Versarien® PLC

Graphene for
Electric Vehicles

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Glossary

2DT	2-DTech Ltd.
AMRC	Advanced Manufacturing and Research Centre
APC	Advanced Propulsion Centre
BEV	Battery electric vehicles
CAGR	Compound annual growth rate
CCC	Climate Change Committee
CFRP	Carbon fibre reinforced polymer
CPI	Centre for Process Innovation Ltd.
DfT	Department for Transport
DMA	Dynamic mechanical analysis
EC	European Commission
EPHA	European Public Health Alliance
ES	Energy storage
EU	European Union
EV	Electric vehicle
FCEV	Fuel cell electric vehicle
FRP	Fibre reinforced polymer
GEIC	Graphene Engineering Innovation Centre
HEV	Hybrid electric vehicle
HGV	Heavy-goods vehicle
ICEV	Internal combustion engine vehicle
ITO	Indium tin oxide
Li-ion	Lithium-ion
NMC	Nickel manganese cobalt oxides
NVH	Noise, vibration and harshness
OEM	Original equipment manufacturer
PHEV	Plug-in hybrid electric vehicle
TDAP	Technology Developer Accelerator Program
TMDC	Transition metal dichalcogenide
TPMS	Tyre pressure monitoring system
TRL	Technology readiness level

Introduction

The last few years have witnessed a rise in adoption of alternative fuel vehicles beyond internal combustion engine vehicles (ICEVs); these include hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs).

In 2020, a report for UK's Climate Change Committee (CCC) on the transition to electric vehicles (EVs) [1], highlights this step as one of the most important actions to achieve the UK's Net Zero target. By 2032 at the latest, the CCC has called for all new light-duty vehicles sold, including passenger vehicles, taxis, vans, motorbikes and mopeds, to be fully battery-electric vehicles. To reach Net Zero, all vehicles – including heavy-goods vehicles (HGVs) – must be fossil fuel free by 2050. For passenger vehicles and vans, this will mean accelerating the uptake of EVs from ~1% of all UK vehicles today to 23.2 million by 2032 (~55%), aiming towards 49.0 million (100%) by 2050.

This report [1] also states that to achieve these targets, UK Government and industry must implement a range of policy and market mechanisms while also addressing wider transportation emissions through reduced vehicle usage. While the steps needed to reduce wider transportation emissions are complex, the pathway to a full transition to electric passenger vehicles is clear and relatively straightforward.

Disruptive technologies such as EVs face barriers in the market because they frequently compare inferiorly to existing dominant designs like ICEVs in terms of price and product functionalities [2]. Driving range is one of the key considerations when buying an electric vehicle, but there are many other factors to take into account. The miles per kilowatt hour (kWh), price and charging time are just three examples.

Currently on the market are EVs that offer driving ranges from 137 (Honda e) - 412 miles (Tesla Model S Long Range). While driving range anxiety is a fear of many ICEV drivers, actually most EV owners do not have such issues, as the average UK journey is under 10 miles [3], meaning there is no need to charge a vehicle for up to a week in some cases.

However, according to the RAC [4], EVs are unlikely to achieve the electric range quoted by manufacturers as a number of factors will affect the actual EV range:

- **Battery age** - the average decline in energy storage is 2.3 percent per year. That means an electric vehicle with a range of 150 miles will lose 17 miles of accessible range after five years. The rate of decline slows down in later years.
- **Battery size** - Generally the larger the size of the battery (measured in kWh), the further you'll be able to travel.
- **Driving style and external factors** - driving range will reduce if you increase the speeds and if air conditioning systems are used, for example. The range falls even further if the temperature drops below freezing meaning lower driving range in winter which is exacerbated by the increased reliance on the blowers, heater and accessories like heated seats.

Although switching to EVs is seen as an environmentally friendly option over ICEVs, according to the European Public Health Alliance (EPHA), improvements to air quality due to switching to EVs does not mean that non-exhaust pollution should be ignored [5]. Particle pollution from brakes and tyres, for example, should be reduced from all vehicles as quickly as possible.

Tyre wear accounts for up to 50% of air particulate emissions from road transport, and is a significant challenge faced by EVs more so than existing ICEVs [3]. EVs have heavier weight compared to ICEVs and have to withstand high instant torque causing more wear. Tight regulation of exhaust emissions by the EU has meant that new cars emit very little particulate pollution, however tyre wear pollution is currently unregulated and can be potentially 1000 times worse, according to engineering consultants Emissions Analytics [7].

First isolated in 2004 by two researchers at the University of Manchester, graphene is hexagonal lattice of carbon atoms in a layer of a single atom thickness - referred to as a two dimensional material. Single-layer graphene has some very impressive properties over and above it's 'parent' graphite, in particular, exceptional mechanical, thermal, electrical and optical properties. Bi-layer and few-layer graphene have properties that measure in the same ranges as single-layer graphene, but as the number of layers increase, these properties tend to reduce significantly. Today, we have a whole family of graphene and related layered materials at our disposal, with wide ranging properties giving the ability to replace conventional materials, or to develop completely novel technologies, which could alleviate or solve some of the current challenges faced by EVs.

Although graphene applications for EVs are potentially vast as outlined in Fig. 1, in this report, selected case studies of graphene-based applications research, development and commercialisation in the automotive sector have been highlighted within three broad areas:

