Ricardo Energy & Environment

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

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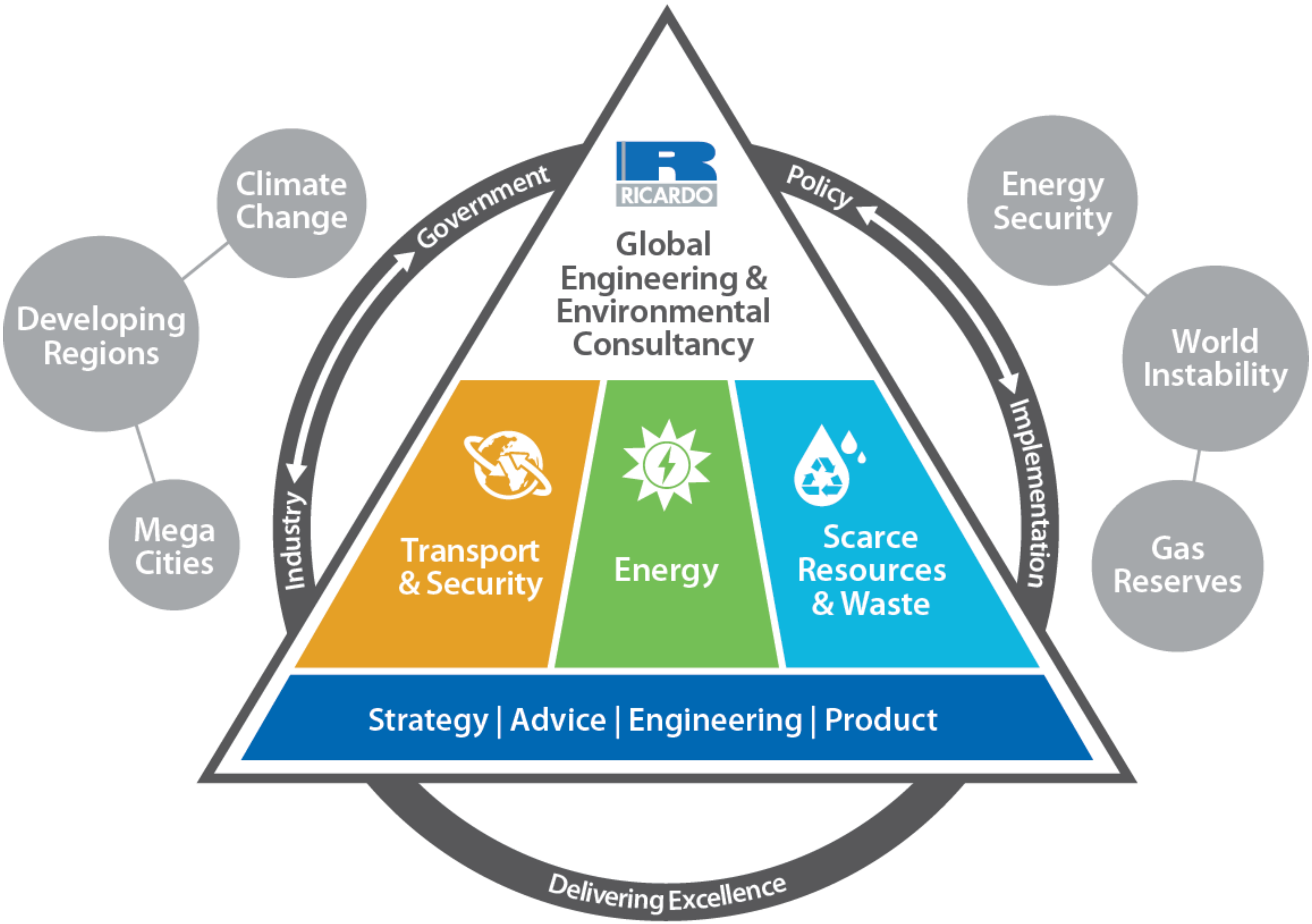


The impact of two scenarios: 'High EV Adoption' & 'Low Carbon Fuels' on GHG emissions, infrastructure, costs & resources are compared

- Concawe commissioned Ricardo to conduct research and provide analysis of the wider potential implications of high EV uptake and alternative scenarios

High EV Scenario

Low Carbon Fuels Scenario

1. What are the Greenhouse 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
Low Carbon Fuels include biofuels and eFuels generated from renewable energy sources

Quantitative analysis of impacts was conducted using SULTAN model with defined inputs, and post-processing of 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

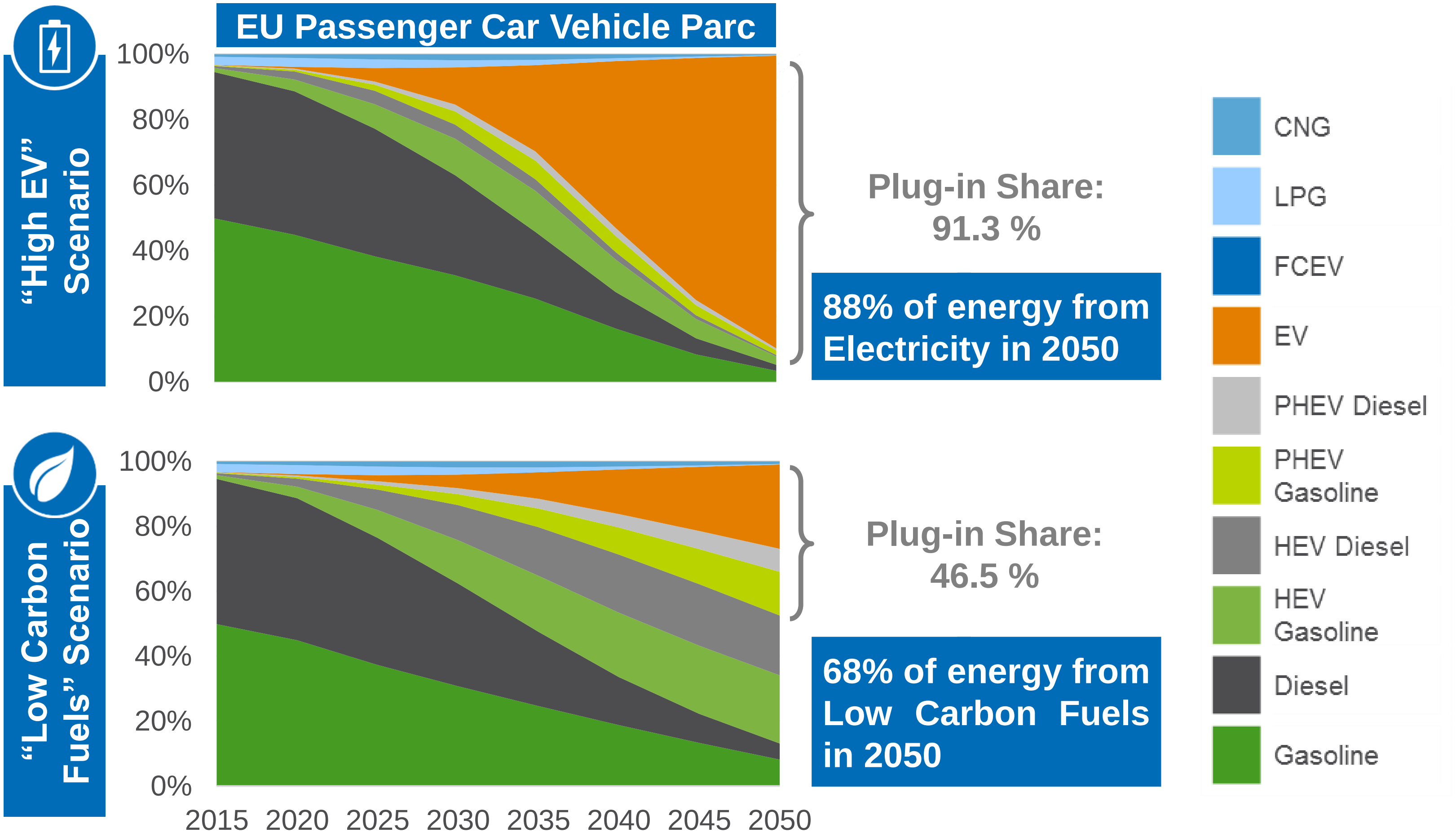
Additional Post-Processing ***
- GHG emissions from vehicle production and disposal
- Alternative fuel infrastructure requirements (# by type, share of energy cons., costs)
- Resource requirements

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

Source: Ricardo Energy & Environment. * SULTAN is 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

Two contrasting scenario options : What if all cars were electric? What if the share of Low Carbon Fuels was significantly increased?

