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impacts. From a life cycle carbon perspective, electrified propulsion is attractive considering the rapid shift to renewable electricity sources. "However, progress still needs to be made in reducing the embedded carbon in production, extending second-life applications of batteries, and efficient recyclability of the materials used," Greaney adds. "The present limited energy density of batteries means pure electrified propulsion will not meet all mobility needs. The development of a green hydrogen economy in parallel to electrification is one of the essential elements to enable defossilisation of high energy mobility sectors such as commercial vehicles, shipping, and aviation. Effective hydrogen energy storage can enable optimised use of variable renewable electricity sources such as solar and wind. For transportation, hydrogen will be used in many ways, depending on the sector and application. This will include fuel cells and internal combustion engines using hydrogen or de-fossilised fuels including e-fuels and ammonia which use hydrogen as a feedstock."

When it comes to determining the clean, efficient propulsion solutions for different transport sectors and vehicles, the Ricardo view is that a technology will be chosen that provides the best solution in the application. What this will continue to mean in practice is the use of a portfolio of different technologies including battery electric, fuel cells and internal combustion engines using hydrogen or de-fossilised fuels.

"Identifying clean, efficient propulsion solutions depends on understanding the pros and cons of the various technologies in relation to key criteria: emissions legislation; the amount of carbon dioxide per kilometre (the tank to wheel ratio); local air quality; existing infrastructure; filling time; and range," Greaney continues. "Cost is also a significant determining factor, either the purchase price or total cost of ownership."

Against these criteria, the most likely mainstream approach for passenger cars is battery electric. It rates highly for its carbon dioxide per kilometre and for its impact on local air quality. The existing charging infrastructure is becoming established internationally and is continuing to be developed; and technology advances are improving charging times and extending range significantly. Against the same criteria, it seems likely that fuel cell technology is the most likely mainstream solution for the most demanding duty cycles in commercial vehicles such as long-haul trucks, off-highway machines, and buses, because the energy density of hydrogen provides long range, zero emissions, fast refuelling, and competitive total cost of ownership.

"Yet, there are pros and cons for batteries and fuel cells for both passenger cars and commercial vehicles alike," Greaney says. "This is evidenced by the fact that well-known brands such as Tesla and Daimler are investing heavily in developing battery electric trucks, while marques such as Toyota, BMW, and Hyundai see a future in fuel cells for passenger cars.

"It is why a portfolio approach is necessary because the technology landscape is constantly evolving. Technology matures creating improved efficiency and performance, and lower costs, and ultimately legislation drives technological advance and implementation. Thus, the most likely mainstream technology solutions today will certainly be different in the future.

The cost of hydrogen fuel cells, which is extremely high currently, will come down. Efficiency improvements will allow vehicles to travel further, have smaller batteries and lower the overall energy demand on the grid."

UPHEAVALS AHEAD FOR AUTOMOTIVE SECTOR

We are facing an era of manufacturing disruption, as the UK's net-zero ambitions drive the shift towards decarbonising transport. Electrification is one of, if not the most important determinant of how quickly and effectively the country becomes carbon neutral. Demand for the crucial lithium-ion battery component will continue its upwards curve, with the ban on new petrol and diesel car sales less than a decade away. The discussion now turns to diversifying the onshore manufacturing supply chain to realise the full scale of this potential.

"A growing choice of electric and plug-in hybrid models, and interest from consumers to improve the environment for less, has seen motorists' commitment to an electric future skyrocket," Kevin Brundish, CEO of AMTE Power, says. "Last year was the best year on record for Electric Vehicle (EV) sales, accounting for more than one in ten registrations, up from one in thirty the previous year. Indeed, the UK is world-renowned for its excellence in battery innovation. However, a plan is needed to support manufacturers in retaining existing capabilities and ensuring they are part of a flourishing supply chain."

AMTE Power is one of five commercial battery cell manufacturers in the UK, and has government-backed plans in development to build a new British Gigafactory. The new plant will have an initial capacity of 2.5 GWh per annum, increasing to 10 GWh by 2030, and will be purpose-built to help the UK cope with the transition to EVs. "This will help combat a significant issue in the manufacturing supply chain, brought into sharper focus by COVID-19, in that there is an overreliance on offshore capabilities," Brundish adds. "The Faraday Institute estimates seven 20GWh Gigafactories will be needed in the UK by 2040 to sustainably meet growing demand for EV batteries. This reinforces the urgent shift away from OEMs overseas and towards producing batteries domestically to preserve the UK automotive industry.

