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

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The impact of two scenarios of mass EV adoption versus significant low carbon fuel use show similar GHG emissions reductions and costs

- The implications of two scenarios to 2050 for Light Duty Vehicle propulsion in Europe have been studied
  - Both scenarios feature electrification and use of low carbon fuels (biofuels and eFuels), but with significantly more Electric Vehicles (EVs) or low carbon fuels in each scenario respectively

High EV Scenario

Represents “mass EV adoption”

100% EV registrations by 2040

~90% EV vehicle parc by 2050

Low Carbon Fuels Scenario

Meeting similar WTW GHG reduction targets to High EV scenario, using a significant proportion of biofuels & eFuels

- Both scenarios result in a similar and significant (~85%) reduction in total life cycle GHG emissions to 2050 at similar annual parc total costs to the end user (when adjusted to maintain Net Fiscal Revenue)
  - A combined scenario “Mixed Fleet” scenario also resulted in similar GHG reduction and costs
  - Up to 2040 the cumulative societal costs of the Low Carbon Fuels scenario are estimated to be €140bn lower than the High EV scenario, but €33bn higher by 2050
- Electricity demand from EV charging in the High EV scenario in 2050 is ~550 TWh, which represents ~17.5% of the EU’s 2015 electricity generation, and is twice that required in the Low Carbon Fuels scenario
- In the High EV scenario, the cumulative cost of a managed EV charging and network infrastructure reinforcement is estimated between €630bn & €830bn to 2050, compared to overall cumulative savings to the end-user between €1,100 & €1,600bn (1.3% - 1.8% of total end-user costs)* vs European Commission Business as Usual reference to 2050
  - In the Low Carbon Fuels scenario the network infrastructure reinforcement cost is estimated to be €326bn

Note: * Excluding adjustment for loss of Net Fiscal Revenue

The modelling suggests an optimal cost-effective GHG reduction solution may lie somewhere in-between the scenarios evaluated

Implications of two scenarios to 2050 Light Duty Vehicle propulsion in Europe continued:

- Significant risks associated with the supply of resources are highlighted, especially in the High EV scenario
  - Peak annual virgin lithium demand (~220kt) is 6 times higher than global lithium production in 2016 (35kt)
  - The Lithium resource requirements for the Low Carbon Fuels scenario are less than half of those for the High EV scenario
- The annual parc total costs to the end user (when adjusted to maintain Net Fiscal Revenue) are similar for the High EV, Low Carbon Fuels and Mixed Fleet scenarios, and below the baseline scenario
  - The estimated marginal capital costs for the High EV scenario are particularly strongly influenced by assumptions on battery prices
- Under the High EV scenario, ~15 Gigafactories (@35GWh p.a.) would be needed to supply batteries to the European EV market by 2050, compared to ~5.5 Gigafactories in the Low Carbon Fuels scenario by 2050
- 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
- 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
- The modelling suggests an optimal solution from the perspective of cost-effective GHG reduction and risk mitigation may lie somewhere in-between the scenarios evaluated

Version History & Disclaimer

Reference Number	Issued Date	Revision
RD18-001912-1	19 June 2018	First issue
RD18-001912-2	24 July 2018	Societal costs added. Executive Summary updated in line with full report.
RD18-001912-3	24 August 2018	Minor plot format modifications

Contents

- **Introduction**
- Key Inputs & Assumptions
- Results
- Conclusions
- Recommendations

The impact of two scenarios: 'High EV Adoption' & 'Low Carbon Fuels' on GHG emissions, infrastructure, costs & resources are compared

- This report summarises findings from a study of the implications of two scenarios for future Light Duty Vehicle* propulsion energy to 2050 in Europe
  - The implications of each scenario have been analysed using the SULTAN** (SUstainabLe TrANsport) model, developed by Ricardo for the European Commission, and by reference to a literature search of over 400 technical publications
  - The study did not consider the implications of Connected and Autonomous Vehicles (CAV) and Mobility as a Service (MaaS) or model consumer purchase preferences

High EV Scenario

Low Carbon Fuels# Scenario

CO_2

1. What are the Green House Gas (GHG) emissions, including life cycle emissions?

2. What are the implications for energy supply and electricity infrastructure?

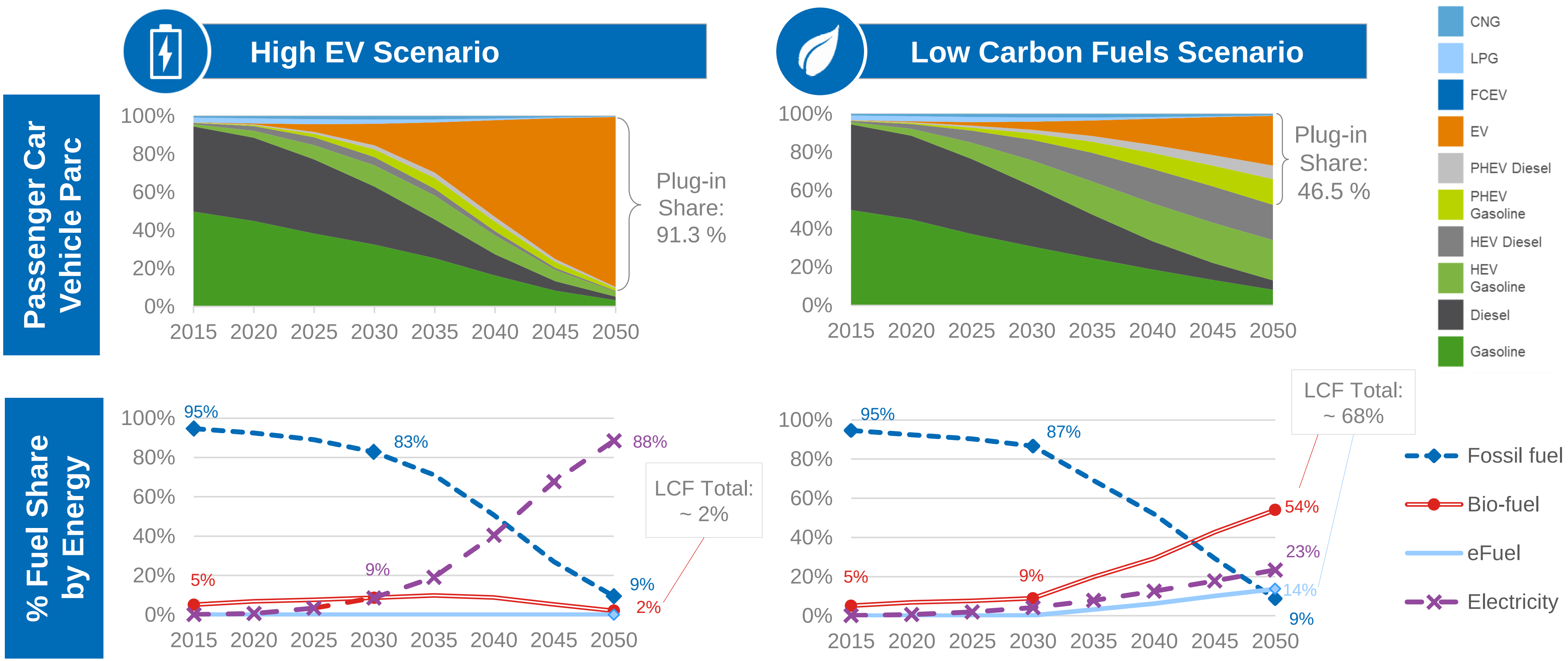
3. What are the cost implications?

4. What are the implications on materials and natural resources?

Note: * 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
** SULTAN : A Ricardo tool developed 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
# Low Carbon Fuels include biofuels and eFuels generated from renewable energy sources

Both scenarios feature significant electrification and use of low carbon fuels (biofuels and eFuels)

- The scenarios examine the implications of hypothetical future vehicle fleet powertrain mixes
  - The scenarios are not intended to be forecasts of the future powertrain mix
- The energy share of each fuel uses energy/km estimates of each powertrain type based on a study* carried out by Ricardo for the European Commission and on Ricardo specialist opinion



Note: New registrations and vehicle parc profiles are calibrated to historic data and projections from European Commission modelling - Comparable scenarios were created form Light Commercial Vehicles – see full report

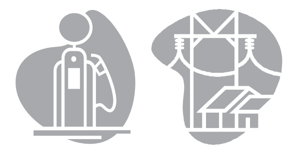
Source: *N. Hill et al., "Improving understanding of technology and costs for CO2 reductions from cars and LCVs in the period to 2030 and development of cost curves," 2014

Total Life Cycle GHG emissions were estimated including vehicle production and disposal, and fuel production emissions

Vehicle life cycle

- 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

- 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

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

To investigate the implication for electricity network infrastructure, the study considered a series of recharging scenarios for plug-in vehicles

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)

Trends in key input assumptions to 2050 are based on recent studies supported by sensitivity studies on key variables

- Key input assumptions are described in the links below:

Fleet average tailpipe CO_2

Electricity GHG Intensity

Battery Costs

Liquid Fuels and Electricity price

Low Carbon Fuel availability

Low Carbon Fuel substitution rates

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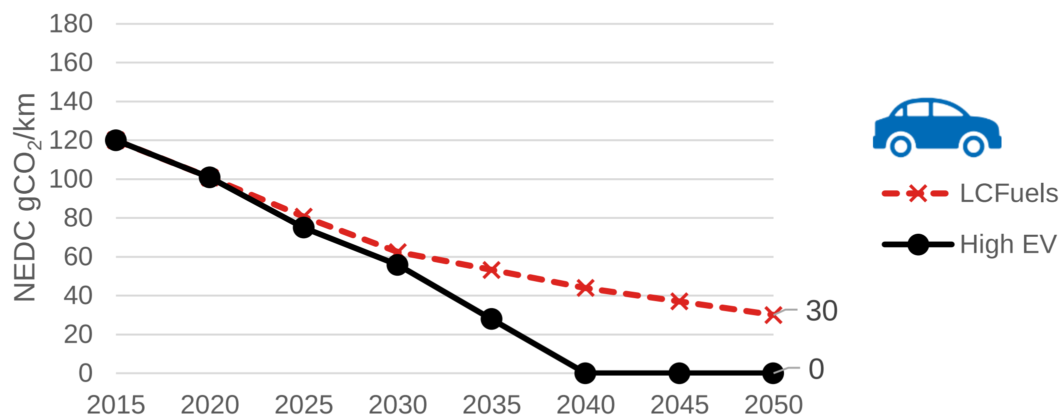
The trajectories for CO_2 improvement were set up to be consistent with the gCO_2/km improvements indicated by the European Parliament

Input assumptions on Tank-to-Wheels (TTW) NEDC gCO_2/km improvement trajectory for new vehicles

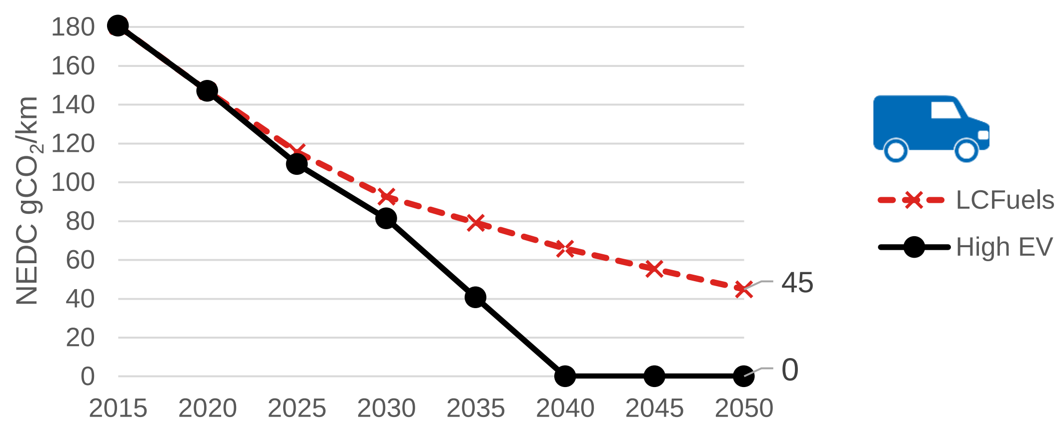
gCO_2/km improvement trajectories for passenger cars

Passenger Cars



gCO_2/km improvement trajectories for light commercial vans

Light Commercial Vans



Source: Ricardo Energy & Environment

- 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 trajectory for the High EV scenario has been set up to be consistent with the upper end of these recommendations, and extrapolated to 2050
- The Tank-to-Wheels (TTW) trajectory for the **Low Carbon Fuels scenario achieves an equivalent Well-to-Wheels (WTW) CO_2 emissions to the High EV scenari**o

