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Published in:
Renewable and Sustainable Energy Reviews

DOI:
10.1016/j.rser.2022.113074

Publication date:
2023

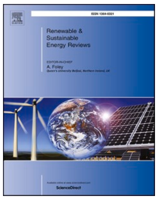
Citation for published version (APA):
Zhou, W., Cleaver, C. J., Dunant, C., Allwood, J. M., & Lin, J. (2023). Cost, range anxiety and future electricity supply: A review of how today's technology trends may influence the future uptake of BEVs. *Renewable and Sustainable Energy Reviews*, *173*. https://doi.org/10.1016/j.rser.2022.113074

Renewable and Sustainable Energy Reviews 173 (2023) 113074

Contents lists available at ScienceDirect

Renewable and Sustainable Energy Reviews

journal homepage: www.elsevier.com/locate/rser



Cost, range anxiety and future electricity supply: A review of how today's technology trends may influence the future uptake of BEVs

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ARTICLE INFO

Keywords:
Battery electric vehicles
Cost
Travel range
Lightweight design
Electricity supply
Breakthroughs

ABSTRACT

In this review paper, we show that the current battery electric vehicle (BEV) scale-up relies on several key technologies which all have detailed roadmaps with good track records for being met. These roadmaps include lightweighting of vehicle bodies using lightweight materials and architecture/structure design, and improvements in BEV powertrain with regard to the powertrain architecture/system design, battery and motor technology development. However, as technology take-up accelerates, our novel analysis suggests supply of zero carbon electricity may become a serious constraint. We find that the technical potential for abating the demand for electricity through powertrain and lightweighting improvements is just over a quarter of the projected total. Four promising avenues to mitigating this constraint – battery reusing and interoperable charging technology, shared mobility, advanced sensing technology, and novel compact space frame construction - are explored in brief, potentially enabling the large-scale deployment of BEVs without exhausting the supply of non-emitting electricity.

1. Introduction

The transportation sector is responsible for emissions of both greenhouse gases and air pollutants such as carbon monoxide, unburned hydrocarbons, and particulate matter. Although atmospheric CO_2 is necessary for vegetation [1,2], global warming is driven by increasing anthropogenic emissions. The transportation sector emitted 8.43 $GtCO_2e$ of greenhouse gas (GHG) emissions in 2019, contributing to 24% of global CO_2 emissions, and road transportation accounts for nearly 75% of that [3–5]. Emissions from transport fell in 2020 only due to the COVID-19 pandemic, but rebounded sharply in 2021 after ease of lockdowns [5,6]. Decarbonising this sector is necessary to limit global warming to 1.5 °C above pre-industrial levels in this century [7,8]; this is both challenge and opportunity [9–11]. On April 17, 2019, the EU Parliament adopted Regulation 2019/631 setting new standards for CO_2 emissions of new passenger cars and vans, from January 1, 2020. The average CO_2 emissions for cars need to be cut by 15% in 2025 and 37.5% in 2030 compared to 2021 levels [12]. Beyond Europe, other government policies for reducing CO_2 emissions in the transportation sector have also been made worldwide [13–18].

A promising choice for achieving decarbonisation and cutting air pollutants is electrification of mobility, especially when the generation of electricity produces low or zero CO_2 emissions [19–22]. EVs are mainly of three types: all/full-electric vehicles (AEVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs). AEVs include battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs) [23–25]. A BEV is totally powered by batteries and has the highest well-to-wheel efficiency of ~70% (14–19% for internal combustion engine (ICE) vehicles) [11,26]. An FCEV uses a fuel cell instead of batteries and has a relatively low well-to-wheel efficiency of

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Abbreviations: AEVs, All-electric vehicles; APC, Advanced process control; BEVs, Battery electric vehicles; BIW, Body-in-white; CAFE, Corporate Average Fuel Economy; CFRP, Carbon fibre reinforced plastic; CMF, Common Module Family; FCEVs, Fuel cell electric vehicles; GHG, greenhouse gas; HEVs, Hybrid electric vehicles; HRE, Heavy-rare-earth; ICE, Internal combustion engine; IIOT, Industrial internet of things; IWM, In-wheel motor; LCA, Life cycle assessment; MDO, Multi-Domain Optimisation; NVH, Noise vibration and harness; OEM, Original Equipment Manufacturer; PHEVs, Plug-in hybrid electric vehicles; PM, Permanent magnet; SR, Switched reluctance; TCO, Total cost of ownership; V2G, Vehicle-to-grid; V2X, Vehicle-to-everything; W-IWM, Wireless in-wheel motor.

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https://doi.org/10.1016/j.rser.2022.113074
Received 21 June 2022; Received in revised form 23 September 2022; Accepted 19 November 2022

~25–30% [11,27,28]. HEVs and PHEVs are not completely fossil fuel (oil)-free vehicles: they have two power sources combining an electric propulsion system with an internal combustion engine system. PHEVs are vehicles with batteries charged from an external source. HEVs are vehicles with batteries charged from the internal combustion engine but not a plug. BEVs are regarded as the most advantageous in terms of achieving long-term socioeconomic and environmental benefits, due to their total independence on oil and zero tailpipe emissions [29,30], and this paper focuses on them. This is despite some drawbacks mostly due to the raw materials needed [31–35].

BEV are only marginally present on the roads today. So far, many governments have announced that they plan to ban the selling of conventional ICE vehicles by 2030 or 2040, creating an environment that stimulates adoption of EVs [36,37]. Nevertheless, BEVs still face challenges for immediate large scale deployment: a higher purchase price, limited travel range and insufficient refuelling (recharging) infrastructure [29,38–40]. Their high upfront cost remains a major barrier for market penetration, although their operating cost is low. The range of BEVs is generally lower compared with their ICE equivalents, which leads to ‘anxiety’ of consumers and can be exacerbated due to the lack of sufficient refuelling (recharging) infrastructure [39]. Also, there are some after-market concerns such as difficulty and high cost for replacement of matched batteries, and the safety of batteries [41–43]. However, the benefits of EVs in terms of total cost of ownership (TCO) might be consistently underestimated using the manufacturer-reported data in standard driving cycles, and TCO of EVs could be lower than ICE equivalents when using real driving cycles [44]. In addition, EV travel range is being continuously improved due to the gradual development of battery technology and the increasing supply of charging infrastructure. The dominant assumption is that current barriers to BEV uptake will be overcome by a series of incremental advances that have low uncertainty level compared to other propulsion technologies [11].

In the last decade, a lot of review articles have emerged in the literature which reviewed the development of BEVs from different perspectives. Some reviewed BEV technology development: Andwari et al. [39] reviewed the BEV technology and readiness levels. They highlighted those technological areas where important progress is expected and concluded that BEVs have to be more competitive than other low carbon vehicles. Un-Noor et al. [45] reviewed different EV configurations, technologies and impacts. They provided an overall picture of all types of EVs by collecting large amounts of useful data and concluded that more research into efficient algorithms of charging and energy management are needed. Yong et al. [46] reviewed the battery technology development in BEVs, with a focus on strategies of charging management. They concluded that Bi-directional chargers and complete EV charging network need further development. Cuma et al. [47] presented a review on various estimation strategies for vehicle control, energy management and battery management of BEVs, concluding that “estimation” is an expanding research area supporting the development of EVs market. Sun et al. [29] reviewed emerging technologies and challenges for the improvement of safety, reliability and efficiency of BEVs. They concluded that the coordination of emerging technologies such as artificial intelligence and vehicle-to-everything (V2X) enhance traffic safety and efficiency, offering real-time communication between vehicles and other smart devices. Judging from the above review, further analysis regarding the challenges during the development of BEV lightweighting technology and powertrain technology, especially on production of electricity is still needed.

Some work reviewed the potential issues and opportunities brought about by the integration of EVs into the smart grid: Mwasilu et al. [48] reviewed the strategy for integrating the EVs into the electric grid back in 2013, showing that integration of EVs into smart grid would reply on advanced metering, management, and communication technologies. Habib et al. [49] reviewed the impact of EVs with a vehicle-to-grid (V2G) system on power distribution networks, showing that vehicle aggregation and charging strategies significantly affect the economic benefit of V2G technology. Yilmaz [50] reviewed the requirements, benefits, challenges, and strategies for V2G interfaces of both individual PEVs and vehicle fleets. Tan et al. [51] reviewed the framework, benefits, challenges and main optimisation algorithms of V2G technologies in both the unidirectional and bidirectional charging, concluding that bidirectional charging is essential for future V2G deployment. Alsharif et al. [52] reviewed the energy management strategy in V2G with the up-to-date standards of charging topology and power conditional units, concluding that the rule-based approach is more frequently used compared with optimisation-based approach due to its ease for handling the constraints and fast decision-making. Those studies mainly deal with technical aspects of V2G, focusing on facilitating load balancing or minimising electricity costs. The role of consumer acceptance, driver behaviour and business opportunities within such V2G systems have also been reviewed [53]. Hannan et al. [54] reviewed the V2G control scheme, charging strategies and social barriers, concluding that a thorough economic justification has yet to be given to smart chargers, and EV charging network needs to be carefully planned to improve consumer acceptance. Sovacool et al. [55] reviewed the business models, markets and policies associated with V2G using innovation activity systems, concluding that 12 priority areas for energy and transport policy can be identified.

Besides the technical factors affecting adoption of BEVs, others reviewed the psychological, economic, and behavioural factors from the perspective of government incentives and socio-economy: Coffman et al. [56] reviewed the internal (battery performance and price) and external (fuel prices and charging stations) factors affecting EV uptake by the public, they showed that further studies disentangling the types, optimal timing, and magnitude of government incentives are needed. Liao et al. [57] reviewed economic and psychological approach for consumer preferences of EVs based on a conceptual framework and discussed a research agenda for improving EV consumer preference studies. They concluded that tax reduction is quite likely effective, whereas toll reduction and free parking still need supporting evidence. Sierzchula et al. [58] reviewed the factors influencing the adoption of EVs, concluding that charging infrastructure and financial incentives were statistically significant factors, while socio-demographic variables (education level and income) were insignificant. Mersky et al. [59] reviewed the influential factors for the adoption of EVs in Norway, and concluded that economic considerations had a greater effect on vehicles with a short range. Rezvani et al. [60] reviewed the drivers and barriers for consumer adoption of EVs, utilising theoretical perspectives for understanding consumer intentions and adoption behaviour towards EVs. An area that needs further research is consumer emotions which can be explored with theoretical frameworks of emotions in psychology, ethics and consumer behaviour.

A factor overlooked by many studies is the effect of BEV uptake on future electricity demand. For BEVs to achieve decarbonisation their increased demand for electricity must of course be accompanied by an increase in the production of zero-carbon electricity. In the past 10 years, this has expanded at a rate of almost 350 TWh/year globally. In the UK there are credible roadmaps to 2050 for an approximately 13 TWh annual increase in zero carbon electricity, nonetheless the scale of the demand induced by the switch to electrification may be underappreciated [16]. Cullen and Craglio modelled future transport emissions and demand for electricity by BEVs in the UK, concluding that making the switch as early as possible is best from an emissions perspective [61].

Therefore, the objective of this paper is to review current technology advances and trends of BEVs, analyse the strategies for cost and range improvement, and identify the challenges for a complete transition to BEVs. Toward this goal, current technological roadmaps for BEV development is reviewed with regard to its major subsystems (Sections 2-3), focusing on key technologies of BEVs for cost and weight reduction. It then provides novel analysis (Section 4) on how far these planned improvements will overcome cost and range barriers and, using the

United Kingdom as a reference, model their potential impact on zero-carbon electricity. Finally an outlook is provided (Section 5) on further breakthroughs in BEV technology and patterns of use that could potentially mitigate any of these constraints, and some key policy recommendations are discussed.

