

Review

A review of current and future powertrain technologies and trends in 2020

Graham Conway^{a,*}, Ameya Joshi^b, Felix Leach^c, Antonio García^d, Peter Kelly Senecal^e^a Southwest Research Institute, United States^b Corning Incorporated, United States^c University of Oxford, United Kingdom^d Universitat Politècnica de València, Spain^e Convergent Science, United States

ARTICLE INFO

Keywords:

Market review

Powertrain technology

ICE

Hybrid

Battery

Light-Duty

ABSTRACT

Fossil fuels are currently the most convenient on-board energy sources for vehicles in terms of energy density and refueling time. However, the increase in global temperature together with the increase in transported people and goods in recent years has forced regulatory authorities around the world to establish strict regulations on pollutant and CO₂ emissions. These scenarios are challenging for vehicle manufacturers, but they also create opportunities for the development of new technologies and concepts. For example, automotive companies and researchers are currently exploring hybrid powertrains with either advanced internal combustion engine technologies and low levels of electrification, or with high levels of electrification combined with simpler internal combustion engines. While these hybridization approaches can provide significant improvements in efficiency and emissions. There is also a global movement at the, consumer, manufacturing and government level to accelerate the adoption of zero tailpipe emitting vehicles (e.g., battery electric vehicles and fuel cell electric vehicles). This paper reviews the current state of powertrain technologies, analyzing first the evolution of emissions regulations in major markets and emphasizing the future tighter measures that will be adopted in Europe and the US. After that, an analysis of current global vehicle sales considering the COVID situation is performed, followed by a forecast of future powertrain technology market share trends. Finally, reviews of internal combustion engine, hybrid, and battery electric vehicle technologies announced in 2020 are carried out.

1. Introduction

The strict regulations on criteria pollutant and CO₂ emissions established around the world will force humanity to stop using fossil fuels for transportation in the next years, despite being the best on-board energy sources in vehicles in terms of energy density and refueling time. In this sense, the established tailpipe CO₂ limits will require a reduction of 3,4% per year in this decade in major markets. Concerning other pollutants, the current scenario shows that gas emission limits in the

USA are the strictest in the world, while the European PN limits have driven a broader adoption of particulate filters, including for gasoline vehicles. Moreover, future regulations such as Euro 7 in Europe and LEV IV/Tier 4 in the USA will tighten the emissions targets focusing on further reductions in NO_x and particulate limits, while also including new species and new procedures to emphasize the cold start contribution. With the adoption of the final Euro 6d regulations and on road testing requirements, modern Euro 6d vehicles are becoming more compliant with NO_x emissions that are well below the laboratory limits

Abbreviations: AI, artificial intelligence; BEV, battery electric vehicle; BTE, brake thermal efficiency; BSFC, brake specific fuel consumption; CARB, California air resources board; CF, conformity factor; CO, carbon monoxide; CO₂, carbon dioxide; DHE, dedicated hybrid engine; EPA, environmental protection agency; EV, electric vehicle; EU-27, 27 countries in the European union; FCEV, fuel cell electric vehicle; FE, filtration efficiency; FTP, federal test protocol; GDI, gasoline direct injection; GHG, greenhouse gas; GPF, gasoline particle filter; HC, hydrocarbons; HD, heavy-duty engine; HEV, hybrid electric vehicle; ICE, internal combustion engine; LD, light-duty engine; LEV, low emission vehicle; LNT, lean NO_x trap; ML, machine learning; MY, model year; NEDC, new European drive cycle; NEV, new energy vehicles; NHTSA, national highway traffic safety administration; NMOG, non-methane organic gases; NO_x, oxides of nitrogen; PEMS, portable emissions measurement systems; PFI, port-fuel injected; PHEV, plug-in hybrid electric vehicle; PN, particle number; RDE, real-world driving emissions; SAFE, safer affordable fuel-efficient; SCR, selective catalytic reduction; SUV, sport utility vehicle; VAT, value added tax; WLTP, world harmonized light vehicles test procedure; ZEV, zero emission vehicle.

* Corresponding author.

E-mail address: graham.conway@swri.org (G. Conway).<https://doi.org/10.1016/j.treng.2021.100080>

Received 10 May 2021; Received in revised form 18 June 2021; Accepted 22 June 2021

Available online 24 June 2021

2666-691X/© 2021 The Authors. Published by Elsevier Ltd. This is an open access article under the CC BY license (<http://creativecommons.org/licenses/by/4.0/>).

even when tested on road [1]. In spite of this, several countries have announced targets for eliminating the internal combustion engine (ICE) by 2025–2040. For this reason, current research is focusing on developing alternative technologies that address the tank-to-wheel CO₂ targets and the air quality concerns in city centers. Electrification will play a key role to reach those targets, starting with the wide-spread adoption of hybrid electric vehicles (HEV) and then looking towards the zero tailpipe emissions vehicle (ZEV) concept, including battery electric vehicles (BEV) and fuel cell electric vehicles (FCEV). The sales trends in 2020 suggest that the global sales of BEVs may continue growing exponentially as the battery-pack cost reduces from the current \$137/kWh and the charging infrastructure increases. With the current growth rate scenario, it is assumed that the 50% BEV adoption point will occur globally around 2040. This will be feasible as battery prices drop significantly in this time frame. The opportunity for increased market penetration of these technologies in the near term is greater for light-duty than for medium- and heavy-duty applications, due the prohibitive battery weight and size, which impact the payload and total cost of ownership. However, considering the evolution of the materials and cost of the batteries it is also expected that these technologies can reach the medium- and heavy-duty sectors in the next decades. At some BEV penetration ‘pushback’ may occur where even the most capable, affordable BEV cannot replace an ICE equivalent for numerous reasons detailed within this paper. The timing and adoption level at the point of pushback is not clear.

This emissions regulations context results in the need for accelerating the technology development to increase efficiencies and reduce the emissions from ICE and hybrid technologies. For this, artificial intelligence (AI) and machine learning (ML) techniques in engineering simulation and design software are increasingly being used. In the heavy-duty sector, the increase of the peak firing pressure, optimization of the fuel-air mixing and the air path, use of exhaust energy recovery, reduction of the friction through lubricants, use of new piston designs and improvement of the engine control have been found suitable strategies to allow breaking the 50% BTE barrier. Light-duty vehicle technologies tend to implement downsizing, boosting, exhaust-heat energy recovery and high compression ratio to increase efficiency and reduce the emissions. Moreover, the addition of hybridization in the light-duty sector has been proved to provide fuel economy gains of around 35% over urban-like driving cycles. This improved efficiency, combined with the new engine exhaust aftertreatment technologies have led to near-zero criteria pollutant emissions for the current vehicles, even during real driving emissions (RDE) tests.

2. Regulations

2.1. Greenhouse gas emission regulations

Road transportation globally accounts for roughly 15% of global CO₂ emissions. About half of these emissions are attributed to the transportation of people via cars and buses [2]. This sector is under significant pressure to reduce greenhouse gas (GHG) emissions associated with fuel combustion, given the dire need to address climate change. Most major automotive markets have established tailpipe CO₂ limits, and these are summarized in Fig. 1. While there are important differences in the measurement methods across these countries, broadly it is seen that meeting the requirements will require a reduction of 3–4% per year in this decade.

Europe has set the most stringent targets for CO₂ tailpipe emissions at less than 59 g/km in 2030, requiring a 37.5% reduction through this decade. There are discussions underway to further revise the target downwards to align it with the European Green Deal [3], which aims for net-zero greenhouse gas (GHG) emissions by 2050. These changes are expected to be published in the European Climate Law in June 2021 [4].

In the US, the Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) issued the Safer

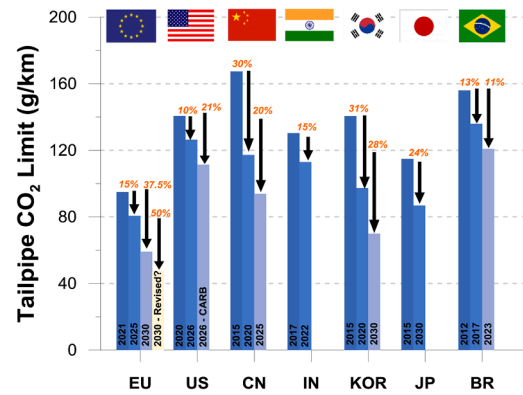


Fig. 1. Summary of CO₂ targets for light-duty passenger cars in major markets. The US numbers are for passenger cars with a footprint > 56 ft² as an example. The China 2025 number is calculated based on the targeted reduction in fuel consumption from 5 L/100 to 4 L/100 km.