- Composites
- Energy storage and generation
- Sensors and connectivity

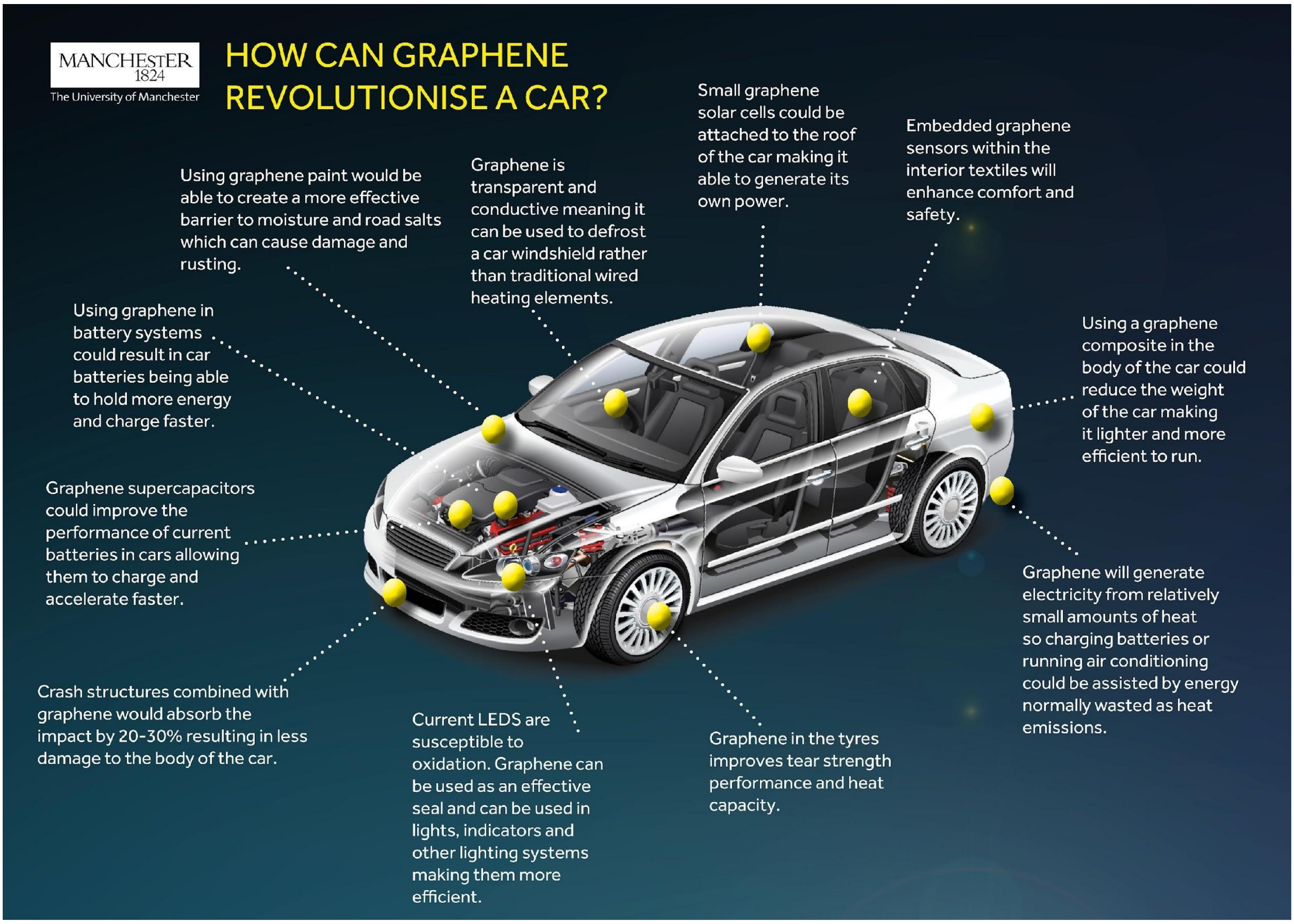


Fig. 1 Schematic showing key opportunities for graphene within automotive applications, used with permission.

Composites

Structural lightweighting

Graphene enhanced fibre reinforced polymer (FRP) composites are the solution to meet the need for innovative & multi-functional next generation lightweight materials, especially for the automotive sector. The wide gamut of possibilities of graphene & fibre/polymer combinations, and the tailorability of their properties enables it to be used in a wide range of target automotive applications.

Among FRP composites, carbon fibre reinforced polymer (CFRP) composites due to their exceptionally high strength to weight ratio, and their inherent energy absorption [8,9] properties make them a suitable contender for replacing various metal automotive components. A medium sized vehicle can achieve an average weight saving of 37% to 45% by employing CFRP composites [7], moreover, CFRP composites are already being used in several versatile automotive components for structure and non-structural applications including chassis members, cosmetic interiors, engine pieces, brake systems, seating and body panels.

With the success of the monocoque on BMW's i3 electric passenger car, more manufacturers are seeking the route of CFRP with benefits to manufacturing, customers and the environment. Upon using a CFRP monocoque, it had an overall weight saving of 250-350 kg of the overall vehicle, compared to using conventional materials [11]. Every ~45 kg weight saving results in 2-3% fuel reduction allowing the customer to benefit directly. The hybrid carbon & aluminium composite wheels launched by BMW resulted in ~7 kg of weight savings and a significant reduction in un-sprung and rotating masses [12].

Upon the addition of graphene into the polymer resin of CFRPs, the mechanical properties can be enhanced further, increasing the stiffness, interlaminar shear strength and modulus. This can allow further weight saving due to the lower amounts of material to be required to match a specific condition. An excellent example of this is the Mono R Model sports car by Briggs Automotive Company launched in 2019 incorporating graphene enhanced carbon fibre panels into every body panel, leading to weight savings and achieving acceleration from 0-60 mph in 2.5 sec [13]. In addition to the Mono R, W Motors based in UAE have launched Fenyr SuperSport, whose exterior is handcrafted with Graphene enhanced CFRP composites making them "ultra-lightweight for the ultimate performance" [14].

Versarien subsidiary 2-DTech Ltd. (2DT) has been working extensively in the area of graphene enhanced CFRP for various applications, many of which can be applied to the automotive sector. 2DT was awarded a Technology Developer Accelerator Program (TDAP) grant from the Advanced Propulsion Centre (APC) in 2020 to develop an innovative low-carbon component which will result in reduced vehicle emissions. The TDAP project has overseen the development of a low weight, high strength automotive component which can be directly applied to multiple areas of any vehicle. 2DT developed a partnership with Lotus Cars, the University of Sheffield's Advanced Manufacturing and Research Centre (AMRC) and other supply chain partners. The outcome from the project is a graphene enhanced CFRP bonnet assembly for the Lotus Evija electric sports car (Fig. 2). Graphene enhanced CFRP in the Lotus Evija Bonnet has achieved three key objectives:

1. Mechanical - improve mechanical performance by at least 10% compared to the base prepreg material (fibrous material pre-impregnated with a particular synthetic resin)

2. Visual - Surface quality to meet Lotus' paint specification

3. Price - Achieve a 10% price reduction (stretch 25%)

All three objectives were achieved using a hot press production process with lower capital costs and quicker TAKT time than autoclave. Further development will continue as 2DT and Lotus further optimise the process for use in any body panel. Versarien has several other projects ongoing that contribute to further development of enhanced CFRPs for conventional structural supports, which could provide an innovative alternative for automotive, aerospace and rail manufacturers.

