EVS26
Los Angeles, California, May 6-9, 2012

Strategic Selection of Future EV Technology based on the Carbon Payback Period

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Abstract

The British Low Carbon Vehicle Technology Project (LCVTP) has developed technologies for future plug-in vehicles. Simulation results indicate significantly lower tailpipe CO_2 emissions when compared to conventional internal combustion engine technology, but how good are the CO_2 savings on a life cycle basis? Do these technologies have higher embedded CO_2 from vehicle production? If so, can this be paid back within the lifetime of the vehicle?

To help answer these questions, building on work completed within LCVTP, Ricardo conducted a life cycle top-down review of hybrid and EV technology architectures to estimate the CO_2 emissions associated with each phase of the vehicle's life. Results showed that these technologies have the potential to reduce the life cycle CO_2 footprint of passenger cars, compared to today's conventional technology. However, the higher embedded CO_2 from vehicle production has to be paid back before these savings can be realised. This carbon payback period is highly dependent on the CO_2 emissions resulting from electricity generation and transmission. This implies that the commercial role out of plug-in vehicles must happen in tandem with decarbonisation of the electricity to ensure CO_2 emissions are really reduced.

Ensuring future low carbon vehicles are truly low carbon will require a shift in focus from tailpipe CO_2 to considering the environmental impact of the whole vehicle life cycle and the energy it uses. By adopting a life cycle philosophy and considering the carbon payback, vehicle manufacturers, policy makers and consumers can select the appropriate low carbon technology for their situation.

Keywords: EREV (extended range electric vehicle), EV (electric vehicle), HEV (hybrid electric vehicle), LCA (Life Cycle Assessment), passenger car

1 Introduction

There are many market drivers for electric vehicle technology, from clean air in cities, to national energy security and reducing global GHG emissions from transport. In Europe legislation on fleet average tailpipe CO_2 for passenger cars, with super-credits for vehicles achieving less than 50 gCO_2/km and financial penalties for non-compliance, has provided a strong incentive to vehicle manufacturers to develop ultra-low emission vehicles.

The British Low Carbon Vehicle Technology Project (LCVTP) has developed a range of technologies for future plug-in vehicles, from the control and integration of advanced battery packs to efficient cooling and thermal management throughout the vehicle. Simulation results show that the LCVTP technologies will help to significantly reduce tailpipe CO_2 emissions of passenger cars when compared to the conventional internal combustion engine. However, tailpipe emissions alone do not necessarily tell the whole story. How do these technologies compare on a life cycle basis? Do these technologies have higher embedded CO_2 emissions from vehicle production than today's conventional technology? And if so, can this embedded CO_2 be paid back within the lifetime of the vehicle?

To help answer these questions, Ricardo conducted a top-down review of the life cycle CO_2 emissions for hybrid and plug-in vehicle architectures using the LCVTP low carbon technologies. The assessment considered the GHG emissions resulting from each phase of the vehicle's life including vehicle production, fuel production, vehicle use and vehicle disposal.

This paper presents the life cycle CO_2 results for a generic large European passenger car, with four different technology platforms considered:

- Gasoline internal combustion engine, representing today's conventional technology
- Gasoline full hybrid with NiMH battery pack
- Range extended electric vehicle (RE-EV) with small range-extender engine and Li-ion battery pack
- Electric vehicle (EV) with Li-ion battery pack

For the UK 2012 energy scenario, the life cycle CO_2 footprint results were 49.8 tCO_2e for the gasoline vehicle, 42.2 tCO_2e for the full hybrid, 41.8 tCO_2e for the RE-EV, and 40.3 tCO_2e for the electric vehicle, assuming lifetime mileage of 200,000 km. The next sections explain of the methodology and assumptions used during the analysis to generate these results.

2 Nomenclature

AC	Alternating Current
APU	Auxiliary Power Unit
CO_2	Carbon Dioxide
CO_2e	Carbon Dioxide equivalent
DI	Direct Injection
EV	Electric Vehicle
GHG	Greenhouse Gases
GWP	Global Warming Potential
HV	High Voltage
I4	In-line 4 cylinder engine
JLR	Jaguar Land-Rover
$kgCO_2e$	Kilograms of Carbon Dioxide equivalent
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCVTP	Low Carbon Vehicle Technology Project
Li-ion	Lithium Ion
NEDC	New European Drive Cycle
NiMH	Nickel Metal Hydride
PFI	Port Fuel Injection
PIV	Plug-in Vehicle
PM	Permanent Magnet
RE-EV	Range Extended Electric Vehicle
tCO_2e	Tonnes of Carbon Dioxide equivalent
TTW	Tank-to-Wheels
V6	V-engine with 6 cylinders
VVT	Variable Valve Timing
WMG	Warwick Manufacturing Group
WTT	Well-to-Tank
WTW	Well-to-Wheels