"As demand swells, an ongoing task within the automotive industry is optimising existing lithium-ion cell chemistries. As carmakers develop the next generation of Battery Electric Vehicles (BEV), they will implement new cell materials that produce improvements in energy density and thermal performance. To help customers overcome range

THE HYBRID CONUNDRUM

The hybrid vehicle has become a popular choice as a bridge to the zero-emission future for mobility. But is this a suitable solution? We look at the environmental credentials of hybrid vehicles.

How environmentally friendly a hybrid vehicle is depends on a great many variables, not least the way in which the boundaries of assessment are drawn. What is often overlooked is the fact that the effectiveness of plug-in hybrid vehicles in terms of their environmental impact depends largely on the levels of driving and charging discipline end users can exercise. For example, pressing heavily on the gas pedal, as opposed to driving in a more measured manner, can lead the battery power to deplete more quickly, particularly in the case of large SUVs or luxury vehicles, which are commonplace in this category, and so bring the hybrid into ICE mode more quickly.

"In any case, longer journeys will inevitably lead to the increased use of the internal combustion (ICE) element of the vehicle due to range restrictions, which in the case of heavier vehicles means far higher fuel consumption in ICE mode," Andreas Minatti, head of business development at Datwyler explains. "If we consider the added weight of a battery and additional electric drive components in this scenario, efficiency levels are greatly reduced. Evidence also suggests that large numbers of hybrid users do not charge their battery on a regular basis, which essentially means they are driving an ICE vehicle even on shorter journeys."

Setting the boundaries of the pollution assessment strongly determines the result when evaluating the environmental friendliness of a hybrid vehicle. "If we look at what we call the 'tank to wheel' evaluation, a hybrid vehicle used to its full potential might outperform an ICE alternative from an environmental perspective." Minatti adds. "However, if we expand our thinking to look at 'well to wheel' (as in oil well), we start to see a different picture emerging. Where did the energy come from that was used to charge the battery? If that energy was produced by green sources – such as wind or solar – then the hybrid may be the greener option. However, if that energy came from a fossil fuel power plant, using coal or gas, for example, the negative environmental impact is simply being shifted to another area."

The most realistic evaluation comes from what is known as a 'cradle to grave' lifecycle assessment perspective, as this gives us a true picture of the environmental impact in its entirety. "Here we must open our minds even further, as the scope broadens even more significantly," Minatti explains. "Electric hybrid vehicles require rare earth elements, which in themselves have an environmental

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impact in terms of how they are extracted and processed. Also, the production of the battery is very energy intensive and needs to be included in the entire balance sheet. At the end of the vehicle's life, is the recycling or scrapping process more complex and intensive because of those materials? Often, it is. The point is, there are a wide range of elements that must be factored into the environmental equation that are often not commonly conveyed to the end user.

"Then there is the aforementioned size issue. If a small hybrid city car is being used for short journeys in built up towns or cities then this will be favourable environmentally as, assuming the vehicle is charged regularly and driven responsibly, it will use its electric power source, which will in turn have an impact on emissions and air quality in the surrounding area. If the vehicle is a two-ton SUV being used for longer journeys, then the hybrid element is often insignificant as the ranges required means the reliance will be on the ICE powertrain.

"This fact begs the question, should more hybrid vehicles use diesel engines as opposed to petrol? The case for diesel is a compelling one, particularly for those that undertake regular long journeys, as it is a far more efficient fuel source which, when combined with highly effective catalytic reduction systems, can produce low emissions levels. It is a hard sell to end users, however, as diesel engines are often more expensive in the first instance and many options have therefore been removed from the options lists of hybrid producers.

"As we have seen, the effectiveness of hybrid vehicles in terms of their impact on the environment, including air quality, depends on whether they are used in the correct manner by the people who elect to purchase them. The boundaries need to be clear as to how efficiencies are measured, and the education process needs to be clear to ensure there is a clear understanding of how to get the best out of the technology in the way it was intended to be used. Simply buying a hybrid vehicle will not have much of an impact if it is a heavy SUV that is not charged and then used on a 300 km journey. A smaller, city-based car that is regularly charged and used on short urban journeys will be a different story."

anxiety, manufacturers are turning to breakthrough concepts, such as using alternative metal-ion chemistries and reducing vehicle and battery pack mass. Such advances will only create incremental improvements in drive range over time, and pave the way to safer, cheaper, and faster-charging vehicles.

"The next few years will prove crucial in giving consumers the confidence to take the leap into adopting EV technologies, but also supporting manufacturers at the centre of the migration. The government has already taken significant strides in supporting the market, but there is a long road ahead to achieving a totally electric fleet in the UK. For a sustainable transition and to establish the UK's position as global manufacturing competitor, a robust industrial strategy must work in tandem to retain and grow engineering talent and attract new investment to scaling Gigafactories."

