Carbon calculus

Manufacturing, operating, maintaining and end-of-life recycling and disposal: vehicles impact the environment at every stage, not just in their use phase. Life cycle assessment, as **Jesse Crosse** finds out, has become a vital planning tool to enable policymakers to see the complete picture when making major strategic decisions

As long as it is well executed, life cycle assessment (LCA) takes into account every aspect of a human-made object's impact on the environment. These impacts can stretch all the way from those first team planning meetings right through to end-of-life and the object's reuse, recycling or disposal.

Whilst LCA has been in active use for decades, it has always been an evolving process. Although it has become a recognized element within automotive product development – and in other sectors too – historically a very diverse set of assumptions and scope have been applied, and some of the common assumptions on vehicle operation have not reflected the real-world situation sufficiently well. In addition, there has been less focus on formulating LCA methodologies that are well-aligned for policymaking purposes in the wider sense and on developing and applying these across the wide range of vehicle types, energy production chains and environmental impact categories. Nor have temporal aspects been widely considered, even though they are particularly important for forward planning.

A new study led by Ricardo Energy & Environment, carried out in collaboration with consultancy E4tech and the Institute for Energy and Environmental Research (ifeu) Heidelberg, is the first of its kind to do just that. It has been heralded as the first

LCA study that comprehensively covers such a wide range of dimensions in such depth, exceeding or equalling the scope of previous projects including those of the Technology-centered Electric Mobility Assessment (THEMLA) project, the GREET life cycle analysis model of the Argonne National Laboratory in the United States, and the well-to-wheels report of the JEC consortium - Joint Research Centre of the European Commission (JRC), EUCAR and CONCAWE. See chart on right.

Commissioned by the European Commission's DG Climate Action, the new report will enable the European Commission to better understand the potential evolution of the environmental impacts of road vehicles between now and 2050. Crucially, though, it also provides a means to develop and apply LCA methodology across a range of road vehicle types, powertrains and energy chains.

The scope of the study is highly ambitious. Rather than focusing on individual vehicles or brands, it assesses the lifecycle impact of a broad spectrum of generic European vehicle types including light and heavy duty vehicles such as cars, vans, trucks, buses and coaches. In doing so, it covers 65 different vehicle type and powertrain combinations; it also analyses the production of 60 different liquid and gaseous fuel chains, and 14 different forms of electricity generation, as well as region-specific generation mixes.

Beyond this, the study additionally encompasses the impact of vehicle and battery manufacturing, vehicle use including operation and maintenance, and end-of-life scenarios including recycling, energy recovery, disposal to landfill, and opportunities for battery second-life. As well as greenhouse gas emissions, the study assesses 13 other impact categories such as use of resources, cumulative energy consumption, mineral and metal depletion, scarcity of water and various impacts from air quality pollutants, including emissions of particulate matter and oxides of nitrogen.

Fact-finding mission

Nikolas Hill was the project manager for the work, and is an associate director and knowledge leader in transport technology and fuels in Ricardo's sustainable transport team. Developing such a significant and huge study – resulting in a report of over 450 pages – is no spur-of-the-moment task, and he explains how the project started with a fact-finding mission with the European Commission, as well as consultation with external stakeholder experts. "An important early part of the work were discussions about which were the key factors that impact sustainable transport policy, and what parameters and impacts were most important to compare powertrains and fuels on a balanced holistic basis," says Hill.

Ultimately, he explains, "the study would be used to assess such things as whether existing policies were likely to lead to the optimal outcome, if plans needed to change, whether negative impacts needed mitigating, should a policy framework be changed, are existing regulations delivering the desired results, and what are the best options from different environmental perspectives."

The point of the study is not to suggest policy, but provide a tool which can help planners form policy by giving them access a massive amount of objective evidence-based information. And for that to be possible, the information has to be easily accessible.

