Life Cycle CO_2 of Passenger Cars

Informing the debate by examining the feasibility of considering a vehicle's whole life cycle

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Moving to a life cycle assessment of vehicle emissions
Monday 14 November 2011
London

Preparing for a life cycle CO_2 measure
Report contents

- Introduction
- Strengths and Limitations of the existing tailpipe CO_2 measure
- Elements and Boundaries for evaluating life cycle CO_2 emissions
- Impact of Regulations on life cycle CO_2 emissions
- Consequences of Technology Evolution on life cycle CO_2 emissions
- Gaps, Accuracy and Further Work
- Recommendations
- Conclusions
- Appendices

A vehicle's life cycle can be divided into four "blocks" – production of the vehicle, production of the fuel, "in-use", and disposal

"Fuel"

Generate

- Fossil fuel production
- Electricity generation
- Hydrogen production
- …

Distribute

- Distribution network efficiency
- Power lines
- Pipelines
- Tankers
- …

Production

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

"In-Use"

- Tailpipe CO_2 from driving
- Impact from maintenance and servicing

RIP

Disposal

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

Source: Ricardo

Ricardo identified >100 elements that contribute to a vehicle's life cycle CO_2 emissions

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Elements from vehicle production contributing to life cycle CO_2 emissions

Design & Development
- R&D / Prototypes
- Test Rigs
- Design process
- Supplier selection
- Homologation Testing

Vehicle Specification
- ● Vehicle size / segment
- ● Vehicle mass
- ● Powertrain technology
- ● Technology options
  - E.g. Choice of battery, electric motor, etc.
- ● Number of components
- ● Model variant

Materials & Energy
- ● Material selection
- ▲ Geographic source of material
- ▲ Extraction process
- ■ Recycled content (primary vs. secondary)
- ■ Material availability
- ■ Energy mix

Production Processes
- ● Manufacturing processes
- ■ Manufacturing / factory efficiency
- ● Location
- ● Waste produced
- ● Re-use of waste material

Logistics
- ● Supply chain
- ● Types of transport
- ● Distance travelled
- ● Packaging
- ● Geography

People
- Number of workers
- Daily commute
- Heat and light for offices / factory
- H&S considerations
- Environmental legislation considerations
- Advertising and sales marketing
- Business trips to visit suppliers, etc

Proposed Element Boundary

Production

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Source: Ricardo

Ricardo identified >100 elements that contribute to a vehicle's life cycle CO_2 emissions

RICARDO

Elements from fuel well-to-tank contributing to life cycle CO_2 emissions

Primary Energy

- ■ Primary energy of fuel
- ■ Source / location
- ■ Energy extraction process (e.g. mining, farming, etc.)
- ■ Embedded emissions associated with mining / extraction facilities
- ■ Embedded emissions associated with electricity generation
- ▲ Feedstock availablity for renewable fuels

Proposed Element Boundary

Fuel

Processing

- ● Type of fuel
- ■ Selected production process(es)
- ■ Process efficiency
- ■ Waste
- ■ Production of by-products along with fuel
- ● Fuel quality requirements
- ■ Embedded emissions associated with production facilities
- ■ Energy mix used during processing
- ● Electricity mix available (e.g. fossil vs. green)

Distribution & Infrastructure

- ● Method of distribution / transportation
  - – Pipelines, tankers, road, etc.
- ● Infrastructure chain
- ● Embedded emissions associated with refuelling stations
- ● Fuel additive packs
- ● Fuel supplier variations
- ● Fuel distributer variations

People

- ● Employees
- ● H&S considerations
- ● Environmental legislation considerations

● Can be measured / known
■ Could be measured / known
▲ Difficult to measure / has to be assumed

Source: Ricardo

Ricardo identified >100 elements that contribute to a vehicle's life cycle CO_2 emissions

Elements from use phase contributing to life cycle CO_2 emissions

Vehicle Specification

- ● Vehicle size
- ● Kerb weight
- ● Powertrain technology
- ● Tailpipe emissions & aftertreatment
- ● Performance
- ● Model variant
- ● Load capacity
- ● Target price
- ● Fuel consumption
- ● Tailpipe CO_2 emissions

Fuel

- ● Fuel / energy type
- ● Fuel specification
- ▲ Fuel quality
- ▲ Fuel supplier
- ▲ Additive packs
- ▲ Standard grade vs. premium product
- ▲ Fuel availablity
- ▲ Fuel price
- ▲ Fuel taxation
- ▲ Actual, real-world fuel consumption

Driver

- ▲ Ownership model
- ▲ Owner affluence
- ▲ Driving habits
- ▲ Duty cycle(s)
- ▲ Journey length
- ▲ Nº. journeys/day
- ▲ Annual mileage
- ▲ Vehicle loading
- ▲ Care of vehicle
- ▲ Use of onboard gadgets (e.g. GPS)
- ▲ Use of air conditioning

Geography

- ▲ Location
- ▲ Terrain (e.g. hills vs flat)
- ▲ Climate and weather conditions
- ▲ Types of road (e.g. motorway vs urban)
- ▲ Traffic management
  - Roundabouts, traffic lights and junctions
  - Speed bumps
  - Speed limits
- ▲ Road congestion

Maintenance & Servicing

- ● Service interval
- ● Oil and coolant changes
- ■ Replacement parts
  - Tyres, brake discs
- ■ Component durability / failure
- ● Service personnel
- ● Heat and light for garage facilities
- ▲ Vehicle life time [years]

In-Use

- ● Can be measured / known
- ■ Could be measured / known
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Proposed Element Boundary

Source: Ricardo

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- ■ Could be measured / known
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Proposed Element Boundary

Source: Ricardo

Ricardo identified >100 elements that contribute to a vehicle's life cycle CO_2 emissions