2. Technology trends: lightweighting for vehicle bodies

2.1. *Why lightweighting*

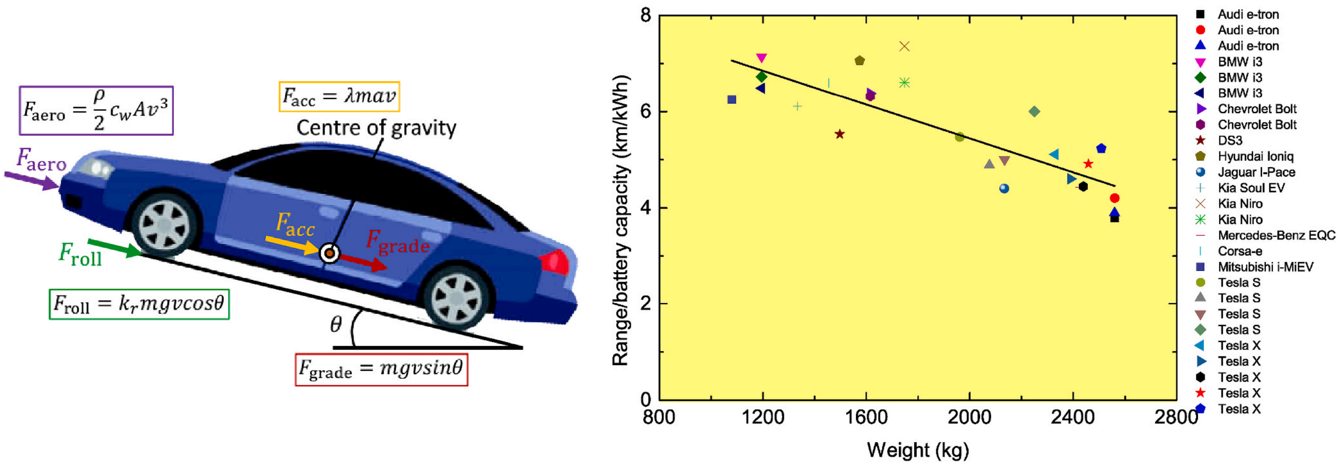
Increasing vehicle travel range requires an increase of specific energy or energy density (Wh/kg) stored in the vehicle [62]. Alternative battery chemistry and manufacturing technologies with improved energy capacity, lower cost will be discussed in Section 3. On the other hand, range can be increased by reducing vehicle weight/mass, which reduces the load/resistance applied on the vehicle, including the friction force (rolling resistance F_{roll}) with roads, acceleration resistance (F_{acc}) and climbing resistance (F_{grade}) [63], as shown in Fig. 1. Reduction of vehicle weight decreases the amount of energy (i.e., fuel, electricity) needed to drive the vehicle (the use phase) and increases acceleration, irrespective of the efficiency of the powertrain system. However, weight reductions in EVs do offer greater improvement in travel range compared to that in equivalent conventional ICE vehicles. Volkswagen evaluated the travel range increase as a result of a 100 kg weight reduction for conventional ICE and battery electric versions of the Golf [64,65], a 2.4% increase in travel range was achieved for a conventional 1.4 L TSI Golf Mk VI, which is lower than the 3.6% found in a corresponding prototype BEV (VW360e). Joost reported that a 10% weight reduction yields an approximately 14% electric range improvement [66]. Lightweight design in electric vehicles provides a cost-effective approach for meeting future Corporate Average Fuel Economy (CAFE) standards [67], offsetting the increased weight of the powertrain system resulting from the lower energy density of batteries relative to liquid fuels [68].

In addition to increasing the travel range, weight reduction also tends to reduce total energy usage and life cycle GHG emissions, though there could be increased energy consumption and GHG emissions in the production or end-of-life phase of the vehicle's life cycle [69–72]. Life cycle energy and emissions benefit of vehicle lightweighting is affected by several factors such as powertrain technology and efficiency, lightweighting technologies, and could be evaluated using life cycle assessment (LCA) [70,73]. LCA has been widely used to quantitatively analyse the environmental performance of both ICE vehicles and EVs from the perspective of well-to-wheel, which contains two stages of well-to-tank and tank-to-wheel [74,75]. Yet, estimation of the life cycle energy benefit of lightweighting vary from a few percent to more than 50% [72]. A general rule of thumb is that weight reduction of 10% for ICE vehicles results in an approximate 3% improvement in fuel economy and CO_2e emissions, based on the assumption that only the weight is reduced without other changes being made to the vehicle (i.e. the vehicle has an increased power-to-weight ratio). If the powertrain is de-powered in tandem with reducing weight to maintain performance (i.e. the vehicle has a constant power-to-weight ratio), an approximate 6.5% (6%–8%) reduction in CO_2e emissions can be achieved [64,76–79]. In other words, a 100 kg reduction in vehicle weight will lead to a fuel saving of 0.3–0.5 L per 100 km and CO_2e emissions reduction of 0.85–1.4 kg per 100 km [63,69,80].

For pure electric vehicles, how much life cycle GHG emissions can be saved by weight reduction depends on how the electricity is being generated and the related GHG emission factors for electricity generation [81], the benefit of BEV lightweighting is more obvious in countries where more carbon intensive electricity is used. Generally, lightweight design in EVs results in lower reductions of life cycle GHG emissions in relative to comparable conventional ICE vehicles due to the higher powertrain efficiencies of EVs [70,82]. Generally the production of lightweight materials is more emission-intensive than base material due to the higher emission factors. In the use phase, GHG emissions of BEVs are largely dependent on the power mix as various sources of electricity provision exist. Renewable electricity grids help to reduce GHG emissions of BEVs, which potentially offsets their environmental impact in the production phase. Generally, the largest contributor to the life cycle environmental impact of different electricity sources was in the use phase, BEVs have a reduced life cycle CO_2e emissions compared to ICE vehicles when considering electricity production. EVs powered by coal-based electricity have around 17–27% higher life cycle CO_2e emissions than those powered by gasoline and diesel [83].

2.2. *Lightweight architecture design of body structure*

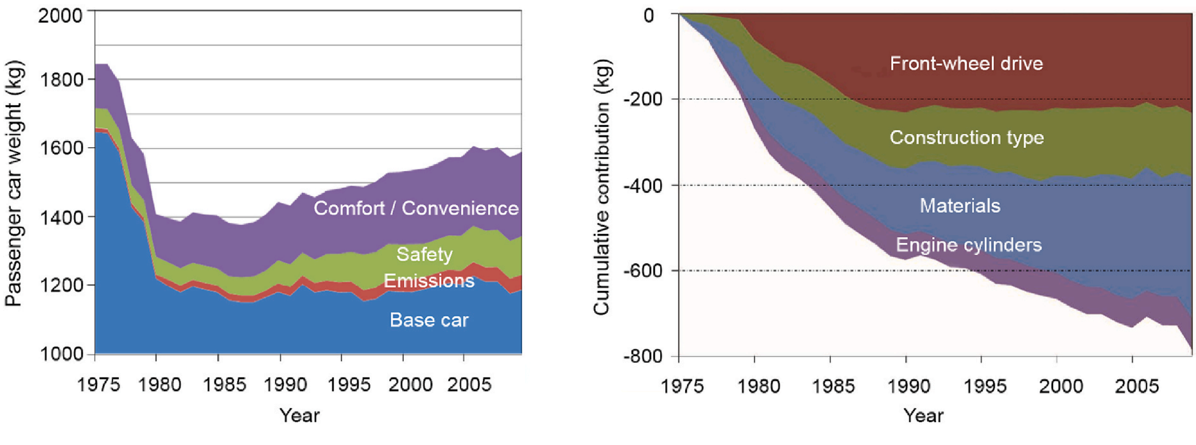
The evolution of passenger car weight, and contributions of technological improvements to weight reduction are shown in Fig. 2 [84,85]. The weight declined from ~1850 kg in 1975 to ~1380 kg in 1988, at which point it began to rise steadily, a longstanding trend that persisted. The decline in weight before the late 1980s is mainly attributed to base car weight reduction, which is resulted primarily from the usage of front-wheel drive, as it changed the design of body structure. Other reasons are the change of construction type and materials (using lightweight materials to replace steel). Since 1990 there has been an annual average increase of ~0.6% for vehicle weight because the customer



(a)

(b)

Fig. 1. Effect of weight on (a) the driving resistance, (b) the range efficiency (km/kWh) of BEVs (data source: websites of BEV automakers).



(a)

(b)

Fig. 2. Evolution of passenger car weight (a) and contributions to weight reduction (b).

demand shifted the preference to larger vehicles with increased contents (e.g., air conditioning, safety equipment). The weight of base car remained almost the same during this period although the vehicle size was generally increased. The major reason is the increasing usage of lightweight materials, this will be discussed in Section 2.3. Most car body structures switched from body-on-frame to the unibody (unit body or unitized body) construction from the 1960s. Today, sheet-intensive unibody structures have occupied most of the car models. The unibody construction is a single structure which integrates the floorplan and chassis into the body by welding preformed stamped sheet panels together. Compared with the body-on-frame construction, the unibody design enables considerable weight savings of the base car body and provides improved space utilisation and ease of manufacturing. A further development is the 'semi-unibody' design, e.g. the global platform strategy. The platform greatly facilitates the standardisation of structural components of vehicles, which generally includes the chassis, powertrain compartment, and underbody. Different vehicle models can be assembled on a given platform, increasing the flexibility of production shift between different factories. The utilisation of global platforms and modular architecture has seen a significant growth in the automotive industry, as an approach to increase production efficiency, volume and cut cost [86,87]. Volkswagen was the first OEM to launch the global platform strategy-Modularer Querbaukasten (MQB), which cut 20% production cost by using a separate chassis manufactured by pressed sheet panels forming a 'platform chassis'. Renault-Nissan quotes a 20–30% cost reduction in components/parts and a 30–40% reduction in the entry cost per vehicle model by implementing the Common Module Family (CMF) [88]. The top 10 major OEMs reduced by 20% of the number of global platforms during 2004–2014, while the number of vehicle models produced from global platforms increased 30%, with more personalised models made for each platform [89]. Since then, the trend has continued. The average number of vehicle models manufactured on each individual platform increased by ~50% in 2020 compared to the 2005 [88]. In 2005 35% of light vehicle manufacture was engineered on global platforms by the major OEMs, and due to platform counts being rationalised and deployed globally this proportion increased to 83% by 2020 [88].

The design of electric vehicles provides an opportunity to completely rethink vehicle architecture. Decreasing the number of platforms while increasing the number of electric vehicle models shared on a single platform, which constitutes approximate 50% of the product development cost, can greatly cut vehicle production cost. This is as a result of the consequent decrease in personalised engineering components and content across different electric vehicle models, whereas consumers' choices for products are maintained. The cost of tooling and purchasing is decreased due to single sourcing of equipment and economies of scale of component sharing [90,91]. Currently, EVs are produced both as adapted ICEs (non-native EVs) and using dedicated platforms (native EVs). The initial capital requirement of developing a new platform is the main obstacle to a definitive move to dedicated platforms. Dedicated platforms allow optimised battery packaging have on average a 25% larger battery pack volume and 10% more interior space compared to non-native EVs [92]. The electric powertrain can be installed in a subframe that sits on one or increasingly both ends of the platform closer to wheels [93]. Also, native EV platforms offer more range at competitive prices (Fig. 3) [94]. The transition of all major OEMs to dedicated platforms, through strategic 'decontenting' for EVs was studied in Ref. [95], indicating that a cost reduction of $5700 to $7100 can be achieved from 2019 to 2025. The modified ICE-based platform often has higher weight and reduced range due to the overdesigned platform and lower battery pack volume, but it decreases the capital investment. On the other hand, the native or purpose-built EV platforms avoid overdesign and provide improved range, acceleration, and interior space at competitive prices [92]. Modularity design in BEV architecture aimed at reducing weight has been proposed in several projects, such as 'SmartBatt', 'SuperLIGHT-Car', 'ELVA', and 'ALIVE', where 200 kg are targetable through body-in-white (BIW) with integrated battery housing [96].