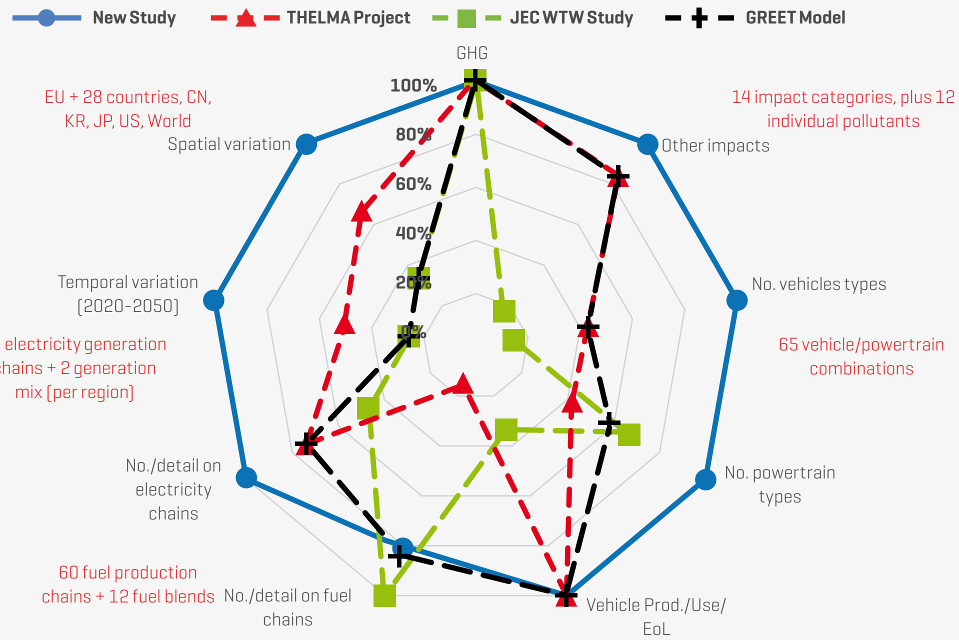
"We had to strike a balance with the huge breadth, complexity and detail, to focus on the most important aspects and messages so that practitioners can understand what we've done and how we got to our answers, but at the same time providing meaningful results," Hill continues. "The policymaker isn't always interested in the detail and sometimes just wants to know what the results and conclusions are. In that case they can, for example, dip into data on greenhouse gas emissions and regulated pollutant emissions and ask what it tells them about the potential holistic impacts of achieving vehicle emissions standards."

In almost every dimension, the new study equals or exceeds the scope of previous projects carried out by other organizations in Europe and the US