Affordable Fuel-Efficient (SAFE) vehicles rule, which requires ~ 1.5% reductions in tailpipe CO₂ emissions for model years 2021 through 2026 [5]. The targets are more stringent in the state of California, where OEMs have signed a voluntary agreement for 3.7% CO₂ reductions year on year. As this article is being written, there has been a recent change in administration, and there are indications that the national standards will be reviewed and possibly made more stringent. Also, the rulemaking for post-2026 model years is expected to begin and result in further tightening of CO₂ limits.

In China, passenger cars must meet fuel consumption reduction of 20% from 2021 to 2025, with average tailpipe CO₂ at 95 g/km by 2025 on the New European Drive Cycle (NEDC). In the latest Technology Roadmap [6], China is targeting peak CO₂ emissions from the transportation sector by 2028 and a subsequent 20% reduction in CO₂ by 2035. By then, the market for new vehicles is expected to be evenly split amongst hybrids and battery electric vehicles.

2.2. Criteria pollutant emission regulations

Tailpipe limits on criteria pollutants – which include particulates, and gases such as oxides of nitrogen (NO_x) and carbon monoxide (CO) – continue to be lowered across developed automotive markets. Fig. 2 shows the case for the US, where tailpipe standards are set for particulates and combined non-methane organic gases (NMOG) and NO_x. It is seen that compared to model year 2000, gas and particulate emissions from modern light-duty vehicles will be required to reduce by ~ 90% and ~ 99%, respectively by 2025. Emissions are measured in the lab using a chassis dynamometer on test cycles such as the FTP-75 (Federal

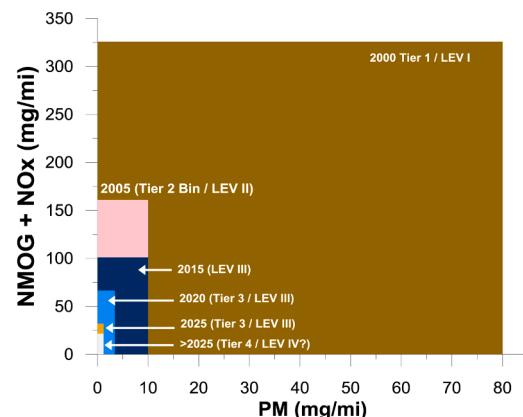


Fig. 2. US tailpipe emissions standards.

Test Procedure).

Europe has also set increasingly stringent criteria pollutant standards, which have been adopted (with some important changes) by other countries such as China and India. NO_x limits are set at 80 mg/km and 60 mg/km for diesel and gasoline passenger cars, respectively, and are measured on the WLTP (World harmonized light vehicles test procedure). Unlike the US, where particulate emissions are regulated on a mass basis alone, Europe has also set a particle number (PN) limit of 6×10^{11} #/km. To ensure compliance with the regulated limits under normal on-road driving conditions, vehicles are also required to be tested under real-world driving emission (RDE) conditions, in which the vehicle is driven for ~ 90 –120 min on urban, rural and motorway routes. The total and urban emissions must meet the laboratory limits multiplied by a “conformity factor” (CF) which provides an allowance for measurement errors associated with portable emissions measurement systems (PEMS). The CF for NO_x has been reduced from 2.1 to 1.43 and will be reduced to 1.0 starting in 2022. For PN, the CF is currently 1.5, although there has been a recommendation [7] to also lower this to 1.34 given the improvements in measurement capabilities. While a detailed discussion of emission after-treatment systems is beyond the scope of this paper, broadly it can be stated that the US gas emission limits are the tightest in the world and have driven advanced technologies for reducing NO_x , while the European PN limits have driven a broader adoption of filters, including for gasoline vehicles.

Other major automotive markets such as China and India broadly follow either the European or US frameworks. The latest China 6b regulations which go into effect starting in 2023 are in some ways even tighter than Europe, with the gas limits set at roughly a factor of two lower compared to Euro 6.

Formal proposals on the next set of regulations are not yet published. However, discussions are ongoing and here are a few key elements being discussed for Euro 7:

- Technology and fuel neutral standards, primarily eliminating the different NO_x limits for diesel and gasoline engines, and extending the PN limit for all vehicles.
- Further reduction in NO_x and possibly PN limits. CO to also be limited on the RDE test.
- PN limit to include sub-23 nm particles, likely down to 10 nm.
- New species to be regulated, including aldehydes and ammonia, and methane and N_2O to be accounted for as GHGs.
- Modifying the RDE test to include a shorter urban driving distance and emphasize the cold start contribution.

The California Air Resources Board (CARB) held a workshop [8] to discuss potential changes to US criteria pollutant regulations as part of a LEV IV rulemaking. Some of the topics under consideration are:

- Fleet averaged limits on NMOG + NO_x emissions at 20 mg/mi (SULEV 20), a 33% reduction compared to the fleet averaged emissions in 2025, and with limits potentially applying to the non-ZEV portion of the fleet.
- Further tightening of cold start emission requirements: Testing to include varying cold soak durations, and a reduction of the idling time in the FTP. A limit for high-powered cold start emissions from plug-in hybrids.
- Tightening of the PM limit under US06 (aggressive driving) by a factor of two, to 3 mg/mi.

The timing on the next regulations in Europe and the US have not been announced but they will likely be implemented in the second half of this decade. The key takeaway from the above summary is that compliance with the future standards will ensure a significantly cleaner fleet, with tailpipe emission concentrations nearing, and at times even lower than, ambient levels.

2.3. Real-world performance vs. targets

To put the CO_2 targets discussed earlier in perspective, it is useful to look at the past trends in improving vehicular CO_2 emissions. Fig. 3 summarizes the significant reductions in fuel consumption achieved in the past couple of decades through improvements in both engines and vehicles. After years of lowering tailpipe CO_2 , it is seen that the improvements have stalled in the last few years. In 2019, CO_2 emissions from passenger cars in Europe increased for the third consecutive year reaching 122.4 g/km (NEDC), an increase of 2 g/km compared to 2018 [9]. The auto industry is facing heavy fines for likely missing the 2021 target of 95 g/km. In the US, the average real-world CO_2 emissions for new vehicles in 2019 increased by 3 g/mi to 356 g/mi compared to the previous year [10]. To ensure that the CO_2 reductions are achieved in-use and not only during certification, new regulations in Europe require on-board monitoring of fuel consumption starting model year 2021.

At least partly, the increase in CO_2 emissions can be attributed to a growing consumer preference for larger (heavier) vehicles: only one third of new vehicles sold were sedans, while the rest were larger SUVs, pickup trucks and minivans. The market share of diesel cars in Europe has declined significantly from almost 50% in 2015 to < 30% in 2020 – again partly leading to this increase in CO_2 emissions. Given the higher fuel economy of diesels (compared to gasoline vehicles), the reduced diesel sales makes the target even harder to achieve. It is evident that a significant uptake of advanced ICE technologies, hybridization and full electrification is imperative to meet the future limits.

Recent years have seen significant advances in both engines and after-treatment systems for meeting criteria pollutant standards [12]. Fig. 4 below shows two example studies which reported on-road NO_x emissions from modern Euro 6 RDE compliant as well as older legacy fleet vehicles. The data highlights the poor performance of Euro 6b and older diesel vehicles which have been found to emit high NO_x while meeting the standards under lab testing. On the other hand, it is seen that RDE norms have been successful in overcoming this limitation: modern Euro 6d compliant vehicles are emitting well below the laboratory limits even when tested on road. Gasoline vehicles are also well within the respective limits and have much better control of NO_x emissions compared to diesels. Future regulations will likely address this gap through technology neutral limits.

2.4. ICE bans

In response to the need to reduce CO_2 emissions, several countries have announced targets for eliminating the internal combustion engine, some of which are summarized in Table 1. There is a spread in the target dates: Norway is targeting the phase out of ICEs by 2025 while countries such as France, Spain and Canada are targeting 2040. The UK has announced a ban on pure ICE petrol and diesel vehicles starting 2030, and hybrids to follow in 2035. In the US, California’s governor issued an executive order also targeting 100% sales of new light-duty vehicles in the state to be zero tailpipe emitting beyond 2035. States such as New York and New Jersey have pledged to also adopt the California targets, although there was no formal executive order issued. Note that the California decision is a target at the time this is being written, and details on the regulatory framework to enable such a transition should be forthcoming in the following years. According to the analysis done by the International Council on Clean Transportation (ICCT), the 17 governments which have announced ICE bans account for 13% of the global light-duty vehicle sales [15].