A lot of research has been conducted over the past decades in order to

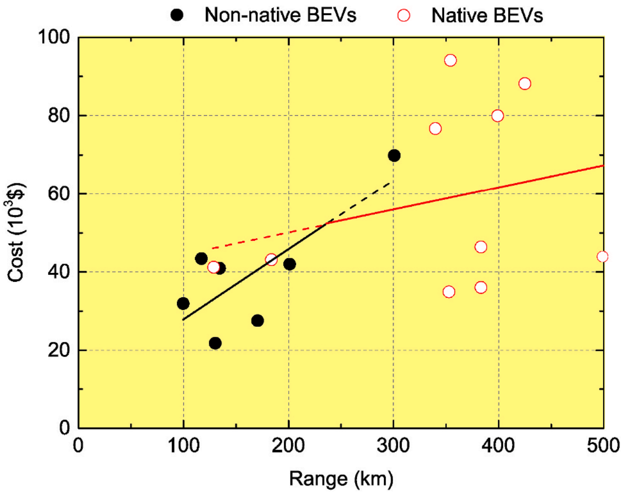


Fig. 3. Evolution of cost vs range for battery electric vehicles with native and no-native platforms.

optimise the design of vehicle components with improved lightweight and crashworthiness levels. For instance, tailor welded/rolled blanks [97,98], the front bumpers [99–101], the crash boxes [102], the front rails [103,104], the front end structures [105–107], the vehicle doors [108–110], the sub-frames [111,112] and the A/B/C pillars [113,114]. In addition to the optimisation on the component-level, some researchers studied the lightweight or crashworthiness optimisation of the vehicle body structure as a whole, such as the topology optimisation. Structural topology optimisation has been increasingly employed in the design process to search for incremental improvement in body structures, especially during the conceptual stage. The section shape or thickness parameter of the panels, which are treated as the design variable, are optimised by exploring the structural response of different geometries or topologies subjected to static or dynamic loads [115–117]. Reed [118] carried out topology optimisation of a BIW based on static loads. Gao et al. [119] monitored the forces generated at different sections and used the Multi-Domain Optimisation (MDO) technique for optimising a BIW. Christensen et al. conducted topology optimisation of a HEV body structure under linear crash load cases [120,121]. Topology optimisation under multiple crash load cases were also studied. Yang et al. [122] studied the topology optimisation of a HEV body structure under different volumetric constraints and load cases: static loads, torsion load during turning and the moment load during braking. Tian and Gao [123] studied four crash load cases (frontal, side, rear impact and roof crush), concluding that the optimised structure under a single load case can seldomly satisfy the other load cases and it is necessary to perform topology optimisation under multiple load cases. Aulig et al. [124] applied topology optimisation to an existing body structure, two crash load cases (front and rear crash loads) and nine static load cases divided between the seat, front, and rear were considered. It was demonstrated that the best trade-off of optimisation results can be achieved by considering both stiffness and crash load cases concurrently rather than considering either stiffness or crash load cases, separately. These incremental improvement in BIW structure design can offer the designer greater flexibility for making stronger, lighter and less expensive structures while maintaining the overall performance.

2.3. Lightweight material design of body structure

Mild steel has long been widely used for manufacturing vehicle components such as body, chassis due to its relatively low cost and satisfactory rigidity and strength. However, its strength-to-weight ratio is relatively low and thus such components are heavy. Since 1975 the role of advanced materials has increased in lightweight design of vehicles, and currently contributes to a greater weight reduction than the adoption of front-wheel drive schemes and construction type (unibody, spaceframe, etc.), as shown in Fig. 2. Alternative lightweight materials, which can be used to replace mild steel in vehicles, include high-strength steel, aluminium, magnesium and polymer composites (glass-fibre and carbon-fibre).

Some automakers have already largely used lightweight materials for designing the body structures of their vehicles, such as Honda (NSX, Insight), Lotus, Jaguar (XJ), and Audi (TT, A2, and A8). The body-in-white (BIW) has a greater weight reduction potential in comparison with other components due to its complexity and increasing number of technological solutions [78,125,126]. 'Multi-material designs' concept has been proposed for BIW, which involves a complex mix of different lightweight materials [127]. The added weight of batteries and 'range anxiety' are making the lightweighting more critical to EVs. The multi-material automotive body is especially promising for the compensation of the added weight of the electrical components [128,129], an example is the LifeDrive concept developed by BMW Group, which consists of a passenger cell made of carbon fibre reinforced plastic (CFRP) and an aluminium chassis/platform housing the battery pack, electric propulsion system, and structural and crash components, offering benefits for weight-minimising construction, low centre of gravity and even weight distribution [130,131]. The principle idea behind the multi-material concept is using the 'optimum' material to achieve the appropriate functions: efficiency, safety and driving performance, providing an overall cost-efficient lightweight design solution. The research by Lotus Engineering [132] pointed out that 38% weight reduction could be achieved at an extra cost of 3% by using a total vehicle, synergistic approach, even though an all-steel body structure is replaced by lightweight materials. Fig. 4 shows evolution of average material content of vehicles [78,133,134]. Lightweight vehicle design using a mixture of aluminium and high strength steel have significantly increased from 2007. The increasing utilisation of lightweight materials has largely offset the additional weight gains brought about by increased vehicle content for safety, convenience and comfort [86]. Consequently, vehicles have become much larger and safer/comfortable without gaining corresponding significant weight [135,136].

The lightweight materials must be cost-effective in comparison with alternative lightweighting technologies, for large-volume mainstream vehicles, low-volume luxury/high-performance vehicles, and new model entries. A rough approximation of the potential relative weight savings and cost of different lightweight materials is given in Table 1 [77,85,137–139]. High-strength steel has more than twice the strength-to-weight ratio of mild steel, it is the most cost-effective alternative lightweight material with a high recyclability. Aluminium has a strength-to-weight ratio approximately 1.4 times that of high-strength steel. It is competing with high-strength steel to replace mild steel for constructing the BIW, chassis and main closures, such as door frames, hoods, roofs, and bumpers [104,127,139–142]. Relatively new area is the all-aluminium or aluminium-intensive BIW construction with increasing 5000 series aluminium alloys parts being replaced by higher strength 6000 series and 7000 series aluminium alloys parts. An emerging application for aluminium in EVs is in the subframe that hosts batteries, which must have high thermal conductivity to cool batteries or warm them in cold weather, all making aluminium an excellent option [143]. However, the high cost in raw material and manufacturing, recycling, and the complexity of joining, are still factors that need to be considered for the massive penetration of aluminium [127,144–147]. Aluminium is difficult to spot weld compared with steel due to its high thermal conductivity and low electrical resistance, hybrid joining techniques combining welding and bonding or mechanical joining and bonding are commonly needed. The strength-to-weight ratio of magnesium is lower than that of aluminium and high-strength steel, also its poor formability hinders its large-scale usage in vehicles. Polymer/composite has the highest strength-to-weight ratio, however it accounts for a limited proportion of materials usage of vehicles, due to its high cost, long production time, and not being able to be recycled easily at the

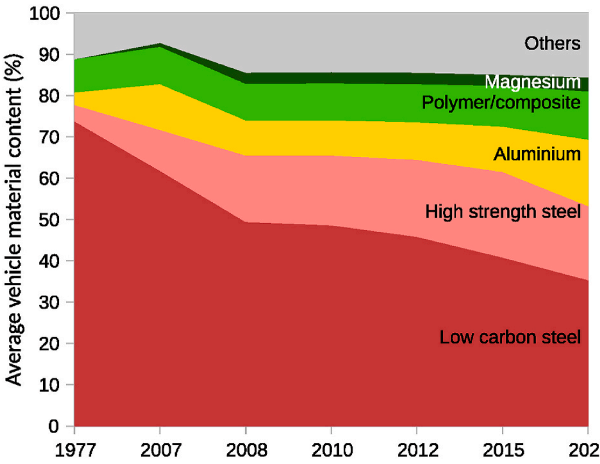


Fig. 4. Evolution of average material content of vehicles (See Appendix A for the dataset in a heat map).

Table 1
Comparison of different lightweight materials [77,85,137–139].

Material	Density ρ (kg/m^3)	Typical strength-to-weight (σ/ρ) (kN·m/kg)	Relative weight savings (%)	Relative cost
Mild steel	7850	59	0	1
High-strength steel	7855	125–178	23	1.5
Aluminium alloy	2810	178–249	45	2
Magnesium alloy	1780	104	60	2.5
Polymer/ composite	1500–2000	620–700	50	10

end of vehicles' life.

Material substitution combined with structural optimisation strategy has been proposed for the construction of BIW that meets the crash and NVH (noise, vibration and harness) standards while minimising weight. Xiong et al. studied the structure-material integrated multi-objective lightweight design of the side structure [148] and front end structure [149] of a car body. Material parameters and thickness of each structural component were simultaneously set as design variables, allowing for allocation of the optimal combination of material and thickness to reduce weight and material cost. Wang et al. [150] studied the lightweight design of a front bumper system using main section shape, thickness and material as variables, 25.74% weight reduction could be achieved using aluminium alloy. Wang et al. [151] further performed multi-objective lightweight design of a B-pillar structure, reducing the weight by 22.55% while guaranteeing well the other impacting indicators. Parrish et al. [152] explored structural optimisation design of a full-vehicle model in which 22 steel parts were replaced with AZ31 magnesium counterparts simultaneously, saving 54.5 kg in weight while maintaining the crashworthiness characteristics. Logan et al. [153] showed that optimisation design of the conventional steel body structure using magnesium alloy can improve the structural performance while offer ~ 40% weight savings. Kiani et al. [154] demonstrated that optimisation design of BIW and substitution of magnesium alloy led to a weight reduction of 46.7 kg (44.3%) and improved vibration and crashworthiness performance compared to the baseline steel design.

In addition to the direct benefits, reducing vehicle weight by optimising design of body structure or utilising lightweight materials also enables secondary weight reduction [155]. If the body is lighter, then the powertrain and chassis systems (brakes and suspension etc.) can also be made smaller (downsized) and lighter without affecting performance. This leads to additional reduction of weight and cost, which can in some way mitigate the increase of materials costs due to the usage of high-cost lightweight materials. The value of secondary weight reduction varied widely among literatures: a 1 kg reduction in primary weight will result in a secondary weight reduction of 0.5–1.4 kg [156–161].

3. Technology trends: improvements in BEV powertrain

3.1. BEV powertrain architecture/system design

A BEV powertrain includes battery, motor, transmission system, and related power electronics (inverter/converter, power control unit, on-board charger) [162]. BEV powertrain weight can be reduced through integration of components, there has been a continuous trend for moving parts of the power electronics closer and integrating them into fewer modules. This can be achieved in the design of the electric cables connecting the main EV powertrain components. A decrease has been observed in both weight (average ~8.7 kg to ~5.3 kg) and total number (average ~12 to ~7) of parts for these cables [92], indicating an increased integration of more recent EV powertrain systems. However, no consensus EV powertrain design either for individual components or overall architecture has emerged.

Fig. 5 shows different powertrain architectures possibly available to BEVs, depending on the arrangements of motor (M), clutch (C), differential (D), fixed gear (FG) and gear box (GB) [163–165]. This is to show how the power from motor can be transmitted to wheels with gradually reduced mechanical transmission components and thus weight, taking an example of front-wheel drive. Electrical energy from the battery is delivered to the motor through a power converter, i.e. the electrical system. Fig. 5a shows a configuration based on conventional ICE vehicles, in which an electric motor is used to replace the engine. It has a gear box, clutch and differential to control the torque and speed. Fig. 5b shows a configuration where the gear box is replaced by a fixed gear and the clutch is omitted. Fig. 5c shows a configuration where the motor, gear and differential are integrated into one module. Fig. 5d shows a configuration where two independent motors are used for the two wheels, this is mainly to increase the cornering performance. The fixed gear can be placed inside the wheel (geared in-wheel drive) to reduce the mechanical transmission, as shown in Fig. 5e. Furthermore, the mechanical gear system of in-wheel drive can be totally removed (gearless in-wheel drive, Fig. 5f) where a low-speed outer-rotor motor is mounted on the wheel rim, in comparison with the high-speed inner-rotor motor in Fig. 5e.

The weight gradually decreases from Fig. 5a to f as less components are used. The most commonly used configuration by modern BEV passenger cars is the one shown in Fig. 5c [166,167]. Note that there is an increasing trend for BEVs to have multiple motors connected with both the front wheels and rear wheels, such as the dual-motor in all-wheel drive BEVs of Tesla, Audi, Volvo, Mercedes etc. The power of the added motor driving the rear wheels can be transmitted using the similar topologies as those shown in Fig. 5 [163,166]. However, In-wheel motor (IWM) configurations lead to significant weight reduction of the powertrain system due to the motor compartment, driveshaft, differential and transmission being removed. As a result, more space for batteries and high powertrain efficiency can be achieved due to minimal losses in transmission of the torque to the road, potentially increasing travel range. They also lower the centre of gravity of the vehicle and improve its weight distribution [168]. IWM configurations provide improved handling/turning of each wheel which can be finely controlled, e.g. rotate freely. Wireless in-wheel motor (W-IWM) configuration was proposed to eliminate the cables connecting the motor with the power and control systems, which could potentially get damaged due to the harsh environment and vibration [169].

3.2. Battery technology

Battery and motor are two major parts of the BEV powertrain system. Battery cost remains one of the main factors for the price difference of BEVs in 2018 and 2025, as shown in Fig. 6 [170,171]. Battery cell and pack costs are expected to go down gradually as a result of improvements in battery material chemistry, battery cell design and decrease in assembly costs driven by increase of production volume/scale and learning. The development of battery technology has been pushed forward by several competitive battery suppliers rather than directly by vehicle manufacturers, which sustains a long-term trend towards more supplier content with fierce competition in the EV market. The cost for batteries used for EVs can be divided into four basic categories: material (electrode, separator, electrolyte), labour, assembly and overhead. The largest proportion is the cost of materials, which accounts for about 60% of the total battery cost (Fig. 7) [172,173].

