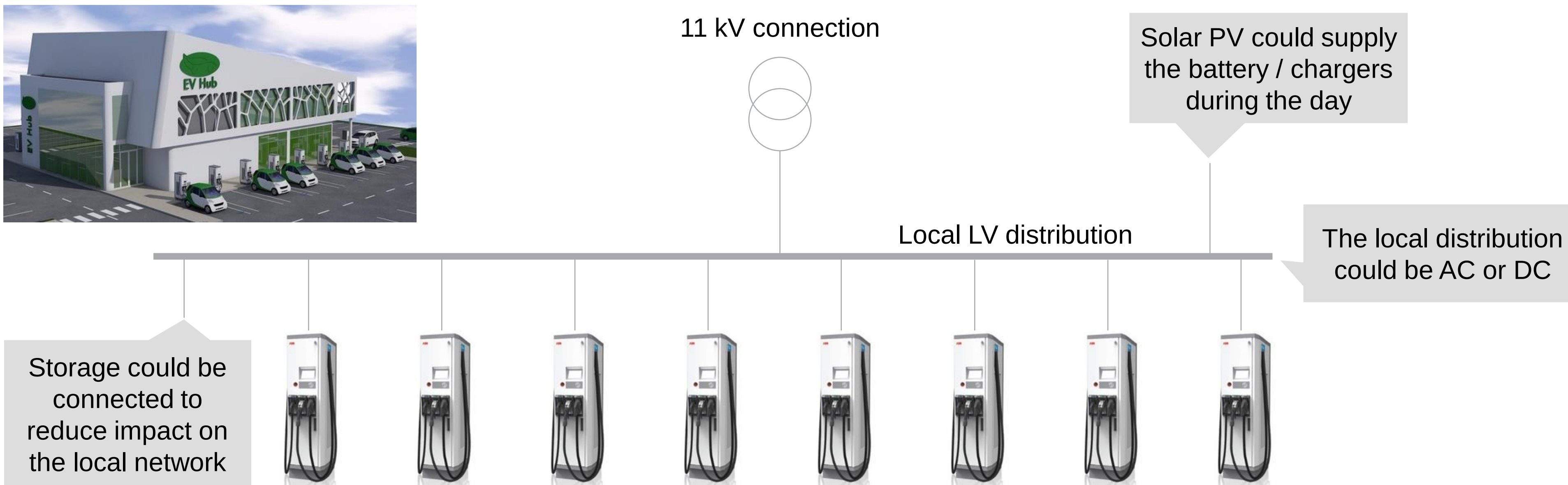
Fast charging stations may be grouped together to form a recharging hub, connected to the MV network (11 kV)

EXAMPLE

Connection of a fast charging station to the electricity grid



- The grid connection for an EV fast charging hub is sized based on the number of chargers. A private charging park (e.g. supermarket) is likely to connect at 11 kV or above and use a dedicated transformer(s) to feed the charging stations with 400 V AC
- For example, a site with **eight** 150 kW fast chargers would require a connection of 1.2 MW from the 11 kV network. The 11 kV network and secondary substations are likely to require reinforcement

Source: Ricardo analysis; picture David Lloyd vision for EV Hub stations

By 2050, Europe is likely to have mix of motorway and urban EV recharging hubs, which could cost c.€19 billion to install

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Note: This is the cost for a fast charging network only

How much will it cost to develop a network of Rapid Charging Stations across Europe?

National Grid –
one solution ***"would be to build a few thousand super-fast charging forecourts of over 3 MW capacity"***

Rapid Charging at:		Motorway / Autobahn Service Stations	Other Road Service Stations	Towns & Cities
Assumptions	**No. per country**	150	300	1000 (1 city = 10 towns)
	No. rapid chargers	31 per station	8 per station	4 per town; 40 per city
Requirements	**Peak Demand**	4.2 MW	1.2 MW	0.5 MW per town
	What's required?	New 11kV substation	New 11kV substation	Some 11kV local reinforcement
	Cost for 28 countries	€ 0.4 m per service station € 1.7 bn total	€ 0.2m per service station € 1.7 bn total	€ 0.55 m per town € 15.4 bn total
TOTAL		**€ 18.8 billion**		

Ricardo has assumed a network of 300,000 rapid chargers by 2050 for the "high EV" scenario, with power rating 150 kW. Assuming these are distributed across motorway service stations, EV recharging hubs and towns and cities, the cost for installing these rapid chargers plus infrastructure could be in the order of € 19 billion by 2050