3. Market analysis & forecasting

Global sales of passenger cars and light commercial vehicles have been declining since 2017. However due to COVID-19, a more substantial sales decrease of 14% from 83.7 million to 72 million vehicles

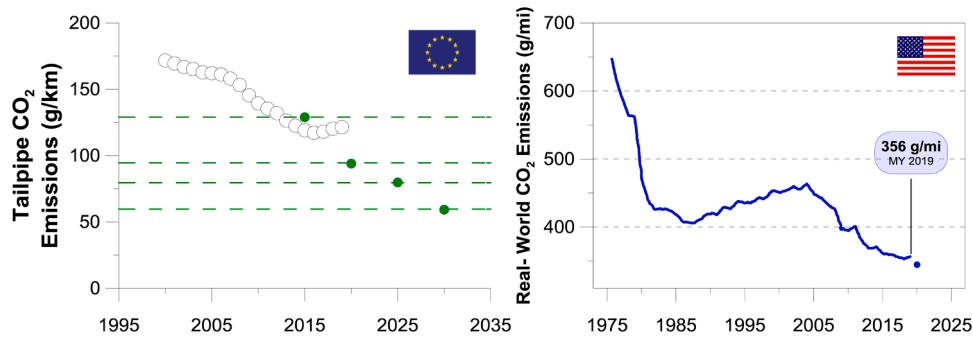


Fig. 3. CO₂ emissions from passenger cars in Europe [9] (left) and light-duty vehicles in the US [11] (right).

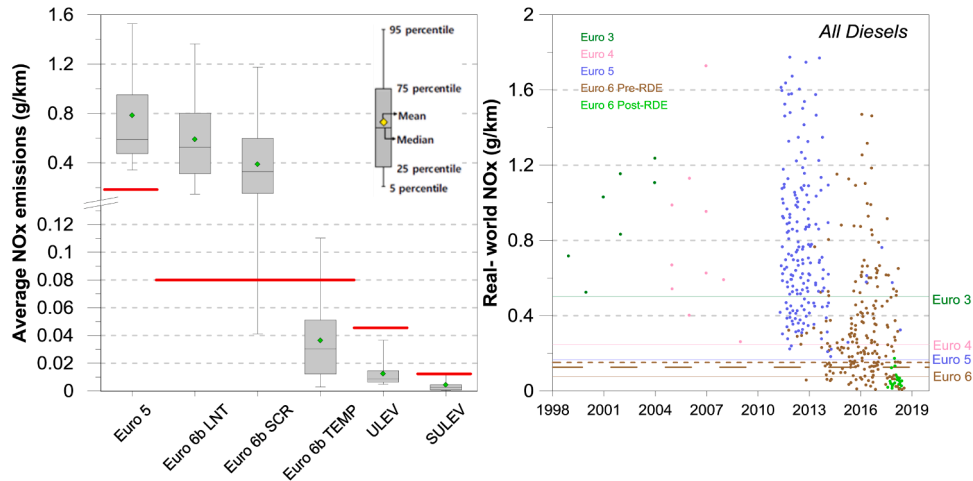


Fig. 4. On-road NOx emissions measured from 74 diesels and 35 gasoline vehicles covering model years 2012–2019 (left) [13], and on-road NOx emission measurements covering Euro 3 – Euro 6 diesel vehicles, (right) [14]. Lines on both plots show the respective regulatory NOx limits at each stage. LNT and SCR are commercialized deNOx after-treatment technologies.

Table 1

Target bans on the ICE announced in various regions of the world.

Target ICE ban	Region
2025	Norway
2030	UK: Pure ICE vehicles; Iceland, Ireland, Israel, Netherlands, Sweden, Hainan (China)
2035	UK: Hybrids; California (US), Columbia
2040	Canada, Egypt, France, Spain, Sri Lanka, Taiwan

occurred from 2019 to 2020 (Fig. 5). Unemployment rates rose to nearly 15% in the USA [16] while gross domestic product dropped by 25% from Q1 to Q2 in 2020 [17]. The drop in automotive sales is attributed to the weaker economy.

Comparing quarterly sales figures between 2019 and 2020 highlighted the challenges caused by COVID-19 (Fig. 6). Sales in Quarter 1 (January–March) and Quarter 2 (April–June) dropped sharply. For example, the United Kingdom registered just 7905 vehicle sales in April 2020 compared to 185,000 over the same period in 2019. While this is primarily caused by economic factors, another barrier was global ‘lockdowns’ which prevented people from visiting dealerships. However, a strong recovery in Quarter 3 (July–September) and Quarter 4 (October–December) saw sales improve to 2019 levels. A strong recovery is predicted in the coming years with sales expected to reach a record high by 2024 [18].

Global

Despite economic challenges associated with the pandemic and an overall decrease in vehicle sales, electrified vehicle sales and their

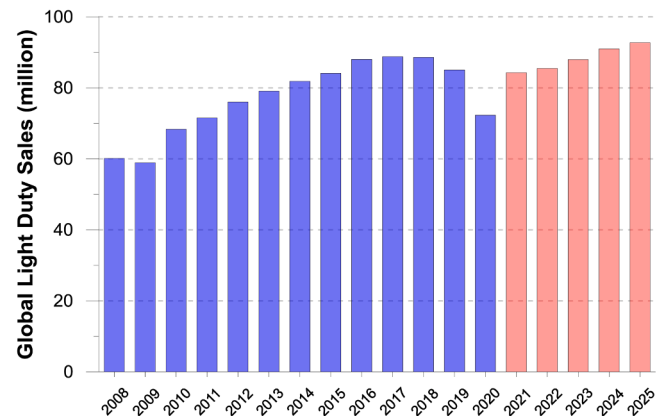


Fig. 5. Global sales of light-duty passenger and light commercial vehicles. Historic data provided by Marklines database, future sales predictions by IHS Markit.

market share increased compared to 2019 levels (Fig. 7). The global hybrid electric vehicle (HEV¹) share increased to 3.2% of total sales compared to 2.8% in 2019. Plugin hybrid electric vehicle (PHEV) sales experienced the largest growth of any electrified segment with market share doubling from 0.6% to 1.2%. Battery electric vehicle (BEV) share

¹ HEV includes 48 V mild hybrid to full hybrid powertrains.

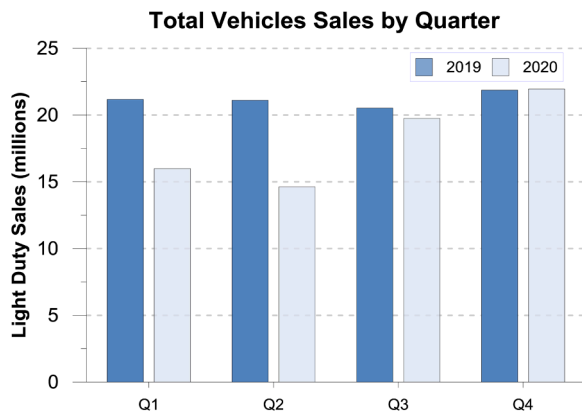


Fig. 6. Global light-duty sales in 2019 and 2020 by quarter.

The EU-27 countries experienced significant electrified vehicle market share growth despite the pandemic. The market share of BEVs increased from 1.1% in 2019 to 3.6% in 2020 while the PHEV share increased from 0.6% to 3.4%. The HEV share also grew but only by 0.6% to end 2020 with a share of 2.7%. The share of plug-in vehicles (BEV & PHEV) was 7%, up from 1.7% in 2019. Overall nearly 10% of vehicles sold in EU-27 countries in 2020 were electrified compared to just 4% in 2019. Increasing incentive programs were largely responsible for the increase as well as gradual improvements in charging infrastructure, vehicle performance, and the availability of new models [19].