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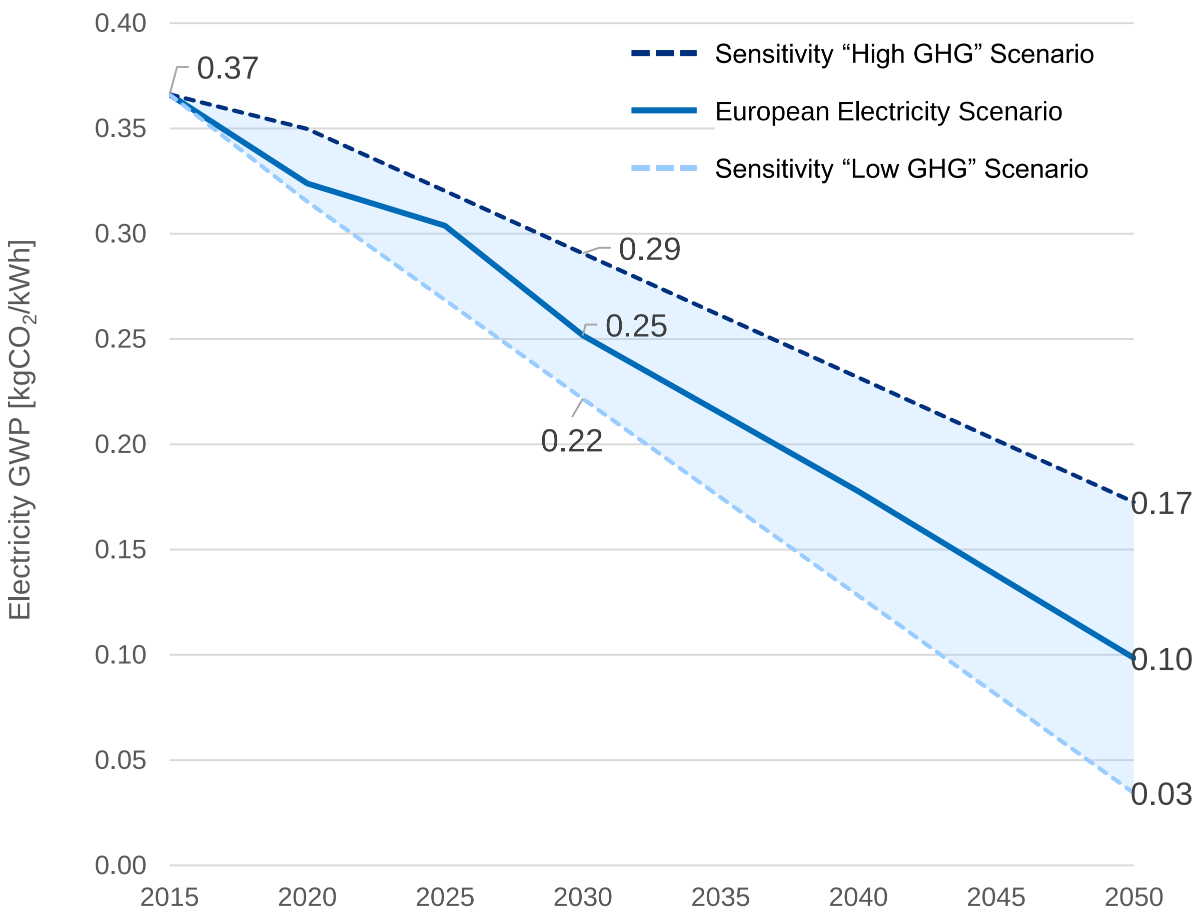
The electricity GHG intensity is based on European Commission assumptions and other previous analysis

The impact of ‘High’ and ‘Low’ GHG intensity assumptions are also analysed

European Electricity Scenario

Electricity Global Warming Potential (GWP) [$kgCO_2/kWh$]



- The baseline trajectory for electricity GHG intensity 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

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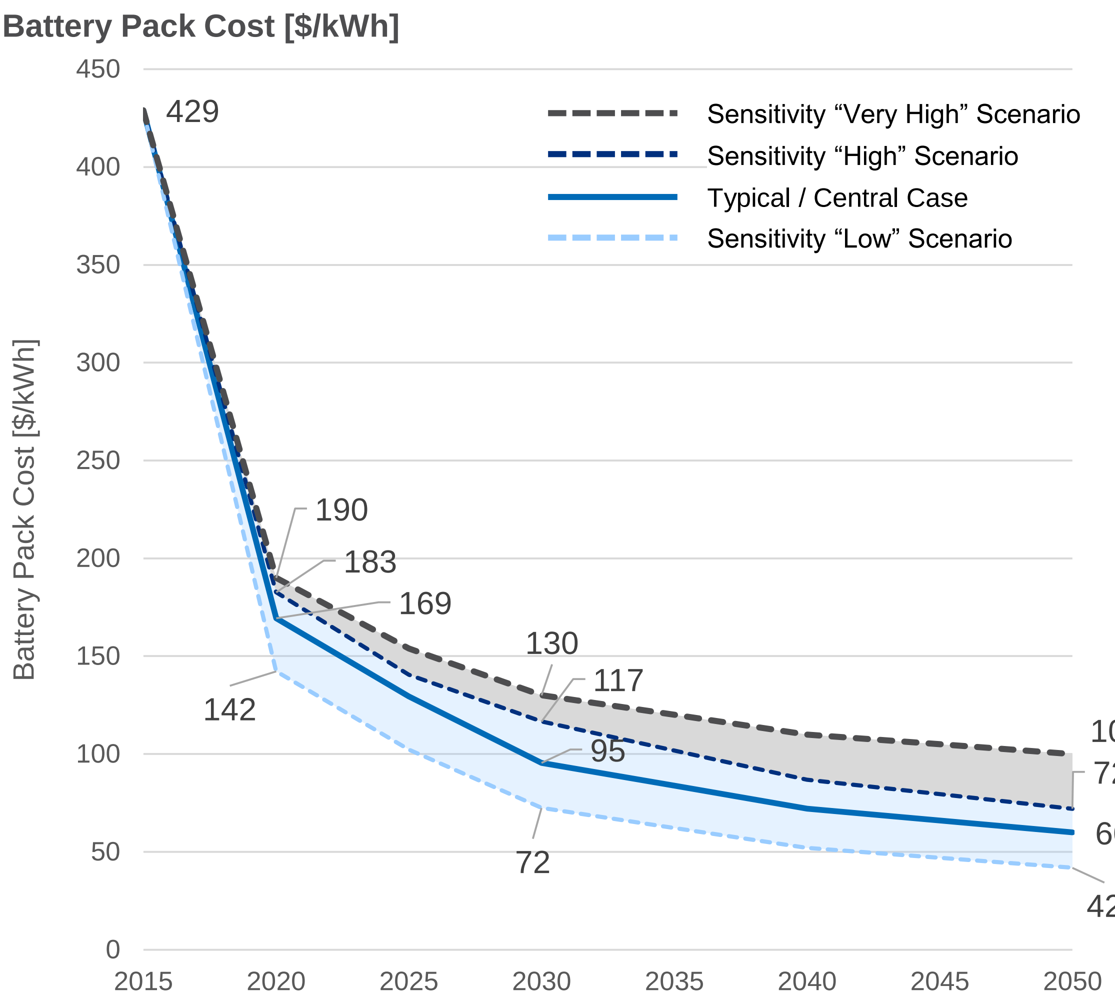
Source: S. Frank et al., “EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050.”,2016; Previous analysis by Ricardo Energy & Environment for the EC and other European projects

Battery costs are a key component of EV costs. Cost/kWh is expected to decline by over 70% by 2030 compared to prices in 2015

Sensitivity studies were also carried out to understand the affect of battery cost on overall costs

Assumed Technology Cost Trends – Battery Pack



Source: Ricardo Energy & Environment analysis

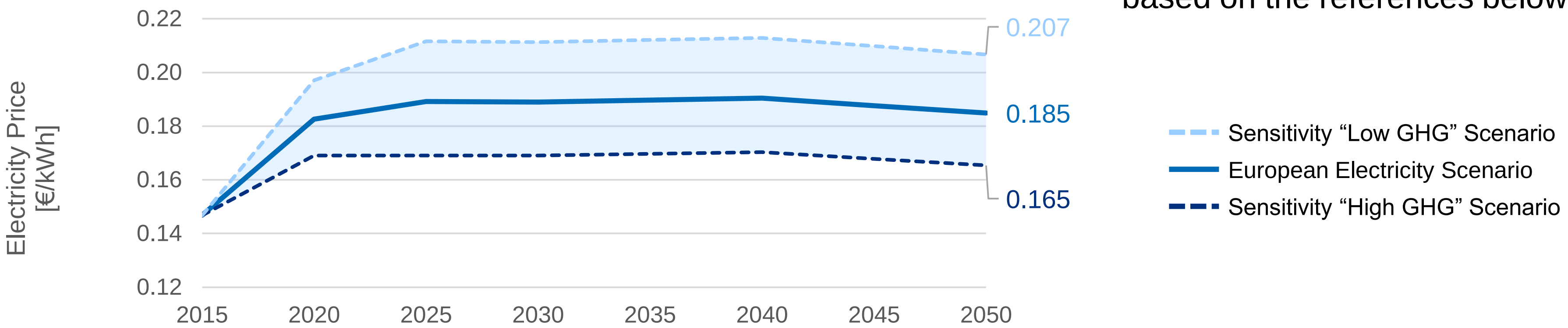
- Estimates for future battery pack costs (including assembly) are based on learning-based cost analysis developed as part of work for the European Commission
- Battery costs are used together with electric range and State of Charge assumptions to calculate the costs of baseline xEV powertrain vehicles relative to conventional equivalents
- Assembly of the battery pack into the vehicle is considered in vehicle costs
- Sensitivity studies were carried out for 'Low', 'High' and 'Very High' battery cost trends
- The average battery pack size for an EV passenger car in 2050 is assumed to be 82kWh (108kWh for an average Light Commercial Vehicle)
  - Battery pack energy density was also assumed to increase to 800Wh/kg by 2050

The price of liquid fuels and electricity has been based on data from published studies

Sensitivity studies were also carried out to understand the affect of electricity and fuel price

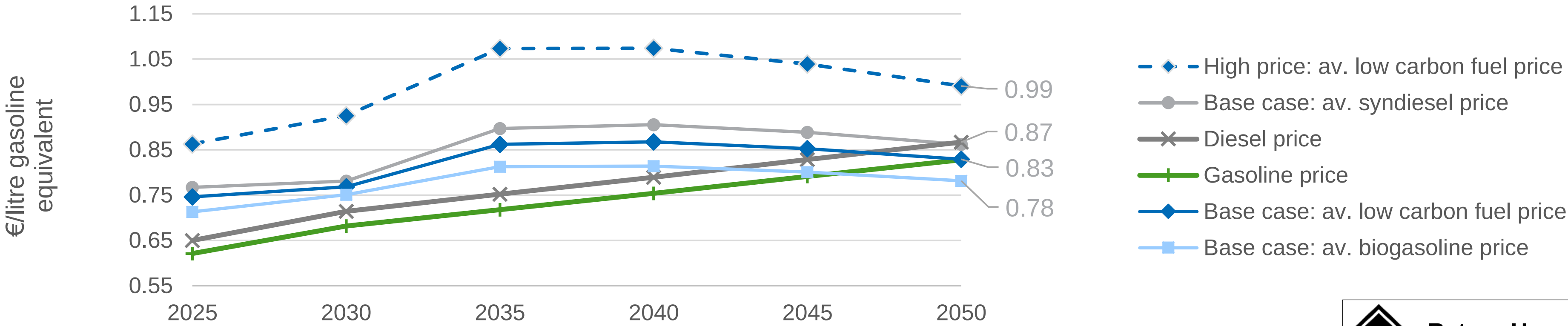
Assumed Energy Cost Trends Excluding Taxes

Electricity Price [€/kWh, excl. tax]



- Assumptions about energy costs are based on the references below

Low Carbon Fuels Price [€/litre eq., excl. tax]