Source: Ricardo Energy & Environment analysis

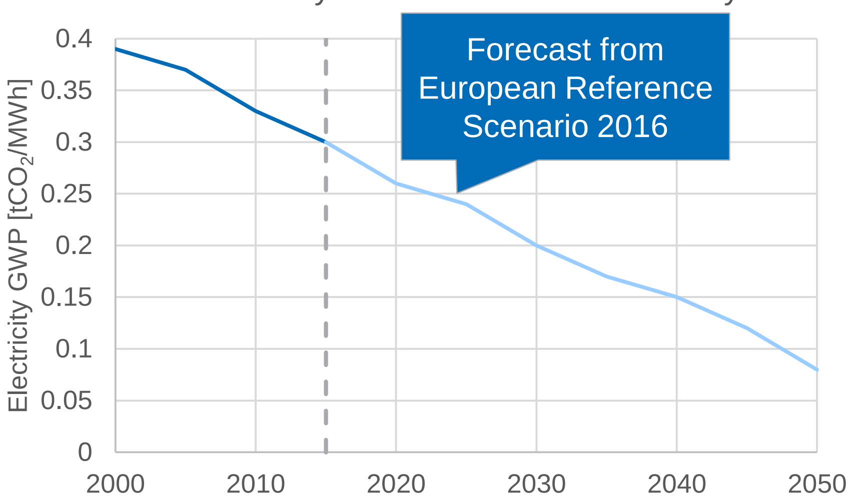
Contents

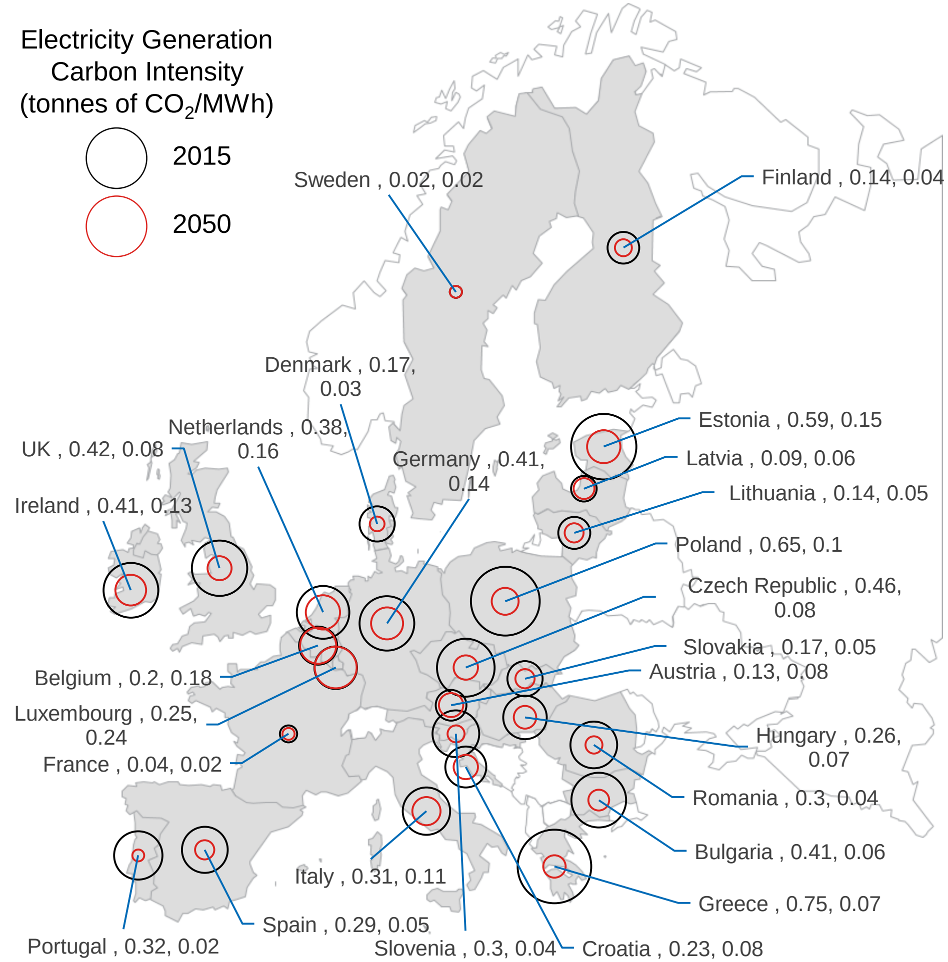
Electricity generation carbon intensity varies across Europe, although the extent of variation is expected to decrease by 2050

Electricity Generation Carbon Intensity

- Although the electricity generation carbon intensity does vary by country, there does not appear to be significant sub-European regional variation
  - For example, there is not a significant difference between Eastern and Western Europe
- Overall decarbonisation of electricity generation is expected to progress significantly, with a 73% reduction achieved across the EU between 2015 and 2030

EU28 Electricity Generation Carbon Intensity





Analysis based on European Commission: European Reference Scenario 2016, comparing 2015 with 2050 scenario

Source: Capros et al. (2016) (#A396); Ricardo analysis; UN Regional Groups of Member States

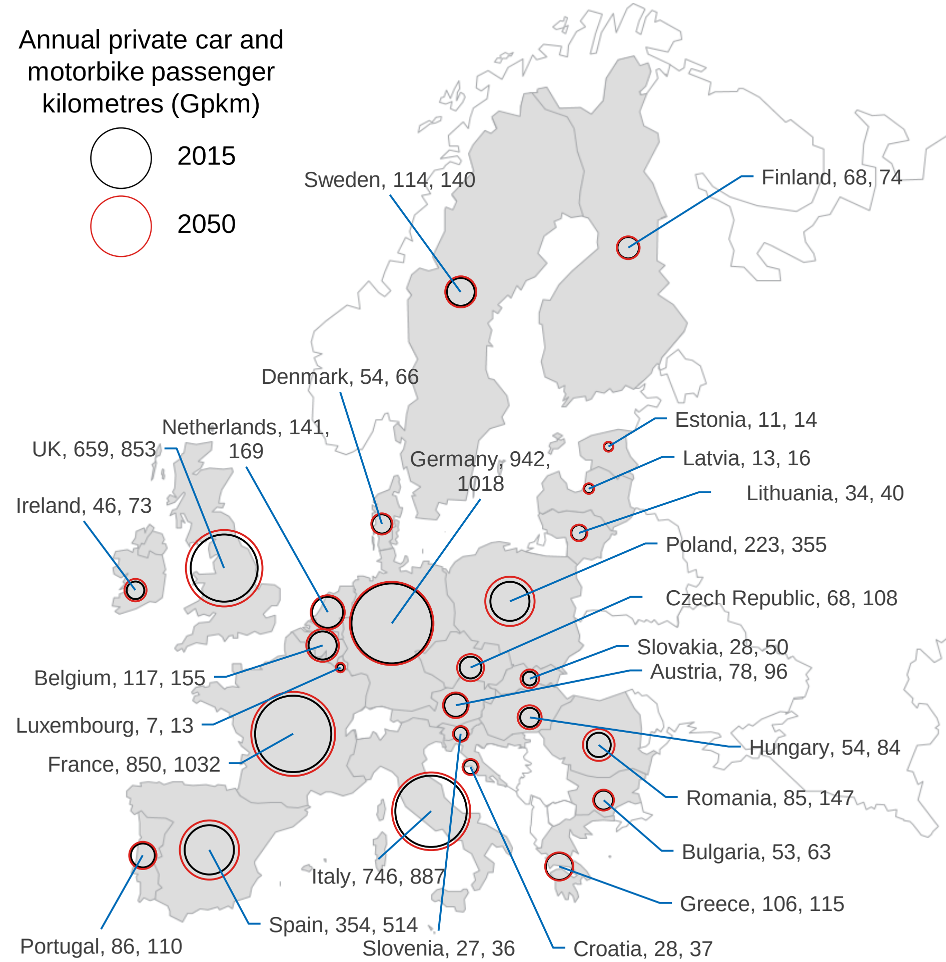
Passenger car use is predicted to continue to increase, especially in Eastern Europe