Fig. 8a shows projections for key features of battery pack deployed in BEVs in 2020–2050 [174–176], from which the cost reduction of battery pack can be shown in Fig. 8b. The global average battery pack price has plummeted from a little under \$1000/kWh in 2010 to approximately \$160/kWh in 2019, and is expected to fall to about \$111 per kilowatt-hour (kWh) in 2025, followed by \$73/kWh in 2030, \$65/kWh in 2040 and \$57/kWh in 2050. Battery cell densities are expected to

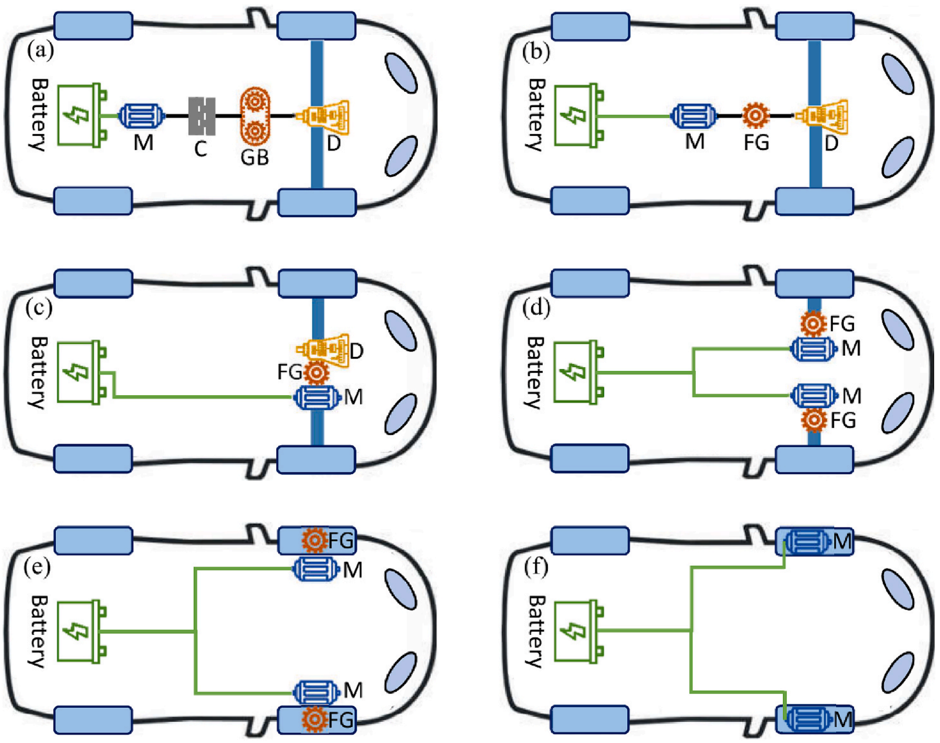
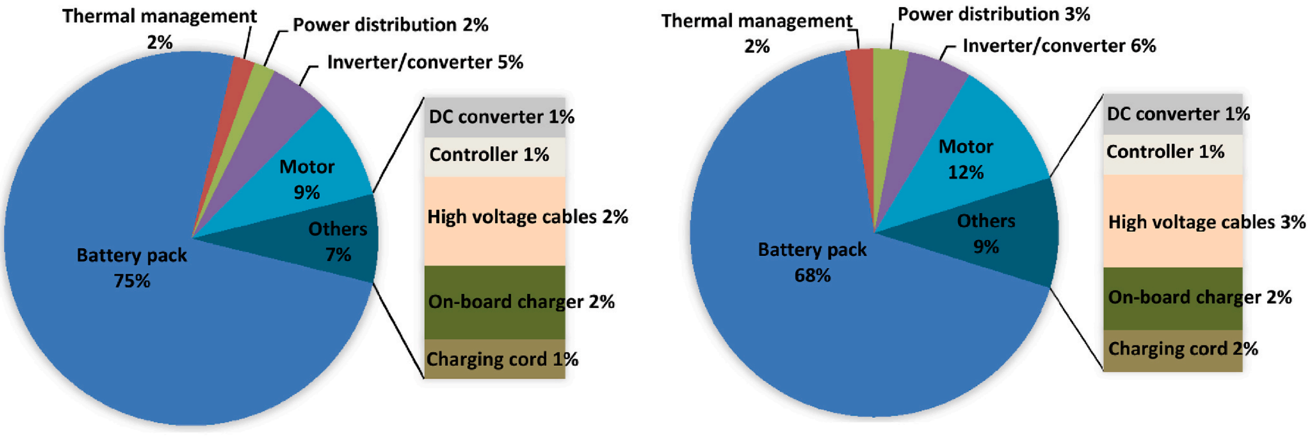


Fig. 5. Main BEV powertrain architectures (front-wheel drive) with a general trend of reducing mechanical transmission components: (a) based on ICE, (b) fixed gear without clutch, (c) motor, gear and differential integrated, (d) 2 motors with fixed gear, (e) 2 motors, geared in-wheel drive, (f) 2 motors, gearless in-wheel drive. (M-Motor, C-Clutch, D-Differential, FG-Fixed gear, GB-Gear box).



(a) 2018 BEV200-car powertrain, $13723

(b) 2025 BEV200-car powertrain, $9360

Fig. 6. Cost breakdown of the powertrain for BEV200-car in 2018 (a) and 2025 (b).

reach 229 Wh/kg in 2030, 254 Wh/kg in 2040, and 271 Wh/kg in 2050. As a result, battery packs will become more compact and lighter.

The main reasons for the rapid decrease of battery cost are alternatives for lithium and other mineral resources, which greatly reduces the material cost. The trend in further understanding the capacity degradation mechanism and finding new battery chemistry to improve energy density and reduce cost is likely to continue, especially for the cathode chemistry, with the aim of reducing the amount of high-cost, cell materials like cobalt and using cheaper substitute metals like nickel and manganese instead [177–185]. As depicted in Fig. 9 [176,186], the largest proportion (40%) of battery chemistry technologies used for BEVs produced in 2020 is NMC 622, which contains a Ni: Mn: Co ratio of 6:2:2. This is followed by NMC 811 containing a ratio of Ni: Mn: Co of 8: 1: 1, which accounts for a proportion of 32%. However, BEVs in 2025 will use a lower proportion (38%) of NMC 622 and a higher proportion (35%) of NMC 811. With the further development of low-cobalt battery technologies, NMC 9.5.5 (9 Ni: 0.5 Mn: 0.5 Co) which contains a much lower proportion of cobalt will dominate the battery chemistry in 2030.

Besides the battery chemistry, other technologies for reducing the cost of battery packs used for BEVs involve reducing the cost in battery manufacturing, in which several aspects for cost reduction have been considered: (1) implementation and improvement of in-line non-destructive (ND) quality control (QC) techniques to reduce scrap rate in battery manufacturing [187,188]; (2) new techniques for electrode fabrication such as high-speed curing with low solvent content or solvent-free spraying to reduce the manufacturing cost and increase

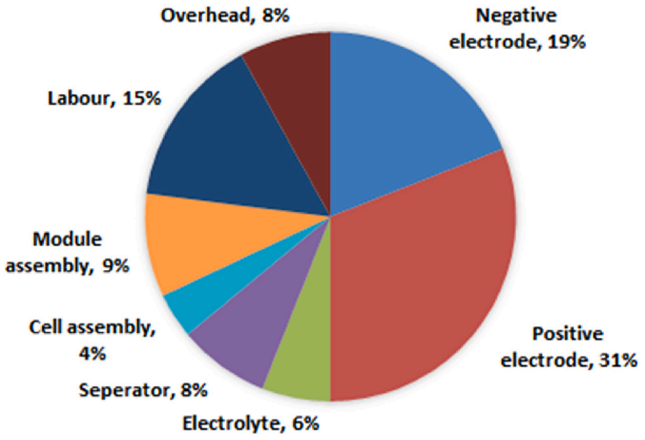


Fig. 7. Cell and materials cost breakdown for a lithium-ion battery.

energy density and production volume [187,189,190]; (3) manufacturing of batteries with low separator tortuosity, large electrolyte interfacial area, small electrode particles, and porous or removed current collectors to improve the energy density [187]; (4) rapid thermal processing [191]; (5) advanced process control (APC) [191]; (6) industrial internet of things (IIOT) [191]; and (7) uniformity in raw materials [191]. By incorporation of these strategies/technologies in the process of battery manufacturing it is expected that a net reduction of manufacturing cost of at least 20% can be achieved, resulting from improved reliability, yield gain and reduced cost of energy management system [191].

3.3. *Motor technology*

The weight of electric motors has undergone significant reductions due to advances in materials and design technologies. There are mainly three types of electric motors that can be used for EVs, permanent magnet (PM) motor, induction motor, and switched reluctance (SR) motor [192]. Fig. 10 shows the comparison of costs, mass/space, and power for the PM motor, induction motor and SR motor [193]. The power density of PM motor is the highest, which can remain at a high efficiency over a wide percentage of its operating range. In terms of materials, rare earth magnets developed in 1983 played a key role in improving motor efficiency and reducing size/weight in the early days. Rare earth permanent magnets are deployed in most traction motors of plug-in electric vehicles (BEVs and PHEVs), among which rare earth neodymium magnets (NdFeB) highlight and offer the maximum energy/power [194,195]. Rare earth PM motors account for approximately two-thirds of the global PM motor market. The price of the PM motor is relatively high due to the high costs of magnets and rotor fabrication, especially for rare earth magnetic materials that have a limited availability. In spite of the challenge in cost, the OEMs of vehicles expect to continue using PM motors for the majority of EVs over the coming decade, due to their combination of small size, lightweight, high output (output-to-weight ratio) and efficiency.

Induction motors offer several attractive features such as high simplicity, high reliability (brushless operation), high starting torque, sustainability to harsh environment, low torque ripple/noise and low maintenances [192,196–198]. Nevertheless, the power density and overall efficiency of induction motors are lower as compared with PM motors. Also, their volume and weight are greater than that of PM motors for the same power rating. Induction motors are commonly seen in various industrial applications, including some BEVs. As the technology for induction motors is well developed, further improvements in volume (weight), cost, power density and efficiency for utilisation on future competitive EV market are difficult and will rely on new designs, or novel control schemes or converter topologies. SR motors are drawing increasing popularity for application on the electric propulsion system of EVs, especially for HEVs and FCVs [199,200]. Compared to PM motors, SR motors are relatively robust with high reliability and low cost, and capable for high-temperature applications due to the absence of permanent magnets [201]. However, the limitations of SR motors

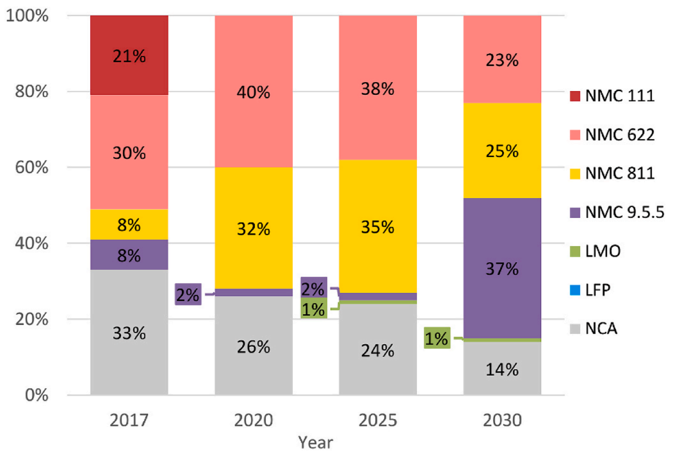
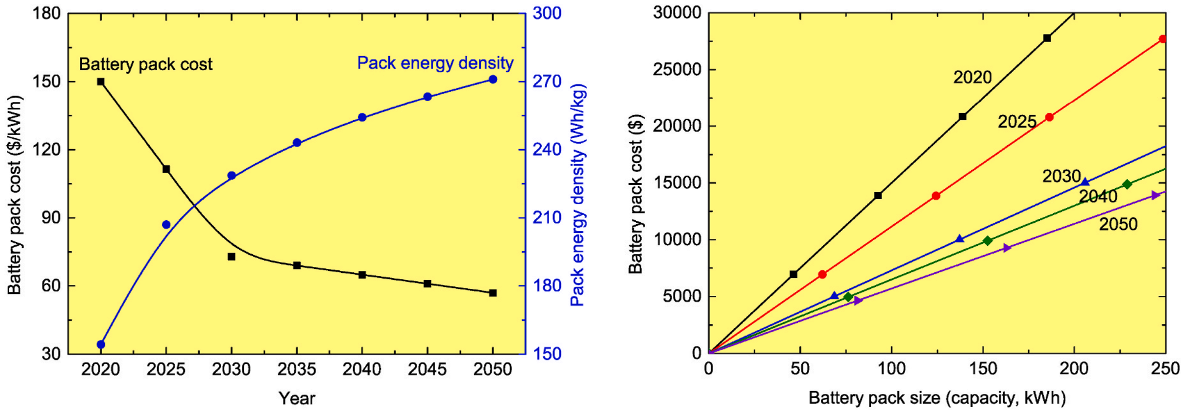


Fig. 9. A McKinsey analysis of EV batteries cathode chemistry evolution. (LMO-Lithium Manganese Oxide, LFP-Lithium Ferro Phosphate, NCA-Nickel Cobalt Aluminium).