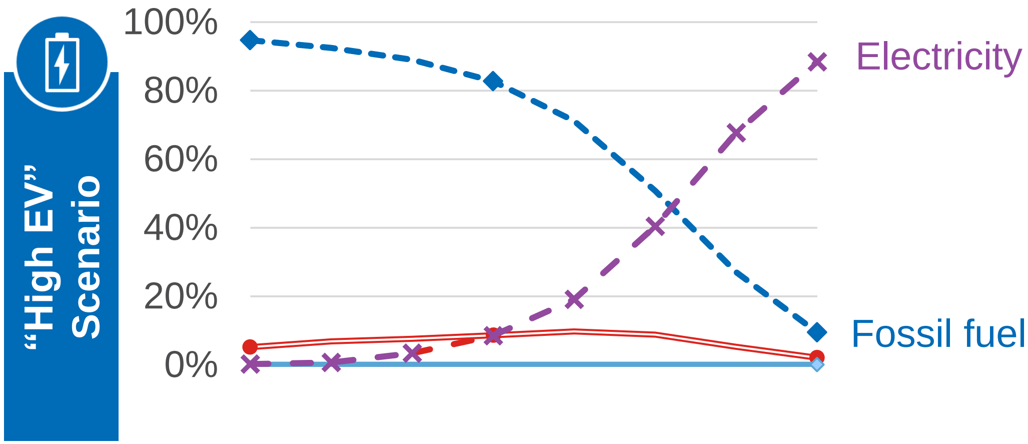
- Both scenarios were scoped to deliver Tank-to-Wheel (TTW) GHG savings of 90 percent compared with 1990 figures



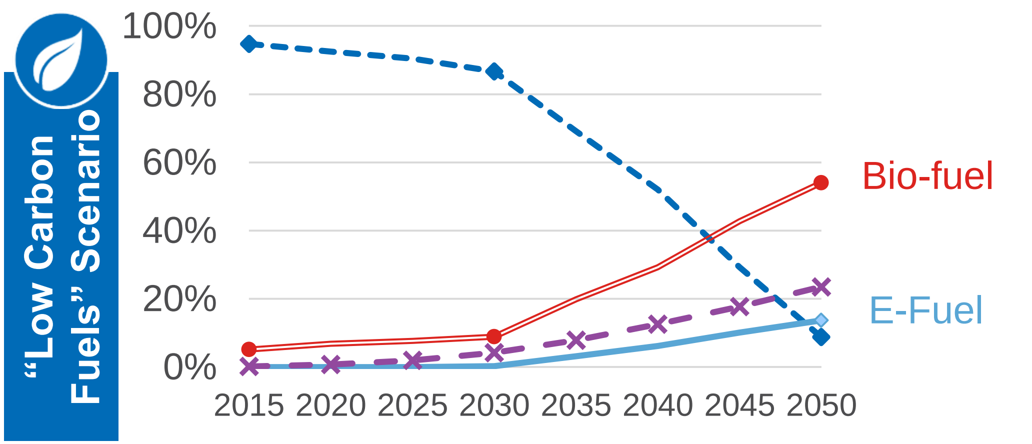
Note: New registrations & vehicle parc profiles calibrated to data and projections from European Commission modelling -Impact Analysis of Mass EV Adoption and Low Carbon Intensity Fuels Scenarios, Ricardo report for CONCAWE August 2018, https://www.concawe.eu/publications

Two contrasting scenario options : What if all cars were electric? What if the share of Low Carbon Fuels was significantly increased?

% Fuel Share by energy



- In the High EV scenario 88% of energy is electrical by 2050

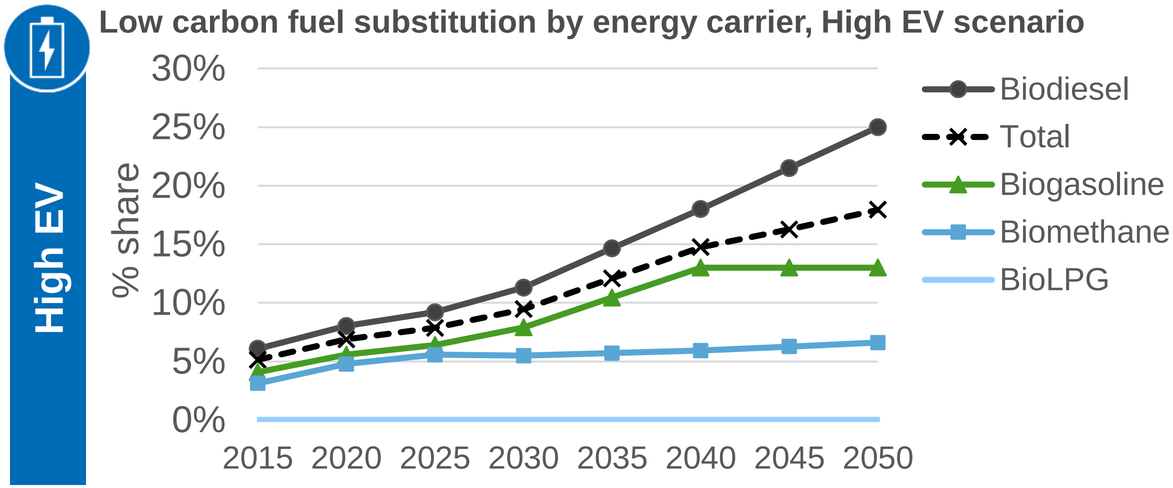


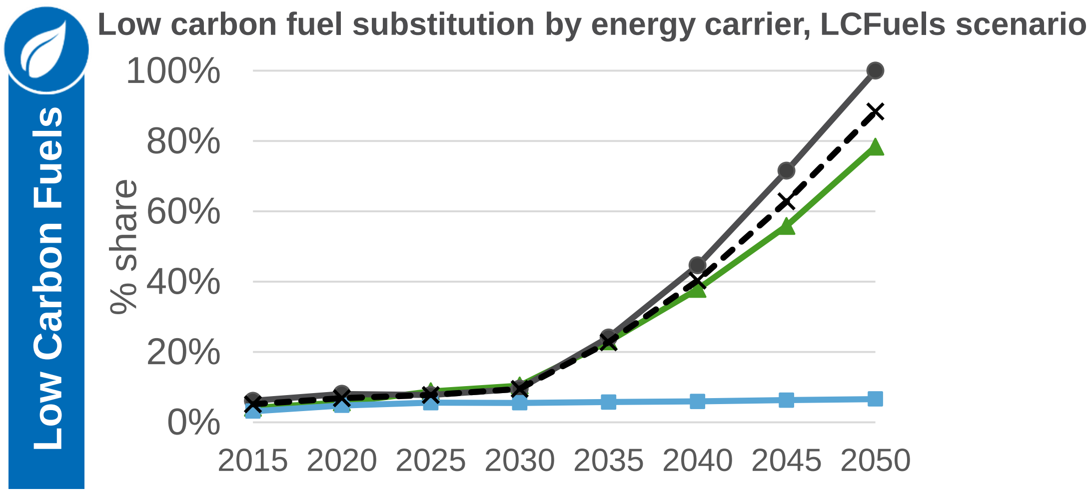
- In the Low Carbon fuels scenario 68% of energy is from bio-fuels and e-fuels and 22% from electricity