Passenger Car Use Across Europe

- The European Reference Scenario 2016 indicates that although Western Europe has high levels of passenger car use, the growth in car use from 2015 to 2050 will be much higher in Eastern Europe
- The table below contains data for the three countries with the highest passenger kilometres in Western and Eastern Europe respectively
  - This approximates vehicle kilometres assuming similar vehicle occupancy across Europe
- The total EU28 passenger car and motorbike passenger distance is expected to increase from **5001Gpkm** in 2015 to **6279Gpkm** in 2050
  - This indicates an expected **26% increase** across the EU28 countries

Passenger Kilometre Change 2015-2050

Western Europe		Eastern Europe	
Germany	+8%	Poland	+59%
France	+21%	Romania	+73%
Italy	+19%	Czech Republic	+59%



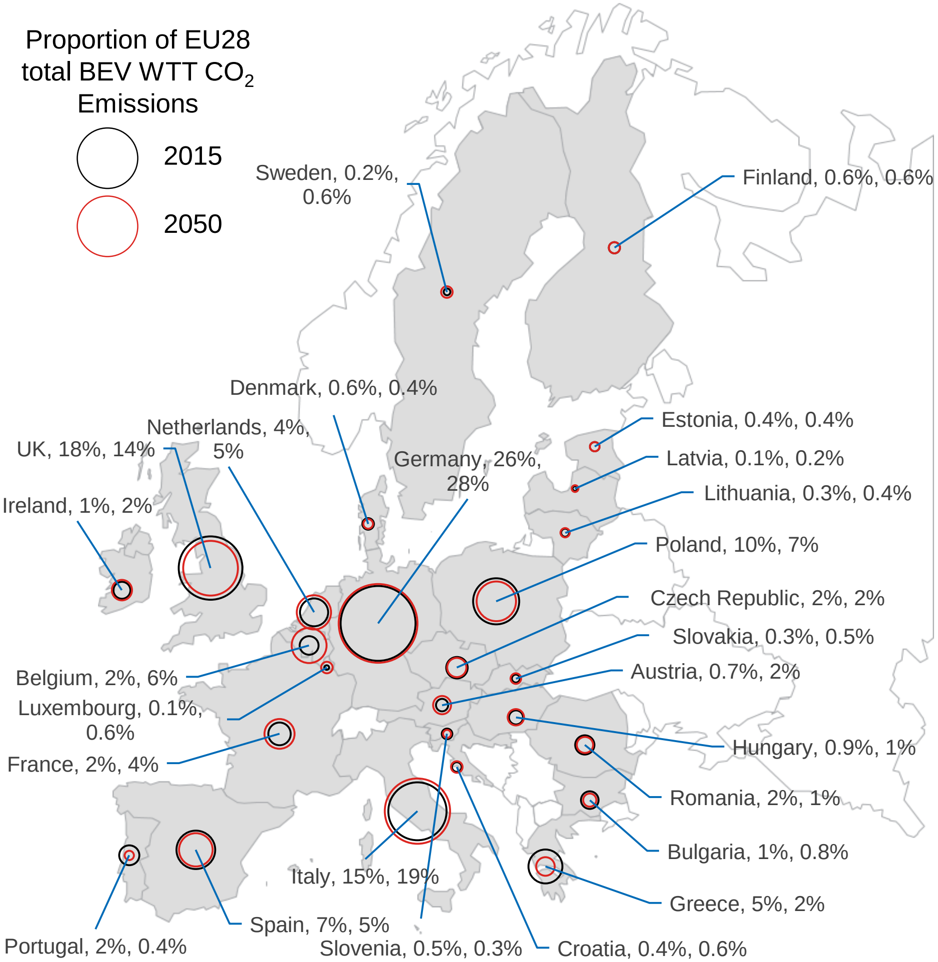
Analysis based on European Commission: European Reference Scenario 2016, comparing private car and motorcycle passenger kilometre data 2015-2050

Source: Capros et al. (2016) (#A396); Ricardo analysis; UN Regional Groups of Member States

In 2050 the majority of EU WTT emissions from BEVs will be produced by a handful of countries

Share of EU28 BEV Well-to-Tank (WTT) Emissions

- The WTT CO_2 emissions of BEVs can be estimated for each country by combining the carbon intensity of the electricity generation with the vehicle use (and therefore energy consumption)
  - The results are presented in terms of share of EU28 total BEV WTT emissions
- The results indicate that Germany, Italy and the UK will produce **61%** of the EU28 total BEV WTT emissions in 2050
- For Eastern European countries, despite the large expected increase in vehicle use, the decarbonisation of electricity generation has kept the WTT emissions of these countries to a low proportion of the EU28 overall



Source: Capros et al. (2016) (#A396); Ricardo analysis; UN Regional Groups of Member States

Mass adoption of EVs could increase electricity consumption in the EU by 18% compared to 2050 baseline; varies ±12% by country

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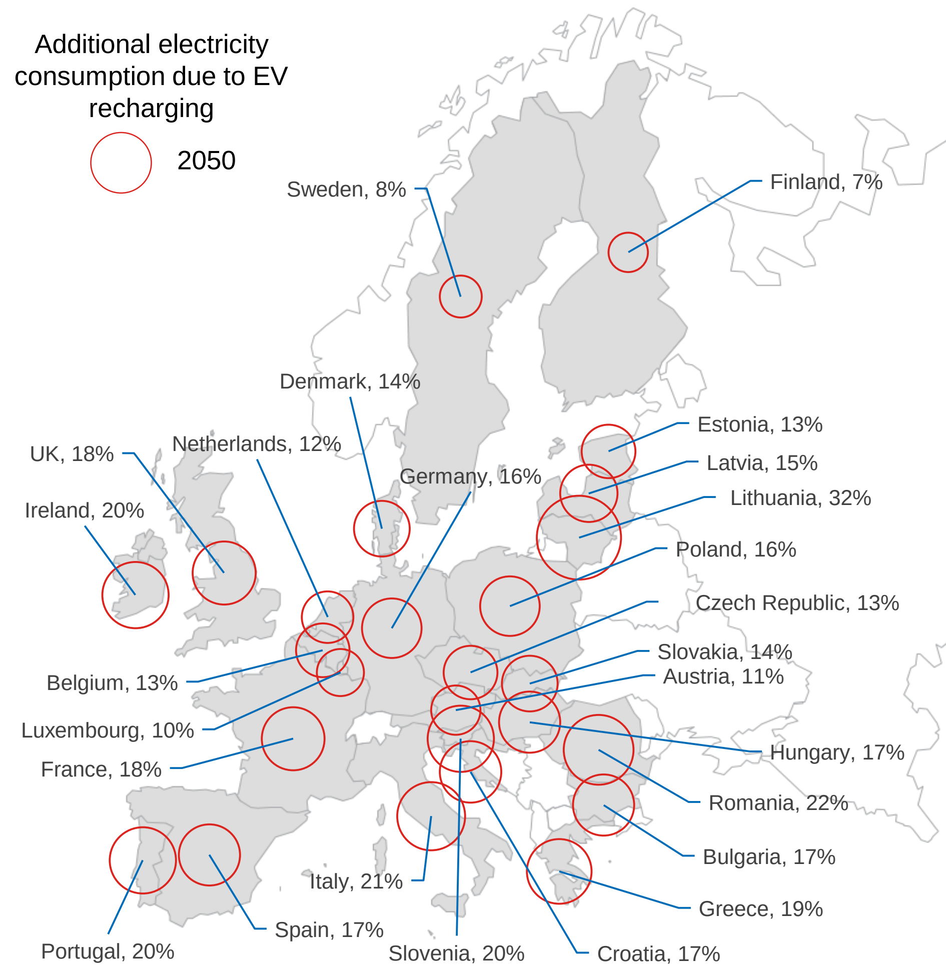
Additional Electricity Consumption for Mass EV Adoption