Moving the game on - significantly

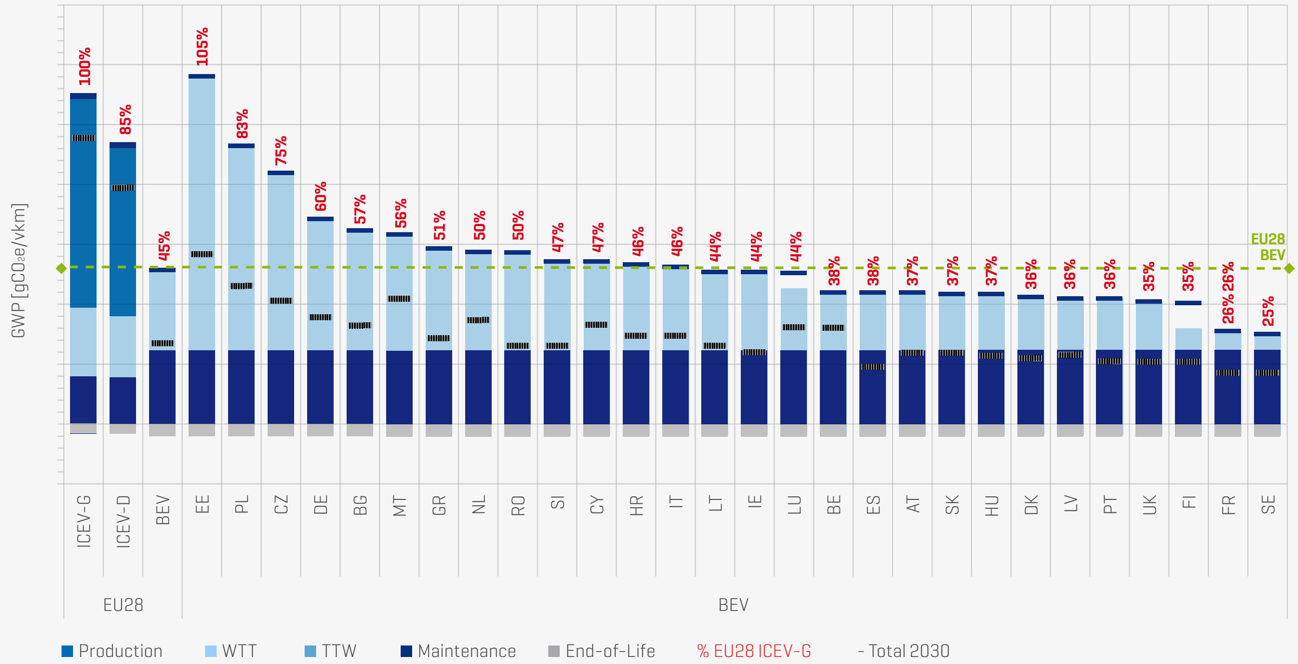
Not only is the study the first of its kind, but it significantly moves the game on, making

Illustration of the comprehensive scope of this vehicle LCA study



Sources: The THELMA project: (PSI/EMPA/ETHZ, 2016), JEC Well- To-Wheels study: (JEC – Joint Research Centre-EUCAR-CONCAWE, 2014b); the Argonne National Laboratory's GREET lifecycle model: (ANL, 2018).

Comparison of lower medium car life cycle global warming potential (GWP) impacts



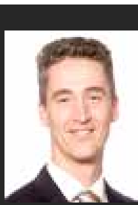
Notes: Results shown for the lower medium car in the baseline scenario. Production = production of raw materials, manufacturing of components and vehicle assembly. WTT = fuel/electricity production cycle; TTW impacts due to emissions from the vehicle during operational use. Maintenance = impacts from replacement parts and consumables; End-of-Life = impacts/credits from collection, recycling, energy recovery and disposal of vehicles and batteries. Additional information on key input assumptions and derived intermediate data include the following: a lifetime activity of 225,000 km over 15 years. 2020 BEV battery of 58 kWh, with 300 km WLTP range (and with 64 kWh and 460 km WLTP range (and with 64 kWh and 460 km WLTP electric range for 2030); an average lifetime EU28 fuel/electricity mix (age-dependant mileage weighted). No battery replacement is needed for BEVs.

it possible to formulate a framework of policies confident in the knowledge that those policies will have the desired effect. "By helping policymakers to understand the critical issues and what the environmental hotspots are, they can better understand the kind of policies they can put in place," explains Hill. "The benefit of this study lies in the huge range of the analysis we've undertaken, as well as sensitivities around the most critical elements. Nothing with this kind of breadth and depth has been done before. We've tried to address what we see as deficiencies in previous LCAs as well as try and expand the boundaries a bit further into new areas. It helps debunk a lot of the myths surrounding the subject, particularly for electric vehicles, and the consistent approach has helped to cement that."

First steps included an exhaustive and essential literature review to thoroughly research what work has already been done in this field, to also help prioritize the most important elements. "Most of the studies are focused only on greenhouse gas emissions or passenger cars," explains Ricardo senior consultant Sofia Amaral. "With this study, the European Commission wanted to explore more impact categories – so in the end we've looked at 14 of those, plus 12 individual pollutants. The greenhouse gas emissions were included of course, but we also looked at other impact categories like water consumption, energy consumption, toxicity and so on."