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

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

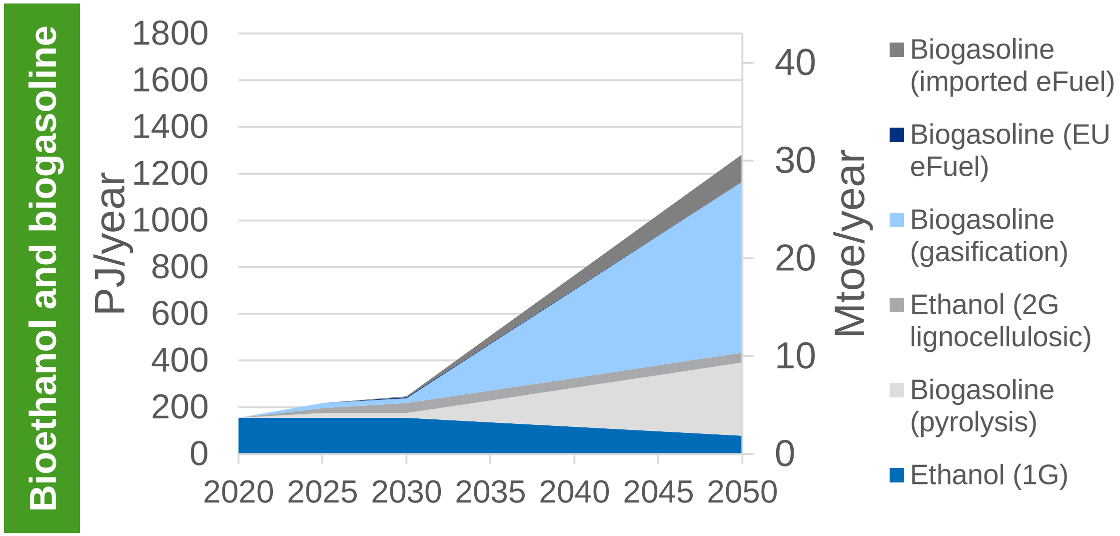


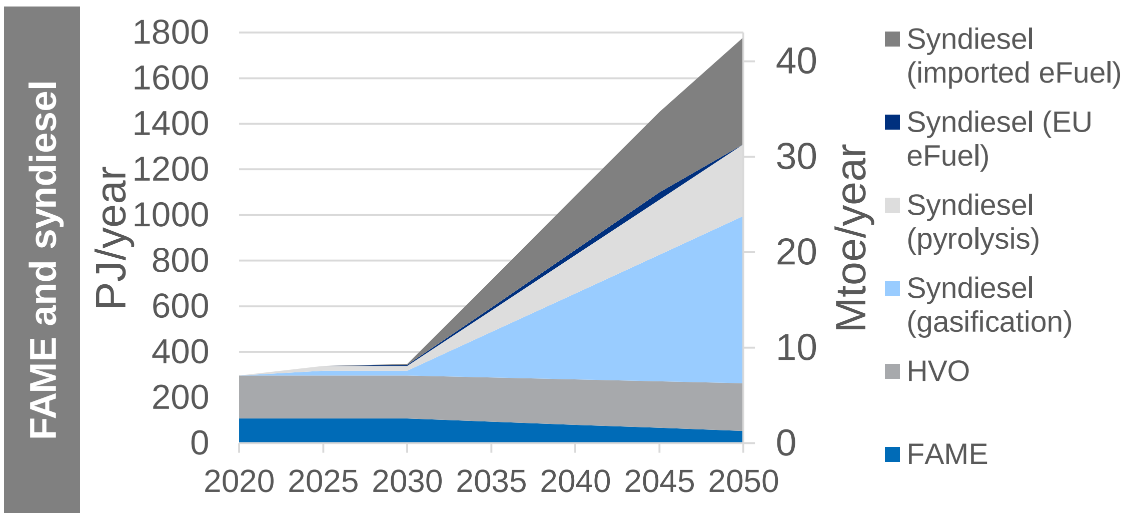


- Net GHG reduction for biofuels is assumed to reach ~85% by 2050
- After 2020: assumed that the share of low/no-ILUC biofuel (i.e. from waste or non-crop feedstocks) will increase to >95% share by 2050
- For the Low carbon fuels scenario:
  - It is assumed that the majority of biodiesel used post-2025 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

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





- Availability of Low Carbon Fuel is intended to reflect scenario where the whole biomass supply chain is optimised to maximise use of bioenergy
- Quantities available to LDVs allow for similar substitution levels in other road transport (e.g. HDVs)
- Use in other transport modes is not considered explicitly

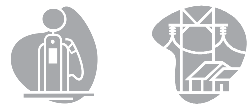
Source: Directorate-General for Research and Innovation (European Commission), “Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe,” 2018;
K. Sub Group on Advanced Biofuels Sustainable Transport Forum, Maniatis, I. Landälv, L. Waldheim, E. Van Den Heuvel,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

The analysis considered the whole life of the vehicle, Well-to-Wheel (WTW) fuel production and use and embedded GHG emissions

Vehicle Life Cycle

Well-to-Wheel (WTW) Analysis - Life Cycle Assessment of the fuel or electricity used to power the vehicle

Vehicle cycle "Embedded" emissions result from from vehicle production; fluid, filter and component replacement during life; and end-of-life activities. A **"cradle-to-gate"** LCA study may only consider vehicle or component production



Fuel & Electricity Production

Assessment of (WTT) environmental impact of producing the energy vector(s) from primary energy source to point of distribution (e.g. refuelling station)

Study Boundary:

Analysis of the **whole vehicle life lifecycle** included embedded emissions from vehicle production, maintenance and servicing, and end-of-life activities, and WTW (WTT+TTW) emissions from production and use of the fuel / energy in operating the vehicle

Vehicle Production

Assessment of **'Cradle-to-Gate'** environmental impact of producing the vehicle including extract of raw materials, processing, component manufacture, logistics, vehicle assembly and painting

Use/Operation

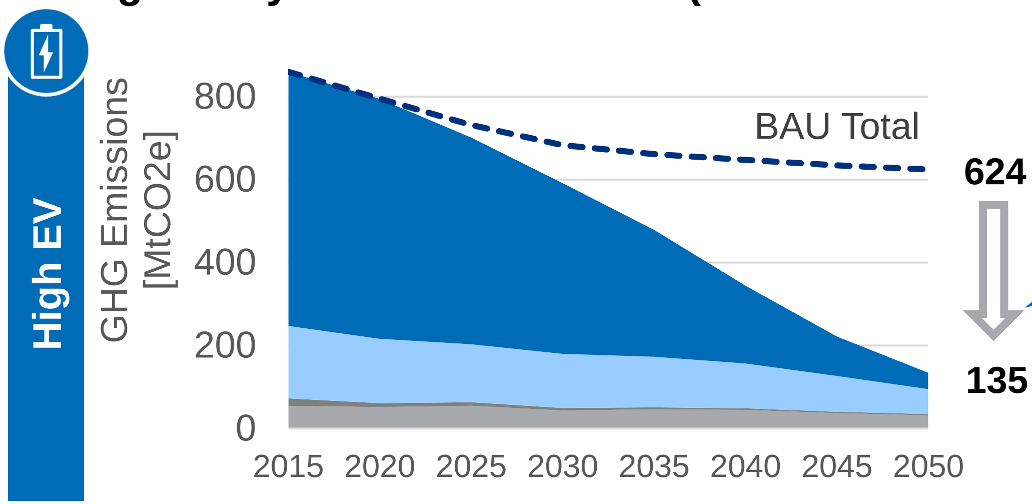
- Environmental impact of driving (TTW emissions)
- Impact from maintenance and servicing