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Elements from vehicle end-of-life contributing to life cycle CO_2 emissions

Vehicle Specification
- ● Vehicle size
- ● Vehicle mass
- ● Powertrain technology
- ● Technology options (e.g. battery type)
- ● Number of components
- ● Model variant
- ● Materials
- ■ Methods for joining parts together

Logistics
- ▲ Vehicle collection
- ▲ Transport of vehicle / components to EoL facility
- ▲ Distributions of recycled materials / components
- ▲ Geographical location of EoL facility (e.g. Europe vs BRIC)

Processing
- ▲ Vehicle disassembly
- ▲ Crushing
- ▲ Sorting materials / components
- ▲ Processing efficiency
- ▲ EoL process effectiveness
- ▲ Cleaning
- ▲ Energy required
- ▲ Energy mix used

Re-Use & Recycling
- ● Recycability of vehicle components
- ▲ Actual quantiy of material / components recycled
- ● Components suitable for re-use or re-manufacturing
- ▲ Allocation of credit for recycling / re-use

Waste
- ▲ Quantity of waste material
- ▲ Waste disposal method (e.g. landfill vs. energy recovery)
- ▲ Disposal of waste fluids
- ▲ Disposal of electrical and battery components
- ▲ Hazardous substances

People
- ● Employees in logistics chain
- ● Employees of waste disposal facilities
- ● People vs machines for sorting materials
- ● H&S considerations
- ● Environmental considerations

RIP

Disposal

- ● Can be measured / known
- ■ Could be measured / known
- ▲ Difficult to measure / has to be assumed

Proposed Element Boundary

Source: Ricardo

European legislation is often designed to reduce a passenger car's environmental impact, but can have unintended consequences

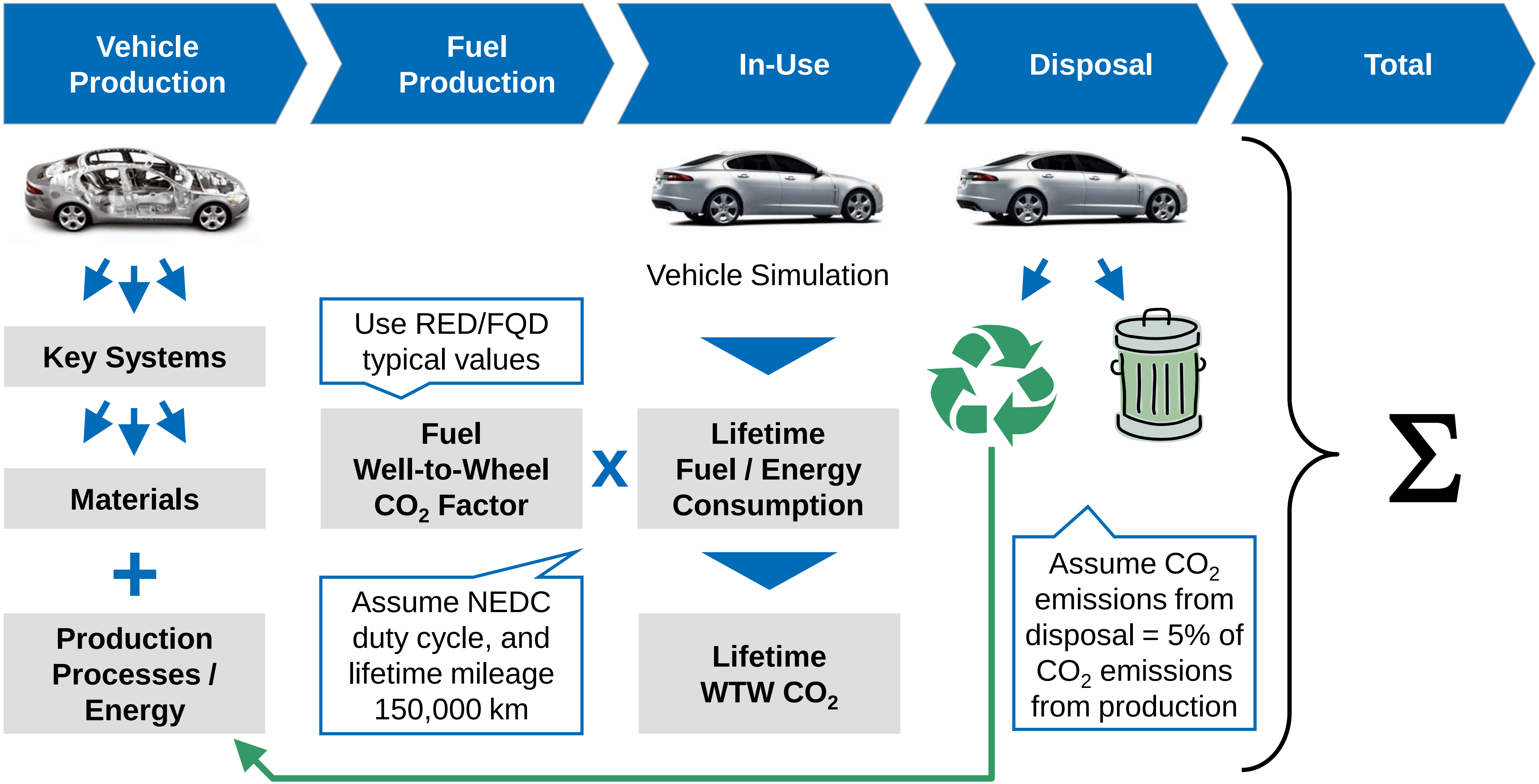
Legislation	Relative effect on life cycle CO_2 emissions				Commentary
	Production	In-use		Disposal	
		WTT	TTW		
Renewable Energy Directive (Directive 2009/28/EC) / Fuel Quality Directive (Directive 2009/30/EC)	-	↓↓ ★	?	-	• Set European targets for increasing use of renewable energy in transport fuel, and for decreasing GHG emissions of fuels
Tailpipe CO_2 (Regulation No 443/2009)	↑↑	-	↓↓↓ ★	↑	• Driver for uptake of new "low carbon" technologies, e.g. hybridisation and electrification
Tailpipe Emissions (Directive 2003/76/EC)	↑	-	↑	↑	• Often strategies compromise on fuel consumption to reduce tailpipe emissions of CO, HC, NOx and particulate
Other Type Approval legislation* (as defined by Directive 2007/46/EC)	↑	-	↑	↑	• The objective of most Type Approval legislation is to improve safety
End-of-Life Directive (Directive 2000/53/EC)	?	-	-	↓↓ ★	• Driver for improving the re-usability and recyclability of automotive components