(a) (b)

Fig. 8. Predictions for key features of battery pack deployed in BEVs in 2020–2050.

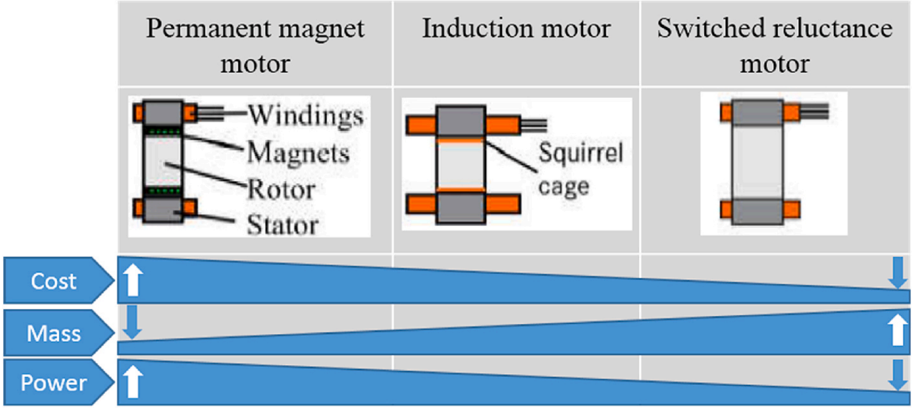


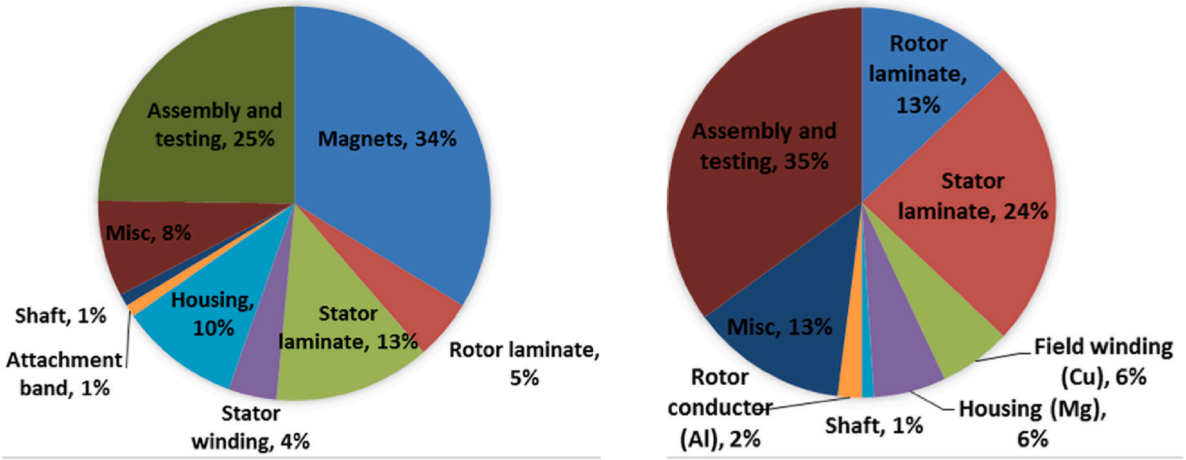
Fig. 10. Comparison of commonly used EV motors considering costs, mass and power density.

include the high torque ripple and acoustic noise and vibration, all subject to active research [202]. In addition, the efficiency of SR motor is lower than other types of motors, and extra sensors and complex controllers are needed, adding overall volume/space and cost of the electric propulsion system.

Fig. 11 shows the cost breakdown of permanent magnet (PM) motor and induction motor [203,204] produced by General Motors. Labour (assembly and testing) accounts a significant proportion for both PM motor (25%) and induction motor (35%) and there is not much room to reduce. The material cost is the largest contribution, magnetic materials (permanent magnets, stator and rotor laminate) account more than 52% of raw material cost of PM motor, and for induction motor magnetic materials (stator and rotor laminate) account for 37% of raw material cost. Overall, induction motors are cheaper due to free of rare earth magnets, although more labour intensive, less efficient, greater in volume and weight, and requiring more expensive/complex drive electronics.

To reduce cost while maintaining and even increasing performance, efficiency, and reliability, R&D in electric motors is exploring new motor concepts that are rare-earth-free and use less expensive materials for laminations and cores like alnico and ferrite. Alnico magnets present high residual magnetic flux density (remanence) and are applicable for operations at high temperature. Nevertheless, one main challenge is the easy occurrence of demagnetisation due to the low coercive field [205]. Ferrite magnets, which are also called ceramic magnets, exhibit very low losses of eddy currents for application on electric motors due to the low electrical conductivity, thus reducing demagnetisation occurrence [206]. However, one main challenge is that they lead to a low energy product. Ferrite magnets account for approximately one-third of the sales of permanent magnets, the other two-thirds are occupied mainly by rare-earth permanent magnets. Ferrite magnets are the most potential candidates for rare-earth-free electric motors to replace neodymium magnet motors for EVs, the costs of ferrite and neodymium magnets are in a proportion of less than 1:25 [207]. Extensive studies have been done on ferrite magnets to improve its magnetic flux density, torque/power density and efficiency, and there has been a tendency to use axial flux ferrite PM motors, especially for in-wheel applications [208–212].

To reduce the motor size/weight and maintain or improve efficiency, the various types of energy loss (such as magnetism) inside motors must be minimised. Meanwhile, the potential excessive rise in temperature due to reduction in heat dissipation performance (reduced surface area for dissipating heat) resulting from smaller size must be avoided. Several design technologies have been developed to address these issues, which involve electric design, cooling design, and demagnetisation design. The design optimisation technique based on a coupled magnetic field and thermal analysis technique has also been developed to simultaneously analyse the magnetic flux and heat flow in the motor, which makes a great contribution to the design of motors for small size [194]. An example is technical developments making Hitachi 5-HP induction motor smaller and lighter. The motor weight was reduced to ~20% of the original motor made in 1910 by adopting aluminium rotor and aluminium frame etc. Also, advancement in production technology resulted in a cumulative production of more than 45 million motors in 2010, when a prototype 5-HP permanent magnet motor weighing only



(a) 32kW PM motor, $522 (b) 40kW Al Induction motor, $450

Fig. 11. Cost breakdown of (a) permanent magnet (PM) motor and (b) induction motor.

1/15 that of the original motor was designed [194].

Today's magnet often consists expensive heavy-rare-earth (HRE) elements such as dysprosium and terbium, which are added to the NdFeB formulations to increase the coercivity [213,214] and allow higher operating temperature. Reducing the magnet size/weight can lead to a reduction of usage of HRE elements, which not only increases the range but also reduces the cost. Fig. 12 shows potential technologies to further reduce the motor weight of EVs [193]. Topology optimisation may be used to achieve optimised weight motor by removing materials in the areas with less stress. Also, better cooling design of motors can increase the surface area and thus cooling capability, which offers the option to reduce magnet mass without affecting the overall motor performance. In addition, advanced manufacturing techniques such as additive manufacturing (3D printing) may lead to an integration of multiple components, decreasing component number, cost and weight of the motor [168]. There are two major benefits/advantages that can be obtained from additive manufacturing of motor parts. The first one is that improved heat removal (cooling) can be achieved since it could produce parts with greatly increased cooling surface areas. The other is multiple components can be integrated, leading to a much lower component count, cost and weight as parts that would have been jointed together previously are manufactured in one piece.

4. Modelling future BEV cost, range and electricity demand, based on technology trends

This paper has reviewed many promising technologies for cost reduction and range increase in BEVs, these are now brought together. A series of projections are made for the overall cost and range performance of BEVs over the period 2020–2050.

Key modelling assumptions are summarised in Table 2. The indirect cost, powertrain cost and other direct cost are given by extrapolating cost projections for 2018 and 2025 from literature [170,171,215] assuming the cost relates to the production *P*. Further details are given in Appendix B. The battery cost is found by solving the resulting quadratic equation from the range efficiency model to achieve a given range. The range efficiency model was found using regression analysis on 24 EVs released in 2019 and 2020 in the UK. The range efficiency model accounts for vehicle mass, power, frontal area and drag coefficient, for which values are given in the table.

To project future electricity usage, the total distance travelled by EVs was first estimated by multiplying projections for total travel distance by the proportion of vehicle-miles driven in EVs. The energy requirement was then found by assuming a population-average range efficiency and accounting for overall charging efficiency. Three core scenarios were considered: 1) current trends with range increasing from 400 km to 800 km between 2020 and 2050; 2) the same as 1, but with an improvement in battery power density; 3) the same as 2, but with lightweighting improvements. On top of this the effect of three further things was modelled: a) reducing average power, b) reducing frontal area and c) the range remains at 400 km.

Most of the costs of electric vehicles are expected to go down as the dedicated platforms are deployed, refined, and the initial difficulties in production ironed out. Electric motors will only marginally improve as they are already extremely efficient and compact. Finally, the cost of batteries will reduce until the material requirements and therefore the price of the raw materials prevent further decreases (Fig. 13).

Because the overall trend is that of a decrease in costs, it is likely that even optimistic previsions of EVs replacing ICEs in the car fleets will be verified. One of the key barriers to adoption is range anxiety, but this barrier should be largely overcome by 2035 when the range of EVs will broadly match that of current ICEs. But a side-effect of this is that with the availability of cheap, energy-dense batteries, the cost of cars and their range will become decoupled, which will probably make consumers favour cars with larger ranges, and therefore batteries than strictly required (Fig. 14).

The projected annual electricity usage by EVs is given in Fig. 15. From today, where the need to electricity for individual mobility is negligible, we estimate that we will need between 64 and 88 TWh of production to satisfy demand. On current trends a total of 88 TWh will be needed, reducing to 82 and 75 TWh respectively in the core scenarios where battery power density and lightweighting improvements occur. Reducing power, frontal area and maintaining range at 400 km each have a small effect on the annual electricity usage (reduced by 5.8%, 7.9%, and 7.0%, respectively – see Table 3). Combining all of these potential efficiency gains together, the electricity demand drops to 64 TWh. Therefore, although all interventions can have some impact, it would be preferable to have policy target the overall design of vehicles, encouraging efficiency.