THE ROAD TO A HYDROGEN ECONOMY

Andy Walker, technical marketing director, Johnson Matthey, explains that the interest in hydrogen as an alternative fuel is largely driven by the potential to manufacture hydrogen at scale with low-carbon emissions. "Cars powered by hydrogen fuel cells have additional advantages over other alternative, zero-emission (at point of use) vehicles, such as those powered by batteries," he says. "They can be refuelled in a few minutes (faster than electric vehicles can be currently recharged) and have ranges typical of current gasoline and diesel-powered cars.

"Where other fuel processes produce energy through combustion, fuel cells produce it electrochemically. Fuel cells, like traditional batteries, consist of an anode, a cathode, and an electrolyte membrane. A typical fuel cell moves hydrogen to the anode, where it is split into its constituent proton and electron. The proton then travels through a membrane electrolyte to the cathode, where it reacts with oxygen (from the air), generating water, while the electrons complete a circuit and, in the case of a fuel cell vehicle,

drive the electric motors. As there is no combustion aspect to fuel cell power generation and there are no moving parts, they operate almost silently as well as very efficiently."

Fuel cells are, effectively, batteries that will not run flat or have their capacity reduced with each charge. Provided there is hydrogen in the tank the process can continue. As fuel cells can be stacked into a series, the more fuel cells you combine, the more power you can generate at any one time.

"While hydrogen and fuel cells' cases are strong in the long term, the main challenge in upscale is in delivering the infrastructure to support this technology," Walker adds. "A hydrogen economy can only be realised with the right level of government support through proactive policy and investment. If we are to expect more people to start using hydrogen fuel cell cars, then more hydrogen refuelling stations must be built and positioned strategically."

What is very clear is that meeting the 2030 emissions reduction targets will require a mix of technologies across sectors: fully battery electric vehicles, fuel cell electric, synthetic low carbon fuel and new thermodynamic cycles.

IT IS ALL IN THE INTELLECTUAL PROPERTY

Although many are forecasting a battle for supremacy between electric and hydrogen vehicles, the future zero-carbon mobility sector will almost certainly need both. However, in a world of fast-track progress and innovative start-ups the business model will be different to traditional automotive development with licensing and IP rights coming to the fore.

In the world of electric vehicles, some commentators, and social media influencers such as Elon Musk, have been trying to pit batteries against fuel cells in a kind of VHS vs Betamax-esque war, where only one technology can win and take all the spoils. However, according to Dr Rebecca Lovell, Chartered (UK) and European Patent Attorney for Marks & Clerk, batteries and fuel cells each have their own different strengths and weaknesses, and neither technology is a panacea for all transport applications, so there is more than enough room in the market for both technologies to happily co-exist. For example, batteries are great for small vehicles and shorter journeys, but they are not very suitable for heavy duty or weight-sensitive applications, which is where hydrogen fuel cells shine.

"It is therefore clear that batteries and fuel cells are complementary technologies, not competing technologies, with both having a necessary contribution to make towards the world's zero carbon energy transition, and so the smart money is betting on both," Lovell says.

For example, Toyota has entered a significant battery joint venture with Panasonic and a fuel cell joint venture with SinoHytec, as well as producing their own battery-powered vehicles, such as the Prius, and fuel cell vehicles, such as the Mirai. Similarly, corporations which have invested in battery-related technologies for many years are now also investing in fuel cell companies, such as Siemens' recent agreement with Riversimple, a Welsh hydrogen car manufacturer.

"Riversimple has interestingly decided to keep its cars open source as part of a cars-as-a-service, circular economy business model, where the cars, fuel, maintenance and insurance are provided as a subscription package," Lovell explains. "However, for many alternative energy companies operating with a more conventional business model of selling products, IP rights are essential to prevent copycats and protect revenue. IP rights, in particular patents, are also crucial for start-ups and university spinouts which often do not have their own factories or tooling, since manufacturing rights can be licensed to OEMs that already have large scale manufacturing capacity.

"Ceres Power, for example, is a former Imperial University spin-out that now has a £2.3bn market cap and ambitions to be the ARM of energy, by licensing out their SteelCell technology to multi-national partners including Doosan and Weichai, for use in vehicles such as forklifts and buses.

"The electrochemical world of batteries and fuel cells is very different from the mechanical world of internal combustion engines, so it is likely that traditional OEMs will be purchasing or licensing products from battery and fuel cell specialists to use in their vehicles for some years to come, until they are able to develop or acquire their own expertise. Therefore, as the EV industry continues to grow, due diligence in contracts and IP rights will remain crucial to ensure that innovators are duly rewarded and achieve the maximum return on their investment in commercialising the new technologies that will be powering the next generation of vehicles."