Legend: ↑ Increases CO_2 emissions ↓ Decreases CO_2 emissions - No significant impact on CO_2 emissions ? Unknown impact ★ Intended impact

Source: European Commission, IFQC, Ricardo analysis

Ricardo have developed a simple method for estimating life cycle CO_2 emissions for a range of vehicle technologies

Ricardo's methodology for calculating high level estimates of life cycle CO_2 emissions

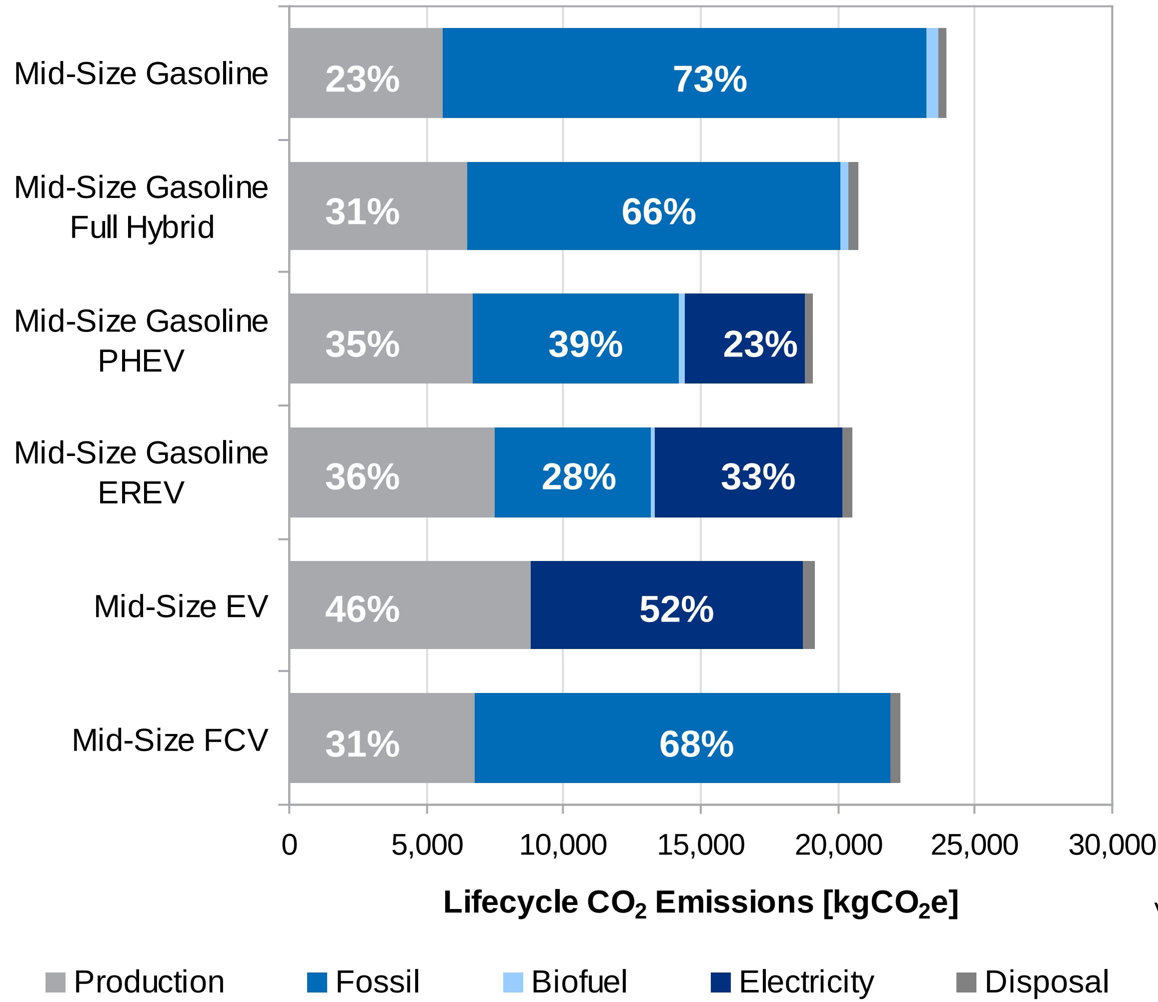


Note: This methodology provides an indication of life cycle CO_2, and is not as thorough as a detailed bottom-up LCA study

Source: Ricardo

Ricardo results show hybrids and EVs will have lower life cycle CO_2 emissions, but embedded emissions will be more significant