China

The Chinese light-duty automotive market saw steady growth in all electrified segments. The BEV share for 2020 was 4.3% which represents nearly 20% of total global BEV sales. Financial subsidies for 2020 new energy vehicles (NEV) were available in China based on battery size and charging speed, but these are now reducing each year and are set to

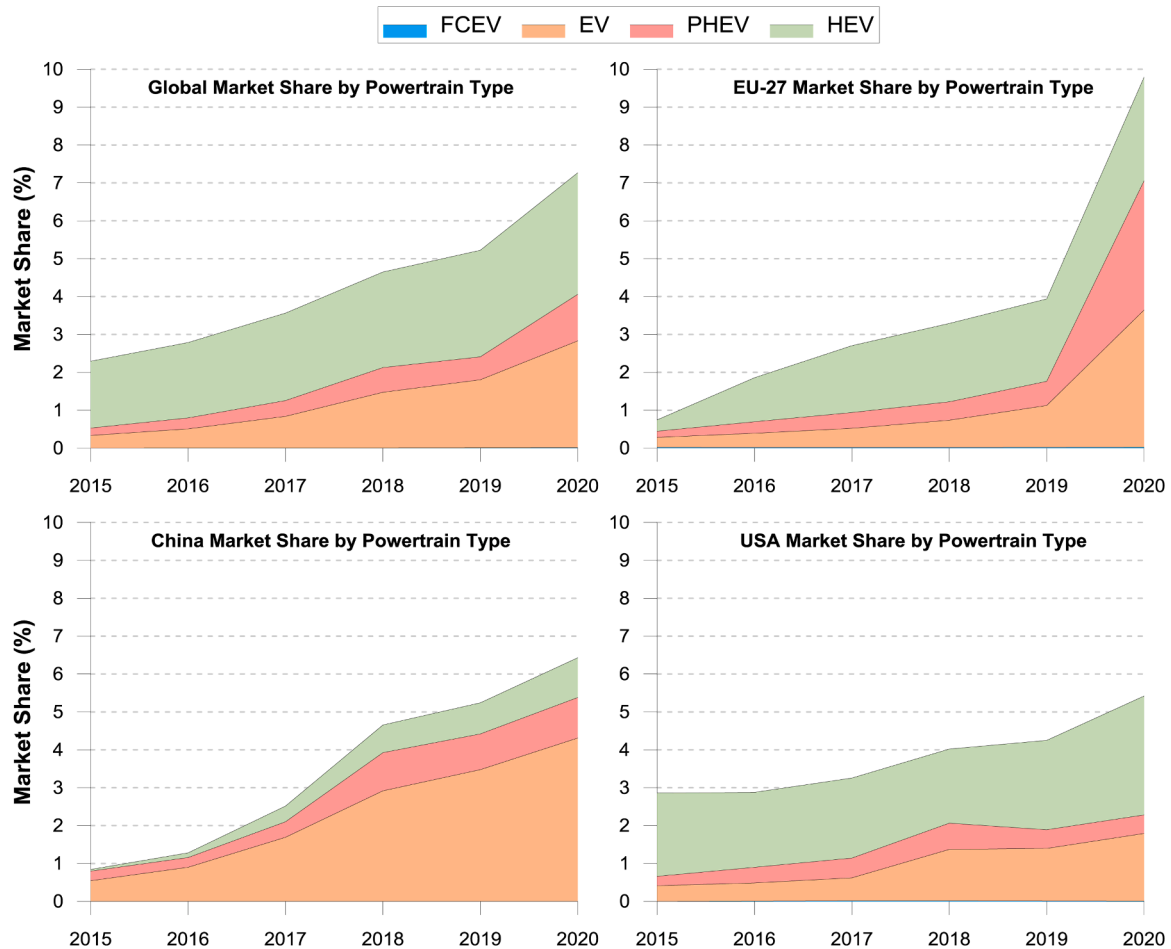


Fig. 7. Respective market share by electrified powertrain type for different markets.

grew from 1.8% to 2.8% representing 500,000 new sales. The increase in sales can be partly attributed to new models being introduced to the market. Key models introduced for 2020 and their sales volumes were the Porsche Taycan² (17,700 units sold), the VW ID.3 (55,800), the Tesla Model Y (70,500) and the Wuling HongGuang Mini EV (127,000). These new vehicles accounted for over half of new BEV sales in 2020.

EU-27

² The Porsche Taycan officially released Q4 2019 however only 33 were sold in 2019.

expire in 2023 [20]. In many large Chinese cities, the purchase of a license plate for an ICE vehicle can take many months while a free and immediate license plate for EVs is guaranteed. This makes the electric vehicle an attractive proposition for those in cities [21]. Another contributor to increasing sales was from small, affordable BEVs which are well suited to the Chinese customer base. The purchase price of a BEV is often cited as the primary barrier to consumer purchase [22]. The low-priced Wuling Honggaung Mini EV sold well despite being just introduced in June 2020. The Wuling Honggaung Mini EV is available from CYN 27,000 (US \$4160 equivalent) up to CYN 35,000 (US \$5600). A 13.8 kWh battery provides 175 km range (NEDC). A 20 kWh motor

provides a top speed of 100 km/h. The specifications and performance are well suited to city driving but are largely unsuitable for rural conditions. Whether this type of vehicle will result in significant long-term market share growth is still unknown.

USA

The USA has not warmed up to PHEV technology and sales volumes remain low at 0.5%, the same level as 2019. HEV sales increased slightly from 2.4 to 3.1%, attributed to two new truck segment HEVs introduced by the Fiat Chrysler Automobiles group (now Stellantis). The largest growth segment for hybrids was from large displacement V8 trucks, specifically the Dodge Ram eTorque in 2020. The trend of HEV increase will likely continue in 2021 as additional vehicles are brought to market [24]. In the USA it is likely that future hybridization will occur in the larger vehicle segments where vehicle price and profit margins are larger and fuel economy is relatively low. Larger vehicle segments (car SUV to Class 2A truck) made up over 60% of sales in the USA in 2020 [23].

BEV market share growth in the USA increased in 2020 in-line with global BEV increase to 1.8%. BEV sales growth stalled between 2018 and 2019 primarily because the two largest BEV manufacturers, GM and Tesla had reached their federal tax credit cap of 200,000 vehicles which removed the \$7500 federal credit on offer [25]. However as new and legacy manufacturers bring BEVs to the market (e.g. Ford Mustang Mach-E) the federal tax credit is again available on these models. In 2021 in the USA alone, six new manufacturers propose releasing electric vehicles; Rivian, Lucid Motors, Lordstown Motors, Karma Automotive, and Bollinger Motors [26]. A further 12 new models from legacy manufacturers, in the USA alone, will likely lead to a further increase in BEV sales during 2021.

The market share of four other markets are also compared in Fig. 8. The market share of BEV sales in Norway rose again in 2020 from 33% to a final share of 44%. PHEV sales also increased from 11 to 17% while HEV sales dropped for the first time in five years from 10% to 7%. The successful BEV market penetration can be attributed to extreme incentive schemes put in place by the Norwegian government to encourage

BEV sales [27]. In 2020 a 1.0 L TSFI gasoline-powered Volkswagen Golf cost the consumer more than a BEV e-Golf. The base price of the ICE golf is actually USD \$11,000 less than the e-Golf, however taxes placed only on the ICE vehicle include: CO₂, NO_x, weight, and VAT (25%). The sum of these ICE-only taxes increases the price to around USD \$800 more than the e-Golf [28]. It is unlikely that many other nations can follow Norway's aggressive incentive strategy and they will have to wait for technology-led cost reductions. Norway has set a target of 100% BEV sales by 2025 and by extrapolation of the previous three years can potentially meet this goal. A BEV market segment growth slow-down is possible before 2025 as lower income families may not have the means to transition to BEV transportation; a potential disruption to this expected trend would be further increases in incentives for BEVs.

Japan leads the world in hybrid powertrain technology since the introduction of the Toyota Prius Hybrid in 1997. A significant portion of Japanese light-duty sales are hybrids, however during 2020 the market share for hybrids dropped from 22% to 20%. EV and PHEV market share also dropped during the same time giving Japan a unique trend of a falling electrified share in 2020. While traditional electrified vehicle market share fell in 2020, fuel-cell electric vehicle (FCEV) sales notably increased from 644 in 2019 to 717 in 2020. Despite this growth, absolute sales were insignificant compared to the 4,428,000 total sales in 2020.

The Indian market continued an increasing trend of electrification where hybrid share increased from 0.5% to 0.9%. BEV sales increased to over 1000 units for the first time but still represent an insignificant share of the market at less than 0.05%. In 2017, Transport Minister Nitin Gadkari announced that the Indian government had set a target for 100% BEV sales by 2030 [29]. That aim was quickly reduced to 30% [30]. Even the reduced target appears to be out of reach unless incentive schemes and affordable BEVs are rapidly adopted by consumers.