- SULTAN modelling output has been used to calculate the additional electricity consumption due to mass adoption of EVs
  - The data is presented relative to the forecast electricity consumption in 2050
- Results indicate that by 2050 the EU28 electricity consumption will be increased by 18% due to EV recharging
- There is variation in the impact across Europe, with the greatest and least affected countries shown in the table below

Additional Electricity Consumption in 2050

Smallest Increase		Largest Increase	
Finland	+7%	Lithuania	+32%
Sweden	+8%	Romania	+22%
Malta	+9%	Italy	+21%



Analysis based on European Commission: European Reference Scenario 2016, comparing 2050 scenario non-EV electricity demand with 2050 EV demand

Source: Capros et al. (2016) (#A396); Ricardo analysis

Contents

Introduction – Resources and materials

- This Appendix provides further details on the analysis of the impact of the High EV resources and materials
- The deep dive analysis has investigated the implications for material resources and recycling, focusing on Li-ion battery packs, infrastructure and recharging analysis examined the following impact questions:
  - What are the critical material availability issues encountered by mass EV adoption?
  - What interplay is there between material recycling and material availability?
  - Can critical materials be produced in enough volumes to satisfy the demand?
  - Are there security of supply concerns associated with critical EV materials?
  - What environmental and humanitarian impacts could be associated with EV material production?

The deep dive has further investigated the implications for material resources and recycling, focusing on Li-ion battery packs

Deep Dive Questions

- What are the critical material availability issues encountered by mass EV adoption?
- What interplay is there between material recycling and material availability?
- Can critical materials be produced in enough volumes to satisfy the demand?
- Are there security of supply concerns associated with critical EV materials?
- What environmental and humanitarian impacts could be associated with EV material production?

Lithium is a key material for mass EV adoption during the scenario period; lithium availability may affect the scenario feasibility

Lithium Material Analysis (1/3)

- Automotive battery technology roadmaps identify lithium-ion batteries as being the dominant battery type used in the period considered by the analysis (2016-2050)
- Lithium-ion is a term applied to a group of battery chemistries that contain various different materials, however they all contain lithium in the cell cathode
  - Cathode material for three main automotive lithium-ion battery chemistries is shown below

Lithium Nickel Cobalt Manganese Oxide (NMC)	Lithium Iron Phosphate (LFP)	Lithium Manganese Oxide Spinel (LMO)
$LiNi_{1/3}Co_{1/3}Mn_{1/3}O_2$	$LiFePO_4$	$LiMn_2O_4$

- It is assumed that market shares of the different lithium-ion battery chemistries will adjust to accommodate for shortages in material supply (e.g. cobalt, used only in NMC batteries yet may face supply issues), however all the battery chemistries are forecast to contain lithium
- Additionally, beyond 2030 these types of lithium-ion battery are expected to be superseded by next-generation battery types such as lithium-air and lithium-sulphur, which may contain very different active materials but will still require lithium
- For these reasons, in this analysis lithium is considered to be the key material required for mass EV adoption
- Only the lithium consumption for European EVs is analysed; lithium use for other purposes (non-battery industrial processes, consumer electronics batteries and grid storage batteries) is not calculated

Source: Foss et al. (2016) (#A256); Kushnir and Sanden (2012) (#A381); Pehlken et al. (2015) (#A175); Lebedeva et al. (2016) (#A275)

To calculate lithium consumption during the scenario, modelling is performed; this is dependant on a series of input assumptions

Lithium Material Analysis (2/3)

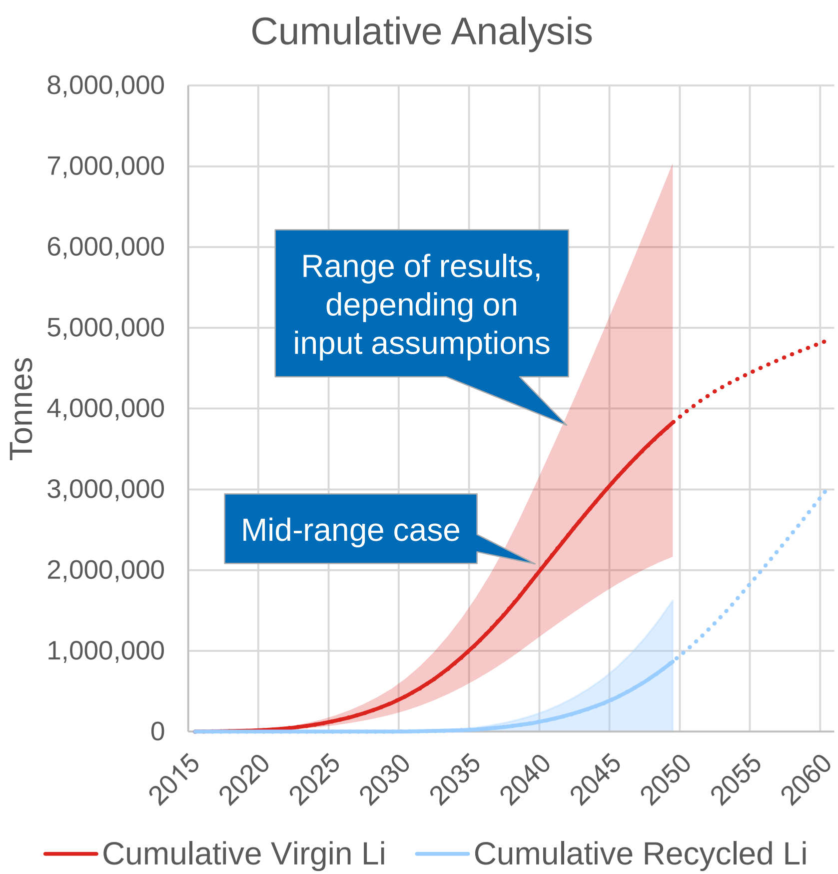
- “RD17-003175-1 Q015713 - Task 3 - Materials and Recycling – Workbook.xlsx” calculates lithium consumption
  - The calculations use the annual vehicle sales and powertrain market share also used in the SULTAN model
  - Many of the input variables have uncertainties associated with them that cause a wide range of results
  - The analysis presented in this report uses a **mid-range case** with the assumptions included below
  - All the input variables have alternative options in the workbook to test using different assumptions