Comparing Technologies for mid-size passenger car in 2015



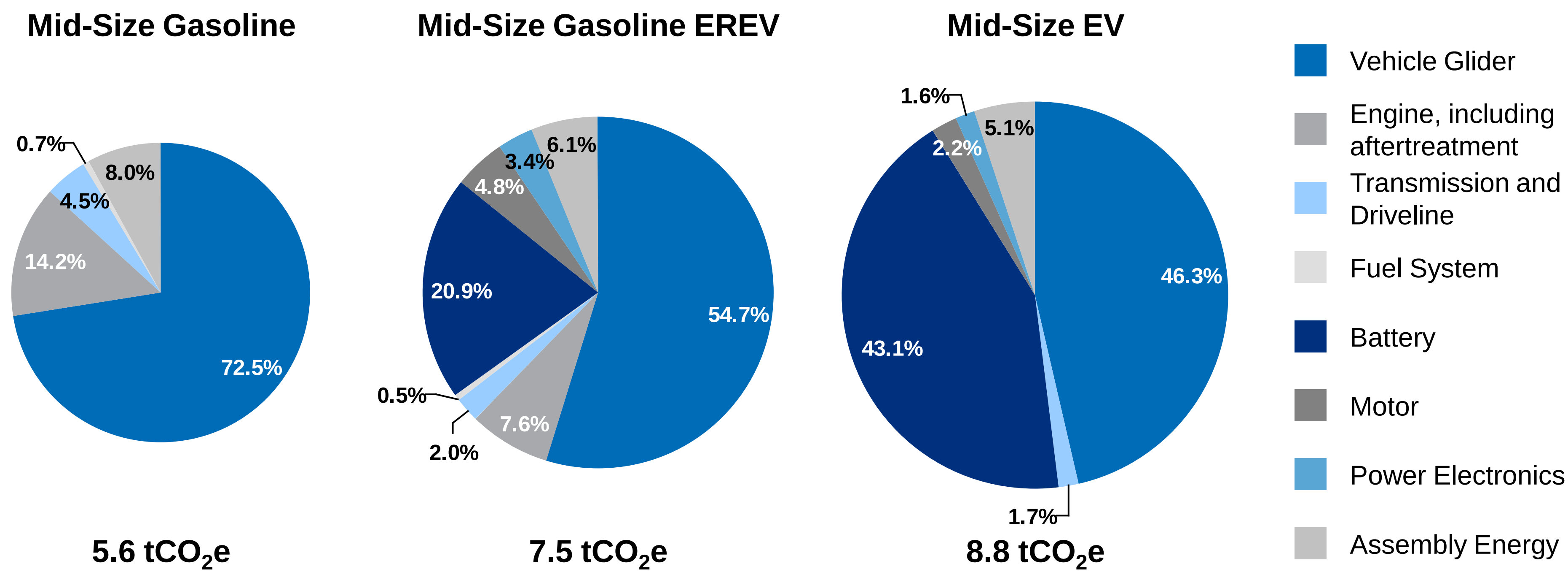
- Predicted improvements in the conventional ICE powertrain designed to reduce in-use tailpipe CO_2, will naturally help to lower the life cycle CO_2 emissions
- Life cycle CO_2 reductions for hybridisation and electrification could be 10-20% (compared to a mid-size gasoline passenger car)
- However, embedded CO_2 from production increases due to the introduction of new components, such as the battery pack

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

The technology evolution to plug-in vehicles will lead to higher embedded CO_2 emissions due to the addition of new components

Embedded CO_2 Emissions [$kgCO_2e$]



- For a standard family gasoline passenger car, >70% of the embedded CO_2 emissions result from the non-powertrain components (the vehicle glider)
- However this balance will change for hybrid and electric vehicles due to the additional powertrain components

Vehicle specifications based on roadmap projections for 2015.
Further details on assumptions is provided in the Appendix 2 of the report

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Many OEMs are already conducting Life Cycle Assessment studies of their vehicles that comply with ISO 14040 and ISO 14044

- The Life Cycle Assessment (LCA) process is outlined in ISO 14040:2006 (general principles) and 14044:2006 (guide for practitioners)
- Many OEMs conduct Life Cycle Assessment studies of their vehicles as part of their Environmental Management strategies
  - PE International's published customer list includes Audi, Daimler, Fiat, Ford, GM, Honda, Renault, Mitsubishi, Nissan, Toyota, VW, and Volvo
- Several OEMs have published Environmental Product Declarations for their vehicles, based on the results from LCA studies
  - Certificates of validity show the LCA is based on reliable data and conforms to ISO 14040
  - But it is not clear if different OEMs use the same assumptions or input data sets

Certificates from relevant technical inspection organisations show that the LCA has been based on reliable data, and conforms to the requirements of ISO standards 14040 and 14044

Source: The Polo Environmental Commendation, VW, 2009 ; Prius Environmental Declaration, Toyota, 2009; www.gabi-software.com/uk-ireland/customers/

Current gaps in understanding surrounding LCA revolve around the LCI data for materials, processes, fuels and energy

Gaps in Understanding

Life Cycle Inventory (LCI)

- Quantify differences between LCI datasets and tools
- Consider new automotive materials, and advanced production processes
- What other environmental impacts should be considered?

Real World Use

- What is the extent of the variability introduced by a population of different users?
- What is the realistic lifetime for a future vehicle?
  - How far will it travel?

Vehicle End-of-Life

- What really happens at the end of a vehicle's life?
- What will happen to new technologies (e.g. EV)?
- How should the environmental impact be allocated between old and new products?

Future Fuels & Energy

- What will be the future biofuel content for gasoline and diesel?
  - What will be the carbon intensity of these fuels?
- What will be the future carbon intensity of the electricity grid?
  - Marginal vs. Mean?