Fig. 2 Photo of the Lotus Evija (top), used with permission. Graphene enhanced CFRP Lotus Evija bonnet produced as part of the TDAP program (bottom).

Tyre elastomers

The holy grail of tyre development has always been to maintain the optimal balance between rolling resistance, abrasion resistance and wet grip, the so-called "magic triangle". The practical interpretation behind these three pillars is correlated to fuel economy, service life and road handling.

Reinforcing fillers like carbon black and silica have been extensively employed as primary enhancement ingredients in rubber formulations to tailor the performance to meet the demands in the tyre industry. However, the use of carbon black has become challenging owing to its oil-dependent production and considerable greenhouse gas emission [15], whereas the application of silica is limited by the poor compatibility with non-polar rubbers and a tendency to agglomerate during processing.

Recently, graphene has been viewed as an alternative to traditional fillers, enhancing the reinforcement in the tyre with improved overall strength and dynamic mechanical performance that reduces rolling resistance whilst maintaining wet grip [16,17]. Graphene also has the advantages of enhancing the crack resistance, wearability and heat dissipation of the elastomers under repeated loading which extend the tyre lifetime [18–20].

Graphene has been used in bicycle tyres by EU manufacturer Vittoria since 2015; they also announced a new range of tyres in 2019. Their Graphene 2.0 tyres have been used by the winning teams in the Vuelta a España and the Tour de France [21]. This was shortly followed by an announcement by Goodyear to launch their own range of graphene loaded tyres called Dynamic:GSR, reporting that the rubber is able to deliver low rolling resistance, improved grip in the dry and wet, and long-term durability [22]. During an 18-month long development study conducted by Gratomic, tyres with surface engineered graphenes were tested on real roads in the UK, concluding a 30% increase in wear resistance over competing brand tyres – equivalent to an additional mileage of 30% before it was necessary to replace the tyre [23].

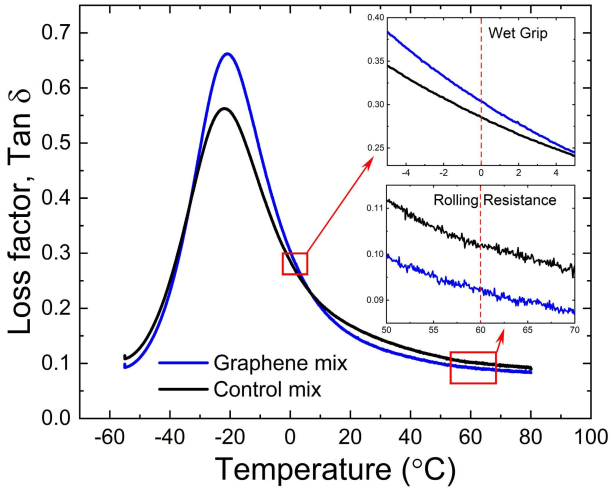


Fig. 3 Effect of Versarien's graphene on dynamic mechanical behaviors of tyre compounds.

Versarien subsidiary 2DT is currently working with ENSO tyres to explore the benefits of incorporating graphene into tyre formulations. The preliminary results show that Versarien's graphene is twice as effective as silica in reinforcing tyres while improving stretchability and tear resistance. These improvements allow a reduction of the tyre mass due to less silica being used. Additionally, there are well-established theories that the loss factor, Tan , from Dynamic Mechanical Analysis (DMA) at 60℃ and 0℃ is proportional to energy loss and can be indicative for the estimation of rolling resistance and wet grip, respectively [24,25]. Fig. 3 demonstrates that by adding Versarien's graphene, tyres will contribute to less energy consumption and enhanced road handling through a lower Tan at 60℃, and a higher value at 0℃. Overall, it is offering the development of "greener" and lightweight tyres.

"Tyres are a major global polluter, contributing enormously to carbon-emissions, air pollution, ocean micro-plastic pollution, toxicity and mountains of non-recyclable waste at their end-of-life. The fast-growing EV-market also presents an even greater challenge to our planet as EVs are heavier and have higher torque, wearing tyres faster and creating even more harmful tyre pollution".

Gunnlaugur Erlendsson, CEO ENSO

Versarien is working closely with ENSO to address this by developing better EV-tyres by making them more energy-efficient, durable and sustainable. This will allow ENSO to extend EV-range (reducing CO_2 from electricity generation) and improve tyre durability (improving air quality and reducing ocean micro-plastic pollution), while sustainably incorporating bio-based materials instead of fossil-fuel materials (further reducing CO_2 impact).

However, addressing the issue of tyre pollution requires not just making better tyres for EVs, but a fundamental shift in underlying business models and the financial incentives of the tyre industry which is at the core of ENSO's mission. ENSO is therefore looking to combine its better EV-tyres with a better 'Direct-to-Consumer' business model, a unique circular combination that has already received substantial traction with EV-carmakers and large EV-fleets.

Fig. 4 ENSO © tyre, used with permission.

Thermal management

Heat generation within automotives can cause extensive damage to various mechanical and electrical components if not correctly managed. The vast majority of heat generation is lost as wasted energy emissions contributing to lower efficiencies and an increased carbon footprint. Lithium-ion batteries suffer greatly from self-heating, reducing life span and reliability of the battery. Developments to assist in increasing heat transfer methods allowing cooling of battery components have seen a resurgence of interest with the incorporation of graphene materials.

Trials have shown graphene integrated heat sinks can assist cooling technology and produce a lower, more even distribution of heat throughout the battery cells, resulting in a more efficient lightweight method of cooling [26]. Not only does this method increase the efficiency of cooling but it also increases the efficiency of the battery. The heat generated from the battery and other sources can also be used to effectively heat other aspects of the car, such as the interior cabin, and more importantly for EVs, heating areas which are susceptible to low temperature environments.

Hyundai and Kia are currently innovating in this area of technology [27]. The Hyundai Kona EV drops only 10% of the battery life in winter driving conditions as compared to the 2020 Tesla Model 3 which in their test saw a drop in driving range of 40% due to higher battery consumption. Recently, Tesla's Model Y has integrated a heat pump system moving heat, rather than generating it, around the EV components and interior cabin. This in turn increases the driving range which would otherwise be reduced by the external environmental temperatures [28]. Graphene, when applied to this thermal management method could provide a more efficient boost to performance over conventional materials.