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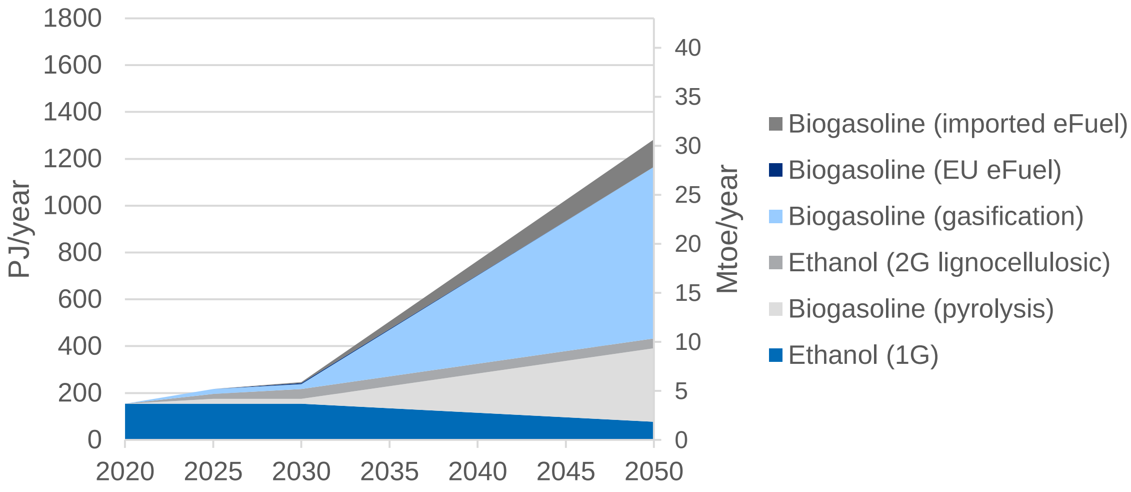
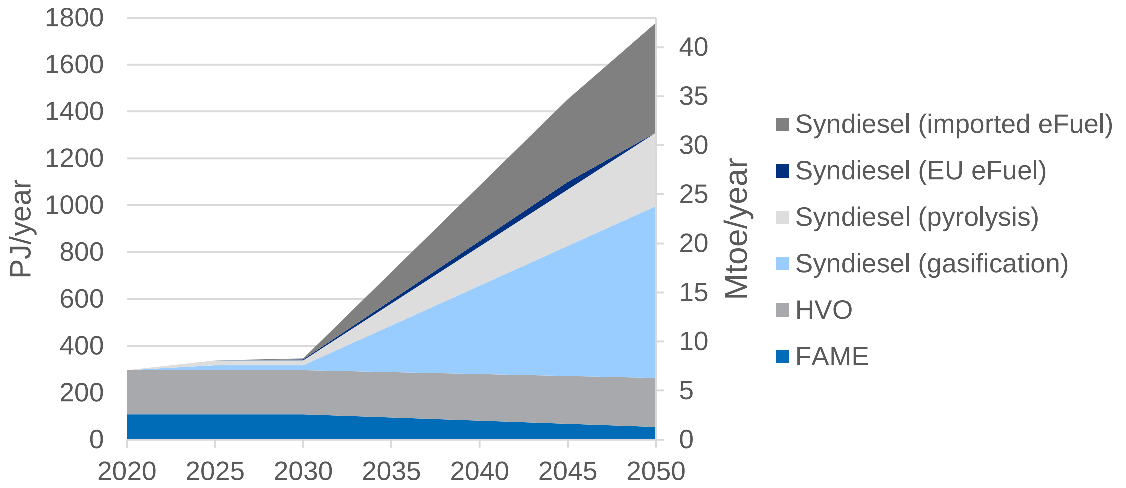
Source: S. Frank et al., “EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050.”, 2016
Directorate-General for Research and Innovation (European Commission), “Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe,” 2018;
K. Sub 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.”

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

Bioethanol and biogasoline



FAME and syndiesel



- Availability of Low Carbon Fuels is intended to reflect a scenario where the whole biomass supply chain is optimised to maximise use of bioenergy
- Assumptions about the availability of Low Carbon Fuels are based on the references below
- 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

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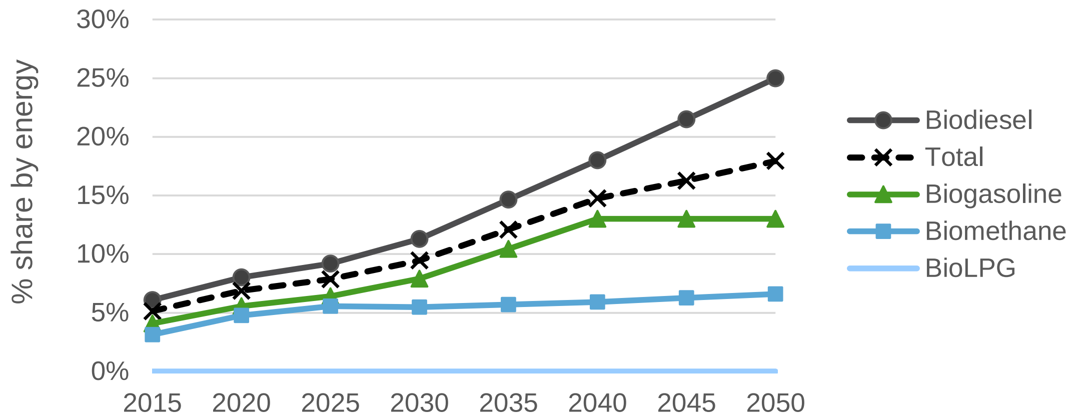
Source: Directorate-General for Research and Innovation (European Commission), "Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe," 2018;
K. Sub Group on Advanced Biofuels Sustainable Transport Forum, Maniatis, I. Landälv, L. Waldheim, E. Van Den Heuvel, 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."

Both scenarios feature substitution of conventional liquid fuels by biofuels, with a higher share in the Low Carbon Fuels scenario

European scenarios for biofuel and other low carbon fuel uptake

High EV

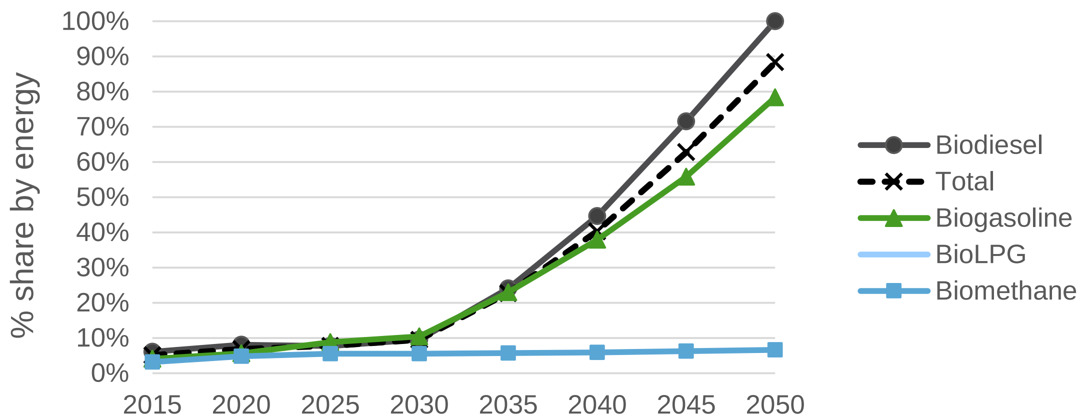
Low carbon fuel substitution by energy carrier



- 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, E20 is assumed to be 100% by 2040

Low carbon fuels

Low carbon fuel substitution by energy carrier



- 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 and reviewed by Ricardo

The study compares the impact of each scenario on GHG emissions, electricity infrastructure, costs & resources

1. What are the Green House Gas (GHG) emissions, including life cycle emissions?

2. What are the implications for energy supply and electricity infrastructure?

3. What are the cost implications?

4. What are the implications on materials and natural resources?

- Selected results are shown compared to a Business as Usual (BAU) reference scenario as used by the European Commission as a baseline for quantifying the impact of future policy changes

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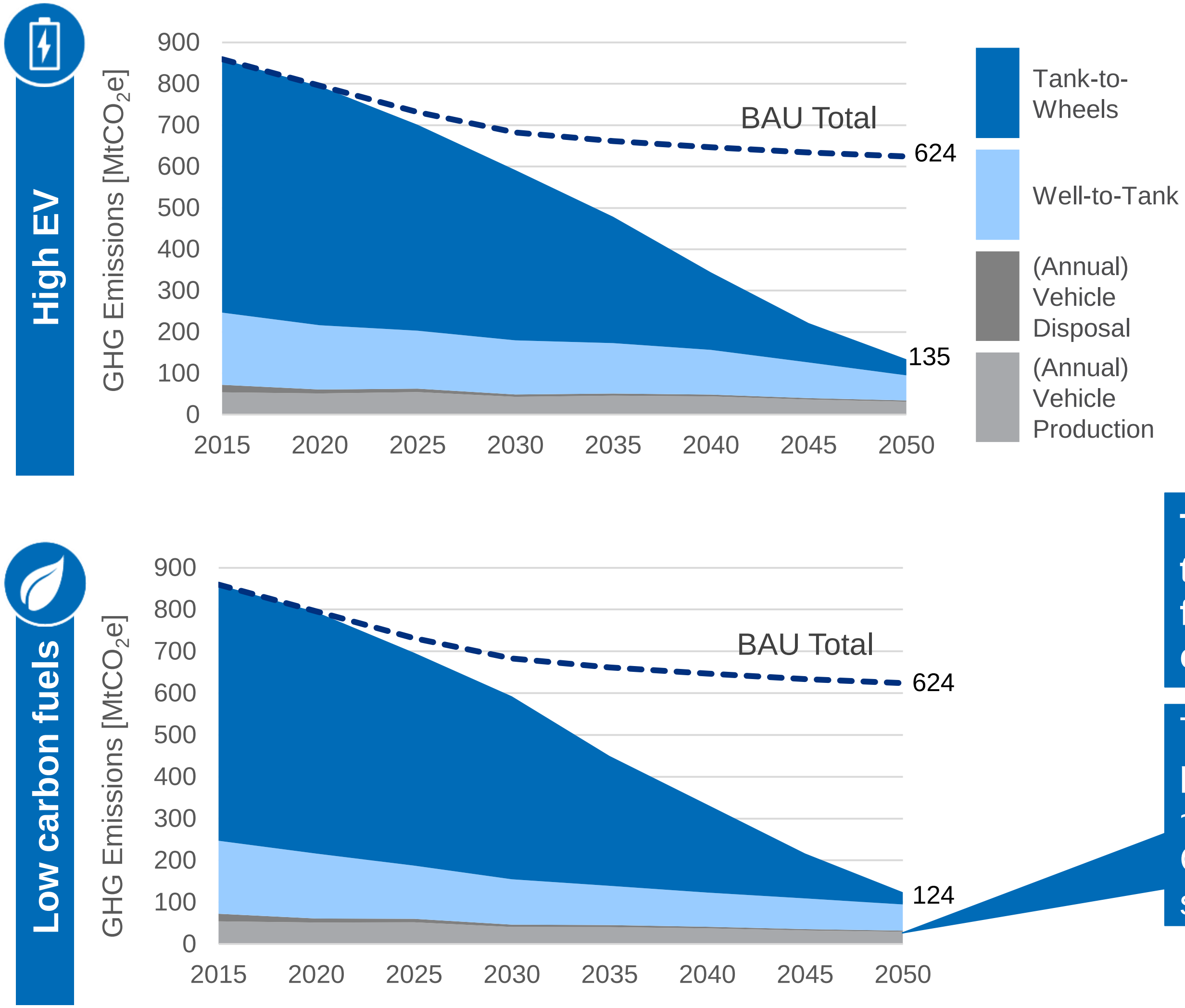
Both scenarios result in a similar and significant reduction in GHG emissions to 2050

GHG Emissions (Well-to-Wheel + Embedded)



- GHG emissions reduce to less than 13% of 2015 value by 2050, for both scenarios
- GHG emissions are substantially less than the European Commission Business as Usual* (BAU) reference scenario
- Well-to-Wheel (WTW) GHG savings vs 1990 are ~92%

Technologies will continue to develop to deliver "zero impact" on air quality from tailpipe but this was not considered in this analysis

The embedded emissions from production and disposal rises to ~25% by 2050 for both the Low Carbon Fuels and the High-EV scenario

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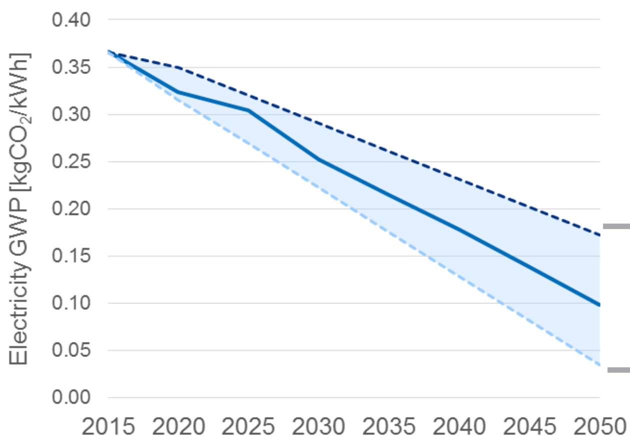
Source: Ricardo Energy & Environment SULTAN modelling and analysis

* BAU scenario as used by European Commission as a baseline for quantifying the impact of future policy changes

Sensitivities on electricity GHG intensity affect which scenario results in lower GHG emissions

Sensitivities on Electricity GHG intensity vs base High EV scenario

Electricity Global Warming Potential (GWP) [$kgCO_2/kWh$]