Table 1: Vehicle Specifications

Vehicle Architecture	**Vehicle Description**	**Vehicle Mass**	**Tailpipe CO_2 (Tank-to-Wheel)**	**EV driving range**
Gasoline	2.9L V6 DI gasoline with VVT, 6 speed automatic transmission	1620 kg	180 gCO_2/km	-
Gasoline Full Hybrid	2.9L V6 DI gasoline with VVT, 6 speed automatic transmission, 2.1 kWh NiMH battery, 70 kW electric motor	1750 kg	140 gCO_2/km	-
RE-EV	1.2L I4 PFI gasoline APU, 18 kWh Li-ion battery, 100 kW electric motor	1780 kg	53 gCO_2/km	60 km
Electric Vehicle	45 kWh Li-ion battery, 100 kW electric motor	1800 kg	0 gCO_2/km	160 km

3 Vehicle Specifications

Ricardo prepared a baseline vehicle specification to represent a generic large European passenger car by averaging the top selling E segment vehicles, such as the Mercedes C-Class, BMW 5 Series, Jaguar XF and Audi A6. This baseline was adjusted to generate the specifications for each of the four technology architectures considered in the study (see Table 1 above). It was assumed that the vehicle glider (non-powertrain components) was common for all technology architectures. The battery pack capacities for the plug-in vehicles were sized for EV driving range.

4 Methodology

The principles and framework for conducting a Life Cycle Assessment (LCA) is governed by the ISO 14040 family of international standards [1]. The many elements that contribute to a vehicle's life cycle environmental impact have been documented in Ricardo's report for the UK Low Carbon Vehicle Partnership [2].

The functional unit of this study was a generic European large passenger car with four doors, five seats, and capable of travelling 200,000 km during the vehicle lifetime. The vehicle lifetime was considered to by 10 years.

This study focused on one type of environmental impact, the impact of greenhouse gas emissions on global warming. The impact assessment method is Global Warming Potential with a time horizon of 100 years. The unit is mass of CO_2 equivalent (tCO_2e).

Ricardo applied their top-down approach to calculate a high level estimate of a vehicle's life cycle CO_2 footprint. The vehicle life cycle was considered in four stages; vehicle production, fuel / energy vector production, vehicle use and vehicle disposal (Figure 1).

Embedded CO_2, resulting from vehicle production, was calculated by dividing the vehicle into its key systems, estimating the embedded CO_2 for each system based on assumptions regarding material content and production processes, then adding the estimates together. In this study the follow vehicle systems were considered:

- Vehicle glider (non-powertrain components)
- Engine and exhaust system, including aftertreatment system
- Transmission system
- Fuel system, including fuel tank
- High-voltage battery pack
- Electric motor, and motor generator
- Power electronics
- Other components, such as vehicle supervisory controller, wiring and high voltage cabling

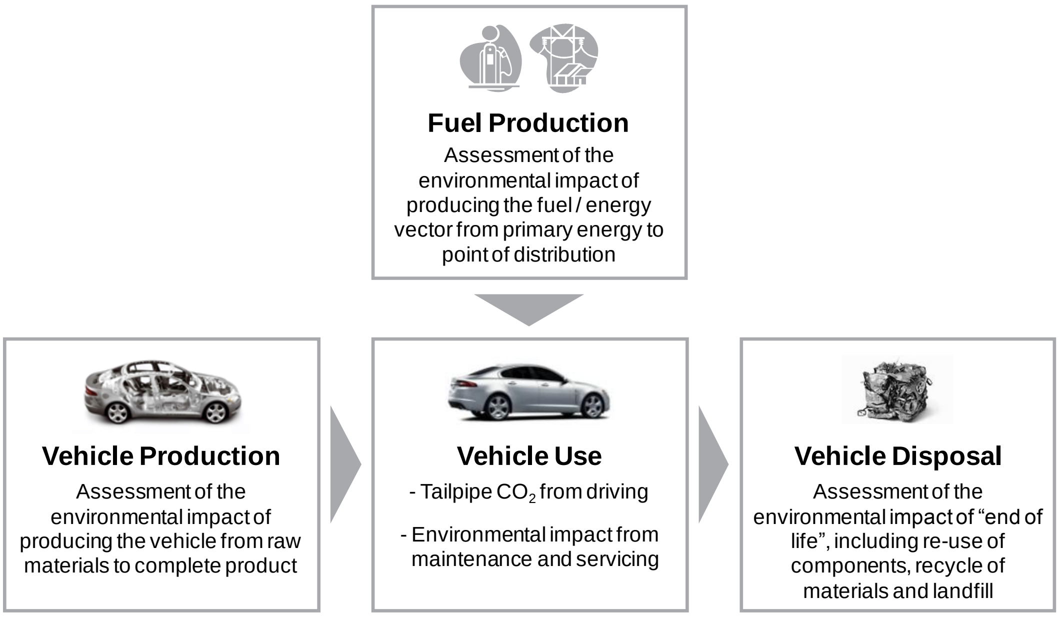

Figure 1: Vehicle Life Cycle

During LCVTP Ricardo conducted cradle-to-gate carbon studies of the battery pack, electric motor and power electronics to understand the embedded CO_2 emissions resulting from the production of these key components. The results from these studies provided input into this study in the form of component CO_2 emission factors [3].