Additionally, researchers at the University of Manchester have found a way in which graphene could convert 3-5% of a car engine's heat into electricity. The composite material, consisting of graphene and strontium titanium oxide, has the ability to produce electric current over a wide range of temperatures, down to room temperature. Thermoelectric technology using graphene could provide a significant benefit to the next generations of hybrid vehicles [29].

Noise, vibration and harshness (NVH)

Noise pollution from vehicles, whether from ICEVs or EVs, is a major source of environmental concern in all major cities. These noise pollutants can induce adverse psychological health effects on human health. With an ever increasing number of vehicles on roads globally, there are calls for a new generation of noise, vibration and harshness (NVH) dampeners that can combat the interior and exterior noises generated while driving. Vehicle NVH can create a vital customer

perception of product quality with physical and acoustic comfort being a significant driver to manufacture components to meet this demand. There is a growing trend to re-visualise NVH products for electric and hydrogen fueled vehicles.

The primary sources of vehicular NVH include the engine, gearbox, the differentials and structural vibrating modes of exhaust systems; the secondary sources of NVH include brakes, electrical and mechanical accessories [30]. Many of these factors can be addressed with the application of graphene enhanced NVH insulating materials. Specifically, graphene enhanced polymers have been shown as an excellent acoustic absorbing material which can absorb over a large frequency range. Graphene has the unique ability to absorb frequencies ranging from 60 Hz to 6300Hz [31]. Predominantly, interior automotive noise lies in the acoustic range of 100 to 600Hz, however this can extend to frequencies up to 4000Hz [32], which makes graphene an ideal candidate to cover all acoustic ranges for automotive applications.

A wide range of graphene foam structures are in development showing improved acoustic absorption including polyurethane and melamine containing graphene [33,34]. Specifically, melamine foams containing graphene have shown to absorb around 60% more noise at frequencies between the range 128 Hz and 4000 Hz compared to commercially available melamine foams [2]. Foam structures are excellent NVH inhibitors due to the porous structure allowing air gaps for energy absorption. The lamella structure in which NVH energy is absorbed results in increased reflections between the graphene sheets offering the potential for enhanced absorption properties, thus reducing reverberation between connecting structures. A recent example of graphene enhanced foams has been commercialised by Ford Motor Company, who have already developed several engine components including pump and engine covers containing graphene enhanced polyurethane foams, improving NVH by 17%. There are now more than 12 foam components used throughout the car across several vehicle lines, including the F-150 and Mustang. Ford plans on expanding on their use of graphene enhanced foams into more vehicles in the future [35,36].

Energy storage and generation systems

EVs have opened up a large number of opportunities for energy storage (ES) technologies, with new and exciting challenges and requirements. Among the various ES devices, batteries and supercapacitors represent the two leading electrochemical energy storage technologies as illustrated in a graph of energy density in Wh/kg vs power density in W/kg known as a **Ragone plot** (Fig. 5). The current internal combustion engine provides both high energy density (~1000 Wh/kg) and power density (~10^6 W/kg), whereas current lithium ion (Li-ion) batteries provide significantly less energy (~180 Wh/kg) and power (~1000 times less) densities, therefore, the battery weight is typically significant. The battery of the Tesla Model S, for example, weighs 544 kg ~24% of the car's total mass (2241 kg) [37].

Obviously there is a great opportunity to be found in the development of ES systems with faster charging, greater energy density and lightweighting being key automotive trends. As the move towards electrification accelerates, ES packs are needed in ever greater numbers to supply not just cars, but a wide range of other vehicles too. The current standard in this new EV era is still the Li-ion battery. Already a mature technology, it still has room for improvement and with a large and growing market among applications, its development will continue for quite some time.

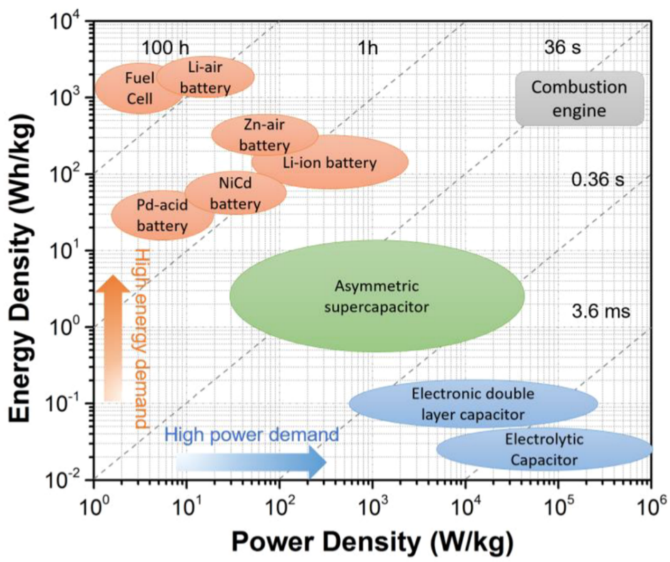


Fig. 5 Ragone plot illustrating the performances of specific power vs specific energy for different electrical energy-storage technologies. Times shown in the plot are the discharge time, obtained by dividing the energy density by the power density. Reprinted with permission from ref. [38]. Copyright © 2018, American Chemical Society.