Total GHG emissions

+33 $MtCO_2e$

-8 $MtCO_2e$

"High" electricity GHG intensity

High EV Scenario produces 33Mt CO_2 **MORE** than the Low Carbon Fuels Scenario

"Low" electricity GHG intensity

High EV Scenario produces 8Mt CO_2 **LESS** than the Low Carbon Fuels Scenario

High EV Scenario

Low Carbon Fuels Scenario

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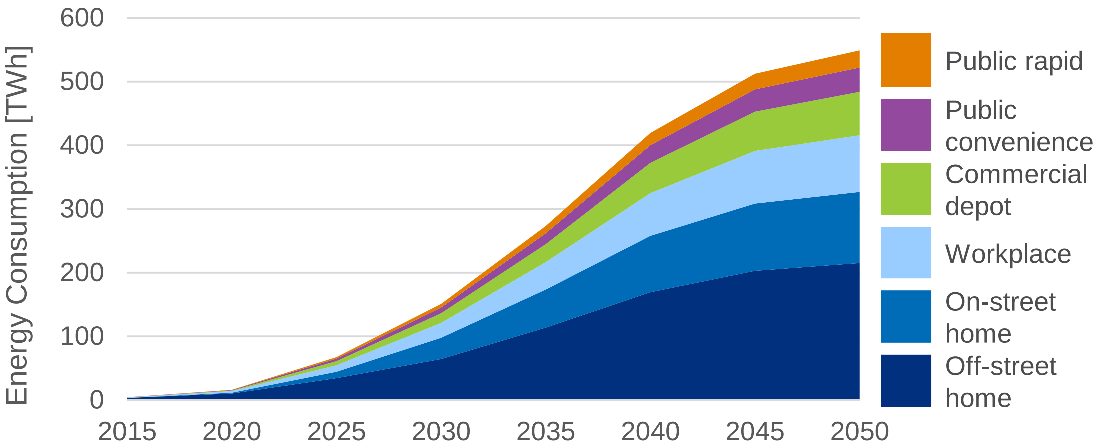
Source: Ricardo Energy & Environment SULTAN modelling and analysis

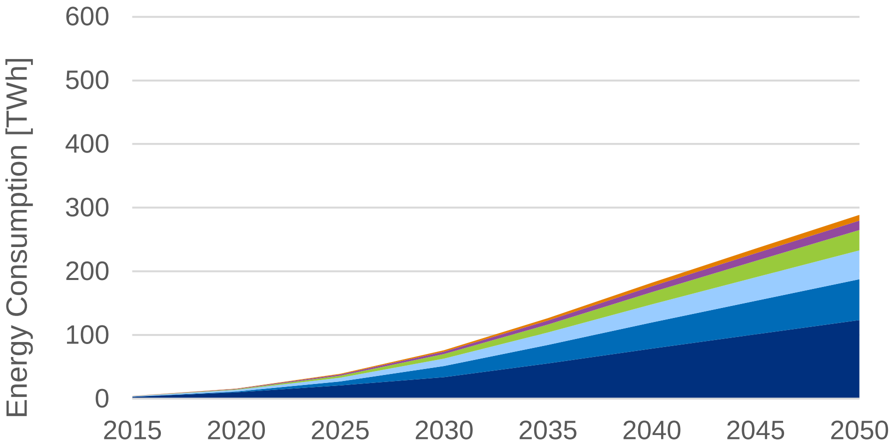
Twice the electrical energy is required for EVs in the High EV scenario compared to the Low Carbon fuels scenario (550 TWh vs 289 TWh)

Electricity consumption from recharging by location (Home Charging Scenario)

High EV



Low carbon fuels



- Electricity demand from EV charging in 2050 in the managed home charging scenario is ~550 TWh (1980 PJ)
  - This represents ~**17.5% of the EU's 2015 electricity generation**
- In the 'Home' charging scenario, most of this energy (~60%) is expected to come from charging overnight in residential areas
- **Charging requirements are ~47%* lower in the Low Carbon Fuels scenario**, with a higher share of charging from residential/home

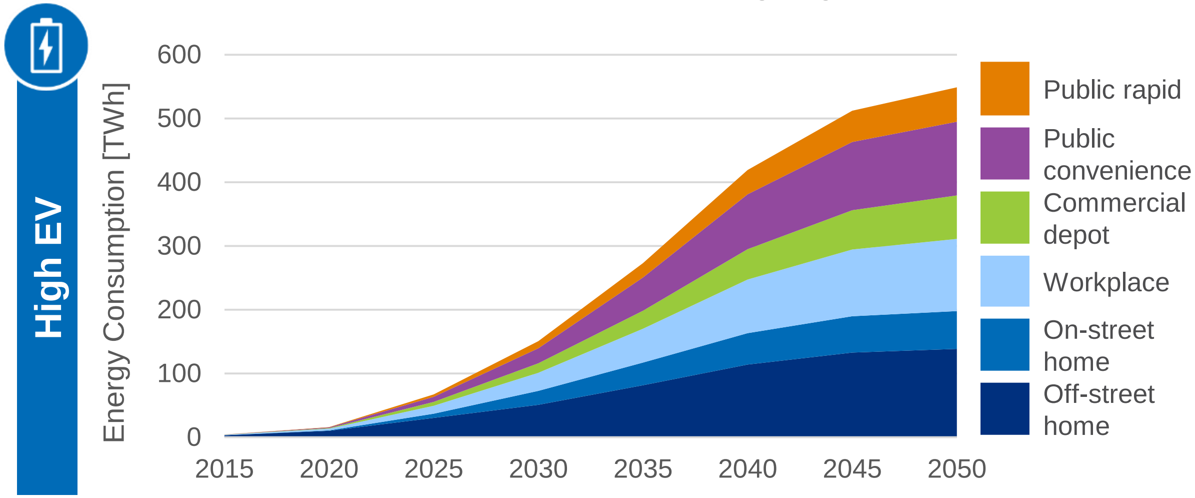
Unmanaged charging would require significantly more upgrades to Low Voltage (LV) networks to support off-street and on-street charging (and therefore much higher cost – more than double the cost cumulatively to 2050)

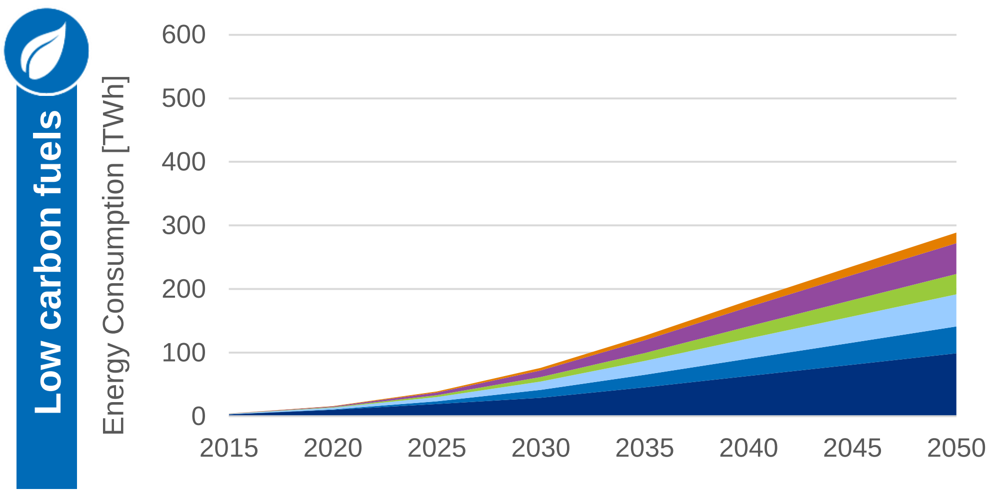
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Note: * Including EU electricity used to produce EU eFuels decreases the difference to 39% lower for Low Carbon Fuel vs High EV

Under a grazing scenario home charging accounts for 36% and 49% of consumption for High EV & Low Carbon Fuels scenarios respectively

Electricity consumption from recharging by location (Grazing Scenario)





- The alternative assumptions for high use of public infrastructure assume a ‘Grazing’ culture with greater reliance on public (and other mostly ‘daytime’) charging options:
- Home on/off-street charging only accounts for 36% of electricity consumption in the High EV scenario and 49% in the Low Carbon Fuels scenario

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

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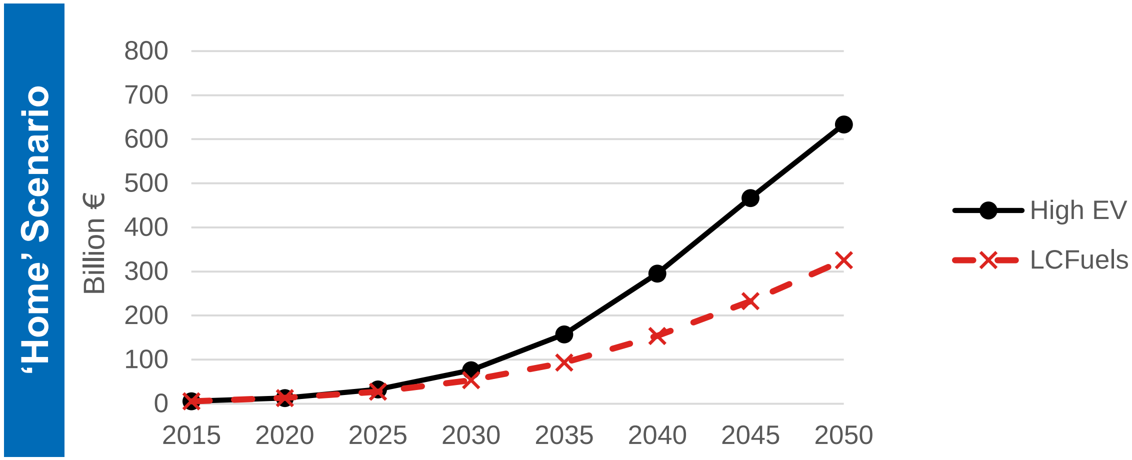
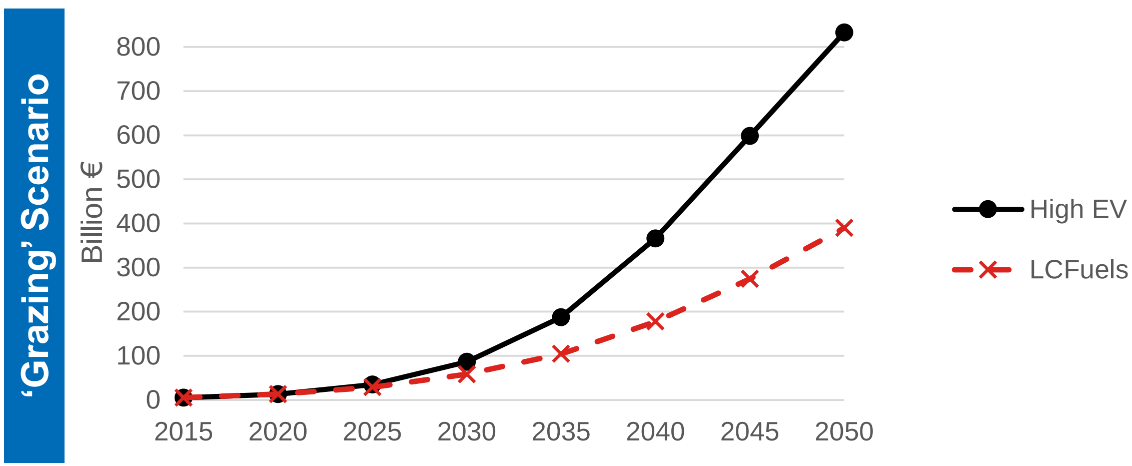
Source: Ricardo Energy & Environment SULTAN modelling and analysis

The cumulative cost of managed EV charging & network infrastructure reinforcement is estimated between €630bn and €830bn to 2050

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



- For the **High EV** scenario, the cumulative charging and network infrastructure reinforcement costs by 2050 are:
  - ‘Home’ charging **~€630bn**
  - ‘Grazing’ charging **~€830bn**