Input Variable	Uncertainty	Assumption for Analysis
Battery Li Content (g/kWh)	• Development of lithium-ion batteries is uncertain • Higher power batteries require higher lithium content (consumer preferences)	160g/kWh
Battery Second Life	• Length of time the battery is used after being removed at the end of vehicle life (e.g. as home storage) • Uncertain if this will be more valuable than recycling the battery	No second life use of the batteries (batteries are immediately recycled at the end of the vehicle life)
Battery Recycling (Li recovery)	• Not all battery recycling processes recover lithium, depends on economic factors	80% lithium content recovered
Battery Size (kWh)	• Depends on consumer preferences	SULTAN trajectory used, scaling factor can be applied in workbook
Battery Lifetime	• Whether the battery lasts the lifetime of the vehicle or if it is replaced during the lifetime	The battery lasts the lifetime of the vehicle

Source: See RD17-003175-1 Q015713 - Task 3 - Materials and Recycling – Workbook.xlsx

In the mass EV adoption scenario, recycling has relatively small effect on cumulative virgin material demand by 2050

Lithium Material Analysis (3/3)



Analysis to calculate cumulative lithium demand for European light duty car sales in a mass EV adoption scenario (100% light duty sales are BEV by 2040). Results and sources can be found in RD17-003175-1 Q015713 - Task 3 - Materials and Recycling – Workbook.xlsx

Source: USGS (2017) (#A321)

- This analysis presents how much lithium must be virgin material (extracted from a mine) and how much can be from recycled sources for European EV manufacture
- Even with significant recycling of lithium from scrapped vehicle batteries (80%), this can only provide ~25% of the cumulative demand by 2050
- The virgin lithium required by 2050 for European EVs, for the mass EV adoption scenario, is **32% of the global lithium reserves** (14Mt) and **10% of global lithium resources** (47Mt), after considering the extraction efficiency (85%)
  - Due to the range of results this could be **as high as 60%** of reserves (18% of resources) **or as low as 18%** of reserves (6% of resources)
  - **Resources** indicate the amount of material which is currently/potentially feasible to extract
  - **Reserves** indicate the portion of the resources which meet current minimum standards and could be economically extracted at the time of determination

…however it is not clear if this scale of lithium production is possible. Europe consumes more than its proportional lithium share

Material Analysis: Europe Within a Global Context

- The results indicate that a significant proportion of the global lithium **reserves** (**18-60%, mid-range case 32%**) must be extracted by 2050 in order to manufacture European EVs
  - This is generally higher than the European share of global passenger car sales (**19%**), which is also forecast to decrease as sales increase in regions such as China
  - Mass adoption of EVs (~100% light duty parc is BEV in 2050) in the USA, Europe and China alone would require **114%** of the global lithium reserves (assuming similar battery technology and sizes)
    - Note that this does not account for the rapid growth of the Chinese market, which was 17% between 2015 and 2016
  - However the European lithium demand would require only **6-18%** of the global lithium **resources**, although the economic or practical feasibility of extracting resources not currently counted as reserves are unknown
- Although the feasibility of the total demand is unclear, the annual lithium demand could be the greater challenge
  - Global lithium extraction investment is limited by the low cost of lithium from the Salar de Atacama in Chile
    - To supply the peak annual lithium demand for European BEVs, roughly half of the surface of the salar (salt flat) would need to be covered in evaporation ponds, with potential impacts for wildlife and tourism
  - Other large lithium resources, such as the Salar de Uyuni in Bolivia – estimated to be the largest or second largest lithium resource globally – are limited in their potential annual output
    - In the case of the Salar de Uyuni, an extraction rate of only 10kt/year would exceed the water replenishment rate of the basin and impact on local agriculture
  - Therefore the feasibility to meet the increased virgin lithium demand by 2040 is not certain

Source: Foss et al. (2016) (#A256); Kushnir and Sanden (2012) (#A381)

Cobalt is a key material for EV batteries in the short and medium term, with cobalt-containing batteries forecast until at least 2030

Cobalt Use in Batteries

- As identified in the literature, cobalt could face shortages in EV mass adoption scenarios depending on the battery chemistries that are used
- In the long term, there are alternatives to cobalt-containing batteries, although some of these may not achieve the same level of performance
- However in the short to medium term (until 2030 at least), cobalt is a key material in EV batteries and has supply concerns and environmental impacts that are worth considering even if the overall material availability may not be a barrier to mass EV adoption

Source: Pehlken et al. (2015) (#A175); Lebedeva et al. (2016) (#A275); Foss et al. (2016) (#A256); Kushnir and Sanden (2012) (#A381)