Source: Ricardo

Future CO_2 metrics will need to consider a vehicle's whole life cycle, but work is required to obtain common methodologies and data sets

Conclusions

- Technology trends show life cycle CO_2 emissions for passenger cars are decreasing, but the embedded portion from production and disposal is increasing
  - The current regulatory frameworks do not recognise this
- Standards, manuals and tools already exist for conducting Life Cycle Assessment studies
  - Many OEMs are using LCA to create Environmental Product Declarations of their vehicles
  - However input data, boundary conditions and assumption can vary between LCA studies
- If a life cycle CO_2 measure is to be regulated, work is required to standardise the process detail, life cycle boundary, and input data, such that results from different manufacturers are directly comparable
- Meanwhile, let's make LCA part of the process
  - Get life cycle thinking embedded within the design process
  - Allow LCA results to drive reductions in both cost and CO_2 footprint ("Clean 'n' Lean")

Thank-you for listening

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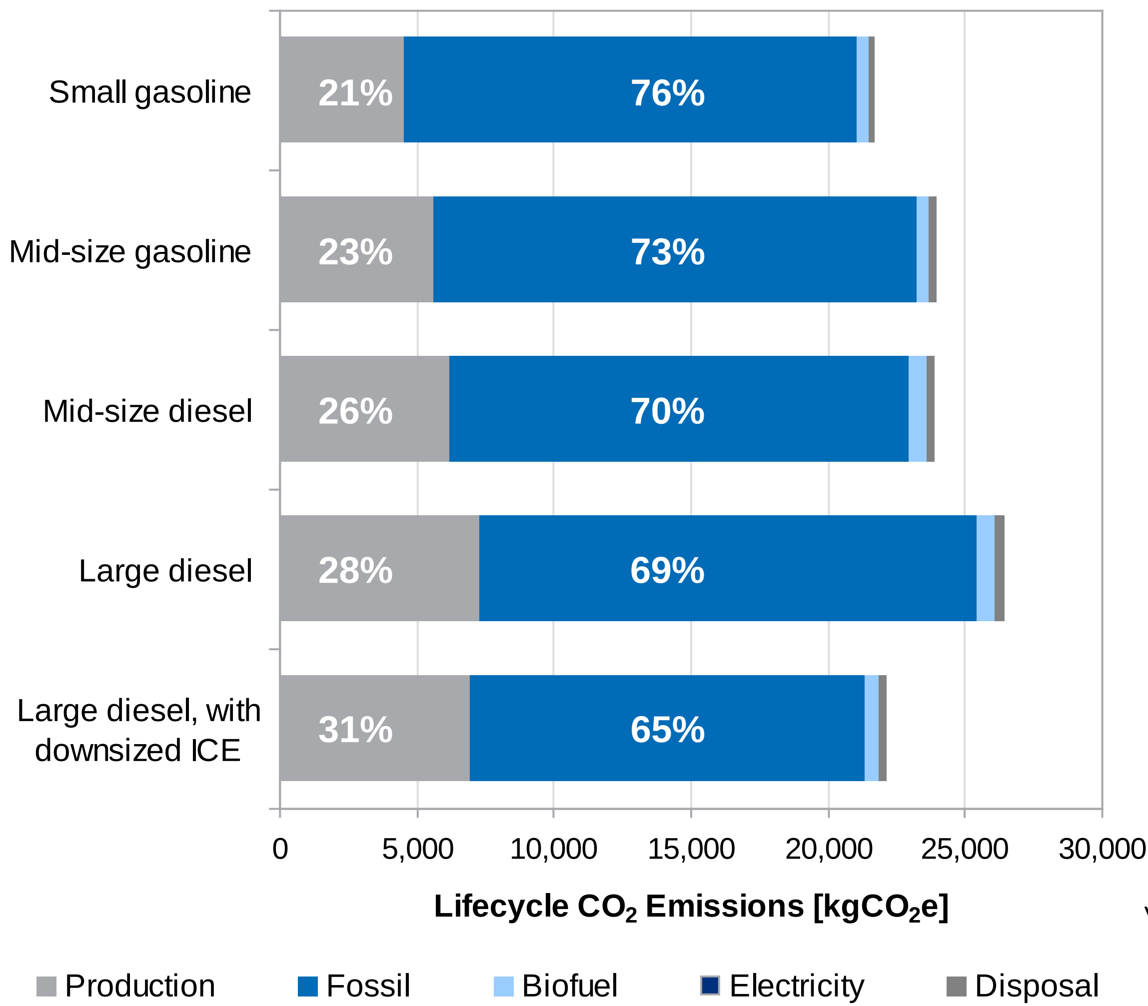
Appendix

Additional material

Diesel and gasoline passenger cars have similar life cycle CO_2 emissions, which generally increase with vehicle size