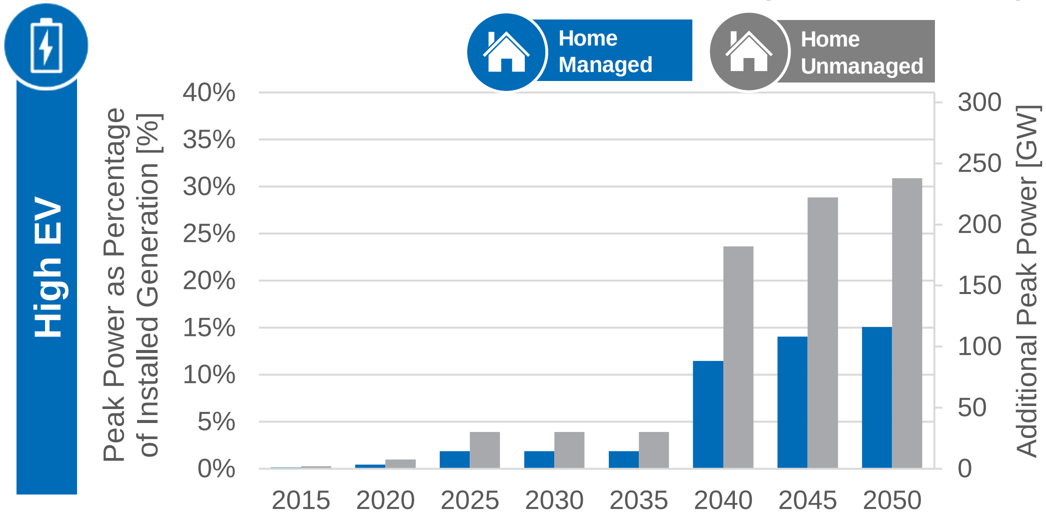


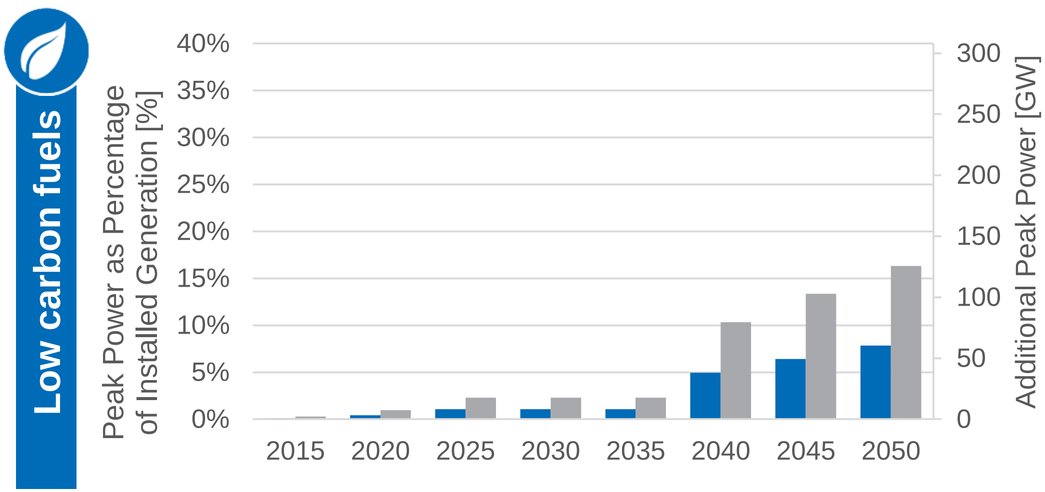
- For the **Low Carbon Fuel** scenario the cumulative costs, are approximately half of this
  - ‘Home’ charging ~**€326bn**
  - ‘Grazing’ charging **~€389bn**

Source: Ricardo Energy & Environment SULTAN modelling and 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





- 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)

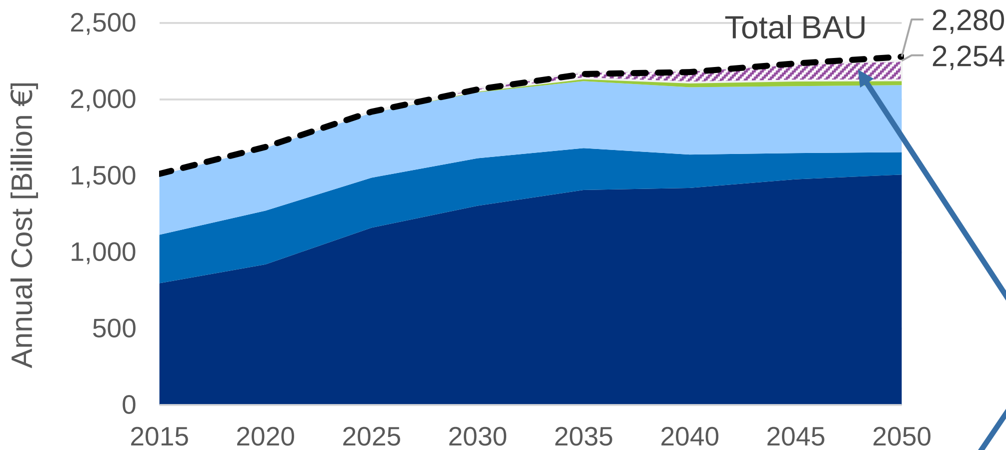
Source: Ricardo Energy & Environment SULTAN modelling and analysis

The annual parc total costs to the end user are similar for the High EV and Low Carbon Fuels scenarios if lost fuel tax revenue is considered

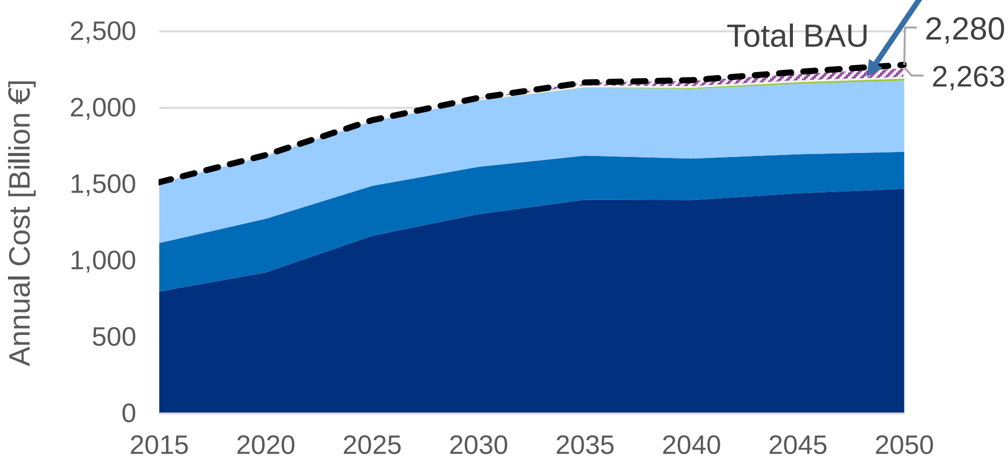
Taxes are applied for all energy carriers at their current and projected (BAU) levels

Total Parc Annual Costs to End-user for All Light Duty Vehicles

High EV



Low carbon fuels



- **Total annual parc cost to the end user is similar for both scenarios in 2050**, when adjusting to maintain Net Fiscal Revenue: **~€2,254bn & ~€2,263bn** for the High EV and Low Carbon Fuels scenarios respectively

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

- Both scenarios result in overall cumulative cost savings to the end end-user between ~€1,100 & €1,600bn (1.3% - 1.8% of total cumulative end user costs)* vs EC BAU** reference to 2050

Cost of electricity infrastructure upgrades

Operation and maintenance costs

Fuel / energy costs

Capital (vehicle)

Net Fiscal Revenue (NFR) loss – Reduction in fuel tax receipts to governments

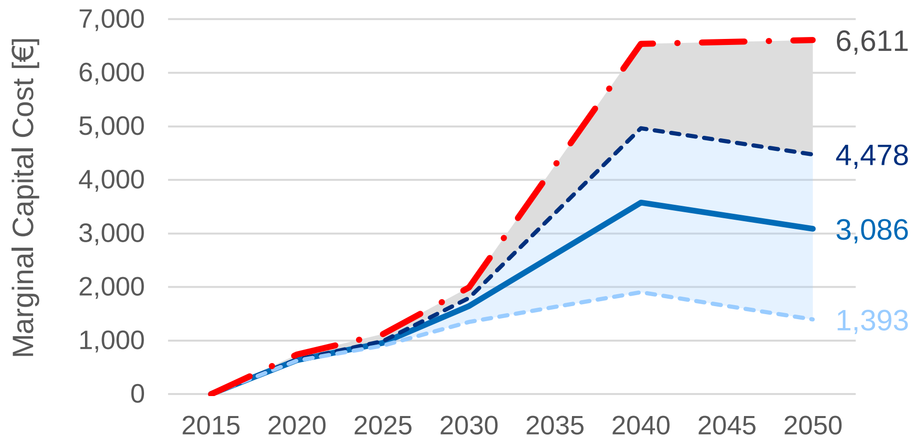
Source: Ricardo Energy & Environment SULTAN modelling and analysis

Note: *Including infrastructure costs but excluding adjustment for Net Fiscal Revenue **BAU scenario as used by European Commission as a baseline for quantifying the impact of future policy changes

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

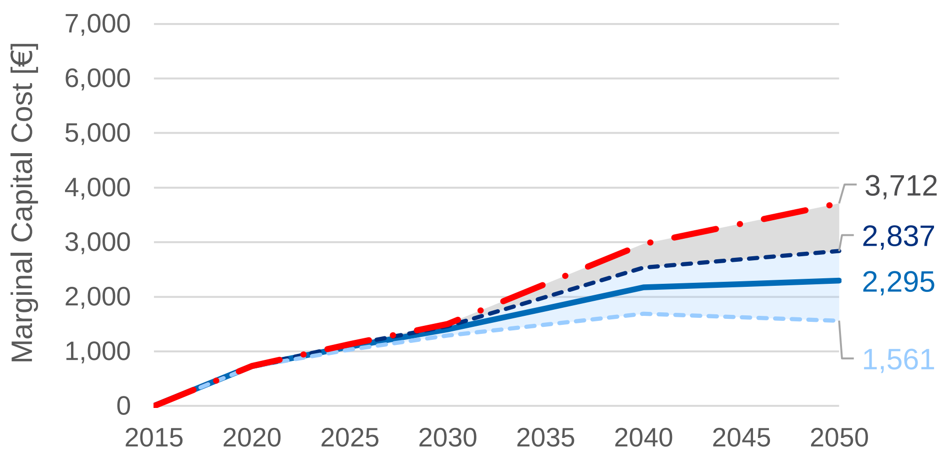
Average marginal additional capital costs per vehicle for passenger cars

High EV



- The average marginal cost increases for new cars under the High EV scenario are significantly higher than those under the Low Carbon Fuels Scenario
- The average marginal cost of new cars is more strongly influenced by uncertainties in battery price in the High EV scenario than the Low Carbon Fuels scenario

Low carbon fuels



Sensitivity Very High Battery Cost
Sensitivity High Battery Cost
Default Battery Cost
Sensitivity Low Battery Cost

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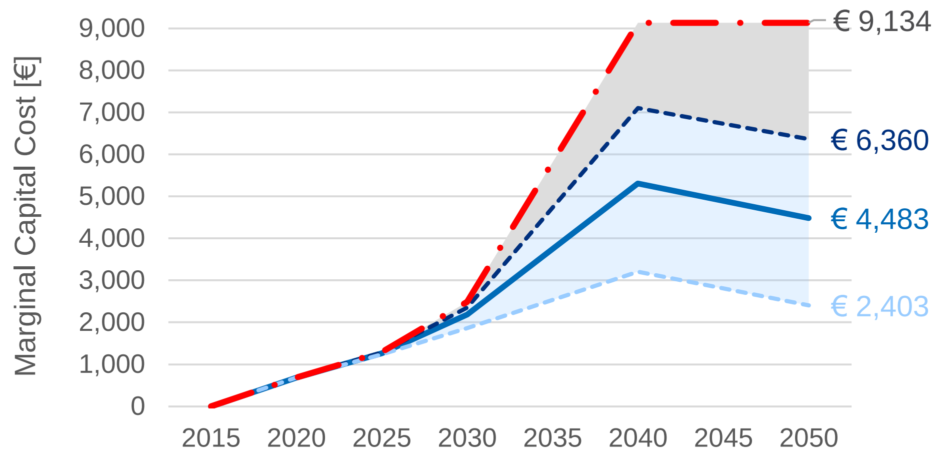
Source: Ricardo Energy & Environment SULTAN modelling and analysis

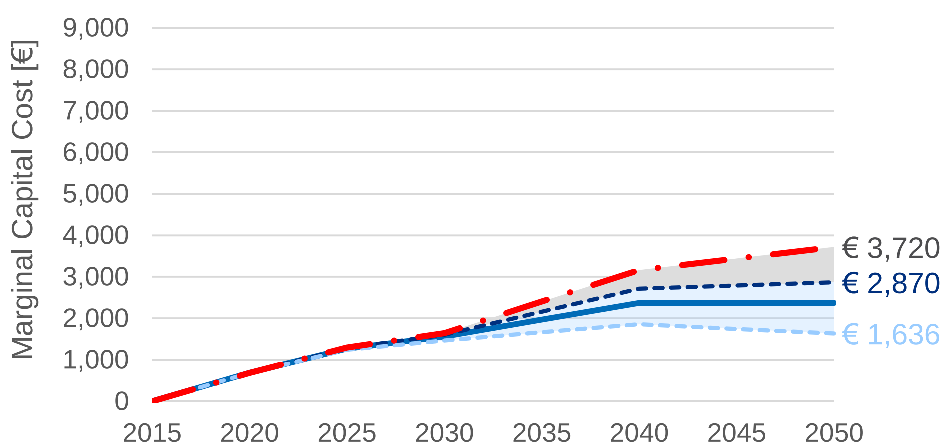
The estimated marginal capital cost increase for vans is larger than for cars, particularly for the High EV scenario