An energy scenario was applied to understand the impact of fuel production. The UK 2012 energy scenario assumed:

- Gasoline contains $5\%_{vol}$ ethanol, with Well-to-Tank factor 0.338 kgCO_2e/L (based on results from JEC's Well-to-Wheels Analysis [4])
- UK electricity carbon intensity 594 gCO_2e/kWh [5]

For the vehicle use phase, fuel consumption and tailpipe CO_2 values for the gasoline vehicle were derived from the baseline specification exercise. It was assumed the gasoline full hybrid would achieve a 22% reduction in fuel consumption compared to the gasoline equivalent. Vehicle simulation models were used to predict the fuel and electricity consumption of the electric vehicle and RE-EV, based on the New European Drive Cycle (NEDC).

Environmental Product Declarations published by vehicle manufacturers suggest that the disposal phase contributes less than 2% to the vehicle's total life cycle CO_2 footprint [2]. Therefore, in this study, the impact of vehicle disposal was considered to be small and has not been included in the reported results.

5 Key Assumptions

The following key assumptions were made in this study:

- Assume the vehicle drives 200,000 km within its lifetime
- Assume the vehicle life is 10 years
- Assume the New European Drive Cycle (NEDC) is representative of how the vehicle is used during its lifetime
- Assume that the Well-to-Tank CO_2 factors for fuel and electricity do not change over the lifetime of the vehicle
- Assume the vehicle's fuel or electricity consumption does not change with vehicle age
- Assume tailpipe CO_2 is the same as tailpipe CO_2 equivalent
- Assume the battery charger efficiency is 90% [6]
- Assume the battery useable capacity is 70%
- Assume the battery pack is not replaced during the vehicle's lifetime

6 Results

6.1 Vehicle Production

Results from the top-down review of vehicle production suggested that the embedded CO_2 emissions would be 8.7 tCO_2e for the conventional gasoline vehicle, 10.2 tCO_2e for the gasoline full hybrid, 12.1 tCO_2e for the RE-EV, and 15.4 tCO_2e for the EV. This confirms that as the level of electrification increases, embedded CO_2 from vehicle production also increases.

Figure 2 below shows the breakdown of embedded CO_2 by vehicle system.

The vehicle glider (non-powertrain components) is the most significant contributor for the conventional gasoline, gasoline full hybrid and RE-EV. However for the electric vehicle, the battery pack makes the largest contribution of the embedded CO_2.

Several factors influenced the embedded CO_2 resulting from the production of the battery pack. These factors include the energy storage capacity, battery cell chemistry and materials, energy intensive production processes, geographic location of production and associated logistics chain.

It was decided to investigate to impact of applying different assumptions for Li-ion battery pack production. Four alternative "emission factors" were considered, as listed in Table 2. Options A, B and C were derived from published studies [7, 8, 9]. Option D was included as a "worst case" example, derived from Ricardo's own cradle-to-gate carbon study of Li-ion battery packs for automotive applications.

Table 2: Alternative CO_2 emission factors production of the Li-ion battery pack

Option	Units	Embedded CO_2 Emission Factor	Source
Option A	kgCO_2e/kg	6	[7]
Option B	kgCO_2e/kg	12	[8]
Option C	kgCO_2e/kg	24	[9]
Option D	kgCO_2e/kg	30	-