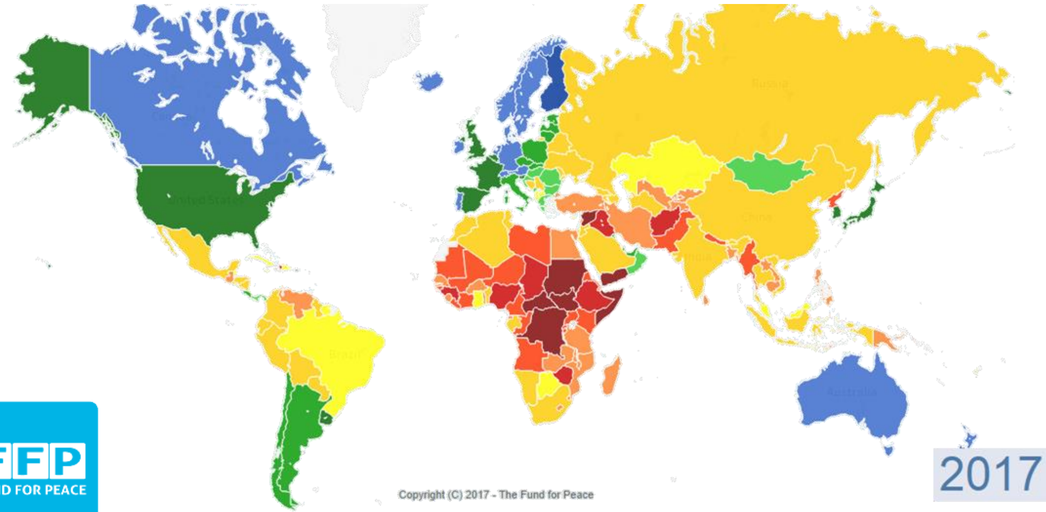
The stability of nations that produce or have reserves of key EV materials is assessed with the Fragile States Index

Assessing Nation Stability

- In order to quantify the potential security of supply risks of EV materials (specifically lithium and cobalt), the Fragile States Index (FSI) has been used
- The FSI is compiled by the Fund For Peace and aims to quantify the pressures placed on states and the ability of the state to resolve these issues
  - A high FSI score could indicate that the country is unstable, the nature of which will vary by state however it is unlikely to be positive for material production and interaction with the global material market
- This map is included to give a global overview of the 2017 FSI results, to put the data on the following slides into a global context
- Lithium and cobalt reserves and production are analysed, although not all automotive lithium-ion batteries use cobalt

FSI Score 2017

Sustainable			Stable			Warning			Alert		
10	20	30	40	50	60	70	80	90	100	110	120



Source: Fund For Peace (2017) (#A382); Foss et al. (2016) (#A256)

The majority of lithium reserves are located in South America; Chile has over half the global lithium reserves

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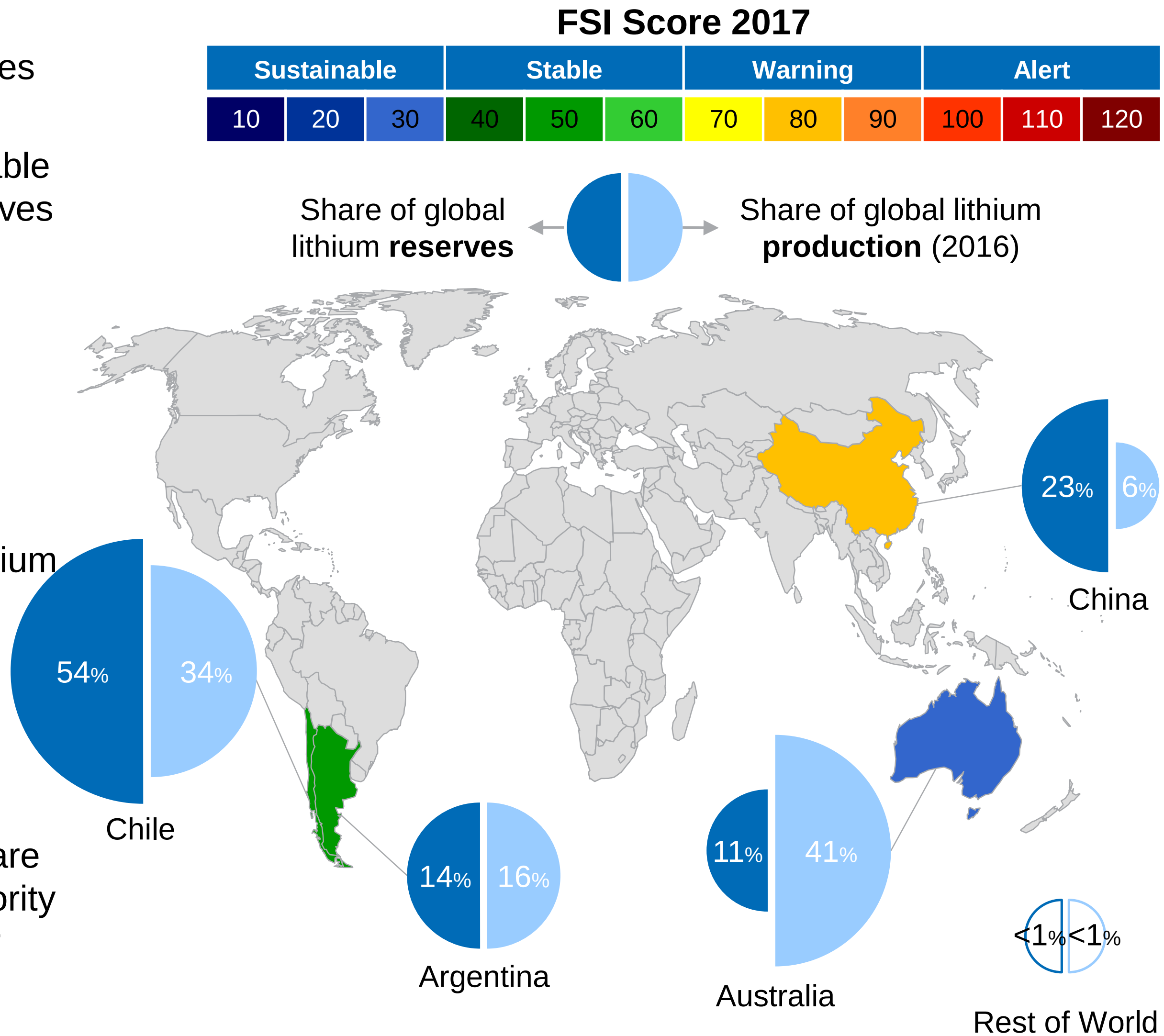
Lithium Reserves and Production

- Lithium is naturally present in brines, ores and seawater
  - Lithium from brines is the most suitable for battery manufacture; these reserves are predominantly located in South America
- Lithium production and prices could depend heavily on the policies of the Chilean government, which is currently planning large mining policy changes
- Within Europe, Portugal has a small lithium industry: 0.6% and 0.4% of global production and reserves respectively
- Overall the countries with large lithium reserves rank well on the FSI, although China has a higher FSI score
  - Even with low FSI scores, as there are so few countries controlling the majority of lithium, supply issues could occur