The UK, having departed from EU-27, has set a target for a total ban on the ICE by 2035 and a ban on non-hybrid powertrains by 2030 [31]. A large increase in electrified vehicle share was seen in 2020 where the UK finished the year with nearly 15% of the fleet with some level of

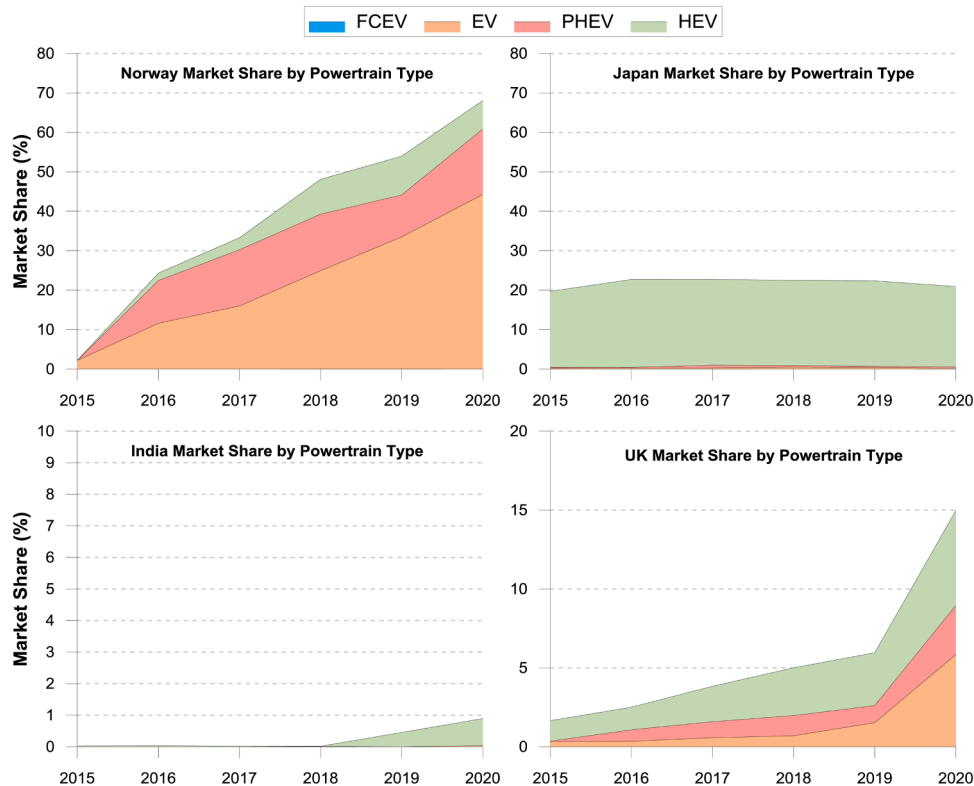


Fig. 8. Respective market share by electrified powertrain type for four unique markets.

plug-in or non-plug-in electrification, compared to 6% in 2019. The UK is expected to trend with EU-27 countries as it is following the same CO₂ target pathway and so the increase in electrified share is required. The BEV share increased from 1.5% to 5.8%, while PHEV sales grew from 1.1% to 3.1%. The exponential growth rate is on track to meet the 2035 target however it is unlikely that exponential growth will be observed continuously for the next fourteen years. Observing future trends from Norway as they approach 100% may provide insight into whether the UK is poised to achieve this target.

The year-on-year global BEV share has been increasing since 2012 when Tesla introduced the Model S to the market. In 2020, nearly 2,000,000 BEVs were sold world-wide—a number that is expected to increase in the future. Electrified vehicle share has increased at a faster rate where 5,250,000 million were sold in 2020. However, the ICE is still a vital powertrain component with 70,000,000 vehicles sold in 2020 97.2% of the fleet. This value is down from 99.7% in 2015 and trends with exponential decay Fig. 9.

3.1. Forecast

The current exponential growth rate for BEVs and exponentially decreasing ICE share is expected to continue in the short-term. While absolute sales and market share will increase year-on-year, the growth-rate will reduce each year. In 2020 BEV growth was 40%, we predict this to decrease to 10% by 2040.

Vehicle cost, charging infrastructure, and “range anxiety” are cited as the biggest barriers to purchasing a full electric vehicle [22]. Range anxiety is a function of charging time and availability of charging stations rather than absolute range. Some high-cost, high-range BEVs are competitive with hybrid and ICE vehicles on absolute certified range. These barriers will reduce over time as battery-pack cost reduces [32] and charging infrastructure increases [33–35]. Technologies to reduce charging time are limited due to inherent challenges with lithium-ion technologies. These challenges mainly relate to thermal degradation at fast charging conditions. New battery chemistries or technologies (i.e. steady-state) may be required before charging rate increases exponentially in-line with other barriers mentioned above.

We propose several possible future scenarios for BEV adoption. The future scenarios follow a Sigmoid curve (or S-curve) where at some point there will be a slow-down in growth rate. The forecasted growth is based on two main factors:

- 1 *Growth rate*: continued improvement in technology and lower cost will naturally persuade people into purchasing BEVs. This scenario predicts that the rate of market share growth will continue at the current rate. A second scenario assumes an accelerated growth rate where either technology improves at a rate faster than present, there is a key technology breakthrough, incentive programs are increased, or outright bans force consumer choices.
- 2 *Pushback*: at some adoption levels there will be a percentage of the global population that will not commit to BEVs as they do not offer

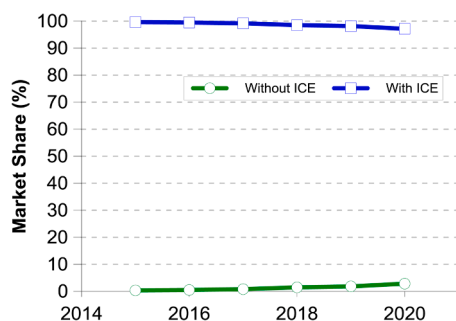


Fig. 9. Historic market share of vehicles sold with an ICE (ICE-only and hybrids including plug-in) and without an ICE (i.e. BEV & FCEV).

the same versatility as ICE equivalents. At some market-share there will be ‘pushback’ from these unique case groups that have needs which exceed the benefits from the growth rate factors mentioned above.

- a People who regularly drive their vehicle long-distances and require shorter recharging times. The longest-range BEV in production at the time of writing is a Tesla Model S Long Range Plus at an EPA-rated range of 402 miles [36]. A 40 min 120 kW super-charger event can recharge 322 of those miles (7.5 s per mile). Compare this to a Toyota Camry Hybrid range of 686 miles (EPA) from a 13.2 gallon tank which can be fully recharged in 100 s (0.2 s per mile) [37,38].
- i As discussed above, decreasing charging time will not continue along an exponential improvement curve without a technology breakthrough.
- b People who utilize their light-vehicle for regularly towing 6000 lbs. upwards. A reduced range due to towing impacts both BEV and non-BEV powertrains however the charging time factors mentioned above are amplified with BEVs.
- c People who wish to buy a large vehicle with an acceptable range at a low price i.e. competition to Ford Expedition, Chevrolet Suburban or Tahoe etc. The Tahoe has a cargo (all seats folded flat) interior space of 122.9 ft³ (\$399/ft³) compared to the BEV Rivian R1S with a cargo space of 108 ft³ (\$718/ft³). Although there is not yet a BEV competitor in the Suburban’s class it is unlikely to beat the 144.7 ft³ (\$357/ft³) that it offers.

The ‘current growth rate’ scenario assumes 50% BEV adoption will occur globally around 2040 while the accelerated rate assumes 50% BEV adoption around 2032. The three separate ‘pushback’ scenarios are at 50%, 70% and 90% market share to give a total of six scenarios in Fig. 10. The situation in 2050 is unclear, as is the timeline for complete ICE vehicle phase-out. Based on the six different predicted scenarios, the BEV share in 2050 ranges from 67% to 99%. These scenarios highlight the need for continued research in all powertrain systems, including the internal combustion engine. The authors feel, that for faster reduction in GHG emissions, rapid movement towards a 100% electrified fleet should be an industry-wide target while simultaneously working towards further adoption of BEVs as technology, infrastructure and costs improve.

Further forecasts have been made for two developed markets, EU-27 and the USA (Fig. 11). These predictions breakdown the powertrain by type to the year 2030. EU-27 countries are pushing towards aggressive CO₂ targets and outright bans of ICE technology. Therefore, the growth rate of BEVs is expected to exceed the global rate of adoption. PHEV share will grow initially as an intermediate step towards BEVs, but then decrease as charging infrastructure and cost reduce for the full BEV. One country which may disrupt the PHEV trend is Germany where the unique operating conditions of the de-restricted autobahns may lead to buyers preferring PHEVs. Around half of the market will be made up by mild and full hybrid vehicles which will be required to meet the 30% reduction in CO₂ by 2030 compared to 2021 [39]. The USA will initially follow a slow increase in all electrified powertrains due to the relaxed SAFE standards. However, it is likely that the fuel economy standards will be reviewed by the new administration which may impact standards before model year (MY) 2026. At this point the hybrid share will rapidly increase. Unlike EU-27, the PHEV share in the USA will increase owing to low gas prices and the requirement for larger, longer-range vehicles.