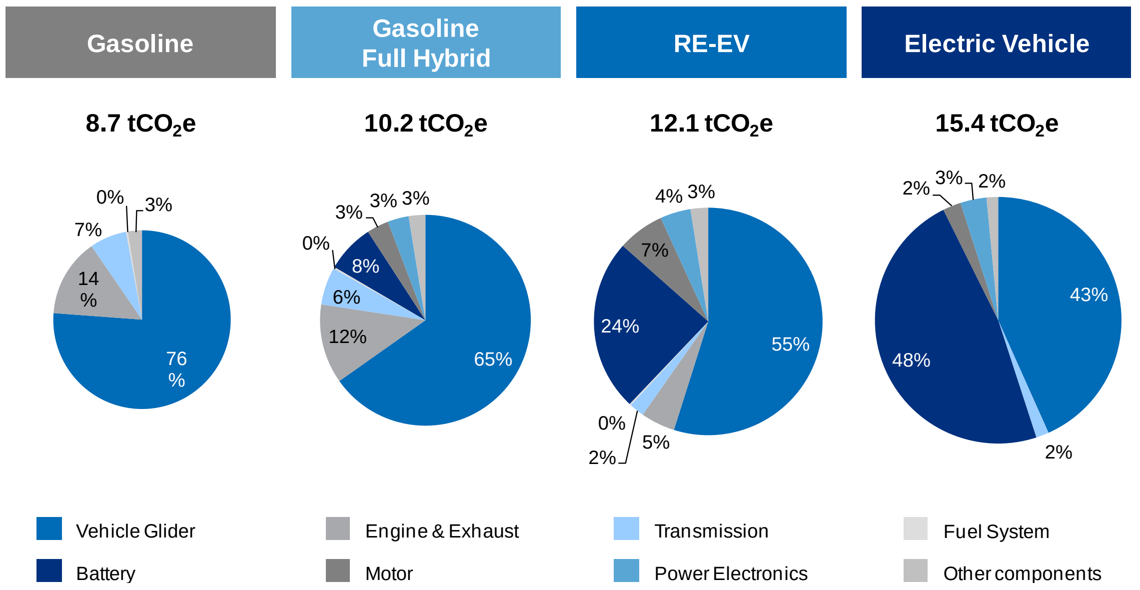

Figure 2: Embedded CO_2e Emissions from Vehicle Production

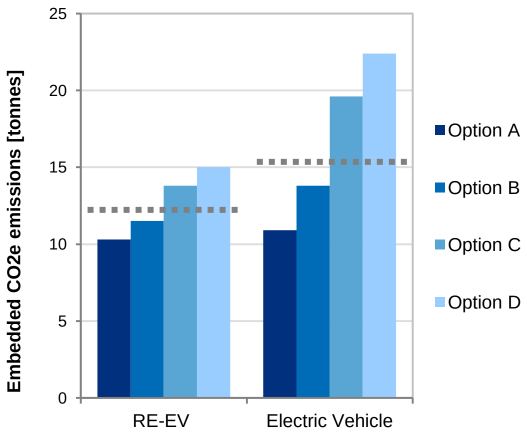

Figure 3: Impact on embedded CO_2e emissions of alternative CO_2e emission factors for the battery pack

The impact of these different factors on the embedded CO2e emissions of the RE-EV and EV is displayed in Figure 3. The dotted line represents the embedded CO_2 value used by Ricardo in this study, based on using an emission factor of 15.3 $kgCO_2e/kg$ for the production of the Li-ion battery pack.

Therefore, embedded CO_2 the EV could be lower, at 10.9 tCO_2e, if Option A was applied; or as high as 22.4 tCO_2e if the "worst case" scenario was assumed. Similarly the embedded CO_2 emissions for the RE-EV range from 10.3 tCO_2e to 15.0 tCO_2e depending on the emission factor option for the Li-ion battery pack.

6.2 Fuel Production and Vehicle Use

The results from the vehicle simulation exercise to predict fuel consumption and tailpipe CO_2 are summarised in Table 3. As expected, the tailpipe and Well-to-Wheel CO_2 emissions are significantly lower for the EV and RE-EV than for the gasoline vehicle. For the UK 2012 energy scenario, WTW CO_2 emissions are 27% lower for the RE-EV and 39% lower for the EV.

However, will these reductions be significant enough to pay back the higher carbon emissions invested during vehicle production?

6.3 Life Cycle CO_2 Footprint and Carbon Payback

Combining the results from vehicle production, fuel production and vehicle use provides an indication of the overall life cycle CO_2 footprints for each technology architecture, as displayed in Figure 4 below.

In this example the UK 2012 energy scenario has been applied, assuming Well-to-Tank factor 0.338 $kgCO_2e/L$ for gasoline, and 594 gCO_2e/kWh for electricity. Lifetime comparison is 200,000 km. The brackets on the chart provide an indication of the potential variation due to applying alternative emission factors for the production of the battery pack.

Table 3: Predicted Vehicle Performance Characteristics

Vehicle Architecture	Gasoline	Gasoline Full Hybrid	RE-EV	Electric Vehicle
Fuel	E5 Gasoline	E5 Gasoline	Electricity and E5 Gasoline	Electricity
NEDC Fuel Consumption (combined)	7.5 L/100km	5.9 L/100km	2.2 L/100km	-
NEDC Electricity Consumption (combined)	-	-	14.8 kWh/100km	21.0 kWh/100km
EV Range	-	-	60 km	150 km
Tailpipe CO_2	180 gCO_2/km	140 gCO_2/km	53 gCO_2/km	-
Well-to-Wheels CO_2 *	205 gCO_2/km	160 gCO_2/km	148 gCO_2/km	125 gCO_2/km

*Applying the UK 2012 energy scenario, with Well-to-Tank factor 0.338 $kgCO_2e$/L for gasoline, and 594 gCO_2e/kWh for electricity