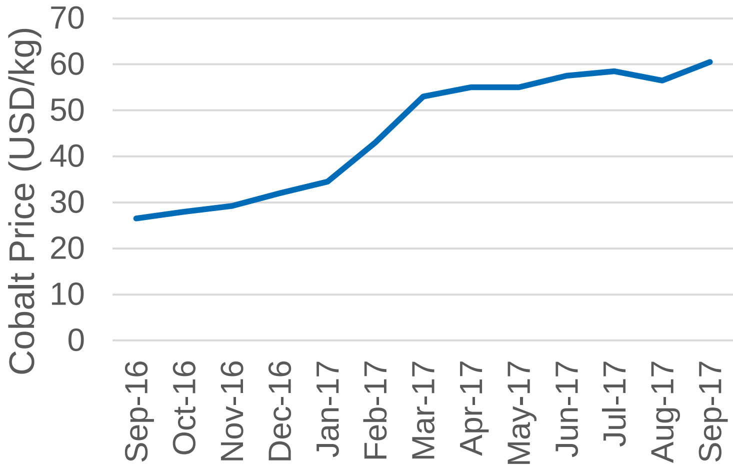


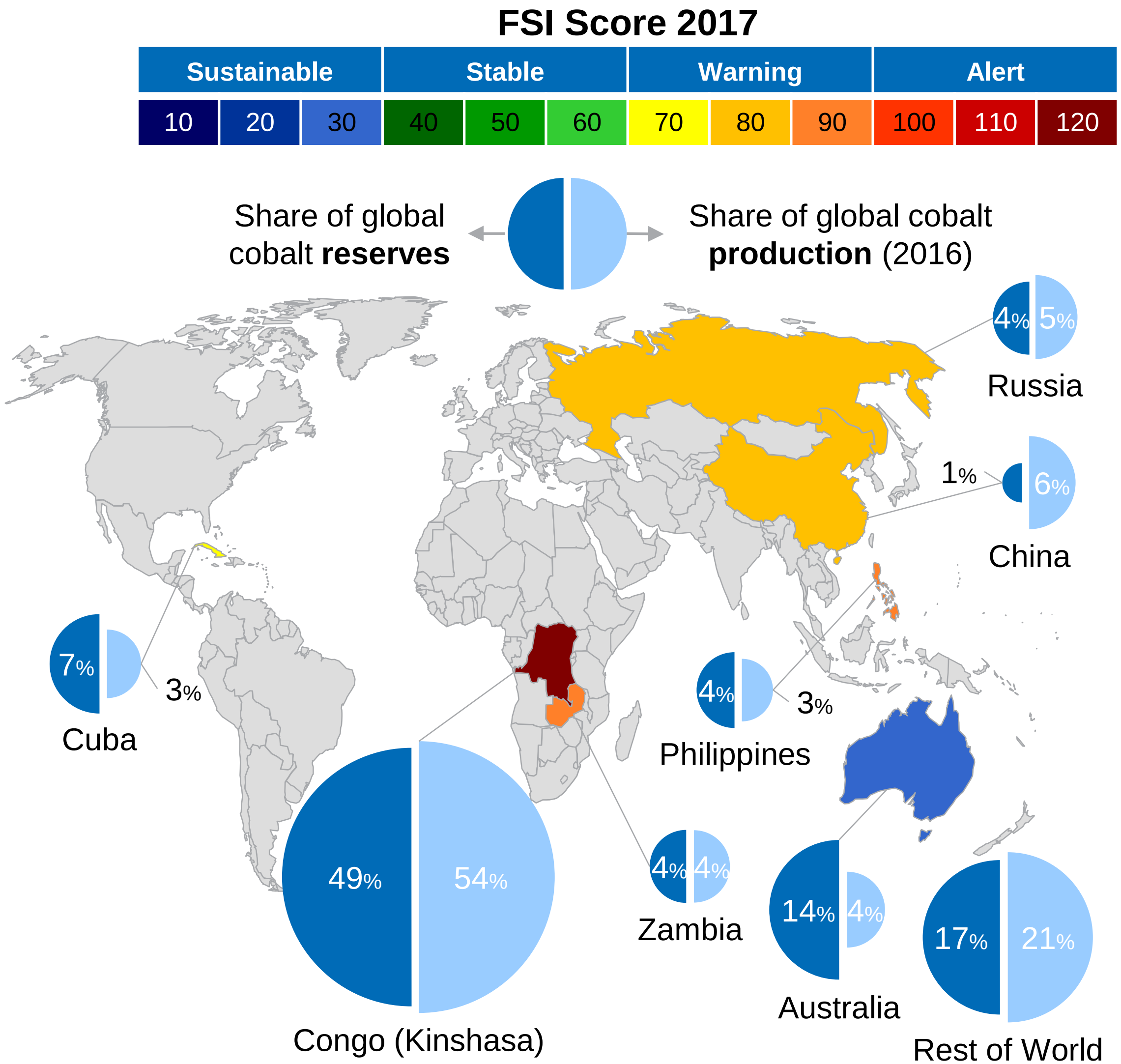
Source: USGS (2017) (#A321); Fund For Peace (2017) (#A382); Dunn et al. (2015) (#A336)

Congo (Kinshasa) produces over half the world's cobalt, however instability within the country has led to price instability

Cobalt Reserves and Production

- Although cobalt reserves are present in many countries, the largest reserves and current production are located in Congo (Kinshasa)
- Many of the countries with cobalt reserves have high FSI scores, however Congo (Kinshasa) has a very high score reflecting the current instability in the country
  - This instability in Congo (Kinshasa) is a factor in the 128% increase in the price of cobalt in 12 months