4. Internal combustion engine & hybrid technologies

2020, as noted elsewhere in this paper, has seen rapid changes in combustion engine and hybrid technologies. The 2020 COVID-19 pandemic had a substantial impact on the sector, with UK engine production falling by 27%, to give one example [40], and UK car production falling by nearly 30% [41]. This had a knock-on effect across the whole

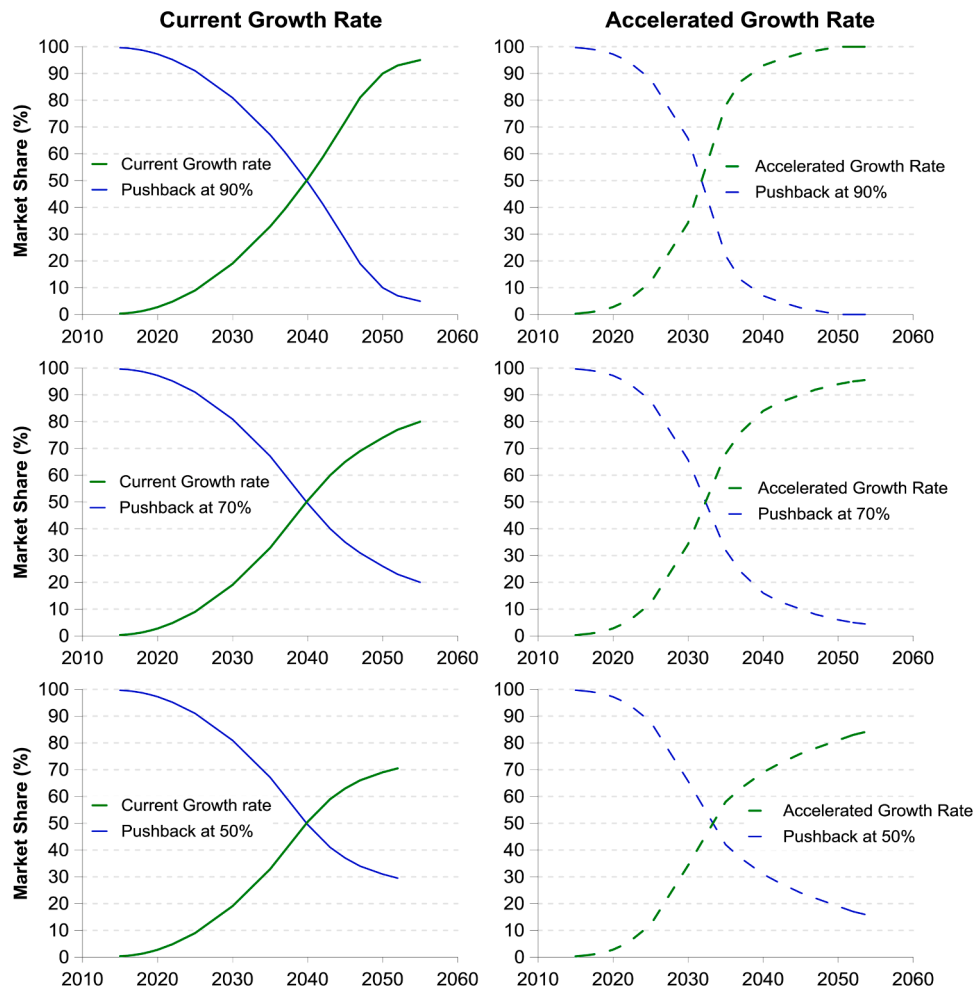


Fig. 10. Possible future scenarios for future global share of vehicles with ICE and those without (BEV & FCEV).

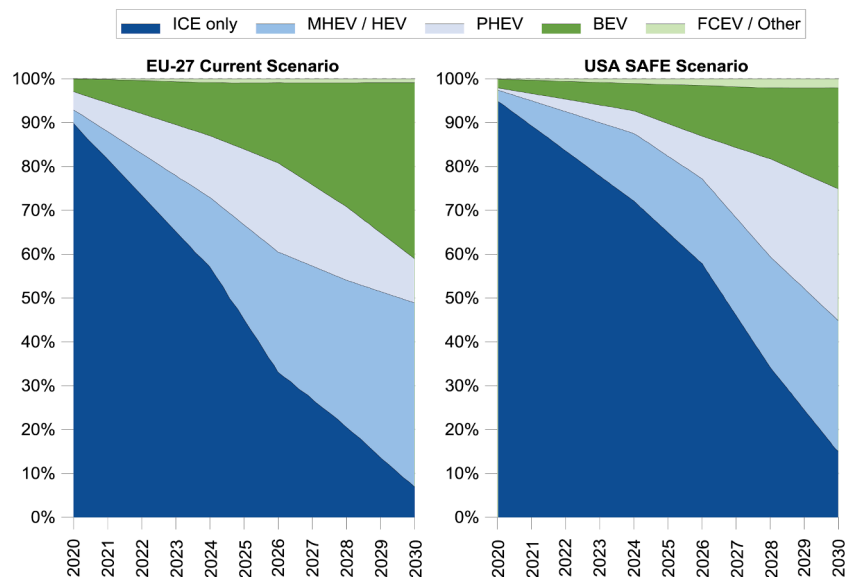


Fig. 11. 2020–2030 powertrain forecast for EU-27 and USA.

industry with more than 10,000 automotive industry jobs lost in the UK alone in 2020 [42].

Nevertheless, the challenges for industry far exceed those of the

pandemic. Both environmental concerns and regulation are driving substantial reductions in both GHG and criteria pollutant emissions. As a result it remains clear that there continues to be a need for increasing

efficiencies and reducing emissions from ICE and hybrid technologies [1]. Fortunately, as a paper published in this journal in 2020 found, there remains significant scope for continued improvements in these areas [43]. 2020 itself saw a number of advances in engines released as well as scientific developments around efficiency and emissions improvements.

Before we discuss engine technologies and emissions, one overriding theme at a number of automotive conferences and events in 2020 was the importance of simulation and the virtual world in engine design. Not least in a special issue of this journal [44]. Similarly there is clear evidence of the growing importance of artificial intelligence (AI) and machine learning (ML) techniques in engineering simulation and design software throughout the design space including in engine efficiency and emissions [45,46]. These approaches offer the ability to accelerate technology development, with optimization and near real-time feedback being possible with few physical experiments (which can be time consuming and expensive). Nevertheless, the market for good-quality experimental data to feed, inform, and validate these models and new tools will become ever more important as the emphasis on this virtual domain expands.

4.1. New engine announcements and research directions

Much of the headline improvements in engine efficiency came from the heavy duty (HD) sector. These include the announcement by Mack Trucks of a new version of their 13 L Mack MP8HE engine [47]. This engine has a 13% improved efficiency compared to its baseline “anthem” engine. This is achieved by exhaust energy recovery through a mechanical turbocompounding system where a turbine in the exhaust is linked through a transmission to the engine’s crankshaft. The engine also features a “wave” piston design (which has previously been used in the heavy duty sector [48] and an increased compression ratio (17:1 to 18:1) for higher efficiency and lower emissions.

With an engine for a similar duty, Weichai announced the world’s first 50% BTE high speed diesel engine [49]. This engine is a 13 L, 560 hp model, with a 2500 bar fuel injection system, and fully complies with the China VI and Euro VI emissions standards. This has been achieved by increasing peak firing pressure, optimizing fuel-air mixing and the air path, exhaust energy recovery, friction reduction through lubricants, and careful engine control. This is a notable achievement as previously efficiencies of this magnitude had only been seen in marine and other lower speed engines. Other HD engine manufacturers have demonstrated efficiencies >50% BTE including Volvo, PACCAR, and Cummins – and series production of these engines is close [50]. The DOE Super-Truck II program is targeting a 55% BTE engine in collaboration with four major US truck manufacturers [51].

Outside of the HD sector, another area of further development has been in downsized and boosted engines for light duty vehicles. Downsized (i.e. using a turbo- or super- charger to boost the inlet air pressure) engines have been in the market for longer than a decade, but nevertheless further improvements are being made to further increase their efficiency and reduce emissions. At the SAE WCX20 event, General Motors reported developments of what they describe as their “disruptive engine platform” [52]. The 3-cylinder (but 2-firing cylinders) 1.1 L engine uses a combination of downsizing and a high compression ratio (13.5:1). There is also a novel exhaust-heat energy recovery system where the two firing cylinders transfer their exhaust into a third, larger displacement cylinder, where the gas is further expanded for energy recover. The combustion is lean/dilute and hence a low(er) temperature type of combustion. All of these technologies are used together synergistically. GM reports increases in fuel economy by up to 38% compared to a naturally aspirated equivalent engine. This engine is not (yet) production ready but shows the direction of development.