Lithium-ion batteries

Most Li-ion batteries use a negative electrode (anode) principally made from carbon in the form of graphite and a positive electrode (cathode). The electrolyte used in Li-ion batteries varies based on the choice of electrode materials,

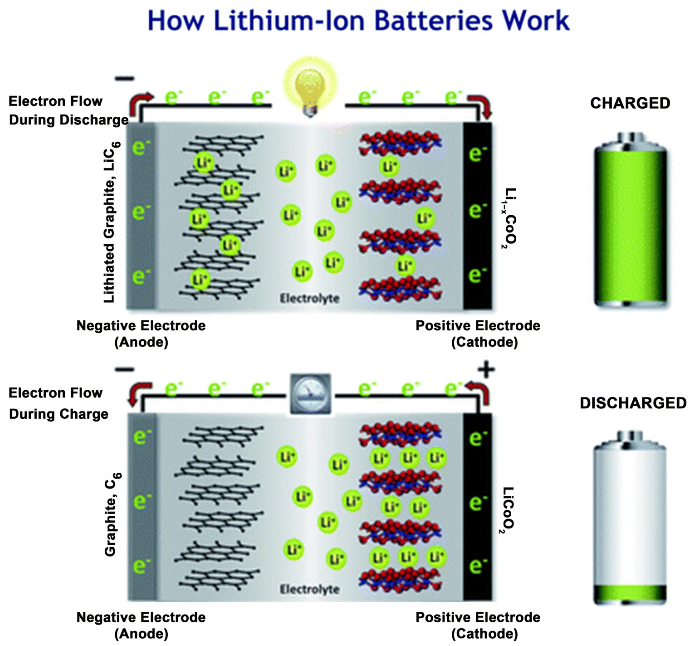


Fig. 6 A schematic illustration of the working principle of li-ion batteries based on the $Li_xC_6/Li_{1-x}CoO_2$ cathode. During the discharging process, lithium ions are released from a lithiated graphite (Li_xC_6) anode to a delithiated $Li_{1-x}CoO_2$ cathode. During the charging process, the reaction is reversed. Reproduced from ref. [39]. https://creativecommons.org/licenses/by/4.0/

but is typically composed of a mixture of lithium salts (e.g. $LiPF_6$) and an organic solvent (e.g. diethyl carbonate) to allow for ion transfer. A separating membrane is used to allow lithium ions to pass between the electrodes while preventing an internal short circuit. Li-ion batteries involve insertion reactions from both electrodes where lithium ions act as the charge carrier, shown in Fig. 6. There are several different cell chemistries that make up the Li-ion battery family.

Graphene can play a key role in the improvement of Li-ion battery performance at various different levels. Li-ion battery manufacturers were initially quite reluctant to introduce potentially disruptive innovations, but customer demands for ever greater range, faster charging and extended pack life are leading to a greater willingness on the part of OEMs to embrace innovation. Some companies such as California Lithium Battery Inc. are pushing to commercialize graphene as a replacement for graphite in the anodes of Li-ion batteries [40]. Versarien subsidiary, Gnanomat (Spain), are developing silicon-graphene and tin-graphene anode constructions (as a substitute for graphite) which offers great opportunities to improve battery capacity, electrical conductivity and power output. Another area in which graphene can improve Li-ion battery performance is in thermal dissipation/management taking advantage of the high thermal conductivity of graphene as described previously.

Generally, cathodes are mixed metal oxides - intercalation compounds from which Li^+ ions can diffuse into or out of. Well known examples of materials used include lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), lithium nickel manganese cobalt oxides (NMC) and lithium manganese oxide ($LiMn_2O_4$). First developed by Sony in 1991, the $LiCoO_2$ battery has been the battery of choice for most personal electronics (laptops, cameras, tablets, etc.) due to their high energy density, long life cycle and ease of manufacturing. However, they suffer from poor thermal stability and must be monitored during operation to ensure safe use. The limited availability of cobalt also makes it more expensive and difficult to be a viable option for use in EVs. Recent developments from UK based companies Nyobolt and Echion Technologies on niobium-based anodes provides an opportunity for ultrafast charging [41].

Metal-air batteries

Metal-air batteries are ES devices that have excellent energy density properties and are much lighter in comparison to Li-ion batteries. Another major advantage is that the components are not only environmentally friendly but fully recyclable at the end of life [42]. The perceived implementation strategy of post Li-ion battery technology is to work alongside other ES systems when power and energy requirements make metal-air batteries more appropriate to the application at hand. Tesla has some patents in this area of technology claiming the combination of a metal-air battery pack and a Li-ion battery pack that can result in a higher driving range. Several other companies such as Phinergy, MAL Research and Development Ltd., and Log9 Materials are also developing metal-air batteries in order to bring this technology to the automotive sector.

Nanotechnology is ideally placed to contribute to the development of metal-air batteries by the introduction of graphene in different components. Catalysts of metal-air batteries could be optimized by taking advantage of the high specific surface area of graphene and the possibility to introduce functional groups or catalytic nanoparticles which, in turn, can improve this critical component of the device. Where porous foams were used as cathodes in metal-air batteries, the application of graphene produced a round-trip efficiency of up to 80% with a stable discharge voltage at 2.8 V and a stable charge voltage below 3.8 V for 20 cycles [43]. Other graphene related materials such as the family of transition metal dichalcogenides (TMDCs) have been observed to exhibit very high electrocatalytic activity for use in lithium-air batteries [44].

Sodium-ion batteries

Sodium is one of the most abundant and affordable metals in the world that could reduce the cost of batteries. However, a significant challenge faced is that sodium ions are larger than lithium ions and have complex interactions with graphite leading to poor (de-)intercalation. Recently, researchers at Chalmers University of Technology, Sweden, presented a concept [45] that allows sodium-ion batteries to match the capacity of today's lithium-ion batteries. Using a novel type of graphene, they stacked specially designed graphene sheets with molecules in between the layers as shown in Fig. 7. The new material allows the sodium ions (in green) to efficiently store energy.