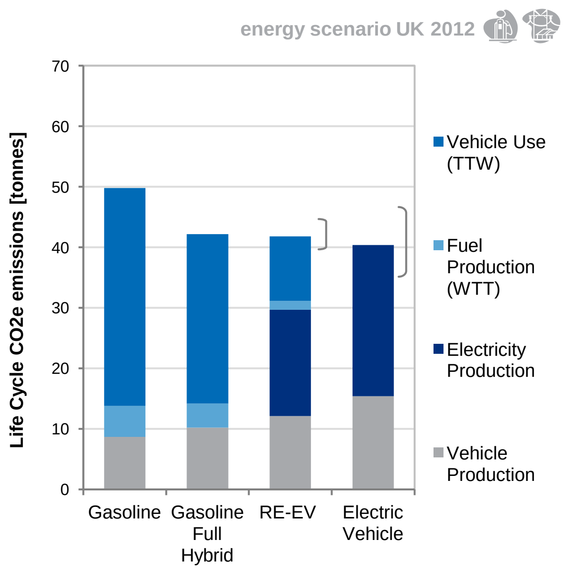

Figure 4: Life Cycle CO_2 applying UK 2012 energy scenario

The calculated life cycle CO_2 footprints are 49.8 tCO_2e for the gasoline vehicle, 42.2 tCO_2e for the full hybrid, 41.8 tCO_2e for the RE-EV, and 40.3 tCO_2e for the electric vehicle. This implies that the EV saves 9.5 tCO_2e over a 200,000 km lifetime compared to the conventional gasoline vehicle. Similarly the RE-EV saves 8.0 tCO_2e and the full hybrid saves 7.6 tCO_2e. But how long does it take to payback the higher embedded carbon from vehicle production?

The carbon payback chart in Figure 5 below shows the cumulative CO_2 emissions with distance travelled for each vehicle architecture. The payback period is determined by when the line for the gasoline full hybrid, RE-EV or EV architecture crosses the line for the conventional gasoline vehicle (indicated by arrows). A summary of the carbon payback periods is provided in Table 4.

Table 4: Carbon payback compared to Gasoline Vehicle, applying UK 2012 energy scenario

Vehicle Architecture	**Carbon Payback**	
	Distance	**Years***
Gasoline Full Hybrid	32,400 km	1.6 years
RE-EV	59,500 km	3 years
Electric Vehicle	82,300 km	4.1 years

*Assuming vehicle travels 20,000 km annually

This means that for the UK 2012 energy scenario, the EV needs to travel over 80,000 km before its net CO_2 emissions are less than the conventional gasoline vehicle. If the annual mileage is 20,000 km, this will be achieved in just over 4 years. However, if the annual mileage is low, say 10,000 km, it will take over 8 years to pay back the additional embedded CO_2 from vehicle production.

The carbon payback chart also highlights when the EV vehicle pays back compared to the gasoline full hybrid and RE-EV, which for this energy scenario is 147,000 km and 135,000 km respectively.

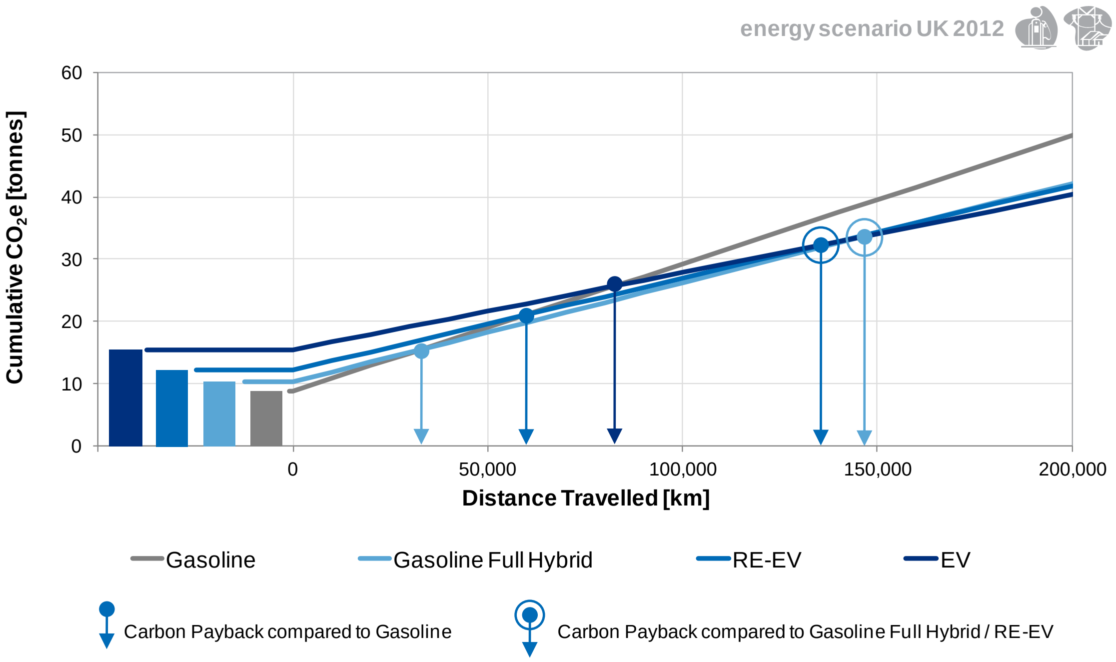

Figure 5: Carbon Payback for UK 2012 energy scenario

6.4 Alternative Energy Scenarios

Three alternative energy scenarios where considered to assess the impact of electricity carbon intensity on the life cycle CO_2 footprint:

- Energy scenario France 2012, representing low carbon electricity with carbon intensity factor 149 gCO_2e/kWh [9]
- Energy scenario USA 2012, with carbon intensity 785 gCO_2e/kWh [9]
- Energy scenario China 2012, representing high carbon electricity with carbon intensity factor 1145 gCO_2e/kWh [9]

The impact of these alternative scenarios can be seen by comparing the vehicle life cycle CO_2 footprints displayed in Figure 6, Figure 8 and Figure 10.