Comparing Vehicle Size



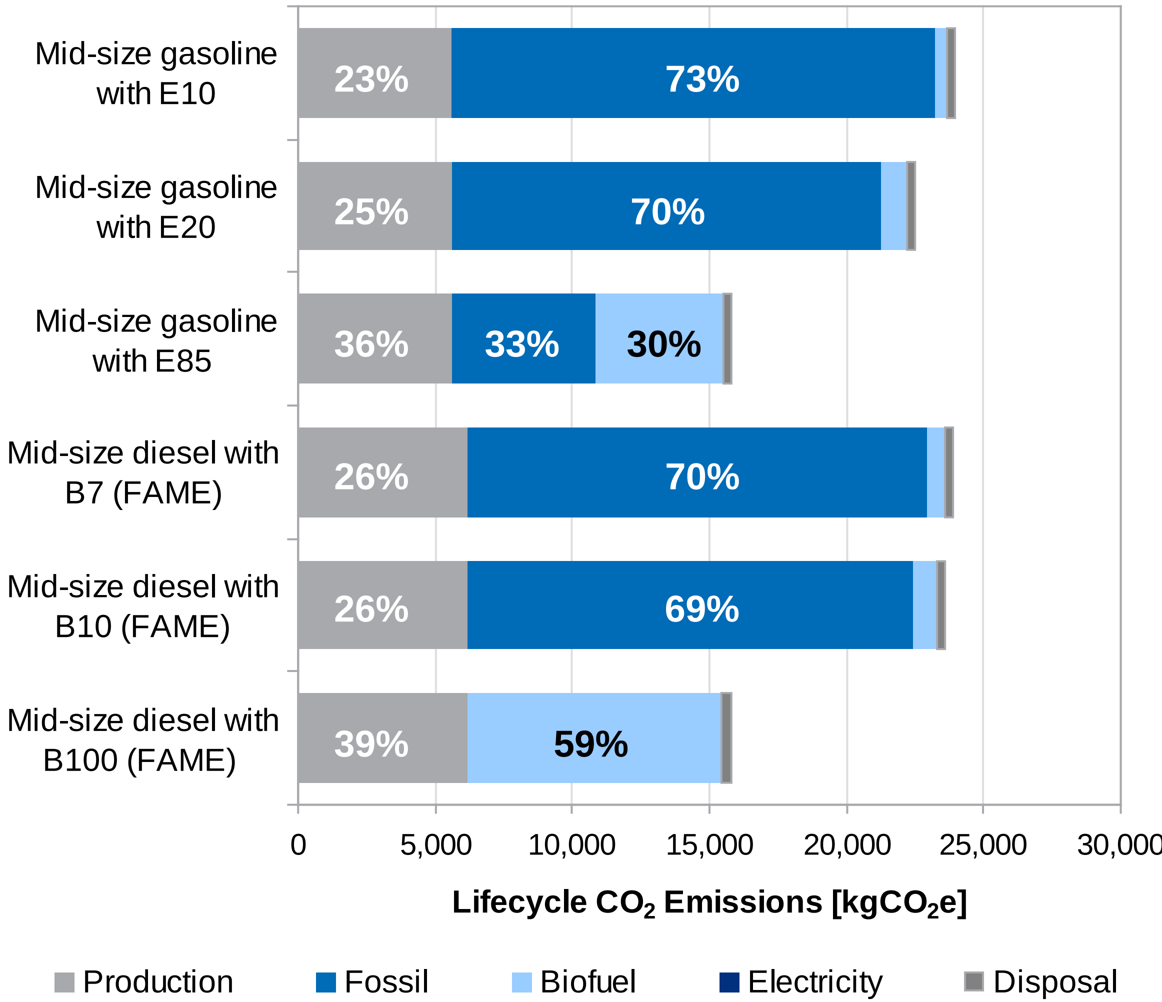
- As expected, larger cars have higher life cycle CO_2 emissions
- The embedded CO_2 for diesel vehicles is higher than the embedded CO_2 for gasoline vehicles. However, since tailpipe CO_2 emissions are generally lower, the life cycle CO_2 emissions for gasoline and diesel passenger cars are very similar (assuming lifetime mileage is 150,000 km)
- Adopting downsizing ICE technology will help to reduce life cycle CO_2 emissions, although this is mainly due to improvements in fuel economy leading to lower tailpipe CO_2

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Increasing the biofuel content helps to reduce Well-to-Wheel CO_2 emissions …

Comparing Alternative Fuels



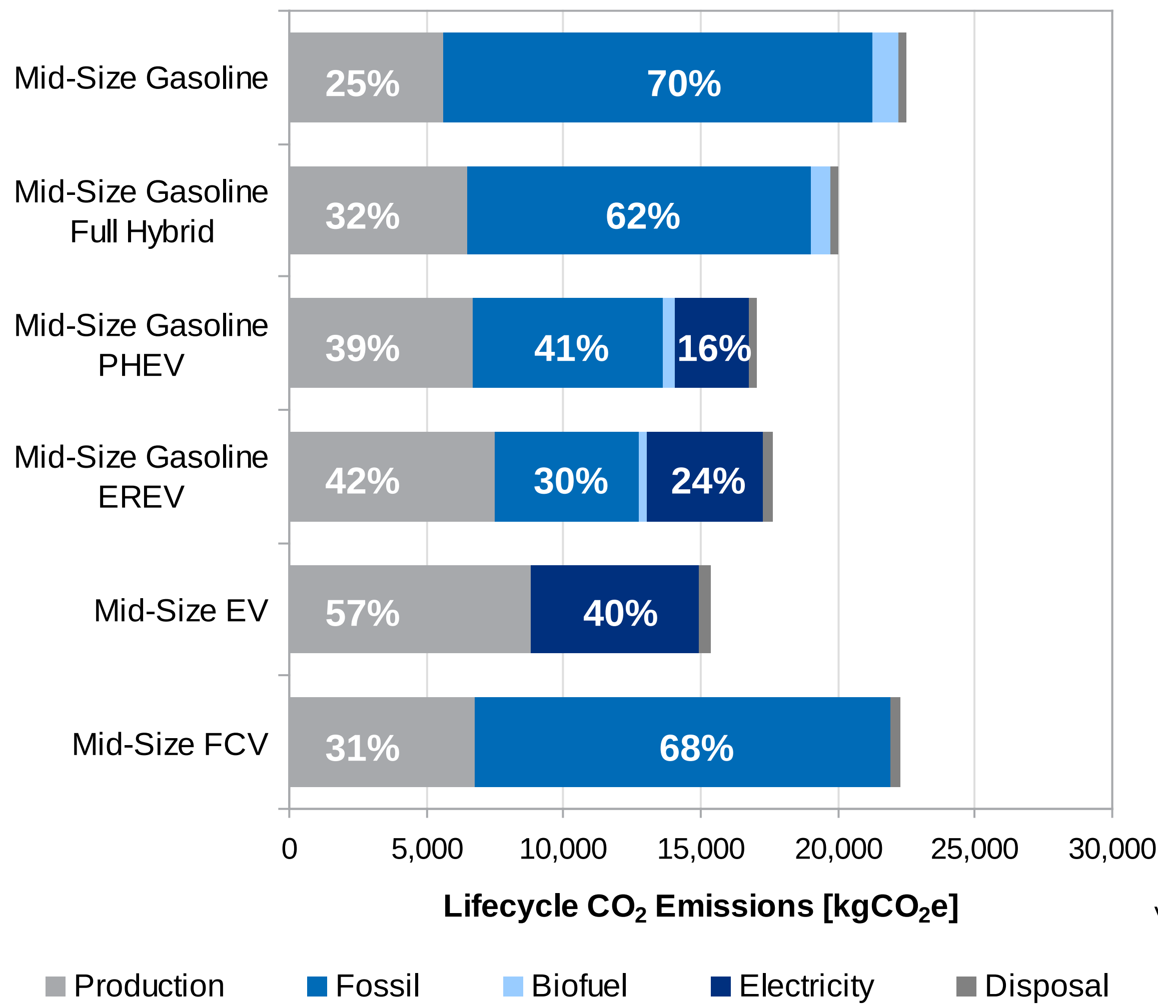
- The higher the biofuel content, the lower the WTW CO_2 emissions resulting from the use of fuel
- The actual level of saving is dependent on the feedstock and production processes used to make the biofuel
- As WTW CO_2 emissions reduce, the embedded CO_2 emissions from production and disposal become a more significant part of the whole life cycle CO_2 metric