Electricity production is being decarbonised at a rapid pace. In the UK, to meet the net-zero target of 2050, and absent carbon capture technologies, approximately 4.3 TWh of gas production will need to be

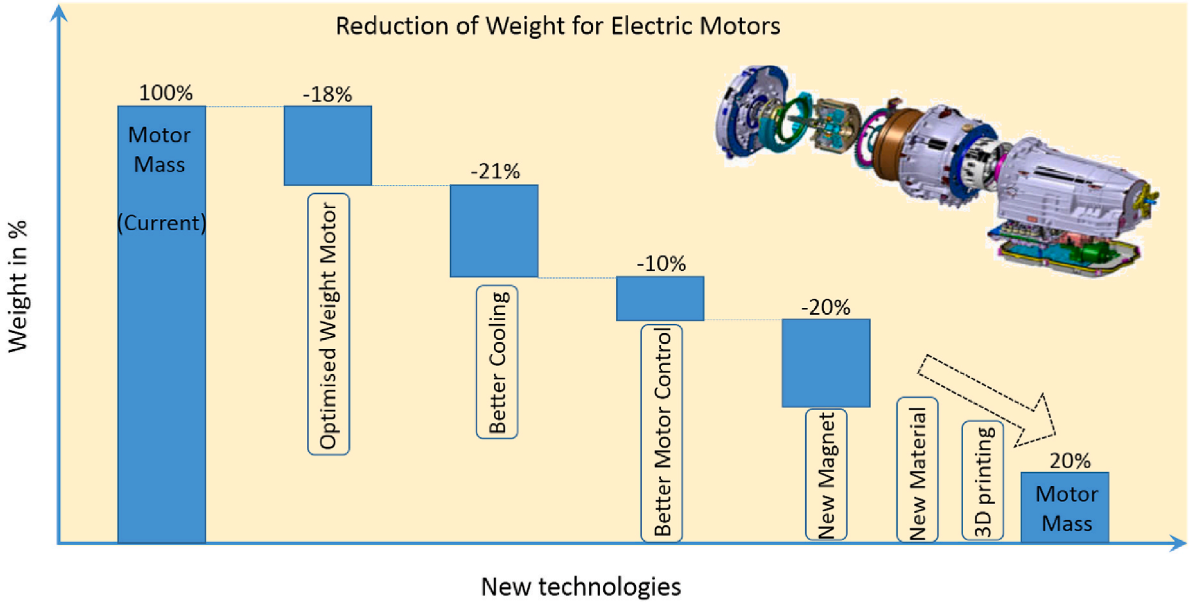


Fig. 12. Technologies for reducing motor weight.

Table 2
Key modelling assumptions.

Parameter	Value	Source
Range efficiency model	$r = 12.11 - 12\times10^{-3}m - 22\times10^{-3}p - 3.6C_DA$ r = range efficiency (km/kWh) m = vehicle mass (kg) p = vehicle power (kW) C_D = drag coefficient A = vehicle frontal area (m^2)	Regression analysis based on data from the UK Euro 6 database for 24 EVs released in 2019 or 2020 [216]
Average mass of car excluding the battery, 2020	1233.5 kg	Extrapolation of EU average light-duty vehicle weight 2005–2015 [217], non-powertrain accounts 75% [126], 147 kg powertrain (excl. battery) for mid-size car [162]
Annual increase in car mass 2020–2050 – current trends	0.60%	The customer demand shifted the preference to larger vehicles with increased content (e.g., air conditioning, safety equipment) [217]
Annual increase in car mass – enhanced lightweighting	−1.23%	[218]
Battery power density	2020: 154 Wh/kg 2035: 243 Wh/kg 2050: 271 Wh/kg	Fig. 8a [174–176]
Average frontal area, 2020–2050 – current trends	2.8×1.007^Y m^2 where Y is years elapsed	[219]
Average frontal area, 2020–2050 – reduced frontal area	2.8×0.996^Y m^2	[219] - Returns to 2001 level by 2050
Average drag coefficient, C_D	0.29	Average of 26 vehicles listed on Wikipedia produced from 2016 onwards [220]
Average vehicle power, 2020–2050 – current trends	106×1.020^Y kW	[219]
Average vehicle power 2020–2050 – reduced power	106×0.998^Y kW	[219]- Returns to 2001 level by 2050
Distance travelled by UK passenger vehicles	2020: 444×10^9 km 2035: 525×10^9 km 2050: 557×10^9 km	Department for Transport, 2018 - Road traffic forecast extrapolated to UK, reference scenario [221]
Electric vehicle sales uptake	2020: 1% 2035: 46% 2050: 100%	Department for Transport, 2018 - Enhanced EV uptake scenario, scaled to reach 100% by 2050 [221]
Average vehicle lifetime	10 years	Estimate of this paper
Overall charging efficiency	86%	[16]
Battery cost	2020: 150 \$/kWh 2030: 73 \$/kWh 2050: 57 \$/kWh	Fig. 8a [174–176]
Indirect cost, 2020–2050	Car: $3736.9 \times (41\%P)^{-0.658}$ \$ SUV: $3707.6 \times (22\%P)^{-0.645}$ \$ $P = 0.0211\ (X\text{-}2012)^2 – 0.0404\ (X\text{-}2012) + 0.1186$ where X is the year	Sales-weighted (Car 41%, SUV 22%) cost extrapolation of year 2018 and 2025 [170,171,215]
Powertrain (excl. battery) cost, 2020–2050	Car: $3092.8 \times (41\%P)^{-0.081}$ \$ SUV: $4322.8 \times (22\%P)^{-0.081}$ \$	[170,171,215]
Other direct cost, 2020–2050	Car: $12{,}730 \times (41\%P)^{-0.036}$ \$ SUV: $14{,}213 \times (22\%P)^{-0.036}$ \$	[170,171,215]

Note: See Appendix B for illustration of cost decomposition.

retired. In the last decade, on average a bit more than 9 TWh of low-carbon electricity, mostly off-shore wind has been added to the mix. A continuation of these trends suggest an additional 5 TWh of low-carbon electricity being added every year [16]. Currently, in the UK, the final electricity consumption is approximately 300 TWh. At the current rate of adding 5 TWh net of low carbon electricity, every year, it will take 13–17 years of adding to the electricity supply at the current rate only to satisfy future demand for individual mobility. This has the potential to trigger shortages if the current rate is not sustained.

But cars are not the only thing which will be electrified, and represent only a fraction of the future electric demand. The current projected gap between demand and production, assuming the trends as above is 388 TWh. To avoid facing an energy crunch, mitigation strategies need to be put in place. The maximum technical potential that we estimate here is 24 TWh, some of which will come from battery improvement, but the rest should come from a mix of lightweighting, better aerodynamics, and policies driving consumers to choose smaller batteries. These factors alone may be insufficient, and changes in usage patterns or breakthroughs in car design are probably also needed.

5. Technology outlook and policy recommendation

The previous section showed that in a developed country such as the UK the electricity used by passenger BEVs alone could exceed 29% of current consumption. In the medium term there may be strong pressures to reduce this and four promising avenues – Battery reusing and interoperable charging technology, shared mobility, advanced sensing technology and novel compact space frame construction - are now explored in brief. Battery reusing and interoperable charging technology could significantly improve the resource efficiency of batteries and cut GHG emissions. Shared mobility could see an increased occupancy of cars, and optimising car design for specialised use; advanced sensing could eliminate some of the need for crumple zones and heavy passive safety system, and novel frame types could offer much larger mass gains than incremental improvements in design. These options can probably work in tandem: novel frames allowing for more specialised vehicles adapted to share mobility. Advanced sensing and autonomy can improve the usefulness of car sharing.

5.1. Battery reusing and interoperable charging technology

End-of-life EV batteries still have 70–80% of their initial capacity, yet they are normally retired due to capacity failing to meet the range requirement. These batteries can be directly reused in less-demanding applications such as stationary energy storage, before being recycled. Battery recycling after secondary use reduces the raw materials demand

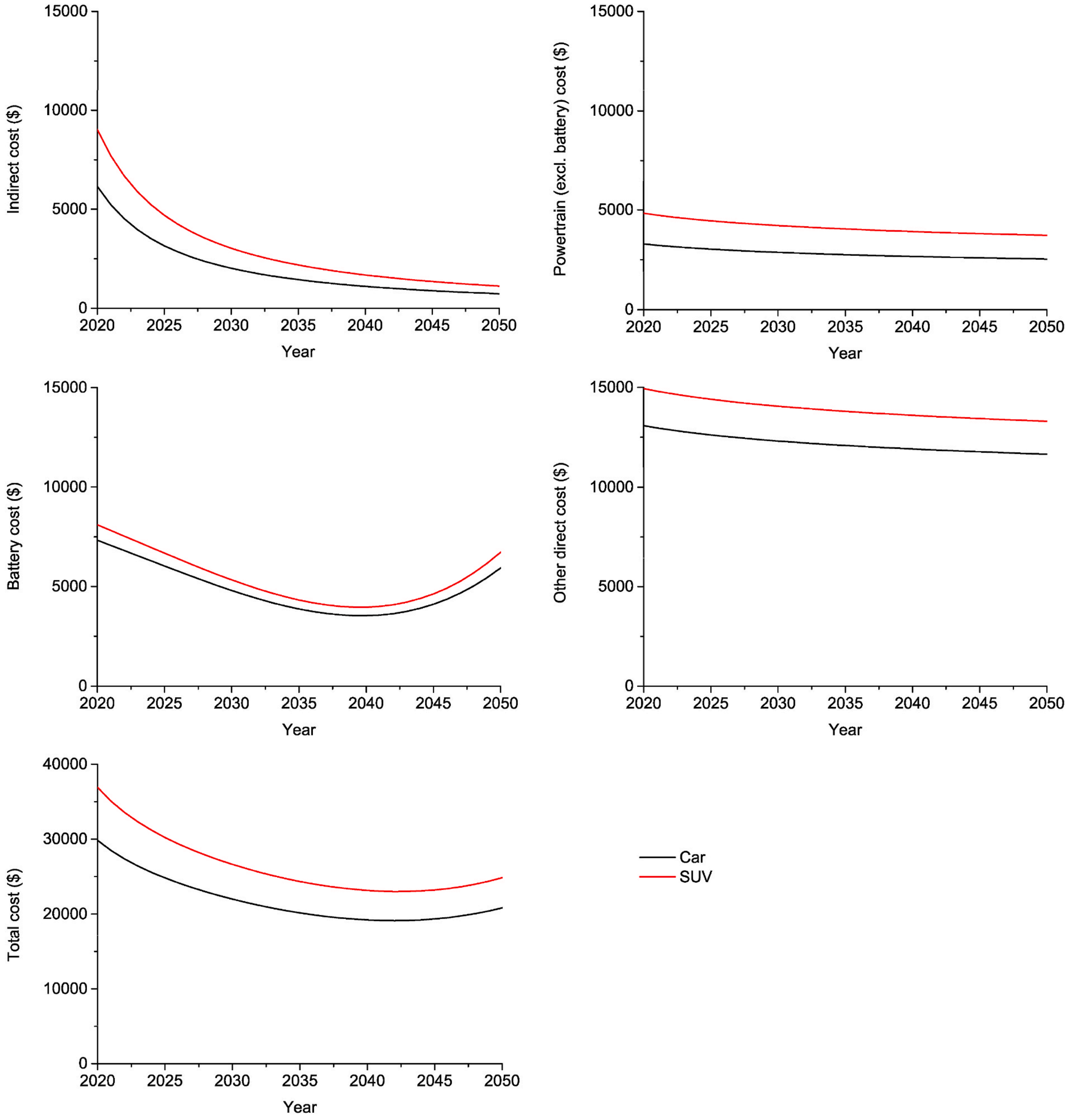


Fig. 13. Projected cost over time (with a fixed range that is 400 km in 2020, with a linear increase to 800 km in 2050).

for battery production, thus realising the closed loop for battery production. Around 13–14.7 tonne CO_2e is generated for producing an EV, which is much higher than the 9.2 tonne of an ICEV [222,223]. Around 35–50% of the total GHG emissions in the production phase of an EV is due to the production of the battery system [83,222]. Thus reusing and recycling of batteries in the end-of-use phase of EVs can significantly improve the resource efficiency of batteries and cut GHG emissions. Conservatively secondary use of EV batteries could cut 50% GHG emissions from battery production, although this could also be affected by the source of electricity used to produce batteries where different carbon footprints or emission factors exist [222]. Using renewable electricity could significantly mitigate GHG emissions in producing Li-ion batteries. GHG emissions caused by direct electricity consumption during cell production drops 57% when coal-dominated electricity is changed to photovoltaic electricity, due to the much lower carbon footprint of photovoltaic electricity [222].