As expected, the life cycle CO_2 footprints for the France 2012 energy scenario are lower than the UK 2012 energy scenario, contributing to greater life cycle GHG emission savings of 28.2 tCO_2e for the EV and 21.2 tCO_2e for the RE-EV compared to the conventional gasoline vehicle.

Carbon payback is quicker than for the UK 2012 energy scenario (see Table 5 and Figure 7), with the RE-EV achieving carbon payback before the gasoline full hybrid and EV. The EV achieves carbon payback in less than 2 years (assuming annual mileage is 20,000 km).

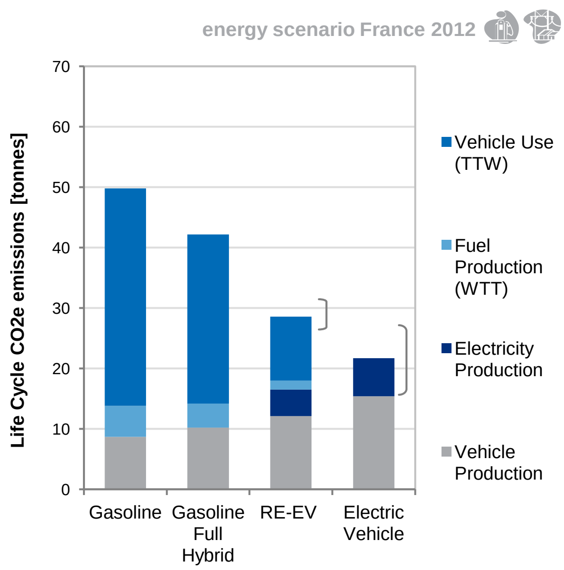

Figure 6: Life Cycle CO_2 applying France 2012 energy scenario

Interestingly for this vehicle and this energy scenario, the carbon payback period between the EV and gasoline full hybrid is very similar to be carbon payback between the EV and gasoline vehicle.

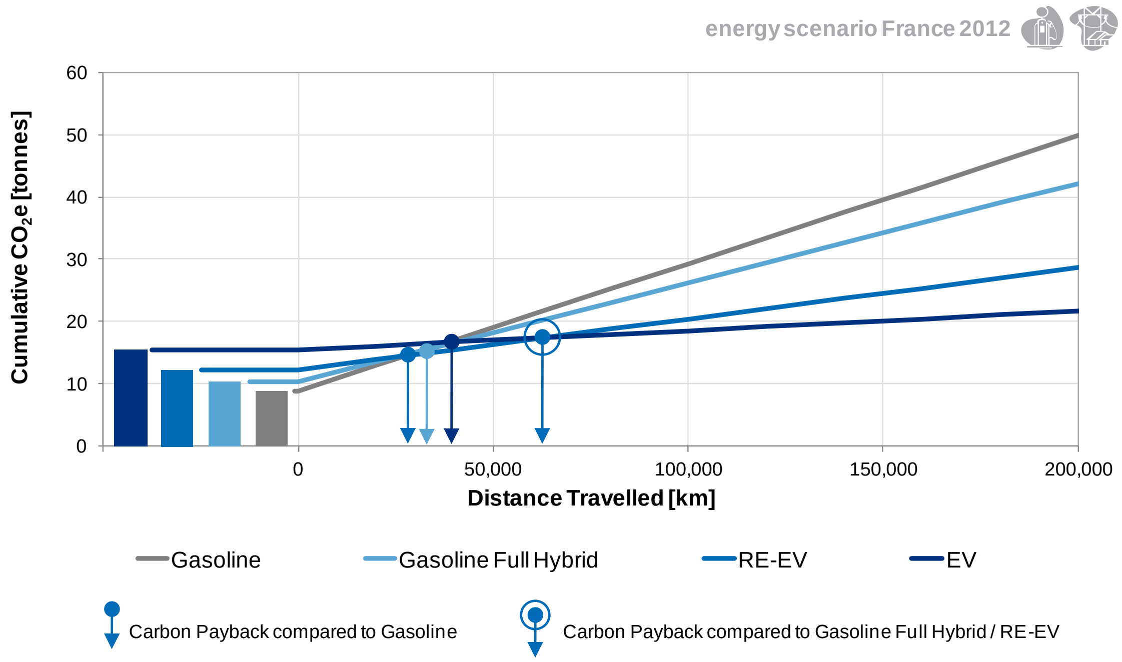

Figure 7: Carbon Payback for France 2012 energy scenario

Table 5: Carbon payback compared to Gasoline Vehicle, applying France 2012 energy scenario