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

… for conventional and alternative powertrain technologies

Comparing Technologies with Alternative Fuels



- The WTW CO_2 reductions achieved through increasing the use of biofuels also applies to other powertrain technologies
- Reducing the carbon intensity of the UK electricity mix also helps to reduce the WTW CO_2 emissions for plug-in vehicles
- But, as a consequence, CO_2 emissions from production become more significant
  - For an EV, >50% of life cycle CO_2 could result from production
- Note: In this study it has been assumed that hydrogen is produced by steam methane reforming of natural gas. If produced from renewable sources, its carbon intensity would be significant reduced by ~90%

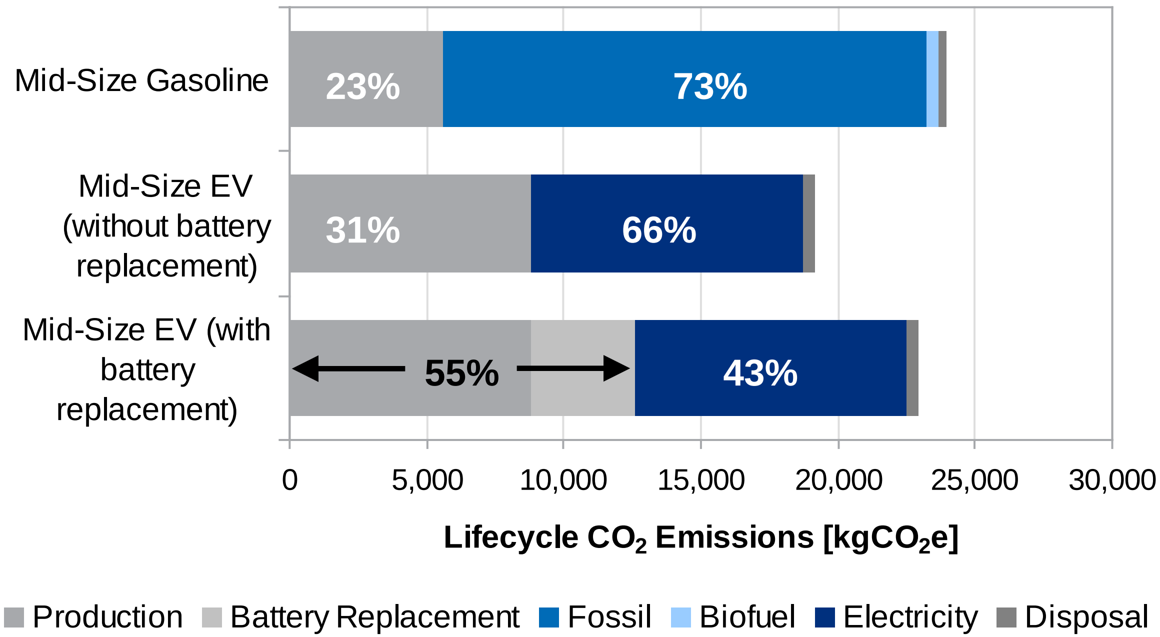
Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E20. Electricity carbon intensity assumed to be 310 gCO_2/kWh. Further details on assumptions is provided in the Appendix 2

Source: Ricardo Analysis – See Appendix 2 for input assumptions

Other assumptions used in Ricardo's high level analysis of life cycle CO_2 emissions from passenger cars

Other assumptions

- Ricardo's top-down methodology provides a high level estimate of the production, in-use and disposal CO_2 emissions of a generic vehicle, useful for providing an indication of future trends in life cycle CO_2. This process does not currently confirm with ISO 14040
- Assume tailpipe CO_2 is equal to tailpipe CO_2e, since tailpipe emissions other GHGs will be very small
- For EVs, EREVs and PHEVs, assume the battery does not need to be replaced during the vehicle lifetime
  - This study has not investigated the likelihood of a Li-ion or NiMH battery pack lasting the lifetime of a plug-in vehicle



HIGH LEVEL ESTIMATE

- If the battery has to be replaced during the vehicle's life, then the embedded CO_2 emissions will increase, as illustrated in the chart left

Vehicle specifications based on roadmap projections for 2015. Assumed lifetime mileage 150,000 km. Fuels E10 and B7. Electricity carbon intensity assumed to be 500 gCO_2/kWh. Further details on assumptions is provided in the Appendices

Source: Ricardo

Ricardo derived a set of vehicle specifications designed to produce equivalent performance characteristics by vehicle size