The full list of impact areas analyzed in

Regional variation impacts of comparison of ICEVs vs BEVs show that in the vast majority of EU countries, pure battery electric vehicles already show significant GHG benefits



"The benefit of this study lies in the huge range of the analysis we've undertaken, as well as sensitivities around the most critical elements" Nikolas Hill, associate director, Ricardo sustainable transport

the study includes global warning potential (GWP), various impacts from air quality pollutant emissions, energy, toxicity and aquatic impacts, land-use change, water consumption, and resource depletion.

Taking the first steps

More planning was needed before work could start. "We had to set the milestones we needed to hit, and it also helped to look at the methodologies and approaches taken by others," says Amaral.

"We talked to other LCA experts in associations and academia and did a two-stage survey to establish whether there was a consensus on different approaches to tackling similar studies. The big first step was establishing the methods we would use to produce the study, and then this stage culminated with a workshop with experts and the European Commission in Brussels."

Some elements were quite different from other studies, especially in terms of the vehicles included. The Ricardo study covers seven vehicle types, from passenger cars to heavy vehicles, all representative of the European market but without focusing on specific brands. It's an important consideration, because there can be significant differences between vehicles within the same segment, something that has not previously been covered in any depth. "When you see how many different combinations of vehicle types and powertrains there are, and the variation of impact they have, it's staggering," Amaral continues. "There's just so much data and so many results."

To be specific, the study covers passenger cars, small trucks, vans, rigid trucks, articulated trucks, buses and coaches. It also covers conventional internal combustion engine (ICE) powertrains, plus hybrids, plug-in hybrids, battery electric and fuel cell electric vehicles (HEVs, PHEVs, BEVs and FCEVs). The range of fuels considered is even more extensive: as well as gasoline and diesel, the study includes biofuels, natural gas, bio-methane, and hydrogen and e-fuels. In all, the study analyses 60 fuel production chains and 12 fuel blends.

Electricity is included in the list of energy carriers covered, too, and is clearly very important as Europe begins making the transition from combustion engines to electrified powertrains. Traditionally, the main impact of vehicles with conventional powertrains has been during the use phase. With an electric vehicle, the impact during use is far less, but much higher during the manufacturing phase and disposal at end of life – although the latter can be mitigated significantly by recycling and second-life battery use – hence the importance of gaining a full understanding of the entire life cycle. The source of the electricity matters too, because the carbon intensity of the power generation mix varies widely across different countries and regions, affecting the effective carbon emissions of the electric vehicle during use. The electricity generation mix also impacts on the vehicle manufacturing and end-of-life stages, particularly for energy intensive battery manufacturing.

The study covers a whole range of sensitivities and uncertainties that could affect the outcome. Examples of these include regional variations, the way operating plug-in hybrid vehicles on electricity is shared across the board depending on charging behaviour, the impact of ambient temperatures on a powertrain energy consumption, and assumptions on future changes in battery technology. Some are more influential than others, but the impact of different sensitivities can be modelled by changing parameters in the data to see how they affect the overall picture.

Perhaps not surprisingly, electricity emerges as the lowest impact form of energy for powering all vehicles, but it is also the factor that most significantly affects the overall comparison. Furthermore, battery electric vehicles, including those also operating via a catenary, perform best across the entire product life cycle. That even includes 40-tonne articulated trucks, although this is based purely on the environmental aspect and discounts the significant practical limitations of today's technology such as the size and weight of the battery pack for a particular vehicle range.

Identifying the best options

"That's the point of a study like this," says Hill. "Whilst there are clearly many layers to consider, this work helps to tells us what we should be aiming for from an environmental perspective, subject to being able to overcome existing technical, practical or cost constraints. Whilst our future projections do consider the potential technical potential based also on consultation with Ricardo's technical experts, there is clearly uncertainty there. We cannot of course guarantee whether we can get there technically or, for example, at what point in time the battery technology improves to a degree that those considerations become less of an issue. However, it's less relevant whether something works in all applications today or not, rather the important thing is to assess what the potential could be for different options and to identify the best option if this technical potential can be achieved."