Vehicle Architecture	**Carbon Payback**	
	Distance	**Years***
Gasoline Hybrid	32,400 km	1.6 years
RE-EV	27,500 km	1.4 years
Electric Vehicle	38,500 km	1.9 years

*Assuming vehicle travels 20,000 km annually

For the USA 2012 energy scenario, the life cycle CO_2 footprints for the EV and RE-EV are only slightly better than for the gasoline vehicle (47.5 tCO_2e for the RE-EV and 48.4 tCO_2e for the EV, compared to 49.8 tCO_2e for the gasoline vehicle). This difference is less that the potential variation in embedded CO_2 from the battery pack, making it difficult to ascertain which technology solution would be most suitable on a CO_2 basis.
For this scenario, the WTW emissions for the EV are 165 gCO_2/km, compared to 205 gCO_2/km for the gasoline vehicle and 160 gCO_2/km for the gasoline full hybrid. As a consequence, carbon payback takes longer at around 165,000 km for the EV and around 120,000 km for the RE-EV.

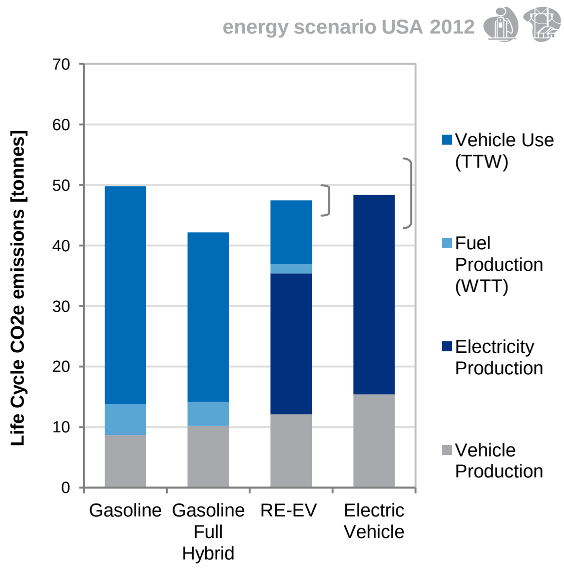

Figure 8: Life Cycle CO_2 applying USA 2012 energy scenario

Table 6: Carbon payback compared to Gasoline Vehicle, applying USA 2012 energy scenario

Vehicle Architecture	**Carbon Payback compared**	
	Distance	**Years***
Gasoline Hybrid	32,400 km	1.6 years
RE-EV	118,600 km	5.9 years
Electric Vehicle	165,000 km	8.3 years

*Assuming vehicle travels 20,000 km annually

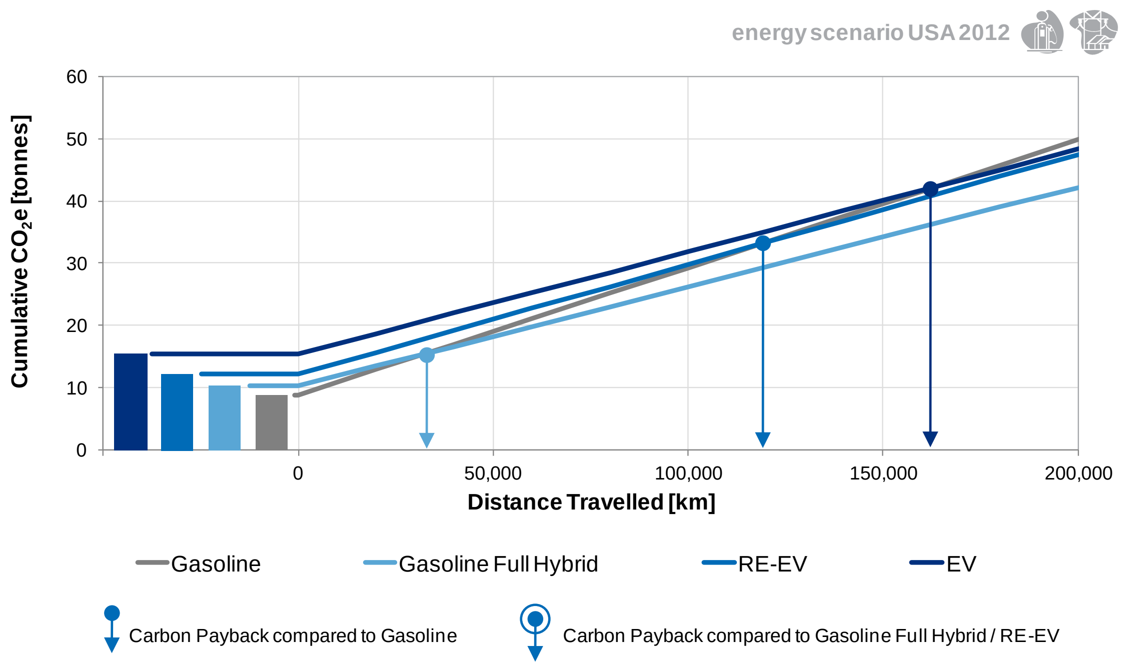

Figure 9: Carbon Payback for USA 2012 energy scenario

For the high carbon electricity scenario (China 2012, Figure 10), the life cycle CO_2 footprints of the plug-in vehicles are potentially greater than for the gasoline vehicle, suggesting that carbon payback is not achieved within the lifetime of the vehicle.