Vehicle Specifications based on Technology Roadmap projections for 2015

Vehicle	Vehicle Description	Vehicle Mass [kg]	Tailpipe CO_2 [gCO_2/km]	EV Driving Range * [km]
Mid-Size Gasoline	1.4L 91kW I4 DI engine with VVT and FGT	1340 kg	109 gCO_2/km	-
Mid-Size Gasoline Full Hybrid	1.4L 91kW I4 DI engine with VVT, 1.8 kWh NiMH battery pack, 56 kW Motor	1430 kg	84 gCO_2/km	-
Mid-Size Gasoline PHEV	1.4L 91kW I4 DI engine with VVT, 4.8 kWh Li-ion battery back, 56 kW Motor	1460 kg	47 gCO_2/km	20 km
Mid-Size Gasoline EREV	1.0L 44kW I3 PFI engine, 13.4 kWh Li-ion battery back, 72 kW Motor	1510 kg	35 gCO_2/km	55 km
Mid-Size EV	32.2 kWh Li-ion battery back, 71 kW Motor	1480 kg	0 gCO_2/km	180 km
Mid-Size FCV	73 kW PEM fuel cell system, 1.8 kWh Li-ion battery back, 67 kW Motor	1410 kg	0 gCO_2/km	-
Small Gasoline	1.0L 59kW I3 PFI engine with VVT	1080 kg	103 gCO_2/km	-
Mid-Size Diesel	2.0L 101kW I4 engine with VGT Turbo	1420 kg	105 gCO_2/km	-
Large Diesel	3.0L 123kW V6 engine with VGT Turbo	1720 kg	113 gCO_2/km	-
Large Diesel, with downsized ICE and reduced vehicle weight	2.0L 123kW I4 engine with 2 stage turbocharging	1680 kg	90 gCO_2/km	-

* Depth of battery discharge for calculating EV range assumed to be 50% for PHEV and EREV, and 70% for EV

Source: Ricardo

Ricardo have developed a simple method for estimating life cycle CO_2 emissions for a range of vehicle technologies

Ricardo's methodology for calculating high level estimates of life cycle CO_2 emissions

Production	In-Use	Fuel	Disposal	Total
• Divide vehicle into key sub-systems • Determine mass and materials for each system • Calculate CO_2 emissions from materials • Estimate CO_2 emissions from production processes • Sum together to calculate total embedded CO_2 emissions for vehicle production	• Build a vehicle simulation model to predict fuel consumption, and tailpipe CO_2 emissions	• Determing energy consumption from use phase • Identify carbon intensity for each fuel (RED/FQD typical values) • Calculate WTW CO_2 emissions for each fuel [gCO_2/km] • Multiply by life time mileage to obtain total CO_2 emissions from Use and Fuel [$kgCO_2$]	• Assume CO_2 emissions from Disposal is 5% of CO_2 emissions from production	• Sum together the CO_2 emissions from each phase to obtain the total life cycle CO_2 emissions of the vehicle [$kgCO_2$]

Life time mileage assumed to be 150,000 km

Note: This methodology provides an indication of life cycle CO_2, and does not comply with LCA ISO standards 14040 and 14044

Source: Ricardo

A variety of alternative fuels were considered …

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Fuel Specifications, and assumptions regarding Well-to-Tank CO_2 emissions (1/2)

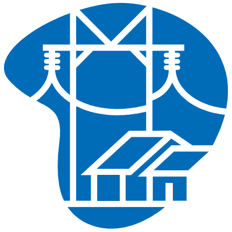
- The study has considered three grades of gasoline:
  - E10 containing $10\%_{vol}$, $7\%_{energy}$ ethanol
  - E20 containing $20\%_{vol}$, $14\%_{energy}$ ethanol
  - E85 containing $80\%_{vol}$, $73\%_{energy}$ ethanol, to allow for seasonal and regional variations
  - Ethanol is assumed to be from a range of feedstocks (70% sugar cane, 20% sugar beet, 8% wheat, 2% corn)
  - Carbon intensity of ethanol is assumed to be 28.7 gCO_2e/MJ_{fuel}, derived from RED typical values
  - Carbon intensity of gasoline is assumed to be 83.8 gCO_2e/MJ_{fuel}, RED default value

- The study has considered three grades of diesel:
  - B7 containing $7\%_{vol}$, $6\%_{energy}$ FAME
  - B10 containing $10\%_{vol}$, $9\%_{energy}$ FAME
  - B100 containing $100\%_{vol}$, $100\%_{energy}$ FAME
  - FAME is assumed to be from a range of feedstocks (40% soy, 25% oilseed rape, 15% tallow, 10% palm, 10% other)
  - Carbon intensity of FAME is assumed to be 43.4 gCO_2e/MJ_{fuel}, derived from RED typical values
  - Carbon intensity of diesel is assumed to be 83.8 gCO_2e/MJ_{fuel}, RED default value

Source: Ricardo, UK Renewable Fuels Agency, European Renewable Energy Directive

… including electricity and hydrogen

Fuel Specifications, and assumptions regarding Well-to-Tank CO_2 emissions (2/2)



- Electricity for plug-in vehicles assumed to be from UK National Grid
  - 2010 UK electricity carbon intensity assumed to be 500 gCO_2e/kWh, 139 gCO_2e/MJ (DECC)
  - 2020 UK electricity carbon intensity assumed to be 310 gCO_2e/kWh, 86 gCO_2e/MJ (CCC Scenario)

- Hydrogen was assumed to be from industrial sources, produced using steam methane reforming
  - Carbon intensity for hydrogen assumed to be 99.7 gCO_2e/MJ_{fuel}

Source: Ricardo, DECC, Committee on Climate Change (CCC), CONCAWE