Even given the significant interest in hydrogen fuel cell vehicles, particularly for longer distance heavy-duty applications, that maxim still holds true. "If you have to transform renewable energy multiple times, for example electricity into hydrogen, then back into electricity on-board the vehicle, then it's not as efficient as using electricity from renewables directly with a battery," adds Hill.

The study also moves on from most other LCA studies in relation to electricity consumption, which is usually based on a single value and applied to the lifetime of the vehicle. Over the last 10 years the greenhouse gas emissions from electricity production across Europe have fallen dramatically, and are projected to continue to decline in the future to meet decarbonization objectives. The study uses outputs from European Commission modelling work on the European energy system for all sectors of the economy. These include future scenarios for different energy chains that factor in changes to the electricity mix, so there is an annual change in the carbon intensity of the electricity that has been factored into models within the vehicle LCA study.

Hydrogen fuel cells have gained significant interest for zero emissions heavy-duty powertrain applications such as long distance trucks and buses, with cities such as London operating demonstration fleets in passenger service since the early 2000s

Results and conclusions

The study arrives at conclusions and provides robust information on different options particularly for powertrain comparisons, electricity chains and conventional fuels. It also provides a clear, evidence-based indication of the relative environmental impacts of different life cycle stages and how future developments in technology (or electricity supply, for example) are likely to affect these powertrain comparisons.

The results confirm that the environmental impacts during the overall life cycle of conventional ICE-powered vehicles and HEVs across all vehicle categories is mainly due to energy consumption during use rather than manufacture. The use phase equates to 82 percent of greenhouse gas emissions for passenger cars and vans and significantly higher percentages for high-mileage heavy duty vehicles. For other types of powertrain, the manufacturing stage is generally responsible for a greater impact, affecting many more environmental areas than just greenhouse gas emissions.

The main impacts of manufacturing result from the materials used in the vehicle – except in the case of battery manufacturing, where energy consumption also plays a significant role. The impact of BEVs and PHEVs is highly dependent on the energy mix across the EU and, in the case of PHEVs, the share of energy use between ICE and electric propulsion modes depends to a large extent on the driving and charging habits of individual users.

In general, the report makes clear the potential for electrification, with BEVs (both light duty and heavy duty vehicles) having a significantly lower impact on greenhouse gas emissions than any other type of vehicle. Those benefits are greatest among large SUVs in the light duty category because they tend to cover higher lifetime mileages, while in heavy duty vehicles the benefits of a battery-electric powertrain are greatest for buses because of their urban duty cycle.

Greenhouse gases are not the only consideration

There are caveats to those findings, however, and the study highlights other non-greenhouse gas considerations relating to electrified vehicles. Whilst electrified vehicles also perform better than conventional vehicles across many non-greenhouse gas impact categories, there are also some hotspots.

Examples are human toxicity potential (HTP) and depletion of non-living resources such as minerals and fossil fuels (abiotic resource depletion). The cumulative energy demand is much higher for FCEVs than BEVs due to the former's less efficient energy chain, which involves converting electricity to hydrogen for use in the fuel cell, and back again.

End-of-life methodologies in the study illustrate the value of a circular economy of extended use followed by recovery and recycling of materials; second-life applications of batteries also emerge as beneficial.

Overall, the study provides a bespoke and, most importantly, a flexible LCA framework. It provides a consistent comparison of the environmental performance of vehicles that was lacking previously, and which covers all stages of a vehicle's life cycle. As well as confirming the significant potential benefits of electrified vehicles, it demonstrates how those benefits increase over time and with the degree of electrification - with BEVs at the top. Results also show that natural gas, bio-gas and synthetic gas-fuelled vehicles can provide significant benefits over their conventional counterparts.