Large-scale EV grid integration needs to ensure successful management of charging/electricity demand peaks [40]. EV charging stations have slow and fast charging. The former has uniform charging standards across all vehicle brands, and is usually located at home or workplace by business owners or government programs. Solar photovoltaics (PV) powered charging points deployed at public car parks could be a new business model likely to grow [224]. Wireless (inductive) charging on road is also gaining attention, e.g. semi-dynamical charging at congested areas such as intersection and waiting lanes, or dynamical charging at certain lanes of highways or roadways [225]. Fast-charging is mainly invested by automakers, around three different charging standards are developed, each not interoperable with the others. Coordinated charging to avoid creating a new peak demand could be difficult, which needs to integrate different charge point brands of different customers. On the other hand, developing common transportation systems and interoperability could facilitate the efficient delivery of reliable and sustainable electrical power. Different market players; automakers, energy suppliers and technology companies, can provide a

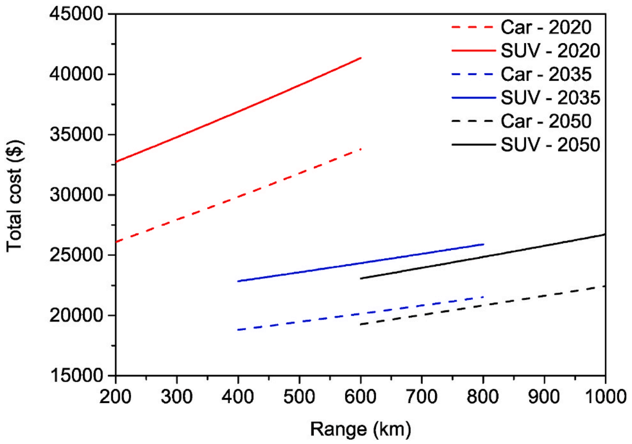


Fig. 14. Projected total EV cost in 2020, 2035 and 2050, as a function of vehicle range.

bulk common groundwork for all participants and enable them to collaborate to optimise charging events. Interoperability of charging systems of different vehicle models and charging infrastructures, i.e. any BEV can charge at any charger, can be achieved by using standardised/common communication protocols and uniform interfaces. This could assure interoperability between new and legacy vehicles accessing fast charging and existing transportation networks, which are critical for coordinating charging demand in electricity grids.

Fast-charging could mitigate range anxiety and thus enable manufacturers to reduce battery size and weight. Similarly, developing a common battery swapping system may lower the requirement for battery capacity, reducing the weight and cost of vehicles. Batteries may also be hired instead of owned. Through battery leasing, customer would own the car but not the batteries, which could potentially overcome the big barrier of high battery cost. The successful deployment of a common battery swapping system depends on a unified battery pack design with interoperability between different models, irrespective of the chemistry among OEMs.

5.2. *Shared mobility*

One important way of reducing indirect cost could be developing shared electric vehicles in high volume production. Car-sharing has seen an increasing development in recent year, it is expected to be significantly deployed in the future. Instead of selling a product as in the traditional go-to-market model, Automakers can switch over to selling e-mobility as a package or service, acting as mobility providers and/or operators in a way similar to bike-sharing [226]. BEVs are attractive for shared mobility operators due to low operating cost, which could compensate for their higher manufacturing/purchase prices.

Table 3
Reduction (%) in electricity usage due to a range of efficiency factors.

Efficiency factor	Electricity usage reduction
Reduction in average engine power from 173 kW to 74 kW	5.8%
Reduction in average frontal area from 3.42 m^2 to 2.63 m^2	7.9%
Average range remains at 400 km, and not 800 km	7.0%
Battery power density average improvement from 0.15 kWh/kg to 0.27 kWh/kg	6.1%
Vehicle mass reduces from 1863 kg to 1273 kg	9.1%
All of the above changes occur together	27.3%

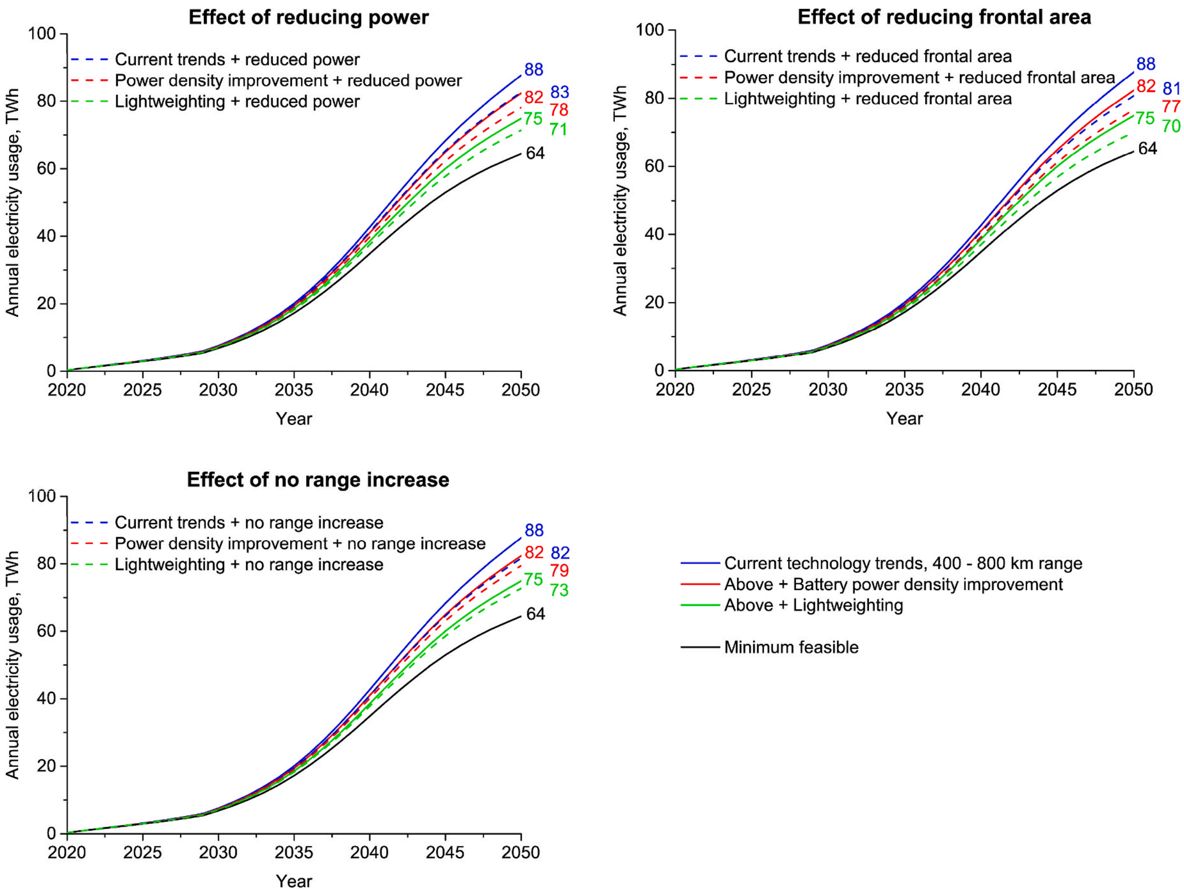
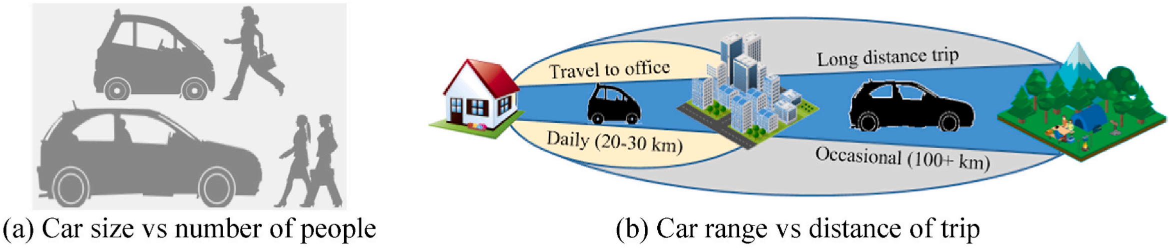


Fig. 15. Projected annual electricity usage by EVs over time.



(a) Car size vs number of people (b) Car range vs distance of trip

Fig. 16. How people choose a shared car.

For shared cars, colour or aesthetics become less important, the car model has a limited type (greatly decreased car model design) or is purpose-built. Individual tailored styles become less important and the functions/costs will be a dominant factor for people to choose a car for their travel. By standardisation of specification and decrease of individuality (model design), it is much easier to achieve large volume production, and the R&D cost of shared electric vehicles could be greatly reduced by large volume production. Also, there will be reduced cost coming from ease of management. As shown in Fig. 16, consumers are offered a customised choice of vehicle models according to their needs. A consumer could choose a vehicle model with smaller size and lower travel range to go to work or commute in the city on weekdays (short trips), and then replace it with a larger SUV with higher travel range for a weekend road trip.

Opinions vary among regulators and manufacturers with regard to the cost in the real world for using lightweight materials to achieve greater weight reduction. This is largely because there are numerous attributes of each vehicle model which are unique to that model and affect its lightweighting. 'Proof of concept' studies have been concentrated simply on reducing weight without fully considering the real world constraints such as the time for development and qualification of new materials, the cost of switching over to new infrastructure, global platforms, and customer demand for extra vehicle content [86]. As mentioned before, shared cars could occupy large amount of future mobility. As the shared car model has a limited type by standardisation of specification and decrease of individuality, the costs of utilising lightweight materials on shared electric vehicles could be largely mitigated due to large volume production.

5.3. *Advanced sensing technology*

One promising way to greatly reduce vehicle weight is to reduce the unnecessary structures/components and make it more compact. Earlier safety improvements tended to add components/structures and increase the thickness of materials, which also increased vehicle weight and cost. The energy-absorbing front crash structure is usually designed to be tough enough to satisfy all crash criteria. With the development of autopilot technology, which provides parking assistance, lane positioning, collision avoidance and warning and alerting functions using video, sensor, radar, and sonar monitoring (Fig. 17), future car should be much safer where there is less possibility for collision to happen. Thus the safety structures/components used in the current car which add weight and cost will be no longer needed. Meanwhile, the indirect R&D cost used to satisfy the safety requirement such as various collision tests can be saved.

Traditionally, the potential of lightweighting as an approach to improving fuel economy was never realised as safety aspects dominated design. Lightweight materials can be used to replace traditional steel parts to reduce weight. However, the safety requirement limits the potential of how much lightweight materials can be used. As mentioned above, when the safety of the car can be guaranteed using advanced technologies such as sensors and radar, passive safety is less important. Then probably a much higher proportion of lightweight materials such as aluminium, polymer composite or plastics can be used. Although their current use in vehicles is limited due to the higher cost, however all these can be mitigated with large volume production and standardisation of model design.

One of the main challenges faced by road transportation is the increasing traffic congestion, which could increase electricity consumption and charging demands. The solution could either be increasing the number of roadway infrastructure or improving the existing infrastructure. The former is generally not preferred due to increasing cost, environmental impact, and space limitations. Technology development in computers, communications, and sensors could transform road transportation into an effectively managed and well-integrated system, where collaborative driving can be implemented using real-time traffic

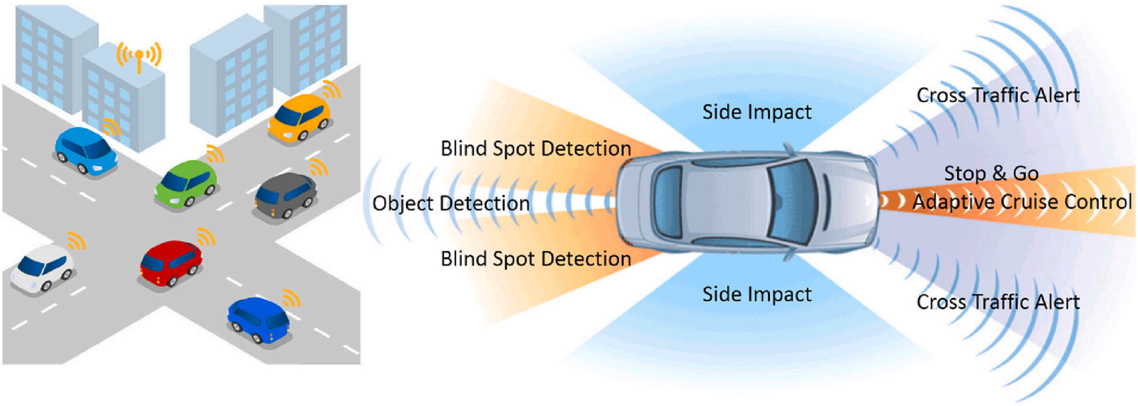


Fig. 17. Sensors used to replace conventional components/structures for safety and reduction of weight and cost.

information. Integration of shared mobility and collaborative driving, enabling interoperability throughout the transportation network, could be a promising solution to traffic-related issues, including route guidance, traffic collision and congestion management and control.

5.4. Novel compact spaceframe body structure

The proper utilisation of extruded (and formed) profiles enables manufacturers to develop novel structural design solutions by integrating parts and incorporating additional functions, which could lead to significant cost and weight savings [227].

Due to the high flexibility of spaceframe structure, the spaceframe design can be further developed with the combination of dedicated global platforms and the body structure can be redesigned to be much compact. Possibly more continuous curved lengths of aluminium extrusion profiles can be utilised to design the optimised compact body structure with greatly reduced weight and increased rigidity.