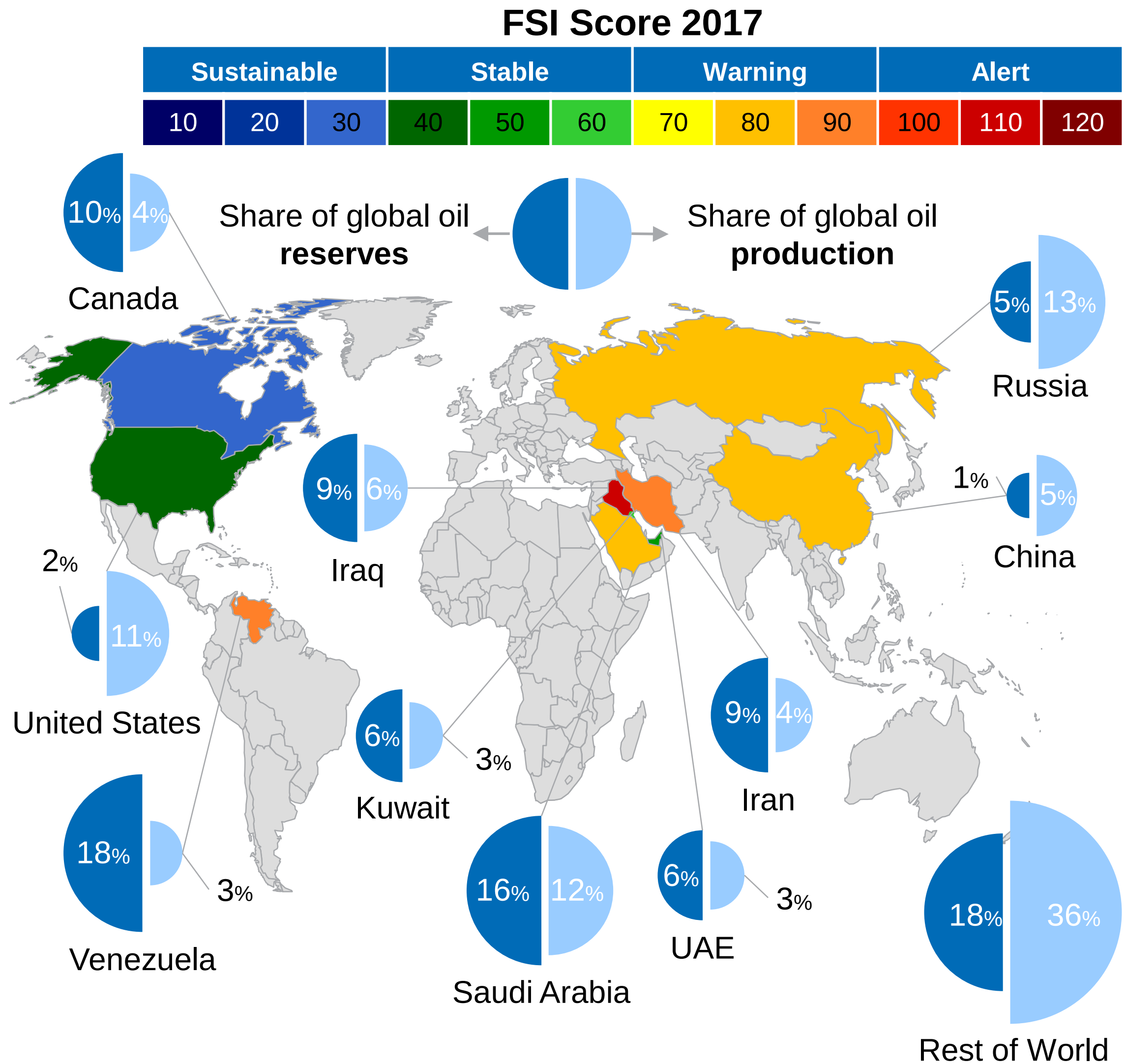


Source: USGS (2017) (#A321); Fund For Peace (2017) (#A382); Shin, J. (2017) (#A369); The London Metal Exchange (2017) (#A393)

In comparison, oil resources are distributed widely across the globe, despite often high FSI scores

Oil Reserves and Production

- The map shows the **top 10** countries with the largest oil reserves or oil production
- The largest shares of reserves or production of any country is 18%, which contrasts with ~50% shares of lithium in Chile or cobalt in Congo (Kinshasa)
  - Therefore the supply is less dominated by any one country, which may be beneficial considering the medium-high FSI scores of some countries with large oil reserves or production
- However, there is a key difference between oil and battery materials:
  - Oil is required to **operate** an ICE vehicle: price effects the **running costs**
  - Battery materials are required to **manufacture** an EV: price effects the **capital costs**



Source: Fund For Peace (2017) (#A382); Central Intelligence Agency (2017) (#A405)

Other studies highlight the impacts of battery material production and concerns that some regions have little control of these impacts

Impacts of Material Production

Impacts of Nickel Production

- Typically uses open cut mining
- Historically has caused significant SO_2 emissions, soil contamination and water acidification, although process improvements are reducing all of these effects

Impacts of Cobalt Production

- Uses open cut or underground mining
- Exposure to cobalt can impact human health, additionally mining for cobalt (where cobalt is the intended product rather than a by-product of nickel or copper mining) often targets arsenide ores, which has further environmental and human health impacts
- Additional environmental impacts occur similar to that of nickel production and in the Congo (Kinshasa) cobalt region it is suggested there is little control of pollutants from cobalt mining

Impacts of Lithium Production

- Lithium for battery production is typically extracted from brines in South American salars (salt flats) with an evaporative beneficiation process carried out in a series of pools. Lithium ore extraction uses open cut mining
- The water requirement for the lithium extraction is significant and puts pressure on local water supplies, which in some cases is heavily relied upon for local agriculture
- Tourism in the salar areas is a major employer and could be affected by increased lithium production

Source: Dunn et al. (2015) (#A336); Foss et al. (2016) (#A256); Kushnir and Sanden (2012) (#A381)

There may be enough lithium for European mass EV adoption, however the rate of lithium production could be the limiting factor

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Conclusions – Mass EV Adoption Scenario

Lithium Resources and Reserves

- European mass EV adoption will consume a larger share of global lithium reserves than European share of global vehicle sales, potentially causing a shortage of lithium if other regions also undergo mass EV adoption
- 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 – additional very few countries have lithium reserves
- Lithium from recycled batteries has a limited impact on the total virgin lithium required by 2050

Lithium Production

- Virgin lithium extraction capacity must be increased significantly in order to reach peak demand in 2040
- Battery recycling to recover lithium could become a large industry by 2050, however it may not be economically feasible for all battery types (e.g. LFP batteries have little recyclable material of value)

Cobalt Production

- Congo (Kinshasa) has half of the global cobalt reserves and production, however there are concerns over the economical impacts and the security of supply results in large price fluctuations

Environmental Impacts

- Environmental impacts from material extraction are being reduced in some regions, however there is a risk that large scale exploitation of lithium and cobalt resources could lead to significant environmental impacts