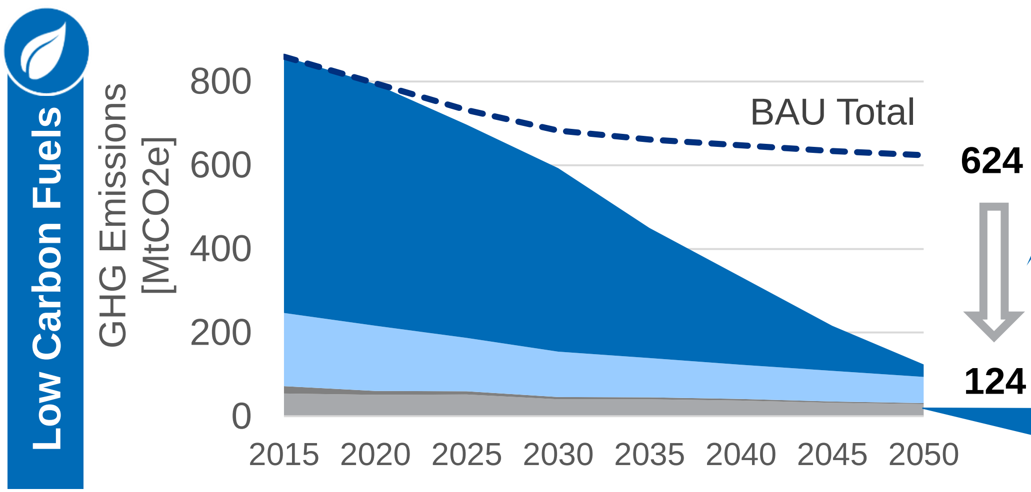
End-of-Life

Adds assessment of environmental impact of "end of life" scenario (i.e. -to-Grave). Can include: **re-using** or **re-purposing** components, **recycling** materials, energy recovery, and disposal to landfill

Both scenarios result in a similar and significant reduction in GHG emissions to 2050, with WTW GHG savings reduced 92% vs 1990

EU Light Duty Vehicle Emissions (Well-to-Wheel + Embedded)





Both scenarios result in significant reduction from Business-As-Usual (BAU) EU reference

- Tank-to-Wheels
- Well-to-Tank
- (Annual) Vehicle Disposal
- (Annual) Vehicle Production

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

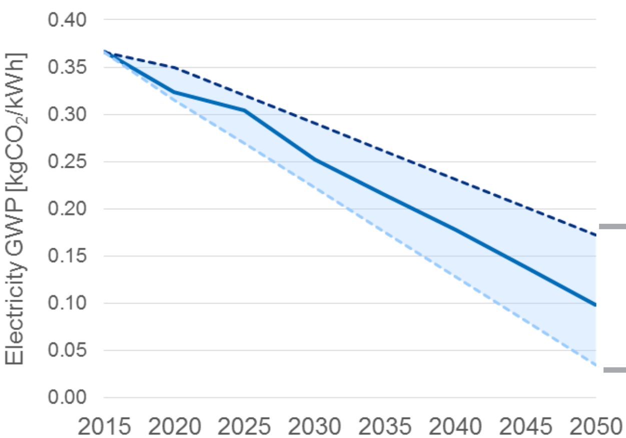
Source: Ricardo Energy & Environment SULTAN modelling and analysis

* 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 $MtCO_2e$

"High" electricity GHG intensity

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

-8 $MtCO_2e$

"Low" electricity GHG intensity

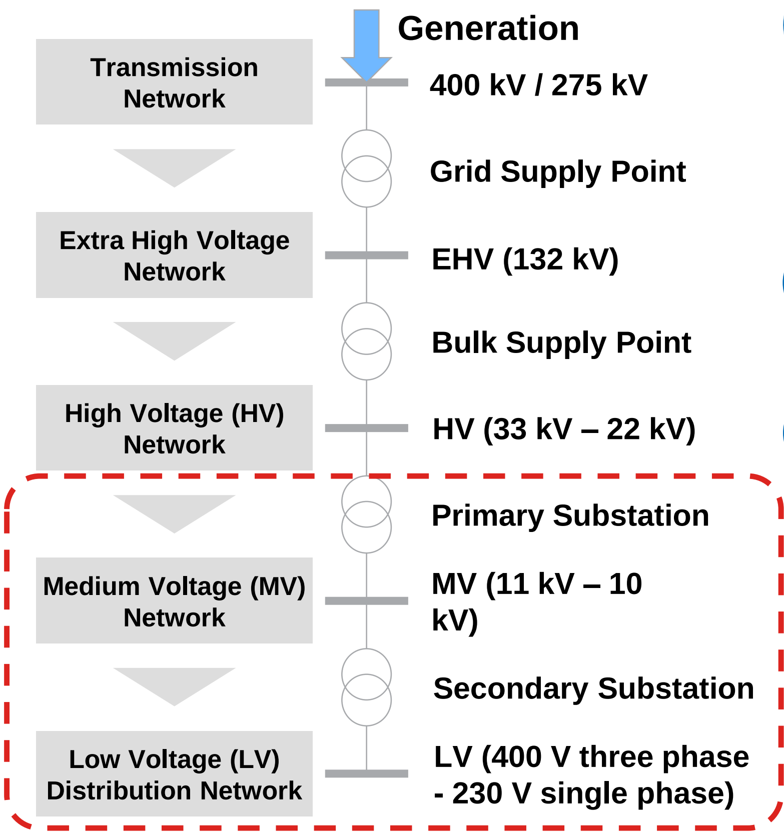
High EV Scenario produces 8Mt CO_2 **LESS** than the Low Carbon Fuels Scenario

- High EV Scenario
- Low Carbon Fuels Scenario

→ Sensitivities on low carbon fuel availability show similar magnitude of variations

Source: Ricardo Energy & Environment SULTAN modelling and analysis

Network reinforcement required beyond 15-20% EV penetration to deliver adequate EV re-charge power will be significant*



Significant Re-enforcement Required

Electricity for EV charging increases to ~550 TWh in 2050, ~**17.5% EU 2015 electricity generation**

- Capital costs for re-enforcing EU EV charging infrastructure & charge facilities for High EV scenario

€630 billion assuming primarily "home" charging (€326 billion for Low Carbon Fuels)

€830 billion assuming "grazing" frequent top-up

- Based on "Smart" network with charge periods selected to minimise local network loads

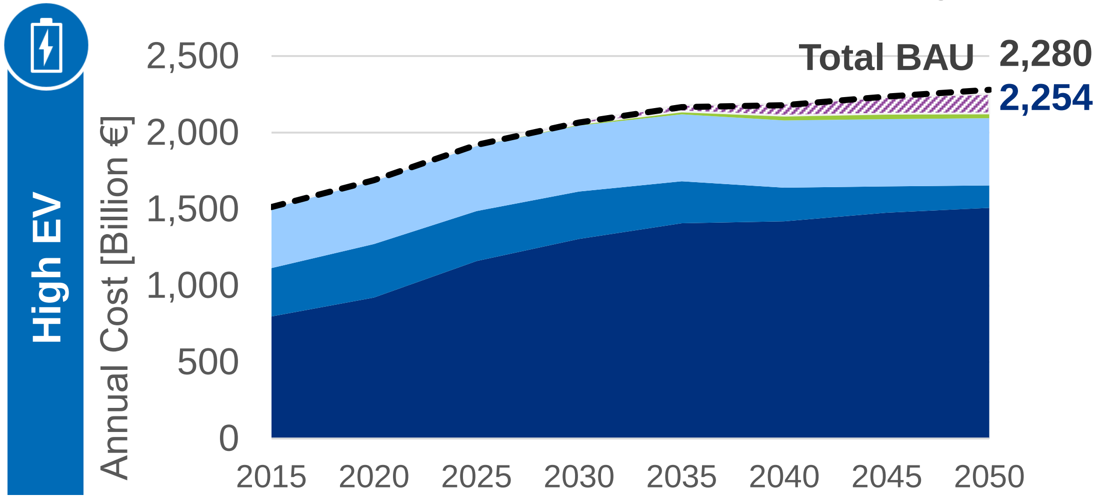
Only a small part of total road transport costs including vehicles and energy, but who pays for this?