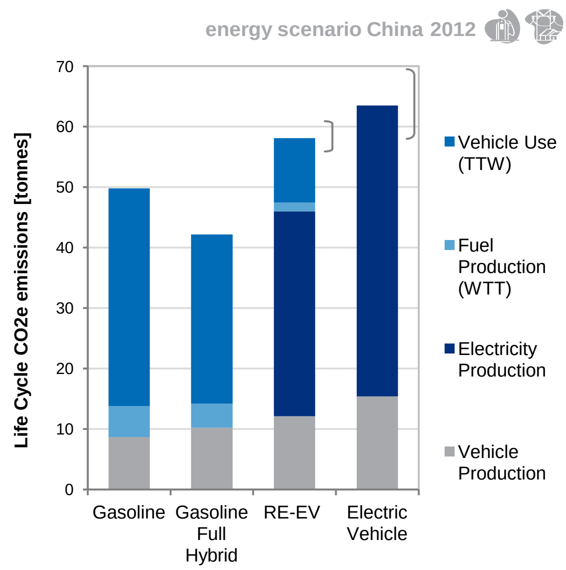

Figure 10: Life Cycle CO_2 applying China 2012 energy scenario

7 Conclusions

The results from this life cycle CO_2 study show that, although PIV technologies help to significantly reduce CO_2 emissions at point of use, they generally release more CO_2 emissions during vehicle production when compared to conventional internal combustion engine technology. This higher embedded carbon content needs to be paid back within the vehicle lifetime through the Well-to-Wheel savings if the plug-in vehicle is to have a lower life cycle CO_2 footprint than the conventional ICE powertrain.

The alternative energy scenarios show that the carbon payback period for plug-in vehicles is highly dependent on the carbon intensity of the electricity used. If the electricity is from low carbon sources, such as renewable energy or nuclear power, then the carbon payback period for the PIV can be within 2 years, when compared with the conventional gasoline vehicle. However, if the electricity is from high carbon sources, such as coal without carbon capture, then the carbon payback period for the PIV may be greater than the vehicle lifetime. This implies that the commercial role out of plug-in vehicles must happen in tandem with decarbonisation of electricity if PIVs are to play a positive role in reducing GHG emissions.

There is another potential implication for policy makers that can be drawn from the results of this study. Current automotive policy considers only the in-use phase of the vehicle's life cycle, and is based around fleet averaging. A vehicle manufacturer is potentially rewarded for selling a low carbon vehicle as a second car, rather than as a replacement. However, if the annual mileage of the PIV is low, the higher embedded emissions may not be repaid within the vehicle lifetime. This would lead to a net increase in CO_2, rather than decrease.

Ensuring future low carbon vehicles truly are low carbon requires a shift in focus from considering purely in-use emissions, to considering the total life cycle impact of the vehicle and the energy it uses. For example, LCVTP has investigated lightweight materials and associated production processes that will help to reduce vehicle mass, and save in-use emissions, without increasing embedded emissions from vehicle production.

LCVTP has supported this transition in thinking to a Life Cycle Philosophy by:

- Organising workshops and training sessions on Life Cycle Assessment and CO_2 footprinting
- Commissioning the development of the Rapid Automotive Life Cycle Calculator, an easy-to-use LCA tool for non-experts based on IDC's LCA Calculator that will aid sustainable design [11]
- Introducing the "Clean'n'Lean" process for using LCA with a lean manufacturing philosophy to cut cost and carbon

Acknowledgments

The Low Carbon Vehicle Technology Project (LCVTP) was a collaborative research project between leading UK automotive companies and research partners, revolutionising the way vehicles are powered and manufactured. The project partners included Jaguar Land Rover, Tata Motors European Technical Centre, Ricardo, MIRA LTD., Zytek, WMG and Coventry University. The project included 15 automotive technology development work-streams that delivered technological and socio-economic outputs that benefited the UK West Midlands Region. The £19 million project was funded by Advantage West Midlands (AWM) and the European Regional Development Fund (ERDF). The project began in November 2009 and completed in February 2012.

Ricardo has completed a series of life cycle CO_2 and cradle-to-gate carbon studies within LCVTP Work Stream 7. These studies have been critically reviewed by Geraint Williams (WMG), Fabian Marion (JLR), Shirley Pugh (SPMJ Consulting) and Christine Hemming (SPMJ Consulting).

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