In this compact aluminium spaceframe body structure, there is also a considerable fraction of shaped sheet components/panels. Particularly, the panels mounted between the frame elements are just for decoration of the body structure, which could possibly be made using lightweight polymer composite or plastics. Generally, the spaceframe results in a high-strength, stiff framework where the larger panels are integrated. Although the production of high quality structural sheets of polymer composite or plastics and extrusion sections of aluminium could be costly, total cost savings can be considerable for large production volumes and standardisation of model design. A similar example of this kind of novel compact spaceframe body structures is shown in Fig. 18, which is Audi M1 2 + 2 concept spaceframe with a distinctive modular interior [228]. It can be switched from the conventional 2-seat layout to the 2 + 2 configuration when the front seats slide back along rails mounted at the bottom. The 2 + 2 configuration maximises the vehicle's carrying capacity, which gives it the uniqueness of transporting up to 4 passengers in an area of less than 2.8 m^2.

5.5. Policy recommendation

5.5.1. Support lightweighting and shift towards shared mobility

Current lightweighting technology mainly focuses on materials substitution of lighter materials, whose weight reduction effect has largely been offset by the increasing size and content (safety, air-conditioning etc.) of vehicles. Consumers are favouring larger and heavier SUV-type vehicles, which are perceived as being safer than smaller vehicles. Manufacturers sell larger vehicles for higher profits. The status quo is hard to shift because of close alignment of the motivations of consumers and manufacturers. A possible solution is to pass government regulations limiting weight of each manufacturer's new car fleets, and incentivise manufacturers to produce and consumers to buy smaller cars. This could be supported by taxing vehicles by weight and expanding the practice of differentiating tax rates to cover all years of ownership. By pairing a tax by weight with a partial rebate for EVs, the government could provide a dual incentive to support the introduction of smaller, more efficient vehicles while accelerating the adoption of EVs. Lighter new cars could come with much longer warranties and new apps to support shared mobility. Policies on taxes and subsidies could also be introduced to support shifts in preferences from private car towards shared mobility and public transport.

5.5.2. Expand non-emitting electricity generation

Due to the high upfront cost, solar charging stations for EVs are more favourably installed in commercial car parks for business. Solar capacity could significantly increase if supported by more ambitious policy, for example if linked to housing policy. Government could use subsidies to encourage anyone who owns a solar energy system to install a solar charging station at its home. This could also come with government housing policy for new-build or retrofitting programmes. Off-grid solar charging station stores the power in solar batteries for future use. A grid-tied (on-grid) solar energy system will feed the power to the grid, by doing so the power is sold to the utility company and can come back in the form of a credit, which can be used to recharge EVs at home.

Crucially, our work highlights the enormous challenges posed by the electrification of the whole economy, here in the case of individual mobility. High levels of investment are necessary to meet this challenge, and should cover all forms of low-carbon energy, from renewable generation to nuclear power.

6. Conclusions

The successful deployment of BEVs depends on several key factors which are closely linked: Government policy, cost reduction, and range increase. A great benefit to the environment, this transition will come with an important challenge in the production of electricity.

Currently the main price differential between BEVs and ICE vehicles comes from powertrain (battery, motor) and indirect cost related to research and development (R&D), administration (overheads). Material costs account for $\sim$60% of the total battery cost and $\sim$52% of the PM motor cost. New battery chemistry technologies are being explored to reduce the materials/battery cost and improve battery capacity, potentially reducing battery volume (weight). New rare-earth-free materials are being researched to replace the expensive rare earth magnets. Also, design optimisation technique and additive manufacturing technique (3D printing) are being used for motor structures to improve cooling ability (surface area) and reduce motor size/weight, which also potentially reduce motor cost due to less usage of rare-earth magnets.

Fig. 18. Audi's compact spaceframe construction (aluminium tubular frame dressed with a carbon-fibre composite outer body, and mounted on a platform that integrates the battery pack).

The price differential between EVs and ICEs is expected to disappear with new batteries and improved platforms. The advances in battery technology will probably help overcome the most important barrier to adoption, range anxiety. This gives us confidence that the optimistic time-lines for the electrification of individual mobility will be realised. However, this implies a considerable increase in the demand for electricity.

Even realising all of the technical potential is likely not sufficient to avoid an energy crush and a shift in usage patterns is required. We find that the technical potential for abating this demand is only 24 TWh, out of a total worse case of approximately 90 TWh yearly demand. This in turn means that use patterns of cars will need to change so that the demand for mobility can be met. Shared mobility could be largely deployed in the future with government support, providing the missing link.

The trend to shared mobility helps mass production and thus resulting in cost reduction. Coordinated fast charging enabled by interoperability facilitates management of charging demand and large scale integration of BEVs into the smart grid with a minimal effect. Breakthroughs in car design taking advantages of sensing technology and novel frames are probably needed to reduce weight and electricity demand, which could probably work in tandem with shared mobility and interoperable charging technology. Non-emitting electricity generation is likely in need of significant expansion by more ambitious government policies.

Author statement

Wenbin Zhou: Conceptualization, Methodology, Investigation, Data curation, Writing – original draft. Christopher J. Cleaver: Conceptualization, Methodology, Software. Cyrille F. Dunant: Writing- reviewing & editing, Visualization. Julian M. Allwood: Supervision, Funding acquisition. Jianguo Lin: Conceptualization, Supervision, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

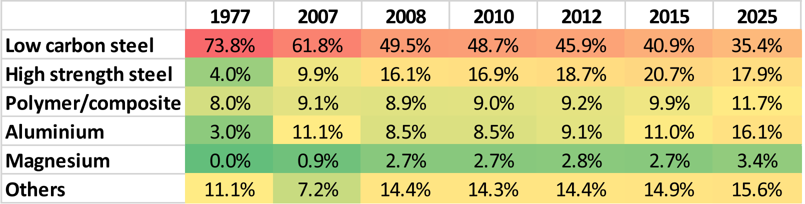
Data availability

No data was used for the research described in the article.

Acknowledgements

The authors would like to thank the funding support by EPSRC under the Grant Agreement EP/S019111/1 on “UK FIRES: Locating Resource Efficiency at the heart of Future Industrial Strategy in the UK” and EP/R001715/1 on “LightForm: Embedding Materials Engineering in Manufacturing with Light Alloys”.

Appendix A. Dataset for the evolution of average material content of vehicles



	1977	2007	2008	2010	2012	2015	2025
Low carbon steel	73.8%	61.8%	49.5%	48.7%	45.9%	40.9%	35.4%
High strength steel	4.0%	9.9%	16.1%	16.9%	18.7%	20.7%	17.9%
Polymer/composite	8.0%	9.1%	8.9%	9.0%	9.2%	9.9%	11.7%
Aluminium	3.0%	11.1%	8.5%	8.5%	9.1%	11.0%	16.1%
Magnesium	0.0%	0.9%	2.7%	2.7%	2.8%	2.7%	3.4%
Others	11.1%	7.2%	14.4%	14.3%	14.4%	14.9%	15.6%

Appendix B. Cost decomposition and comparison of BEVs and ICE vehicles

Fig. B1a shows the cost breakdown of conventional ICE and electric vehicles in 2018 and 2025 (projected) for cars and SUVs [170]. BEV powertrain (excl. battery) includes motor, transmission system, and related power electronics (inverter/converter, power control unit, on-board charger). Conventional ICE powertrain includes engine, transmission, exhaust, etc. Other direct cost includes vehicle assembly (primarily body and chassis) materials and staff cost, supplier components (interior, safety, etc), optional features cost [171]. It also includes the incremental costs of vehicle improvements needed to meet efficiency standards. Indirect cost is all remaining costs excluding the powertrain and other direct cost, including research and development (R&D), administration (overheads), depreciation, and amortization, etc. Fig. B1b shows costs relative to conventional ICE vehicles (conventional ICE = 1). The cost increase (~$700) for ICE cars in 2025 is due to increases in other direct cost and powertrain to improve vehicle performance and meet efficiency standards. For the ICE SUV, the related cost increase is greater at ~$1000. The significant decline in BEV cost in 2025 is mainly due to the decline in battery pack cost (~$3900 for BEV200-car, ~$6000 for BEV200-SUV) and indirect cost (~$5900 for BEV200-car, ~$8500 for BEV200-SUV). Meanwhile the cost of BEV powertrain (excl. battery) marginally decreases (~$420 for BEV200-car, ~$620 for BEV200-SUV) and the other direct cost decreases slightly (~$740 for BEV200-car, ~$850 for BEV200-SUV). By 2025, the price of BEVs is expected to reach parity with ICE vehicles.

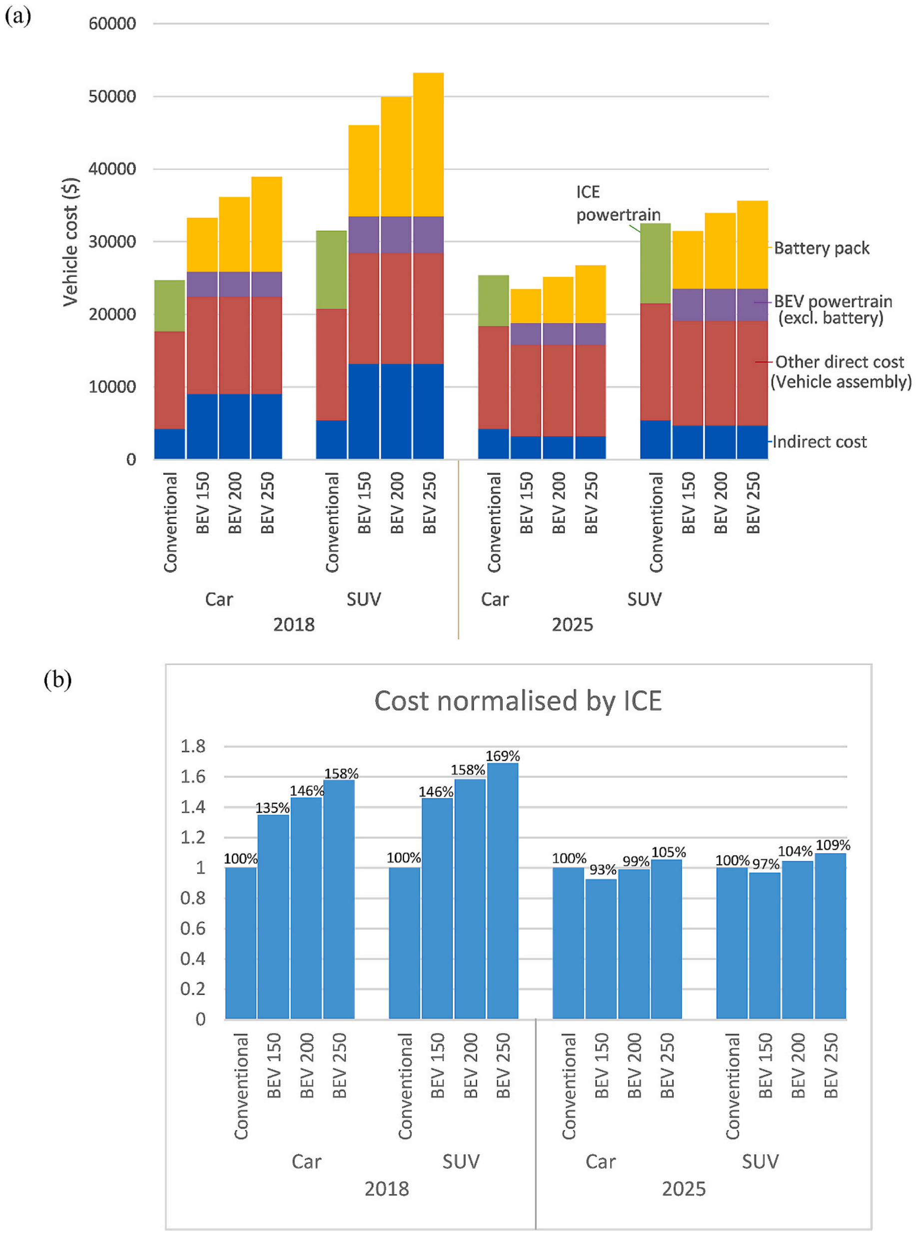


Fig. B1. (a) Cost breakdown of conventional and electric vehicles in 2018 and 2025 for cars and SUVs, (b) cost comparison using conventional ICE vehicle as baseline cost (conventional ICE = 1). 150, 200, and 250 represent travel range in miles. Data adapted from [170].

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