Source: The Energy Technologies Institute & *Household Electricity Survey - A study of domestic electrical product usage Intertek Report R66141 ; Impact Analysis of Mass EV Adoption – Ricardo; Defossilizing the transportation sector - FVV

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

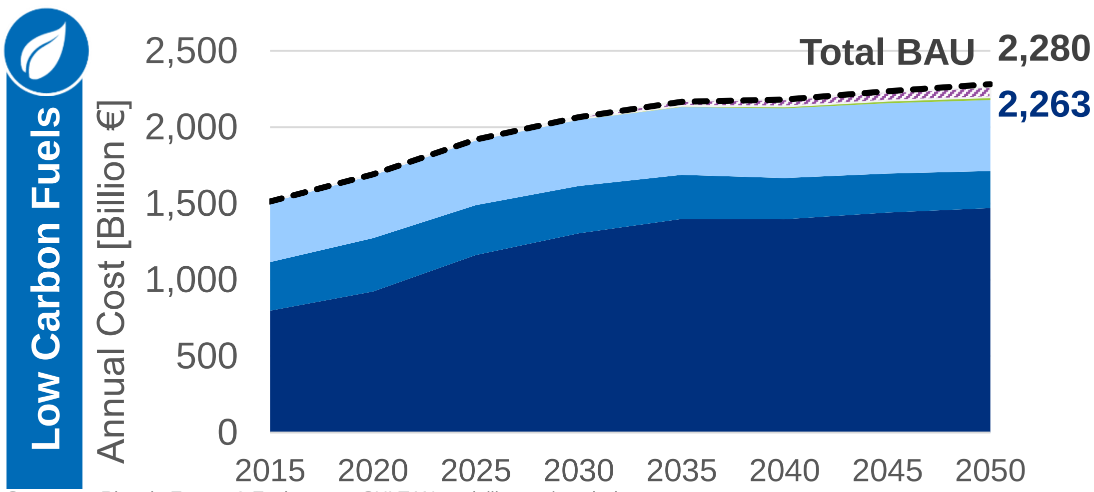
Taxes are applied for all energy carriers at their current and projected (BAU) levels

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



- **Total annual parc cost to the end user is similar for both scenarios in 2050**, when adjusting to maintain Net Fiscal Revenue

Cumulative cost savings to the end end-user between ~€1,100 & €1,600bn (1.3% - 1.8%) 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

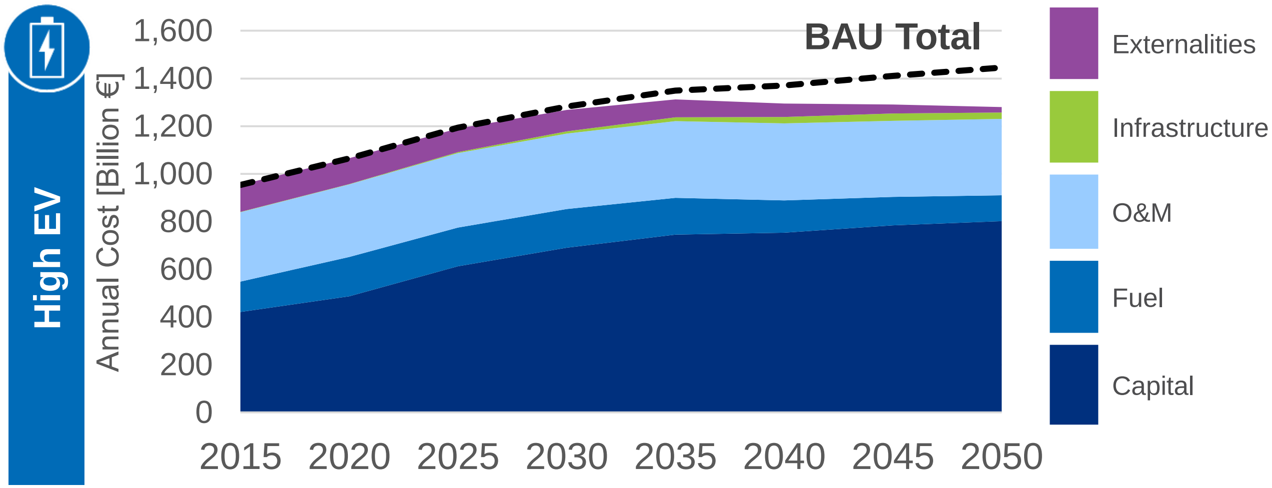
Source: Ricardo Energy & Environment SULTAN modelling and analysis

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 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

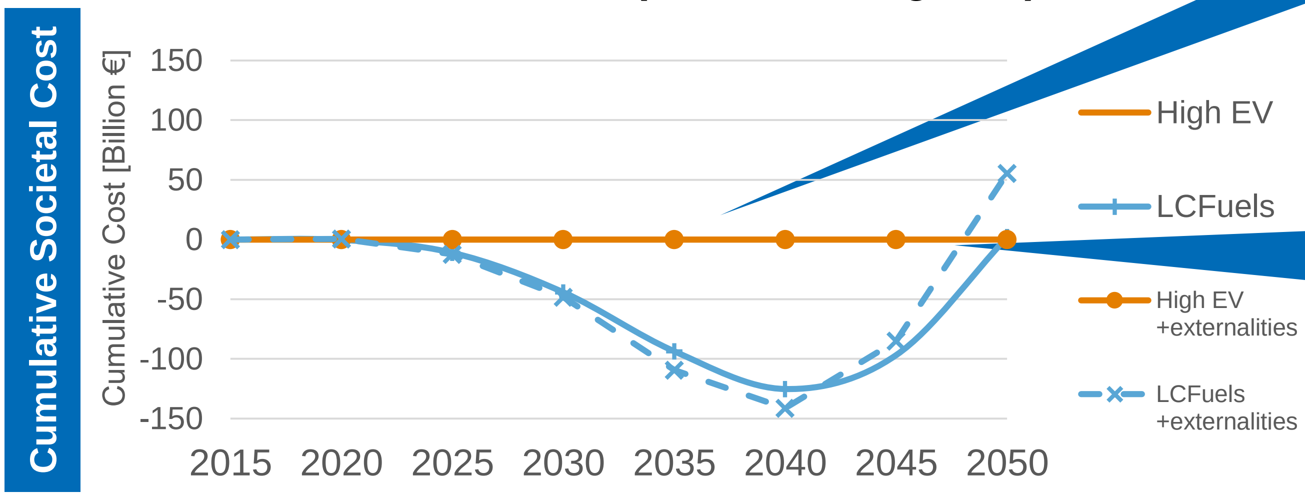
Total Parc Annual Societal Costs (excl. tax), including Externalities



- Emission externalities contribute to significantly lower social costs for both scenarios
- *Note*: Societal costs exclude all taxes

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

Cumulative Net Societal Costs (relative to High EV)