Similarly, John Dec at Sandia National Laboratories has been working on a low-temperature combustion technique known as LTGC-AMFI to provide low emissions and high efficiency, reporting 45.5%

BTE from a light-duty gasoline engine at the Thiesel 2020 conference. This potential and direction of development for SI engines is clear.

On a more scientific front, KTH and Wärtsilä have reported a detailed exergy analysis, with the aim of identifying the most important areas to improve engine efficiency, in a 350 L four-stroke marine engine [53]. The areas identified included combustion losses, heat dissipation (thermal) losses, and gas exchange (pumping) losses. By far the most important source of exergy losses was combustion irreversibility which was responsible for up to 2/3 of the total exergy destruction and is therefore a clear target for future work.

Hybridization continues to be an important avenue of development for SI engines, particularly for increased efficiency. At the 2020 SAE WCX20 event a paper from SwRI reported that a 1.0 L engine with as little as 5 kW of electric power can reduce the engine load by 3 bar BMEP. Ultimately through a technology termed “Hybrid Boost,” BTE can be increased by 2% through this technique, which provides better results at high engine load (so may suit pick-up trucks and SUVs). Overall, the paper reports fuel economy gains of around 35% over urban-like driving in the FTP75 cycle [54].

In a keynote talk at the Thiesel 2020 conference, Piotr Szymański of the JRC noted that while BEVs and PHEVs may account for up to 50% of new LDVs sold in Europe by 2030 and this may reduce oil dependency, it will increase the need for a variety of raw materials such as rare earth elements and cobalt that are needed to produce batteries. Minimizing the impact of this increased demand will require a different approach to recycling and the production, use, end-of-life cycle.

Emissions

The complexity of turbulent combustion as well as advances in propulsion technologies means that continuous advances are being made both in the understanding of emissions formation as well as control – particularly through engine exhaust aftertreatment.

Formation

The use of novel piston bowl shapes (such as steps) for soot (PM) emissions reduction in light duty diesel engines is well documented [55], however, Punch Torino have, in 2020, developed an additive manufacture designed piston that can provide PM reductions in the region of 30–80% (as well as a BSFC improvement of 2%), which Alberto Vassallo presented at THIESEL 2020. This is the first use, that the authors are aware of, of additive manufacturing being used to enable emissions reduction – but as additive manufacturing becomes cheaper and more mainstream, it is likely that this will not be the last!

At the ASME ICEF 2020 conference a number of papers reported on new developments in NO_x emissions formation. Notably on using machine learning techniques to predict NO_x [56], the effects of injector dribble on NO_x [57], and NO_x formation in natural gas engines [58]. SCR remains the dominant technology that is highly effective at NO_x aftertreatment, nevertheless efforts to reduce the burden on aftertreatment as well as underpin the fundamental science behind NO_x formation are welcome.

Another area of further research and interest has been that of sub-23 nm particulate emissions. While currently an unregulated emission, these are likely to become regulated in the EU with the introduction of the Euro 7 legislation. Studies discussing their formation, characterization, and filtration with gasoline particulate filters (GPFs) have been reported throughout 2020 [59–63]. While there are some challenges to the industry here, namely increases in reported tailpipe PN, particularly under certain conditions, the studies all report that the sub-23 nm particulates are controllable with existing GPF technology. It is therefore likely that all Euro 7 vehicles will have a GPF or equivalent technology.

Aftertreatment

Recent advances in engine exhaust aftertreatment technologies have led to near-zero criteria pollutant emissions from many vehicles. An increased focus in lifetime vehicle emissions, rather than just when purchased or certified, has been a focus in 2020. For example the US DoE Annual Merit Review [64] has stated as a target “90% conversion of criteria pollutants (NO_x, CO, HCs) at 150°C for the full useful life of the

vehicle.” To achieve this a number of areas are being explored in the aftertreatment space, notably thermal management (which is important not only for fast-warm-up and other RDE scenarios – see the next section, but also for catalyst lifetime performance). Similarly, SCR on DPF technologies are established in the heavy duty space and increasingly in the light duty space. Finally, catalyst aging remains an area with scope for further development, including both on-engine tests and rig-based testing such as with the Catagen test reactor [65].

SCR is well established as the dominant NO_x control technology from engines that run lean of stoichiometric (notably diesel engines, but also a number of the high-efficiency technologies described in this paper). However, SCR typically requires active injection of an aqueous urea solution known as AdBlue or DEF. Systems are under development by Oak Ridge National Laboratories that would dispense with this requirement, and were this to become commonplace in the market, would transform the NO_x aftertreatment market [66]. Given the potency of methane as a greenhouse gas, further development of methane slip catalysts is being maintained to remove impact of any methane emissions [67].

RDE

Real driving emissions (RDE), regulated in the EU since Euro 6d, continue to be an area of development. A number of recent reports have shown not only gasoline engines, but also Euro 6d diesel engine vehicles remain very clean [1,43]. Independent studies report that all regulated gaseous emissions and PM were well below the respective Euro 6 limits [68].

This is generally achieved on most vehicles with a variety of catalyst technologies, some close-coupled, others in the more traditional tailpipe locations. This enables good cold-start performance alongside good steady-state conversion. For example, this is the strategy employed by SwRI [69] in their near-zero emissions concept, alongside engine control and thermal management strategies integrated to achieve this [70].

In the medium- and heavy-duty space a similar technological approach has been employed [71]. Reports have also been released of RDE emissions from heavy duty vehicles such as in-service buses, which also reveal the importance of good thermal management [72]. New engine technologies have also reported low emissions levels such as the Achates opposed-piston 10.6 L diesel achieving 0.02 g/bhp-hr NO_x with only a conventional diesel aftertreatment system utilizing a single SCR catalyst [73].

Looking ahead

There were a number of projects and announcements that will have impact well beyond the year 2020. Ricardo and Achates announced a partnership with ARPA-E funding for the further development of an opposed-piston gasoline compression ignition (OP GCI) engine intended for full-size pick-up trucks [74]. The Achates OP engine has been developed for a number of applications including stationary power generation, military, and truck engines.

Gasoline compression ignition remains a technology of interest. An EU Horizon 2020 project involving Shell, PSA and others reported a GCI concept that would run on standard EN228 RON 95 E5 gasoline [75]. This engine would require spark assist at low load, but otherwise demonstrated diesel-like efficiencies with a gasoline-fueled engine.

Running gasoline internal combustion engines very lean for high-efficiency remains a key technology going forward. Nissan (strictly in a 2021 announcement) announced a headline figure of >50% BTE for their new engine, which was achieved by running the engine in a dedicated hybrid mode and with exhaust gas energy recovery [76]. Nevertheless, by running the engine very lean $\lambda > 2.0$ alone, they achieved a 46% BTE from that engine. At these air-fuel ratios, ignition of the pre-mixed, dilute air-fuel mixture is challenging, and technologies such as lasers, pre-chambers, and low-temperature plasma are under consideration to overcome the problems. So-called ultra-lean engines like these, alongside controlled end gas auto-ignition and gasoline compression ignition will be key future pathways to high efficiency.

Biofuels, which are derived from recent biomass, are a potential net-

zero solution for the existing ICE fleet. Such fuels, predominantly ethanol in the gasoline market and a wider variety of fuels such as FAME in the diesel market, have been in consumers' tanks for at least two decades. In the EU, E10 (increased from E5) is becoming more common in markets – approaching levels already seen in the USA. Nevertheless, sustainability concerns as well as indirect land use change impacts, mean that biofuels will never completely replace fossil fuels, and where they do it will be for high energy density applications such as marine and aviation.

There continues to be a lot of activity and interest in the area of e-fuels [77]. These fuels, also known as electrofuels and power-to-liquid fuels, can be made from CO₂ and, if combined with renewable zero-carbon energy, can enable net-zero transportation from the existing ICE fleet. There has been a number of studies that focus on how to meet the EU CO₂ reduction targets of 3.7 Gt CO₂ between 2030 and 2050. Clearly BEVs will play a substantial role in this, but biofuels, e-fuels, and hydrogen might provide as much as one-third of the required CO₂ reduction required [78]. Similarly, AVL calculated that 33 million tons of e-fuel per annum would be required to meet the 2 °C warming scenario, even with electrification [79].

The use of hydrogen, arguably the simplest e-fuel, is gaining interest in internal combustion engines, with some studies suggesting efficiencies from modern ICEs now approaching those of fuel-cells, and when existing infrastructure is taken into consideration there is significant interest in hydrogen internal combustion engines – H₂-ICE. Notably AVL, an automotive consultancy, is developing a heavy-duty hydrogen internal combustion engine targeted at the truck market [80]. Activity is picking up rapidly in this area as the search for zero-tailpipe emission solutions suitable for all sectors continues.