Average marginal additional capital costs per vehicle for light commercial vehicles

High EV



Low carbon fuels



- The marginal capital costs of vans is particularly strongly affected by battery costs

Sensitivity Very High Battery Cost

Sensitivity High Battery Cost

Default Battery Cost

Sensitivity Low Battery Cost

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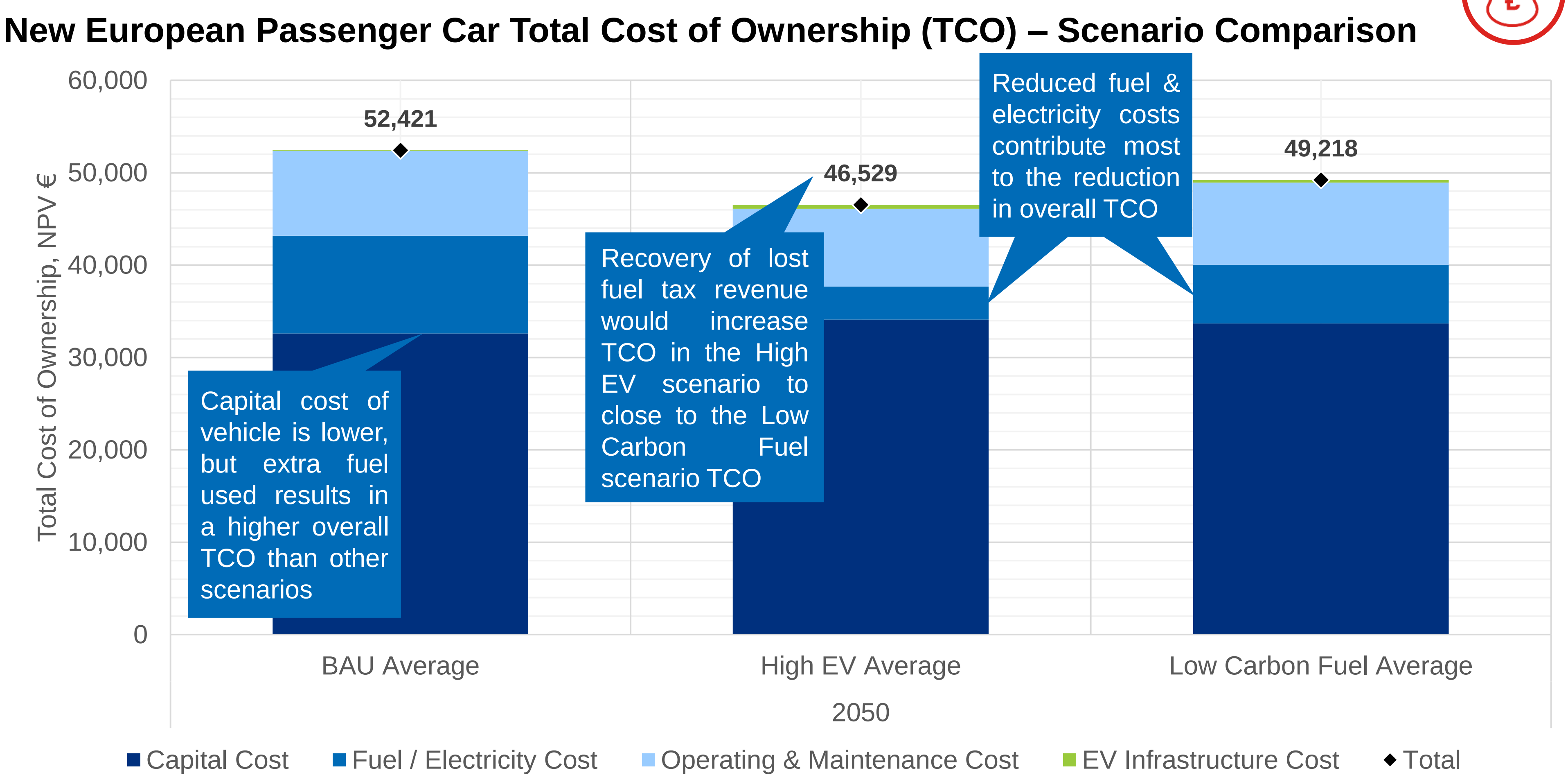
Source: Ricardo Energy & Environment SULTAN modelling and analysis

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

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



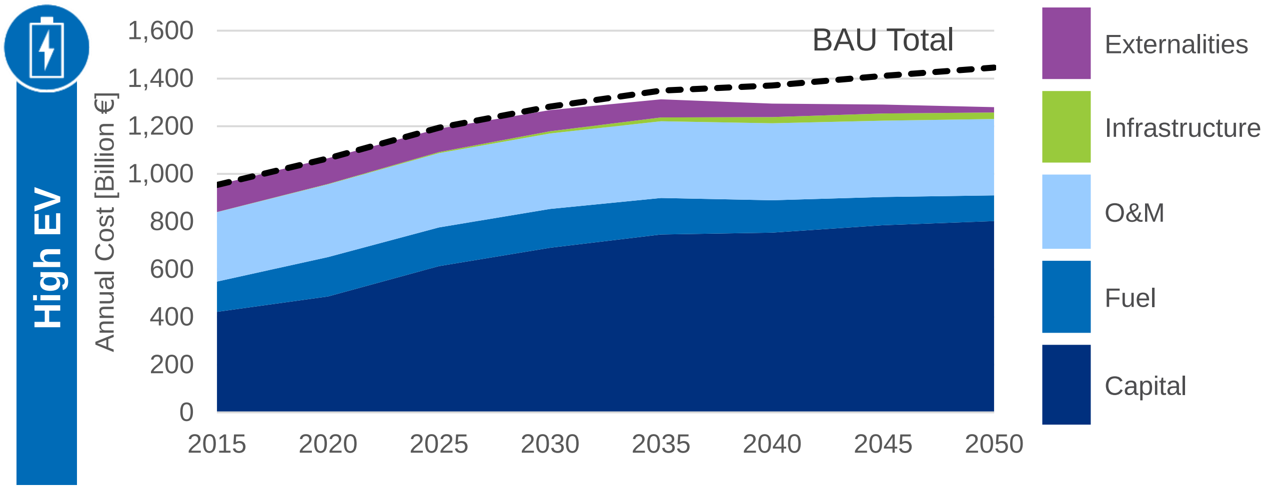
- Assumes lifetime 210,000 km over 15 years
- End-user perspective (including all taxes) with future costs discounted to Net Present Value (NPV)*

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

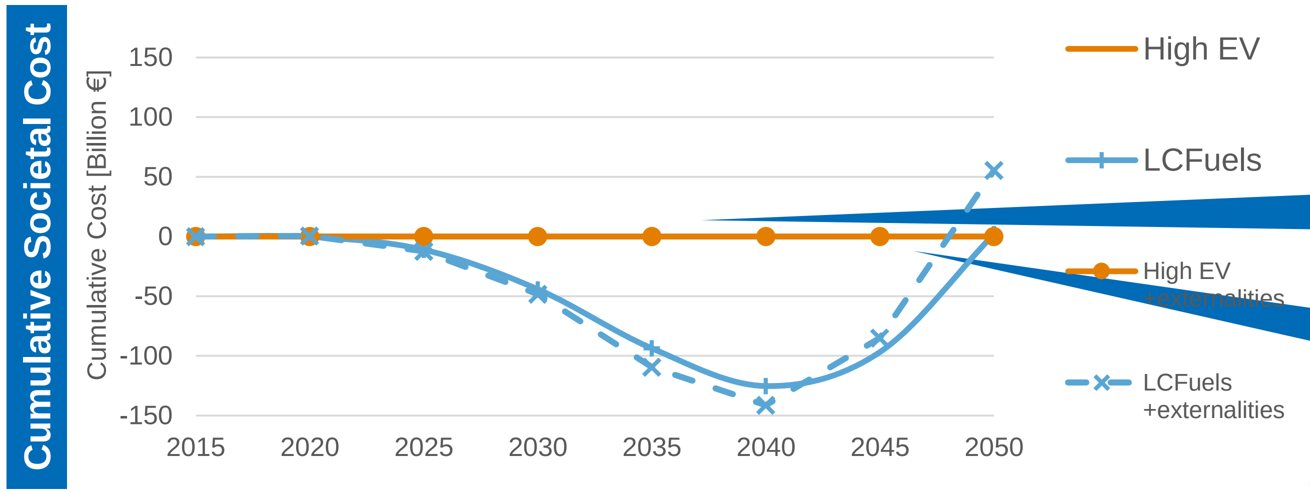
The net societal cumulative costs are lower for High EV scenario only in later periods

External costs (or ‘externalities’) are the monetary value attached to GHG and Air Quality emissions

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



Cumulative Net Societal Costs (relative to High EV)



Source: Ricardo Energy & Environment SULTAN modelling and analysis

- 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, total *annual* 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

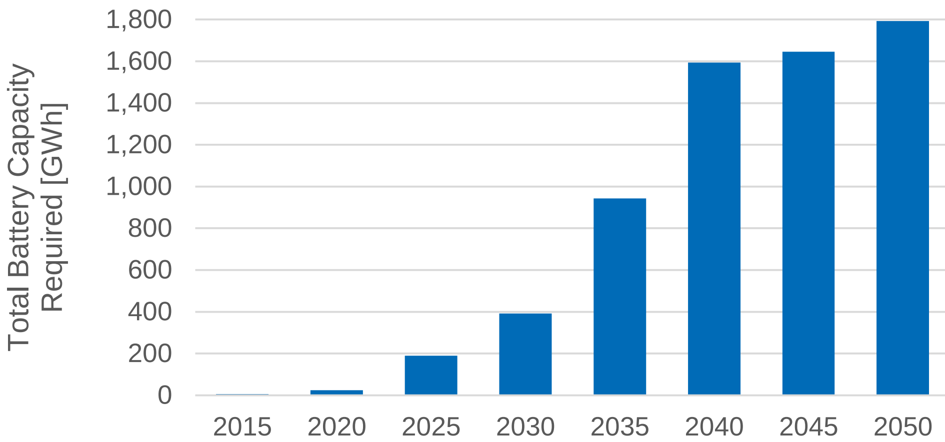
Overall cumulative cost-effectiveness is best for the other scenarios up to 2045-2050

- *Note*: Societal costs exclude all taxes

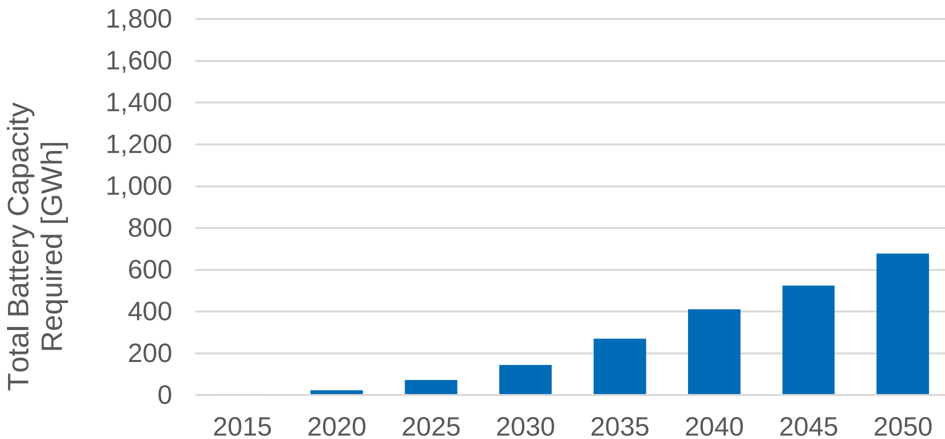
Under the High EV scenario, ~15 Gigafactories would be needed to supply batteries to the European EV market by 2050

Resources & Materials – Annual Battery Capacity [GWh]