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

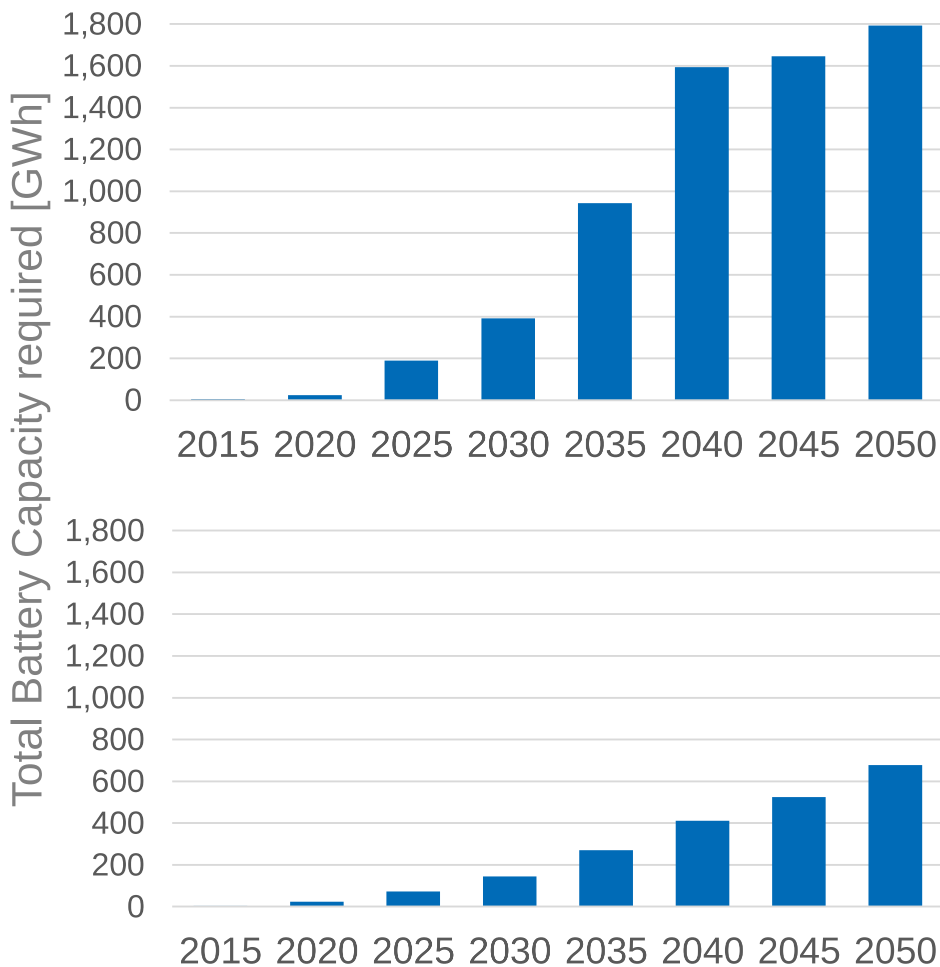
Source: Ricardo Energy & Environment SULTAN modelling and analysis

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

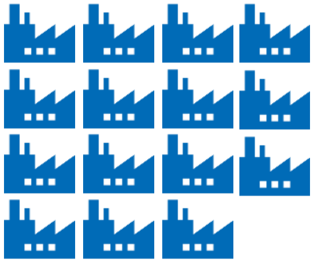
Resources & Materials – Annual Battery Capacity [GWh]

High EV

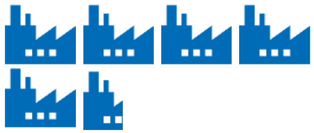
Low Carbon Fuels



Estimated number of battery Giga-factories required for Europe



- The High EV scenario requires almost **three times the total battery capacity** compared to the Low Carbon Fuels scenario

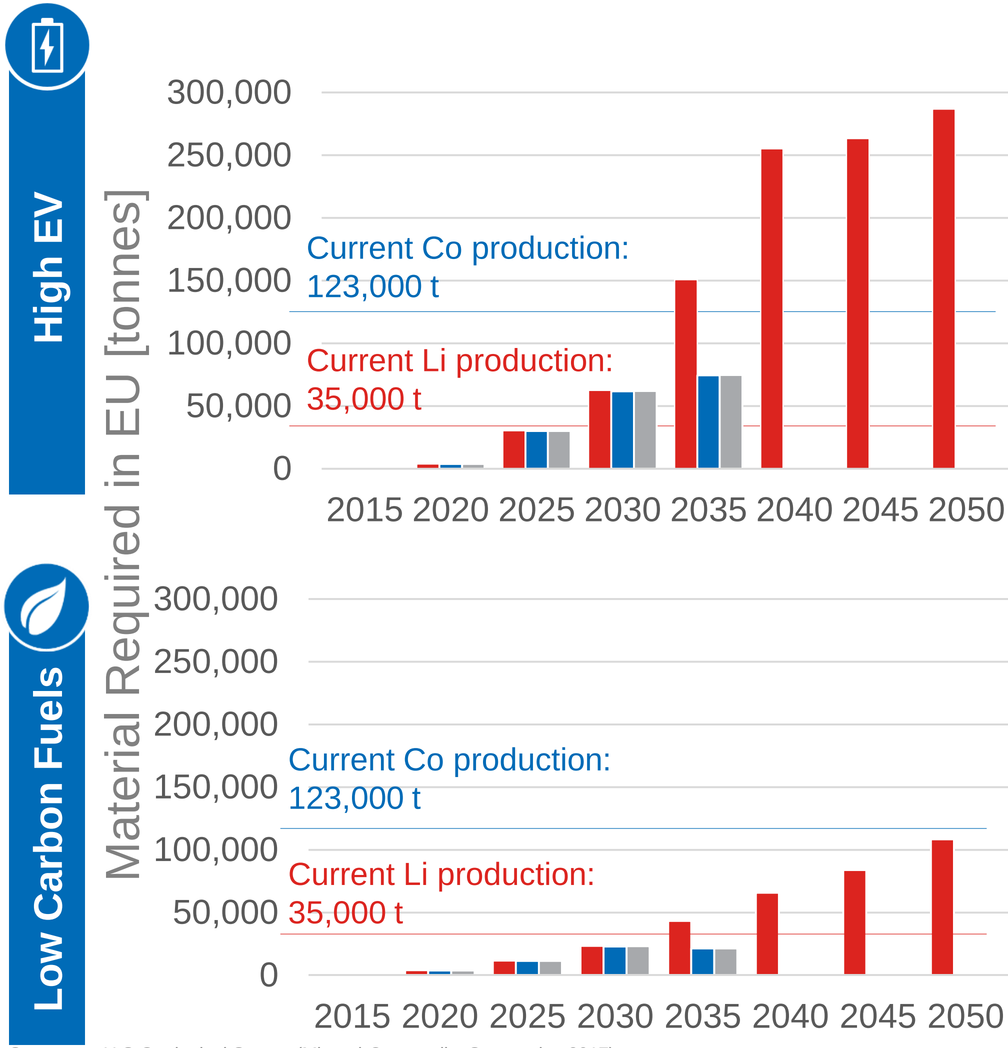


Note: Tesla Giga Factory estimates factor in anticipated battery energy density improvements per unit from 2025-2050 This output should be expected to scale with increased battery kg/Wh*

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

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



- 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
  - Co : 123 kt

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

Both scenarios have significant challenges. A broad range of solutions, including liquid low carbon fuels, would minimise the risks in achieving our future targets

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

- A broad range of solutions should be considered, **including electrification and liquid or gaseous fuels,** to minimise the risks associated with a single scenario
- The efficiency and emissions of ICEVs will need to continue to develop, and to **accept future low carbon fuels**