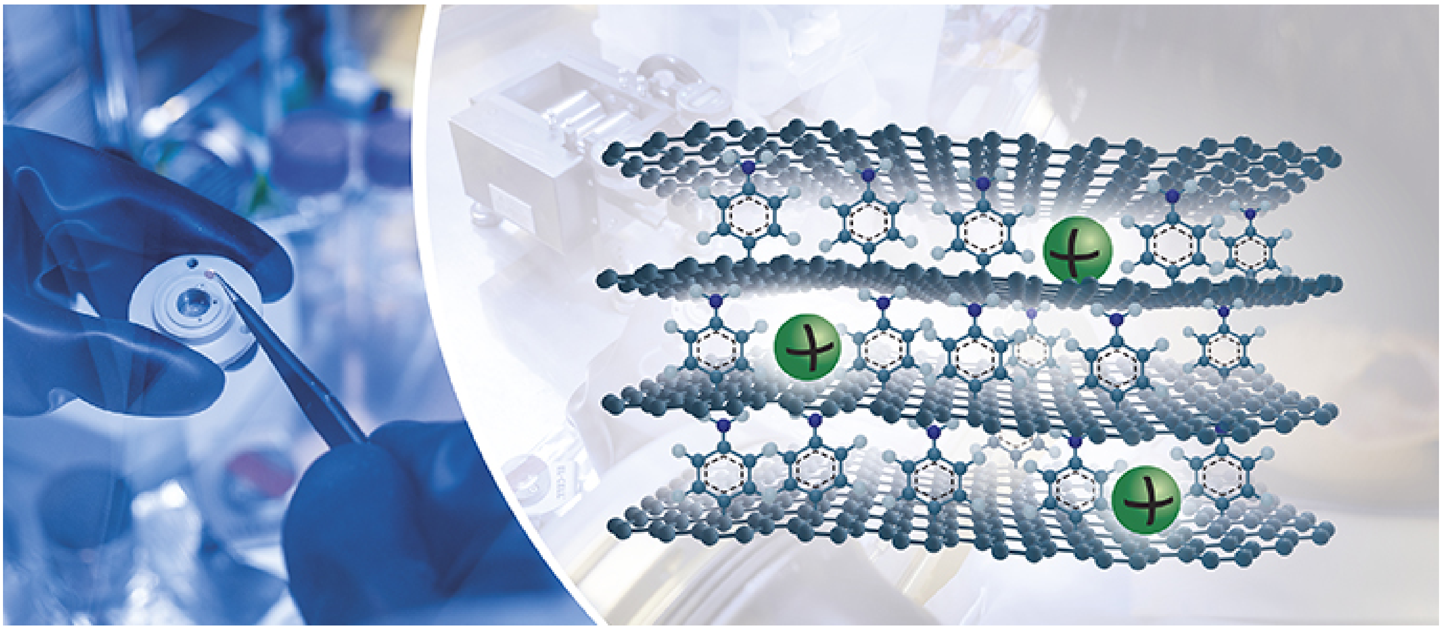


Fig. 7 Sodium ion intercalation into graphene-based materials. Image from Marcus Folino and Yen Strandqvist, Chalmers University of Technology.

Supercapacitors

Supercapacitors, or ultracapacitors, are ES devices that maintain excellent power input and output over 100,000 charge-discharge cycles but at the expense of lower energy density compared to traditional batteries. Batteries have higher energy density but with lower power input and output they degrade faster than capacitors especially when operating at the boundaries of their performance envelope. The differential and complementary performance profile of supercapacitors in contrast to batteries can yield great performance improvements when both ES devices are used in conjunction: for vehicle functions that demand more energy, the power pack can utilize batteries, and for other tasks (start-up, electric windows, regenerative braking, acceleration, etc.) can take advantage of the greater power input/output capacity provided by supercapacitors.

The implementation of supercapacitors in the automotive sector is already a reality and some companies like Toyota, use supercapacitors to assist in powering hybrid vehicles such as the Toyota Prius C, where supercapacitors can supply spurts of power for functions such as electric window operation and heating [46]. In 2012, Berlin-based company, Bombardier Transportation, produced the Mitra supercapacitor system that is used in Mannheim trams, leading to endless possibilities of use in other electric transportation systems. In 2019, Maxwell, a world leader in the area of supercapacitors, was acquired by Tesla as part of its corporate strategy [47], reinforcing the promising future of supercapacitors.

Previously, Volvo had announced that it was working on development of carbon nano-technology enhanced body panels that also double-up as supercapacitors for the storage of electrical energy [48]. This feature is likely to be of particular use in PHEVs which require only modest size batteries but struggle to fit a combustion engine, fuel tank, battery pack and electric drivetrain into the vehicle. More recently this idea has been taken forward by BMW and also Lamborghini who are currently working with the Massachusetts Institute of Technology (MIT) [49].

Graphene's high specific surface area (2670 m^2/g) and enhanced electron conductivity (10 times more conductive than graphite), low density, flexibility, and ease of chemical processability makes it an ideal material for supercapacitor electrodes [50,51]. A San Francisco based company has recently launched high-powered "Powercell" ultracapacitors capable of massive power output and 10-minute charging, containing a combination of graphene and aluminium. Although this battery will be more expensive than Li-ion batteries, it will be capable of a much higher number of running cycles [52].

Gnanomat have also developed new supercapacitor ES devices exploiting advanced graphene nanomaterials in the electrodes. These devices provide outstanding performance that will, in turn, facilitate the penetration of graphene into the sector. In tests, industrial prototypes including Gnanomat's hybrid graphene/metal oxide nanoparticle composites exhibit remarkable improvements in energy storage capacity, in excess of 300% more when compared to market standard devices. Examples of these devices are shown in Fig. 8. Versarien is, therefore, well placed to optimize and address industrial opportunities in the supercapacitor field.

Versarien are currently working with key partners Westfield Sports Cars, the Centre for Process Innovation Ltd (CPI) and others have recently been awarded grant funding from the UK Department for transport (DfT) for the development of asymmetric pseudocapacitor technology and include it in a pack to be used as a technology demonstrator for zero emission port side vehicles.

Supercapacitor technology is of particular interest to the marine and aviation industry as unlike Li-ion batteries, there is very little risk of fire, something that has acted as a brake on the adoption of EV technology in the sector until now. It is also of interest to the sports car industry where the high power density can be utilised for acceleration and braking events, extending range and extending the life of the battery pack by reducing the load profile.

The SUPPORTIVE project will conclude in 2022 and then it is hoped to move into full scale production.

Fig. 8 Pouch cell sized supercapacitors developed boosted with Gnanomat's graphene/metal oxide nanoparticle composites.

Fuel cells and hydrogen storage

Fuel cells are an ES alternative with many interesting properties when applied to EVs. Fuel cells can use a range of different fuels but the most commonly used fuel is hydrogen. Hydrogen is an extremely energy dense fuel (120–140 MJ/kg), far higher than petrol (46.4 MJ/kg) [53]. The refuelling time of an EV with compressed hydrogen is much faster than charging a battery. The only emissions from hydrogen fuel cells are water vapour. As such this technology can be considered a clean and sustainable energy source when so-called "green hydrogen" is used (hydrogen produced using renewable energy). Due to the lower power density of fuel cells they are typically used in combination with other ES systems, most commonly Li-ion batteries.