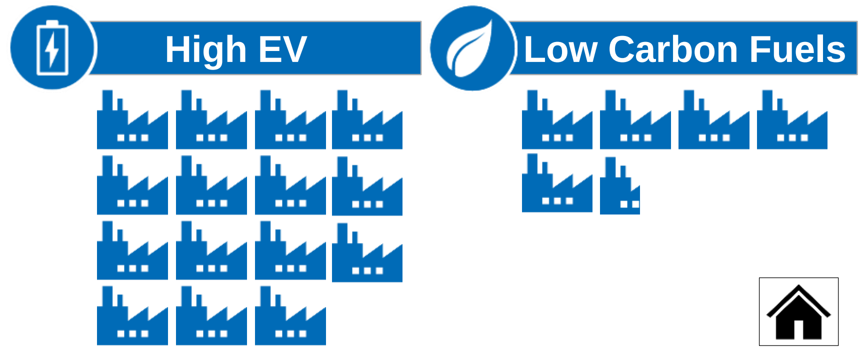
High EV



Low carbon fuels



- 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*

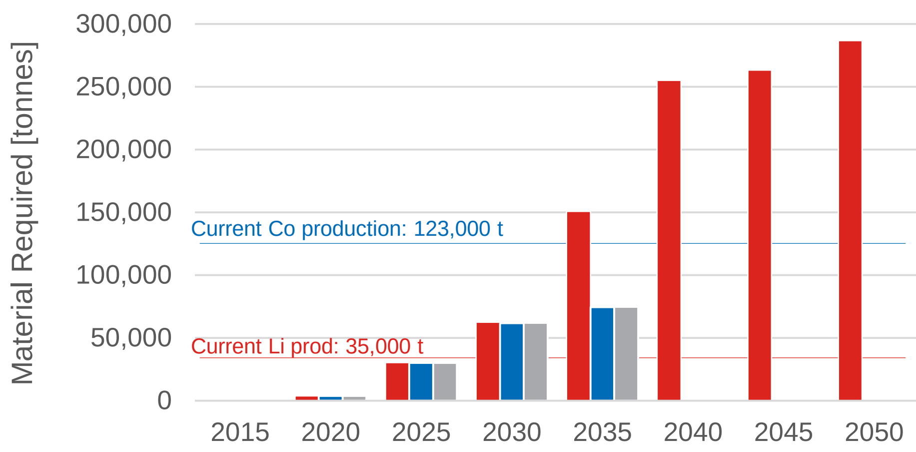
Source: Ricardo Energy & Environment SULTAN modelling and analysis;
* Tesla (https://www.tesla.com/en_CA/gigafactory)

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

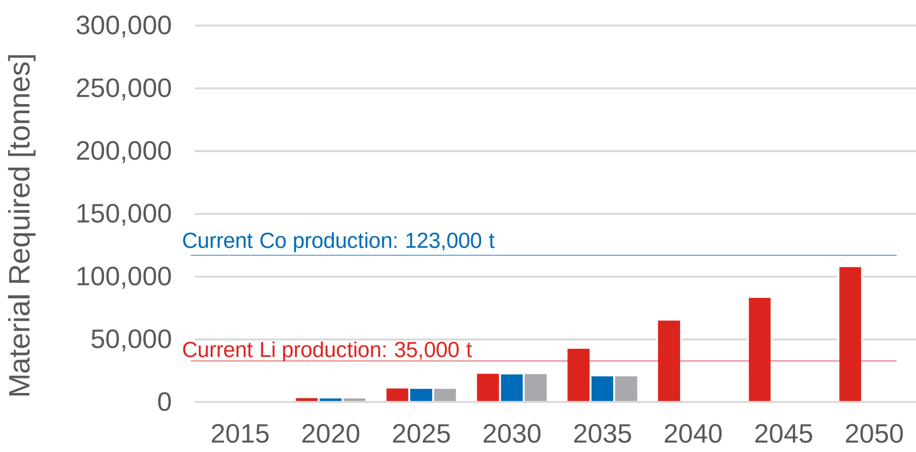
RICARDO

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

High EV



Low carbon fuels



3 **Li** Lithium

27 **Co** Cobalt

28 **Ni** Nickel

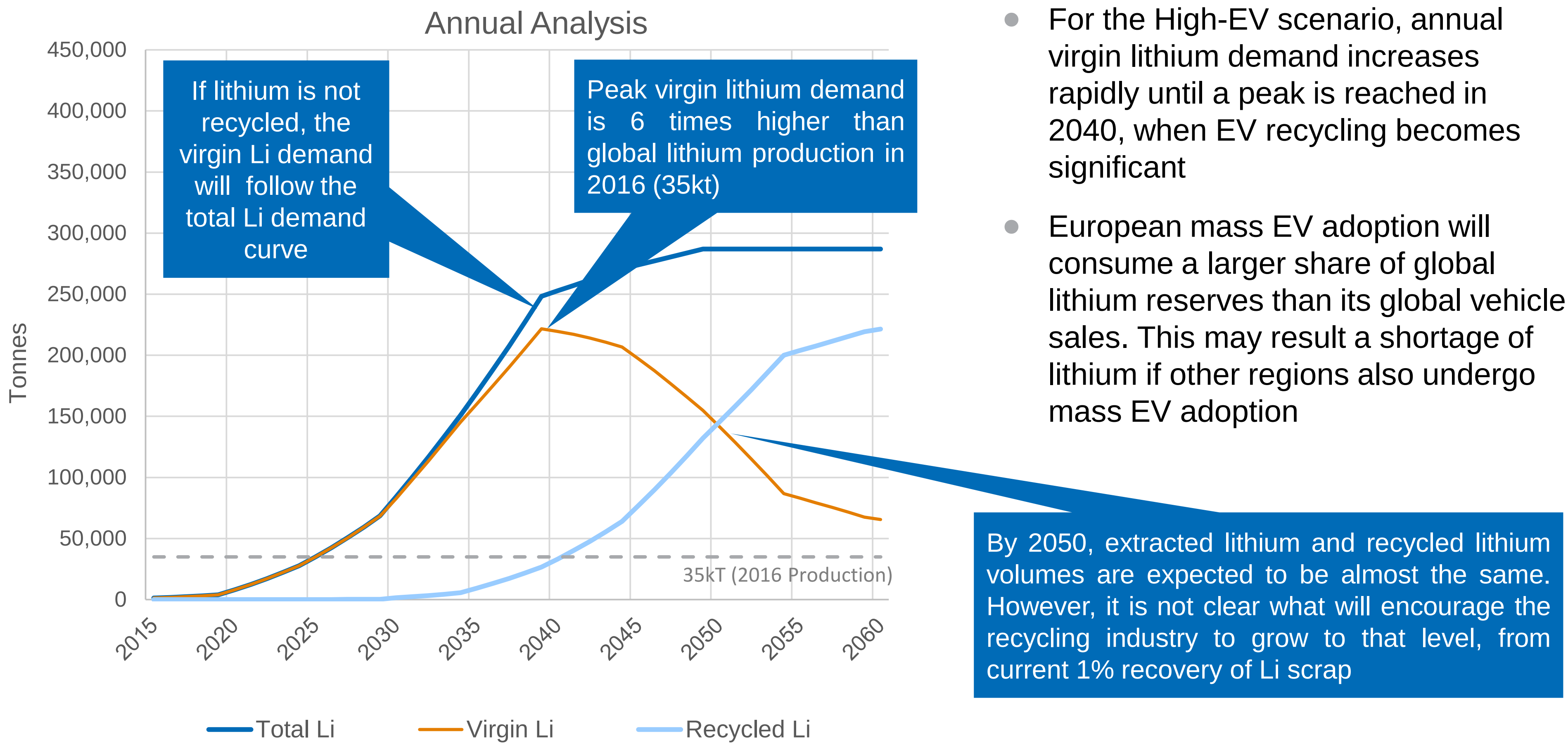
- Assuming current chemistry mixes the resource requirements for Lithium, Cobalt and Nickel would increase very substantially over the period to 2050, which would pose a potential availability risk
- Current global total production p.a.:
  - Li : 35 kt (with 14 Mt reserves)
  - Co : 123 kt (with 7 Mt 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

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

Lithium extraction and recycling would have to be increased significantly to reach peak demand in 2040 in the High EV scenario

Lithium Material Analysis – High EV scenario

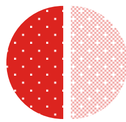


- For the High-EV scenario, annual virgin lithium demand increases rapidly until a peak is reached in 2040, when EV recycling becomes significant
- European mass EV adoption will consume a larger share of global lithium reserves than its global vehicle sales. This may result a shortage of lithium if other regions also undergo mass EV adoption

Source: JRC for EU Commission: L. Lebedeva, F. Di Persio, and L. Boon-Brett, “Lithium ion battery value chain and related opportunities for Europe” 2016;
CEE: R. Verma, M. M. Foss, G. Gülen, C.-H. Tsai, and B. Elliott, “Battery Materials Value Chains Demand, Capacity and Challenges,” 2016;
D. Kushnir and B. A. Sandén, “The time dimension and lithium resource constraints for electric vehicles,” Resource Policy, vol. 37, no. 1, pp. 93–103, Mar. 2012

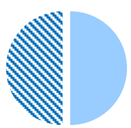
The majority of lithium and cobalt is located in a few countries which is a potential risk for prices and security of supply

3
Li
Lithium

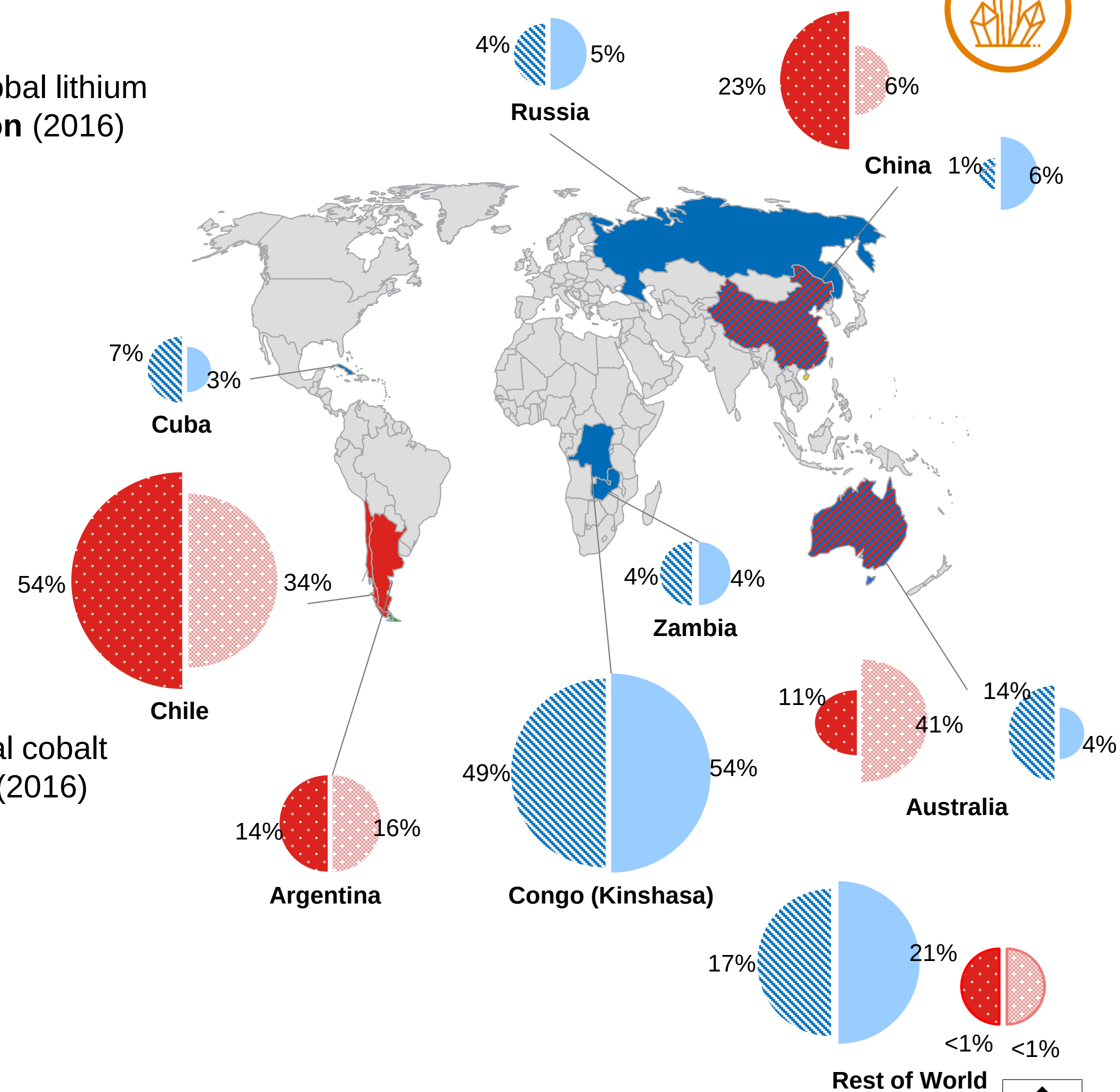
Share of global lithium **reserves** ←  → Share of global lithium **production** (2016)

- The majority of lithium reserves are located in South America; Chile has over half the global lithium reserves
- Lithium production and prices could depend heavily on the policies of the Chilean government