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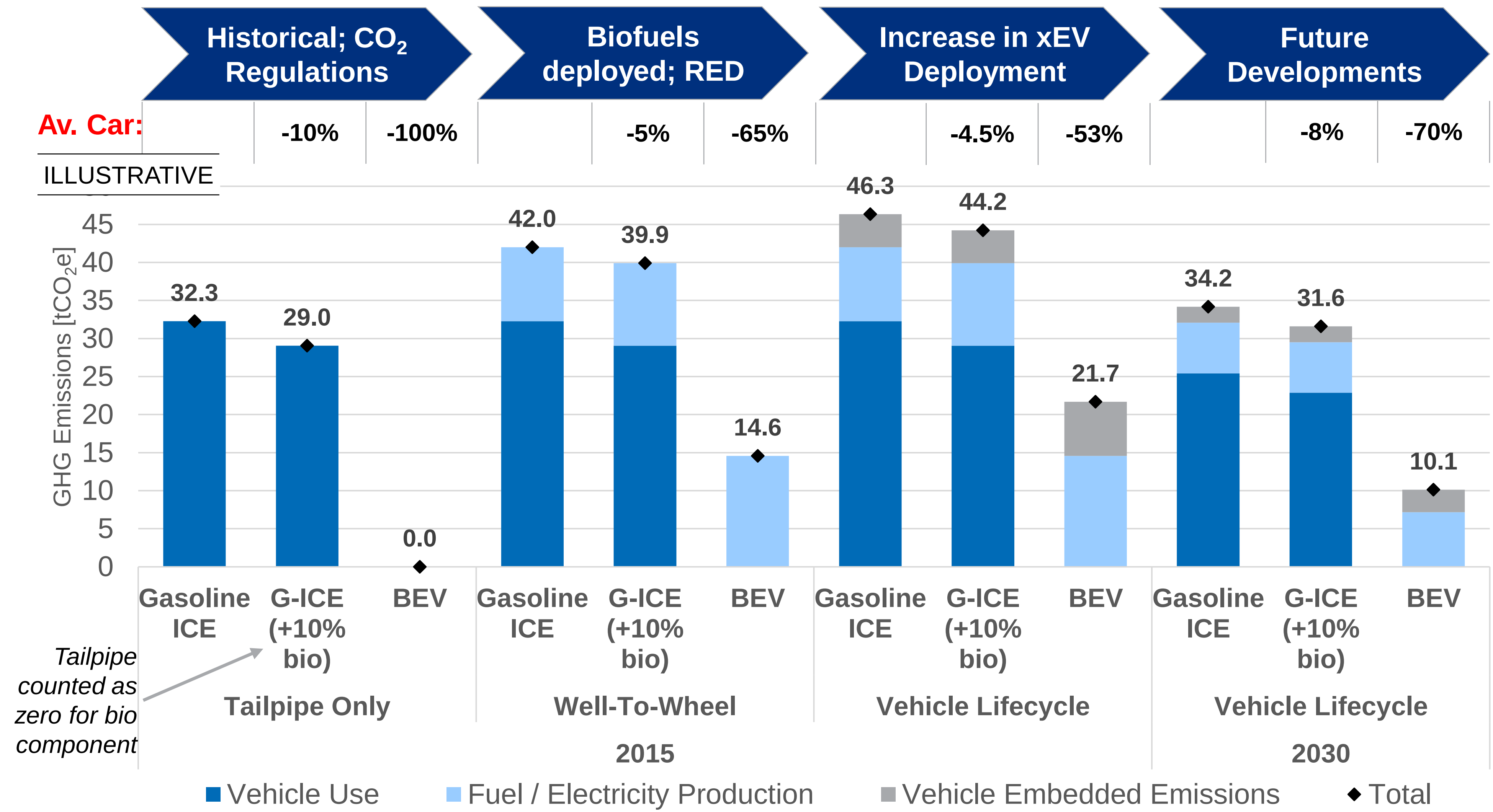
Additional slides

Why are we interested? Combination of changes in the regulatory environment, as well as the uptake of new fuels and powertrains



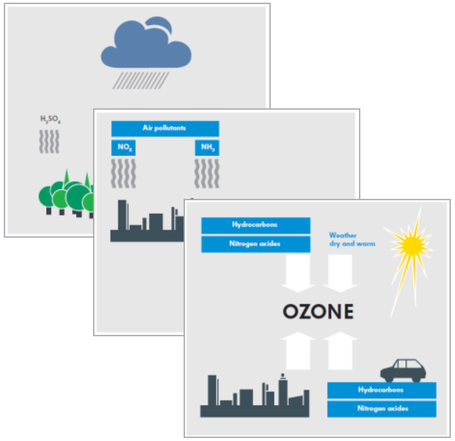
Source: Ricardo life cycle analysis (2018) for average EU passenger car. Assumes lifetime 210,000 km, uplift of NEDC to real-world fuel consumption (~35%/40% for ICE/EV). GHG from fuel/electricity consumption is based on the 2015 average fuel/grid electricity factor; Literature average 15.3 kgCO2e/kg battery. Avoided burden approach – including credits for recycling.

It isn't all about Greenhouse Gases – other impacts and factors also influence the overall comparisons of impacts…for example:

Primary Energy

- How much / what types of source?
- What is the most efficient use of renewables?
  - BEV = 1x
  - FCEV = ~3x
  - eFuel = ~5x

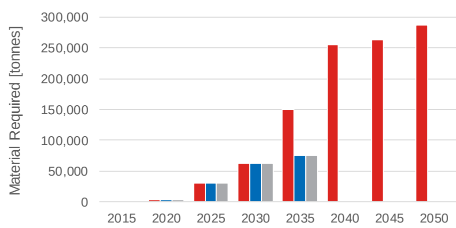
Air Quality Pollutants



- Emissions impacts vary by:
  - Powertrain
  - Lifecycle stage
  - Location
- Can influence conclusions

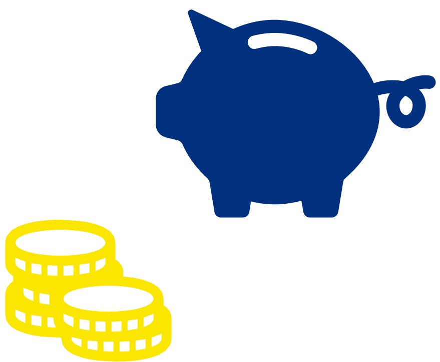
Resources

3 **Li** Lithium | 27 **Co** Cobalt | 28 **Ni** Nickel



- Availability of key materials for batteries, motors
- Biomass supply for bioenergy *and* other uses
- Water consumption

[Lifecycle Costs, i.e. TCO]



- Total Cost of Ownership ≈ LCA for money
- Environmental externalities (costs) added for societal analysis

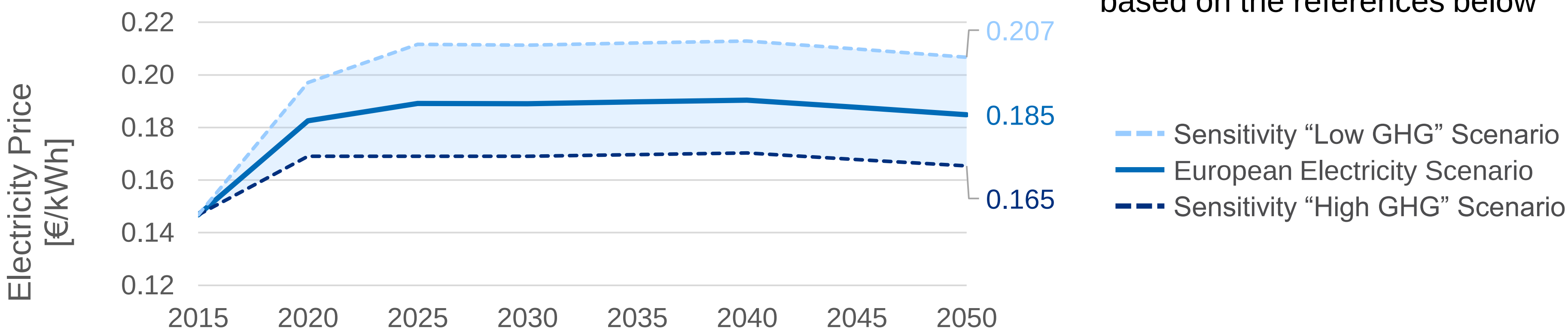
The price of liquid fuels and electricity has been based on data from published studies

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

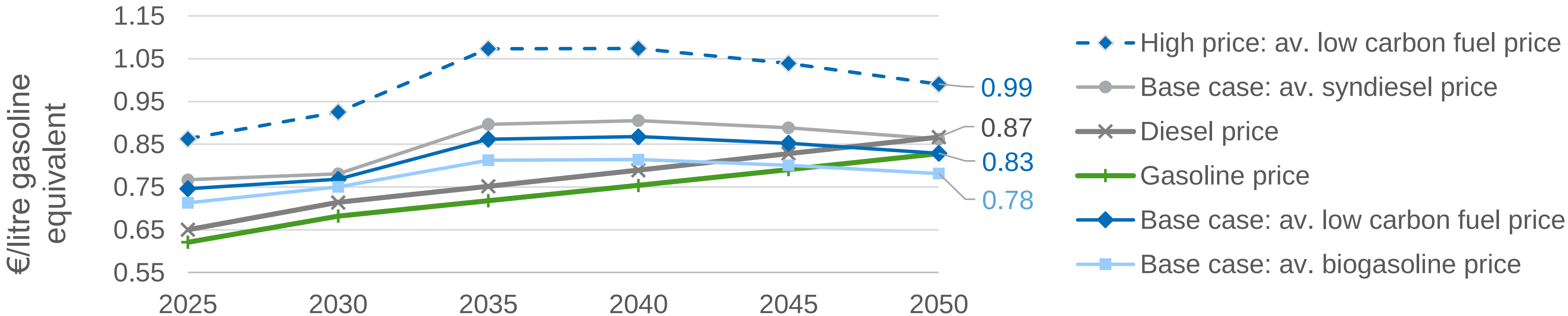
Assumed Energy Cost Trends Excluding Taxes