"When you see how many different combinations of vehicle types and powertrains there are, and the variation of impact they have, it's staggering"
Sofia Amaral, Ricardo senior consultant

As might be expected, the study concludes that the benefits of BEVs, PHEVs and FCEVs increase significantly with decarbonized electricity and hydrogen production as well as with improvements to batteries and EU manufacturing techniques.

Improved process efficiency clearly increases benefits, and of course the generation mix used in the production of raw materials influences the outcomes, as do improved recycling recovery rates and a shift to lower carbon electricity to drive the recycling process.

Next steps

There are still challenges in the field of life cycle assessment, and work continues at Ricardo to make further improvements, building on the considerable experience gained in the field over a number of years and culminating in this major project for the European Commission.

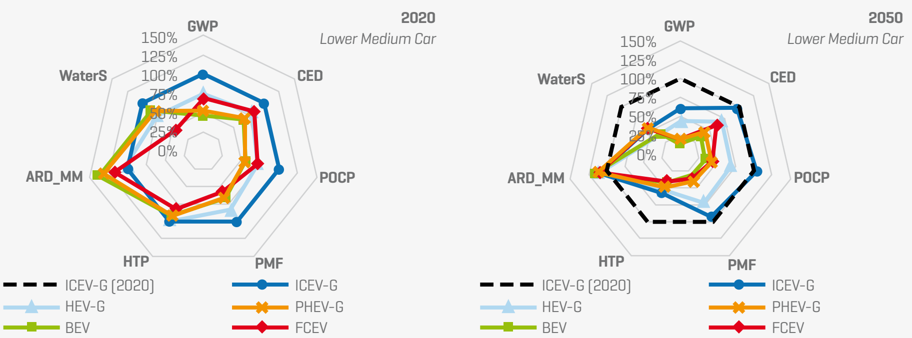
A specific example is the uncertainty surrounding future battery recycling, the recovery levels of materials and the impact those factors might have. Another issue is that key resources such as lithium, cobalt and nickel are not always well covered by current LCA impact categories and can better benefit from a system-wide resource modelling analysis. And again, the lack of clear policies, legal definitions and measures regarding second-life batteries makes it much more difficult to establish methodologies to assess them.

That said, however, the EC Vehicle Policy LCA project has already been a huge success. It is implemented using a modular Excel-based modelling framework developed by Ricardo, and incorporates a results viewer for easier access to its findings. The expectation is that this extraordinarily in-depth study will have a significant role to play in helping the EU to achieve its ambitious environmental targets over the next 30 years and beyond.

Road based overhead electrification systems such as Siemens' eHighway *(above)*, **demonstrate the efficiency of electrified railways with the flexibility of trucks on dedicated routes**

LCA results for lower-medium size passenger cars based on current and projected 2050 scenario *(below)*

Summary of the relative impacts for lower medium cars



Notes: Total emissions are presented relative to a 2020 conventional gasoline ICEV = 100%.
Powertrain types: G- = Gasoline; ICEV = conventional Internal Combustion Engine Vehicle; HEV = Hybrid Electric Vehicle; PHEV = Plug-in Hybrid Electric Vehicle; BEV = Battery Electric Vehicle; FCEV = Fuel Cell Electric Vehicle. **LCA impacts:** GWP = Global Warming Potential, CED = Cumulative Energy Demand, POCP = Photochemical Ozone Creation Potential, PMF = Particulate Matter Formation, HTP = Human Toxicity Potential, ARD_MM = Abiotic Resource Depletion, minerals and metals, WaterS = Water Scarcity.

The report ***Determining the environmental impacts of conventional and alternatively fuelled vehicles through LCA*** *and its associated documents are available for download from the European Commission DG Climate Action's web pages: https://ec.europa.eu/clima/policies/transport/vehicles_en#tab-0-1*