In 2013, Hyundai launched the Tucson model, the first FCEV. In 2015, Toyota commenced with the commercialization of the Mirai, followed by Honda with the Clarity in 2016. The Clarity FCEV offered a seating capacity of five persons, two hydrogen storage tanks and hydrogen compression pressure of 70 MPa [54]. While it has not become a dominant technology, the adoption level is still low, market researchers are predicting the market to grow at a Compound Annual Growth Rate (CAGR) of 11.23% [55]. In order to convert hydrogen into electricity, fuel cells require a catalyst. Typically the catalyst is made of platinum nanoparticles supported on an amorphous carbon framework. However this arrangement is not only expensive, it's also fragile and this is hindering the advancement of fuel cells. Researchers have found in accelerated life tests that by replacing the carbon with graphene the life of the cell can be extended by 30% [55].

By far the biggest factor slowing down hydrogen fuel cell roll out is a lack of the infrastructure required to make, distribute, store and dispense hydrogen safely. Hydrogen is a very small molecule and is very light; in order to store enough hydrogen to be useful it must be stored under very high pressure. In addition, hydrogen is very reactive and can attack steel containment vessels and pipes making them brittle.

Graphene can help with the storage of hydrogen in a number of ways. As described previously, when added to CFRP composites, graphene can greatly increase their strength meaning that new tanks could store hydrogen at far higher pressures more safely. Further, the morphology and high aspect ratio of graphene could help reduce leakage rates from storage tanks. Additionally, when incorporated into surface coatings it can protect steel from degradation.

By functionalising graphene with metals it may also be possible to store hydrogen within the atomic structure of graphene itself releasing it only when it is required. So-called “solid state” storage systems are still at a low technology readiness level (TRL) but there are great hopes for storing hydrogen safely and effectively in the near future [56].

Solar cells

The use of solar cells in vehicles, especially EVs is a technology being explored by several car manufactures. The German EV start-up Sono is currently taking pre-orders for it’s Sion model which incorporates solar cells into the bodywork of the car. Sono are claiming that the integration of solar cell technology can add up to 5800 km of electric range per year [57]. Hyundai is also investigating the advantages of solar energy, and has announced its luxury brand car: Lightyear One model car, that incorporates solar panels on the roof of the car, and is set to go on sale in summer 2022 [58].

By replacing the mesh wires on top of the cell with transparent highly conductive graphene, cell output can be maximised for any given surface area. Currently, transparent solar cells use indium tin oxide (ITO) as a charge carrier but not only is this very expensive it is also very brittle and can easily be damaged. Unlike rigid domestic roof-mounted solar, automotive cells require a certain amount of flexibility to follow the curves of the vehicle's body accompanied by tolerance to vibration and moderate levels of damage. Tough, transparent and flexible graphene is therefore an ideal contender to replace ITO in automotive applications.

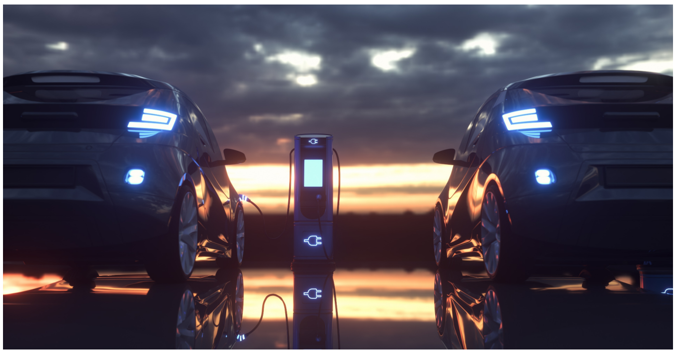
In lab tests graphene-based perovskite solar cells have already exceeded 20.3% efficiency [59]. Predicted outputs for perovskite cell technology exceed that of traditional silicon cells; by adjusting the band gap within cells and stacking them one on top of the other it is theoretically possible to exceed the Shockley–Queisser limit (the maximum theoretical efficiency limit of a single junction solar cell) and head toward 40% efficiency [60]. All of this could be done with cells utilizing graphene that are flexible, simpler, less expensive to make, and have a considerably smaller environmental footprint than existing silicon technology [58].

One drawback of solar cells is that they don’t work very well in bad weather, however, graphene offers a possible solution. Researchers in China have developed a graphene coated solar cell that takes advantage of electrochemical interactions with rain. In lab tests these cells have so far yielded efficiencies of 6.5% [61].

On the whole, graphene-based solar cells could potentially solve problems with the currently available solar cells and enable more efficient usage of solar energy which is one of the cleanest sources of renewable energy.

Grid storage for EV charging

In Braintree, Essex, UK Gridserve has built the world's first dedicated EV charging forecourt [62]. With some modern EVs now able to charge at very high rates, it is essential to position charging infrastructure close to high power grid connections in order to maximise the customer charging experience. However at peak times even this isn't enough so companies like Gridserve are using large battery banks to supplement the grid connection. Already discussed previously, ES systems with higher energy density, able to charge and discharge faster and higher cycle capability [63] would be welcomed. Graphene based ES technologies could also be used to balance the local grid and this will speed the transition to the future, where renewable energy plays a larger part in powering our homes and businesses as well as increasing the financial viability of such charging stations [64].



Sensors and connectivity

The eventual goal of autonomous driving systems is to reach 'Stage 5' autonomy where there would never be any need for the driver to intervene and take control, with a possibility that some vehicles might not even be fitted with driver controls. Great leaps forward in electronics and software have taken place over the last few years and most high end vehicles now have some form of advanced driver assistance. One thing that is becoming increasingly obvious though is that any system is only as good as its sensors. How an autonomous driving system sees the world is key to its ability to function.

Currently, self-driving cars use visible cameras, but in dense fog, these cameras are still insufficient. The Autovision Spearhead Project [65], part of the European Graphene Flagship, is developing a new high-resolution image sensor for autonomous vehicles, which can detect obstacles and road curvature even in extreme and difficult driving conditions.

Current tyre pressure monitoring systems (TPMS) are limited in the bandwidth they can transmit (typically 1 message every 60 seconds). A new type of printed graphene tyre monitoring system has been proposed [66] that can not only monitor and transmit pressure data in real time but can also measure stress within the tyre and be self-powered.