- Assumptions about energy costs are based on the references below

Electricity Price [€/kWh, excl. tax]



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



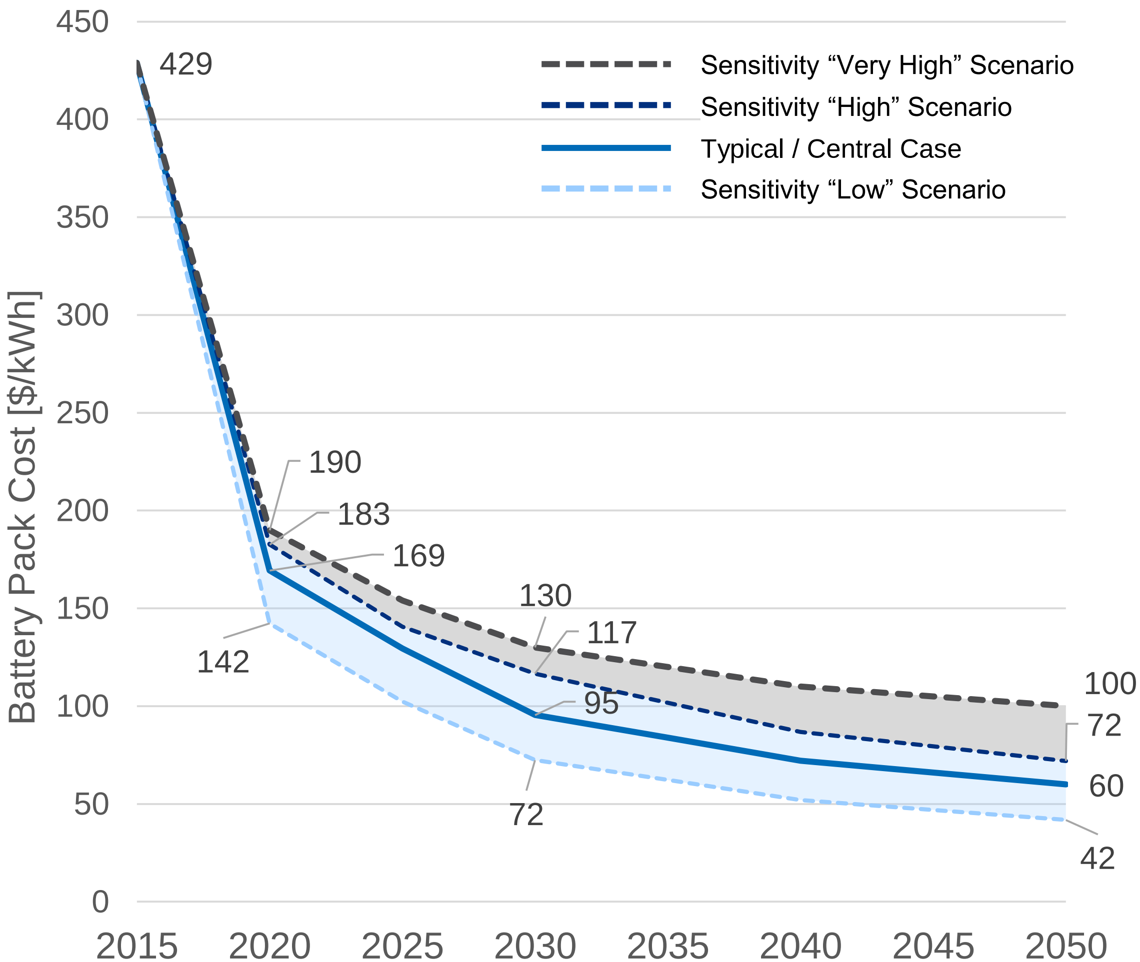
Source: S. Frank et al., “EU Reference Scenario 2016 Energy, transport and GHG emissions Trends to 2050.”, 2016
Directorate-General for Research and Innovation (European Commission), “Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe,” 2018;
K. Sub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

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

Battery Pack Cost [$/kWh]



- 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 assumed to increase to 800Wh/kg by 2050

Source: Ricardo Energy & Environment analysis

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

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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

Notes: 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)

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)

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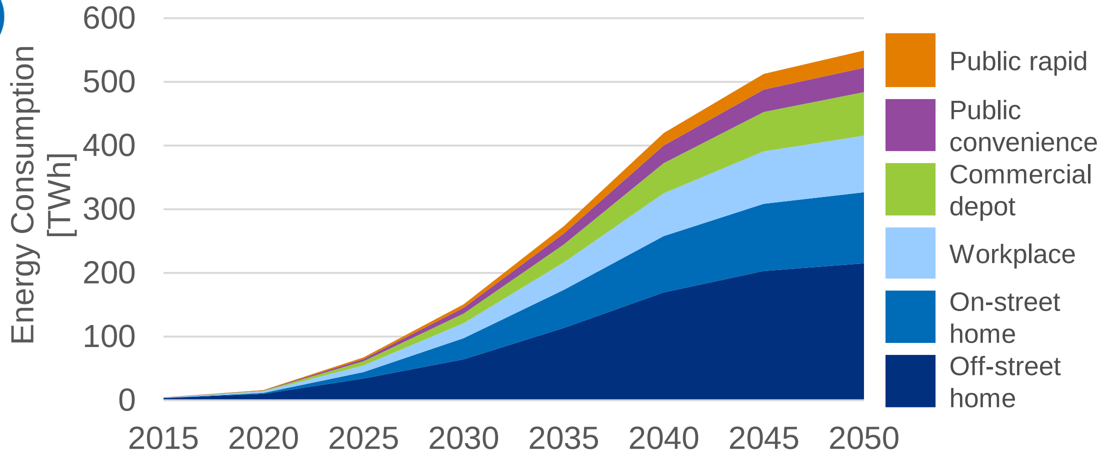
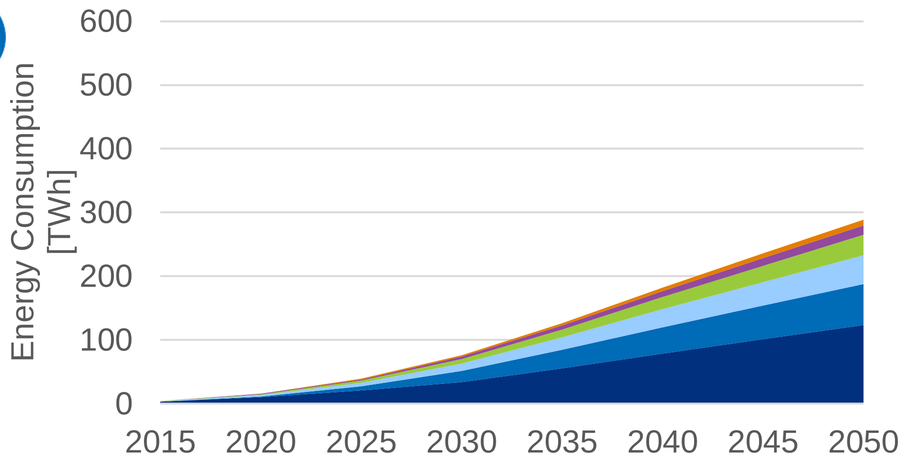
Electricity consumption from recharging by location (Home Charging Scenario)

High EV



Low Carbon Fuels



- EV charging electricity demand in 2050 in the managed home charging scenario is ~550 TWh (1980 PJ)
  - **~17.5% of the EU's 2015 electricity generation**
- For 'Home' charging scenario, most of this energy (~60%) is expected from overnight residential 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