27
Co
Cobalt

Share of global cobalt **reserves** ←  → Share of global cobalt **production** (2016)

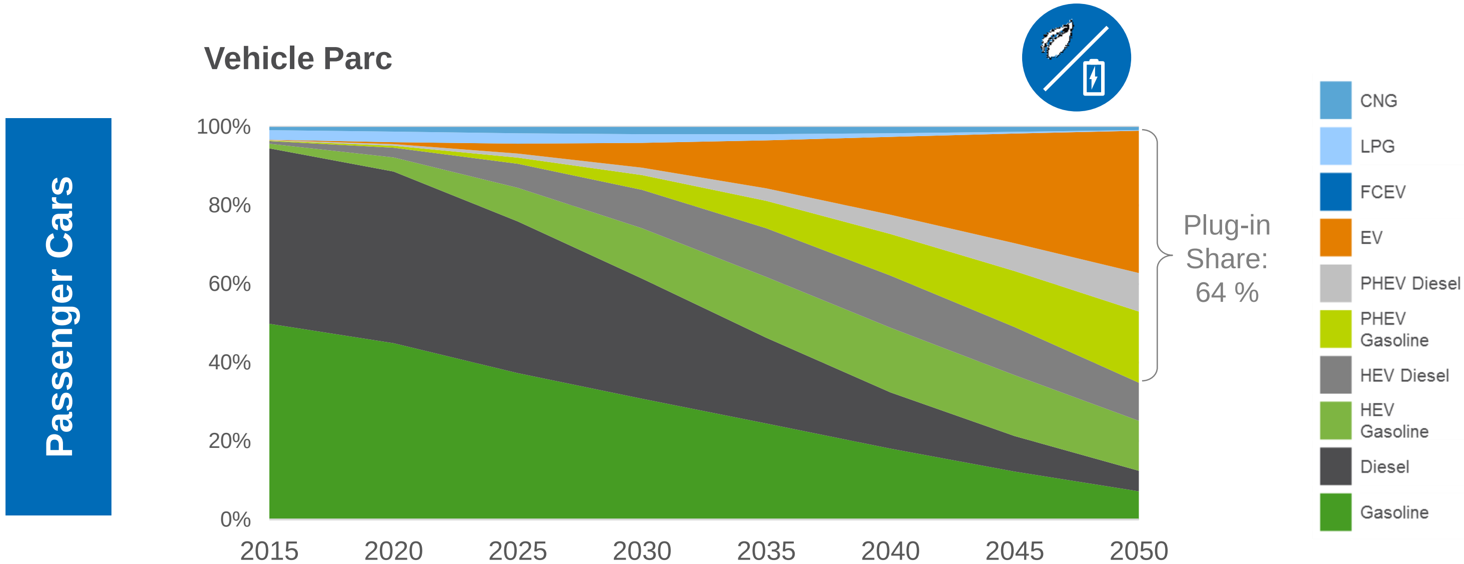
- Although cobalt reserves are present in many countries, the largest reserves and current production are located in Congo (Kinshasa)
- Instability in this region is a factor in the 128% increase in the price of cobalt in 12 months*



Source: U.S Geological Survey (Mineral Commodity Summaries 2017);
* The London Metal Exchange (Sep 2016 – Sep 2017 Values)

Finally, a scenario was 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 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

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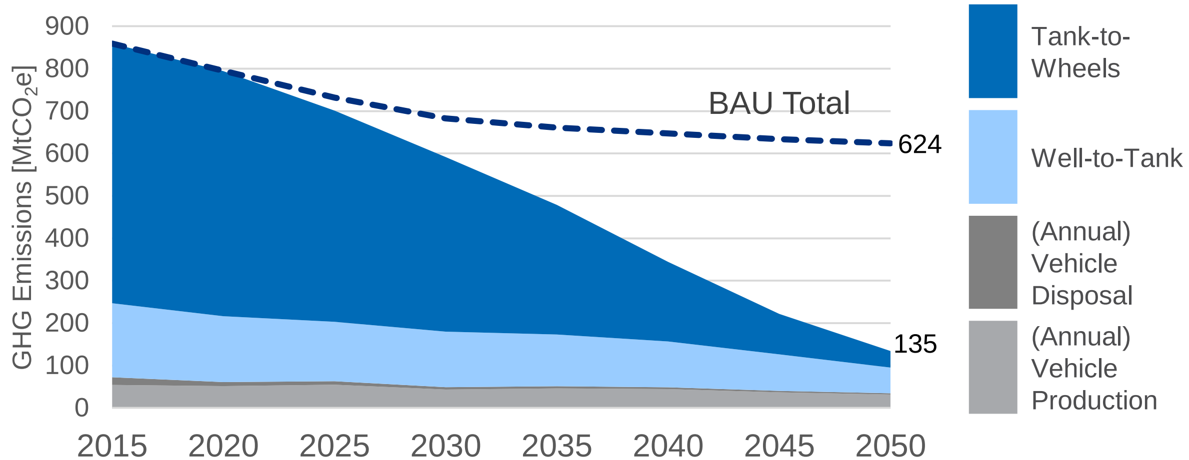
Source: Ricardo Energy & Environment;
ERTRAC: European Road Transport Research Advisory study to be published

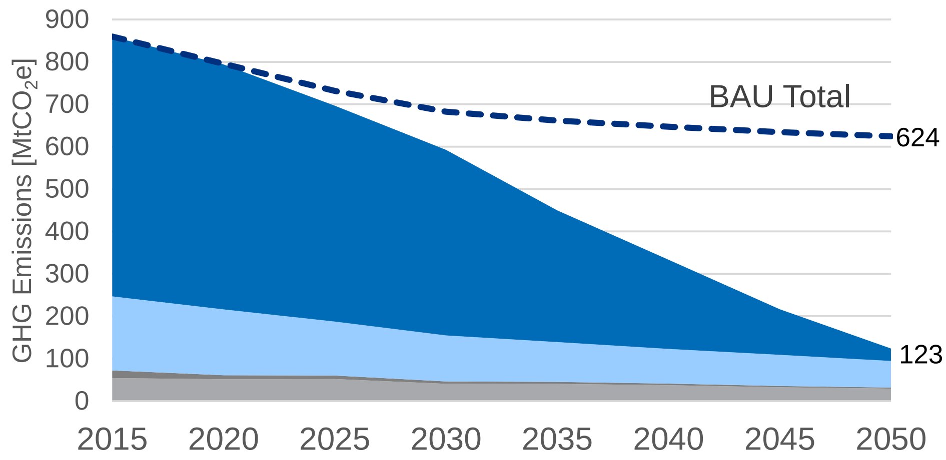
The Mixed Fleet scenario also shows a significant and similar reduction in GHG emissions to the other scenarios

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

High EV



Mixed Fleet



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

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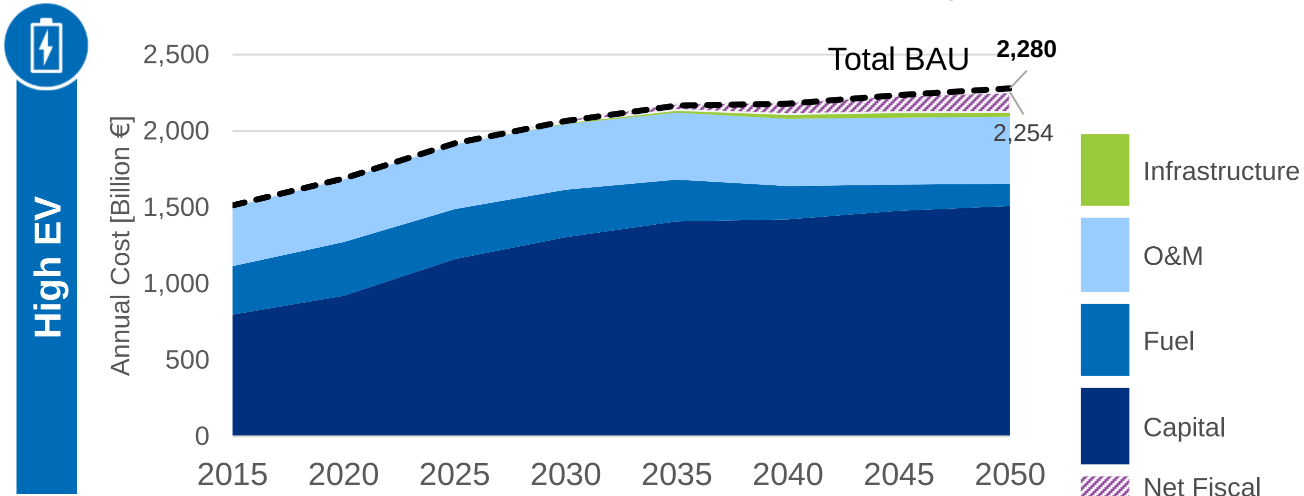
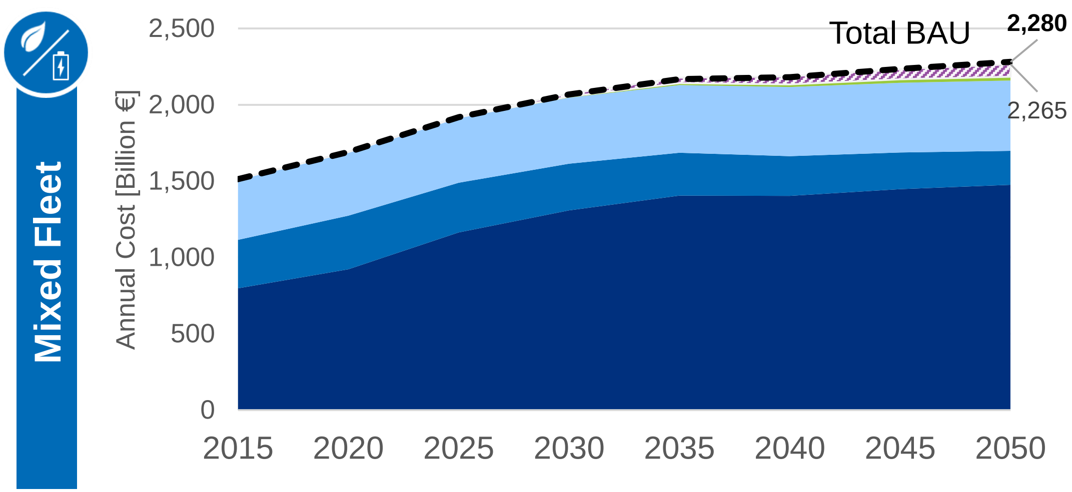
Source: Ricardo Energy & Environment SULTAN modelling and analysis

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 fleet scenario by 2050
- Including Net Fiscal Revenue (NFR) loss (vs BAU) closes the gap to €11bn p.a.
- All scenarios reduce GHG emissions/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

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Source: Ricardo Energy & Environment SULTAN modelling and analysis

Both scenarios significantly reduce GHG emissions at similar cost but require large increases in battery production or low carbon fuel supply

- **All scenarios result in a similar and significant (~85%) reduction in GHG emissions to 2050**
  - The key assumptions on GHG intensity of electricity supply, and low carbon fuel availability, affects whether the High EV or the Low Carbon Fuels scenario results in lower total GHG emissions
- **Electricity demand from EV charging in 2050 in the managed home charging scenario is ~550 TWh**
  - This represents ~17.5% of the EU's 2015 electricity generation, and is twice that required in the Low Carbon Fuels scenario
- **The cumulative cost of a managed EV charging and network infrastructure reinforcement is estimated between €630bn & €830bn to 2050,** compared to overall cumulative savings to the end-user between €1,100 & €1,600bn (1.3% - 1.8% of total end-user costs)* vs European Commission Business as Usual reference to 2050
  - For all recharging scenarios, the need to replace secondary substations contributes most to network infrastructure upgrade costs
- **The annual parc total costs to the end user (when adjusted to maintain Net Fiscal Revenue) are similar for the High EV, Low Carbon Fuels and Mixed Fleet scenarios, and below the baseline scenario**
  - The estimated marginal capital costs for the High EV scenario are particularly strongly influenced by assumptions on battery prices
- **Under the High EV scenario, ~15 Gigafactories (@35GWh p.a.) would be needed to supply batteries to the European EV market by 2050, compared to ~5.5 Gigafactories in the Low Carbon Fuels scenario by 2050**
- **In the High EV scenario, peak annual virgin lithium demand (~220kt) is 6 times higher than global lithium production in 2016 (35kt)**
  - The Lithium requirements for the Low Carbon Fuels scenario are less than half for the High EV scenario

Note: * Excluding adjustment for loss of Net Fiscal Revenue

Further work recommendations

- It is recommended that further work should :
  - Explore the impact of combinations of the scenarios presented here
  - Further investigate the risks associated with supply of raw materials for battery production
  - Study what framework would be required to support investment in low carbon fuel availability, alongside electrification