Precision Varionic International Ltd., UK, with funding from European Commission in 2017, developed graphene based potentiometers (GrapheneSens) [67,68], using screen-printable graphene inks (with conductivity between 100 to 1000 ohm/sq) for thermally curable resistive tracks. These graphene coatings enabled track lifetimes of greater than 10 million cycles using only a single track layer, and with enhanced conductivity of the graphene, the resistive track layer thickness could be reduced below 30 µm (without compromising wear performance) enabling cost effective use of the graphene. The graphene also helped reduce noise leading to greater sensor accuracy and reliability.

Another application where graphene could revolutionise automotive sensors, is magnetic field sensors which are essential for contactless measurement of angle of rotation and angular speed of the car. These sensors need to be highly precise with good usability. A graphene based Hall effect sensor was developed by Paragraf in 2017, which has proven to have excellent properties over other conventional materials such as silicon, gallium arsenide, and indium antimonide due to its high carrier mobility [69].

With the potential of graphene to be used in a range of automotive sensors yielding higher precision data, a whole new exciting future of graphene sensors in automotives awaits, and with autonomous vehicles becoming the future of vehicles, there will be an ever increase use and innovation of graphene based sensors.

Summary and future outlook

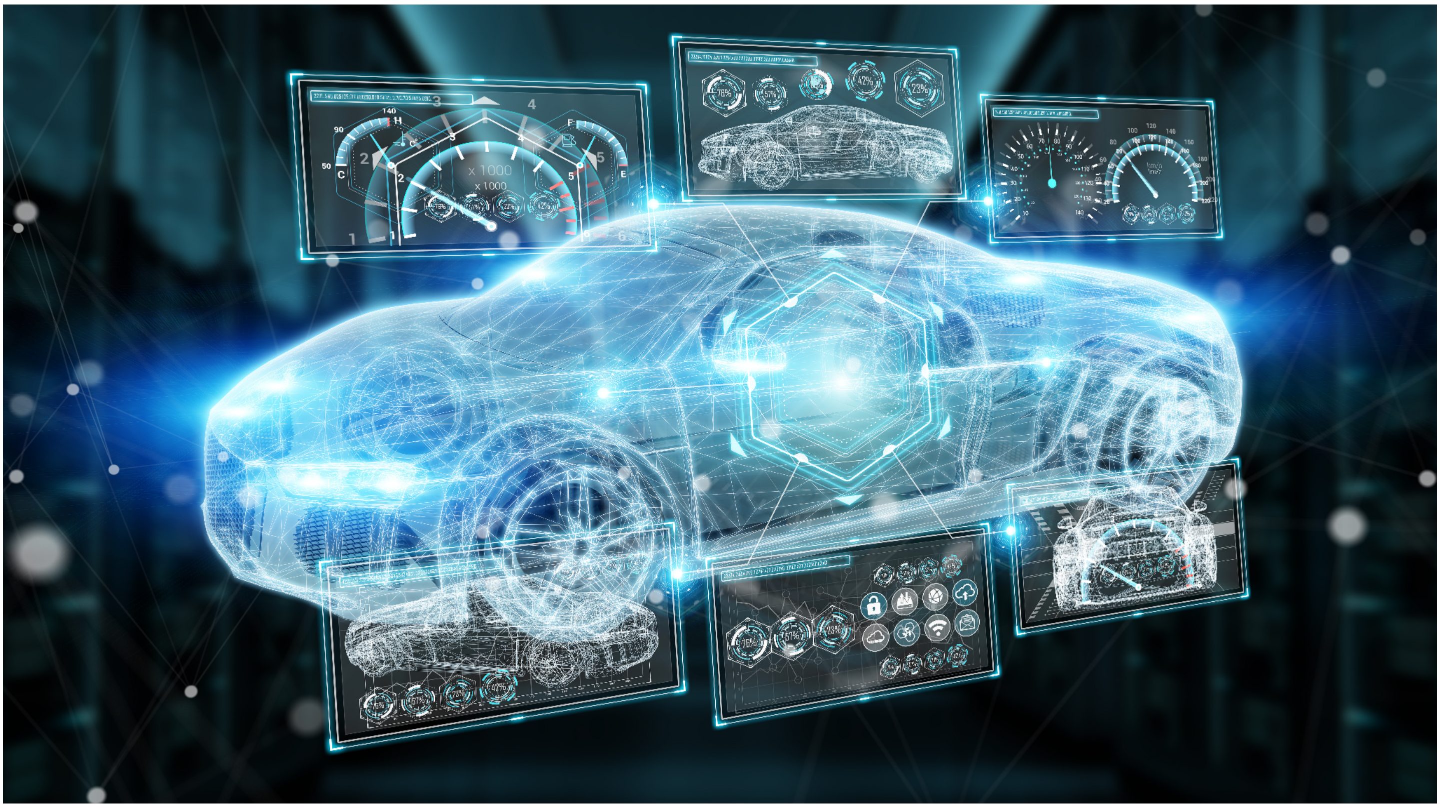
This report has highlighted a number of key case studies where graphene is enabling the improvement of components for the automotive sector, with multinational companies such as Ford being early adopters of graphene. Graphene enhanced composites for structural lightweighting, tyres and NVH applications are at the forefront and leading the way, with several avenues being explored in energy storage and sensor technologies.

Graphene will no doubt play a pivotal role in the next-generation of vehicles, underpinned by significant funding from the UK government and the European Commission. Across Europe, the €1 bn EC funded Graphene Flagship project views automotive as a key sector for graphene and related materials applications. Three out of its eleven Spearhead projects have focused on automotive applications. Competition from other regions will increase, in particular from China who is witnessing the fast development of its automotive industry, and already the world's second largest passenger EV market after the EU.

The UK has a long history of automotive production and now with the world’s most highly regarded centers of excellence for graphene research (National Graphene Institute, Cambridge Graphene Centre) and the ability to accelerate development through the Graphene Engineering Innovation Centre (GEIC), there is a serious case to be put forward for UK-centred projects to build on these strong foundations.

The Nissan LEAF, the world's first serious affordable mass produced EV has long been made in Sunderland and battery manufacturing company British Volt is now in the planning stage to build the UK’s first battery gigafactory close by at Tynemouth. These and other developments will keep the UK at the forefront of the automotive industry as it has been since Herbert Austin founded the Austin Motor Company in 1905.

With all these aforementioned advantages that graphene can bring, improvements to the automotive sector could be vast and the companies incorporating graphene enhanced components to the next generation of electric vehicles could allow manufacturers to obtain a significant edge over their competition.



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