Hydrogen need not simply be used on its own either. Because of its limited energy density and challenge to store on vehicles, certain sectors, notably marine, are pursuing ammonia (NH₃), which has a much higher energy density, as a hydrogen carrier [81]. In 2020, Wärtsilä developed the first full-scale ammonia test engine [82] – and the research activity on ammonia as an energy vector and hydrogen carrier in the marine and energy-storage space is growing quickly.

5. Electric vehicle news

As previously described, 2020 was a year of growth for battery electric vehicles. 2.8% of new cars sold globally were BEVs, compared to 1.8% in 2019. Europe led the charge, with an increase in BEV sales from 1.1% in 2019 to 3.6% in 2020 (specifically in the EU-27).

The increased sales of BEVs can be attributed to a few factors. First, 2020 saw an expansion in the number of BEV models available. Couple this with improvements in range and reductions in battery cost, and BEVs are becoming an attractive option for more of the population.

Still, a limited range continues to be one of the main barriers to entry for battery electric vehicles. However, for around \$70,000 you can now drive a Tesla Model S Long Range Plus with an EPA-estimated range of 402 miles. The longest range currently quoted for near-production vehicles (as far as we know) is from the Lucid Air Grand Touring edition, with a starting price of \$131,500. It has a projected range of 517 miles (according to Lucid's website) but will not be available until the summer of 2021. The Lucid Air has a projected range of 406 miles and starts at \$69,900. That version will not be available until “early 2022”. It will be interesting to see if future versions of this review paper include the Lucid models in the top spots for range. Until then, however, the Tesla Model S Long Range Plus holds the range crown.

Table 2 shows a summary of the ten BEVs with the longest range as of November 2020 [83]. A BEV's range is largely a function of its battery pack size, however there are many other factors that also affect range.

As shown in Table 2, the Tesla Model S Long Range Plus was the BEV with the longest available range in 2020. It had an EPA estimated range of 402 miles and a starting price of around \$70,000. Tesla actually held the top four spots, with the Long Range Model 3 coming in with the

Table 2

Summary of the ten longest range BEVs available as of November 2020. Data from [83]. Note that the listed vehicle starting costs do not include any purchase incentives or credits.

Car	Range (miles)	Battery Size (kWh)	Starting Cost (\$)
Nissan Leaf S Plus	226	62	38,200
Polestar 2	233	78	59,900
Kia Niro EV	239	64	39,090
Jaguar I-Pace	246	90	70,875
Hyundai Kona Electric	258	64	37,190
Chevrolet Bolt EV	259	66	36,620
Tesla Model Y Long Range	326	75	48,490
Tesla Model 3 Long Range	322	75	45,490
Tesla Model X Long Range Plus	371	100	78,490
Tesla Model S Long Range Plus	402	100	67,920

lowest starting price of around \$45,000 for a 322 mile range. You can drop below the \$40,000 mark with a Chevy Bolt, a Hyundai Kona Electric, a Kia Niro EV, or a Nissan Leaf S Plus, but with a trade-off in range of 225–260 miles per charge.

The evolution of the mean and median range of BEVs available in the USA from 2013 to 2020 is shown in Fig. 12. A consistent increase in range is shown.

Extreme weather can significantly impact the range of battery-powered vehicles. Recently, the Norwegian Automobile Federation tested 20 BEVs in Norway in the winter. They found that, on average, BEVs lose nearly 20% of their range and take longer to charge in cold weather [99]. In a study by Car and Driver, three tests at 70 mph were performed for a Tesla Model 3 on a 3 °C (38°F) day: the first with all HVAC (air conditioning) turned off, the second with HVAC set to 22 °C (72°F) on auto, and the third with HVAC on maximum with all five heated seats turned to the highest setting. Compared to the first test, the second test reduced the range by about 15%, while the third test reduced it by about 26% [100]. ICE vehicles similarly experience reduced fuel economy and range when temperatures reduce. However for ICE vehicles, the inefficiencies of heat rejection can be used to heat the cabin. According to the US EPA fuel economy website. A conventional gasoline car mileage is 15% lower at 22°F vs 77°F while an EV range may drop by 41% over the same temperature drop. [1]

Another study, by Motoaki et al., quantified the effect of cold

weather on charge time for DC fast chargers in the USA [101]. They calculated the charging efficiency for a Nissan LEAF on a median temperature day, starting at 20% charged. After a 30 min charge, the state of charge ranged from as low as 49% in northern states to as high as 74% in southern states, demonstrating a significant deterioration in charging efficiency in cold temperatures.

The ability to charge faster can alleviate some of the range anxiety issue. While Level 1 and 2 chargers require conversion of AC to DC power onboard the vehicle, DC fast chargers significantly increase charge speed by providing DC power directly. For comparison, a Chevy Bolt charges in about 10 h with a Level 2 system [83]. On the other hand, a DC fast charging system can provide up to 100 miles of range in 30 min of charge time [85]. Tesla's Supercharger (their version of DC fast charging) charges a Model S up to 80% in about 30 min and provides up to 44 miles of range per hour at home with their Wall Connector charging system [86]. Supercharger charge times can increase if other cars are using the charge post at the same time. Thus, Tesla recommends parking at a Supercharger shared with a car that is almost done charging (or, for that matter, not sharing). On the other hand, Urban Superchargers (a more compact version designed for highly populated city centers) do not share power, so charge time should be consistent regardless of whether or not someone is charging in an adjoining stall [87].

Another way to potentially reduce range anxiety (and charge times) is through battery swapping, which saw a return in 2020. Battery swapping has been around in various incarnations for nearly as long as BEVs themselves. The first modern company to deploy this concept commercially was called Better Place, founded in 2007 in California but operating in Israel as a testing ground. Their offering was coupled with the Renault Fluence ZE, the only model available for battery swapping at the time. Better Place subscribers paid around \$350 per month to lease access to the batteries and the switching stations [88]. In 2013, after \$850 million in investments, Better Place filed for bankruptcy. There seem to be several reasons for the company's downfall, including the massive investment needed to develop the swapping infrastructure and low market penetration of compatible cars. Indeed, according to Woody [89], only the Renault Fluence ZE was compatible with their battery swapping system.

The Chinese electric car company, Nio, has brought back battery swapping in 2020. They believe that Better Place failed because the BEV market was too small at that time and also because they did not make their own cars [90]. Nio has recently released their own version of

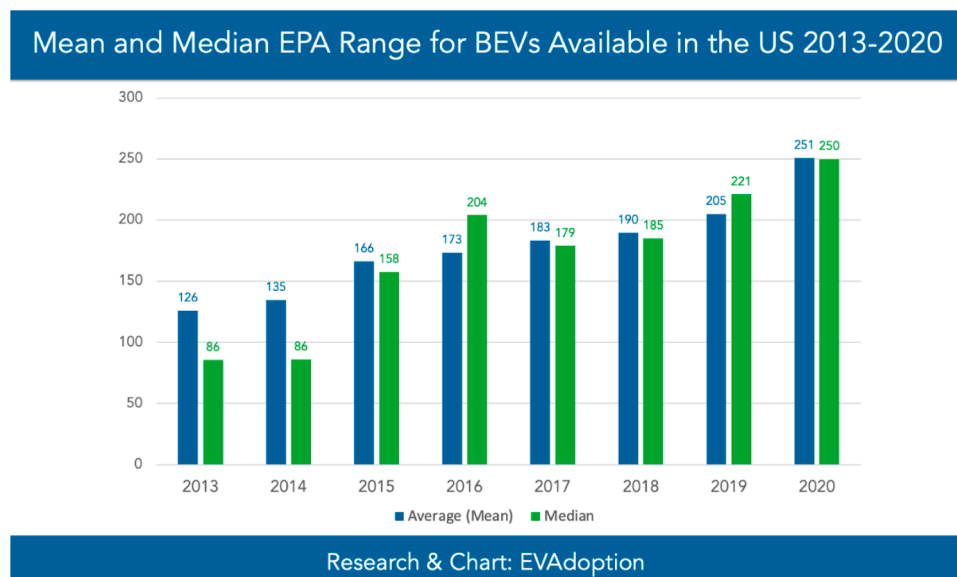


Fig. 12. Mean and median range of BEVs available in the USA from 2013 to 2020 [84].

battery swapping, called BaaS (battery as a service). Under this model, car buyers can save \$10,000 at the time of purchase because the battery is not included in the purchase price. According to Car and Driver, a 70.0 kWh pack with six swaps per month is priced at around \$142/month [91]. It will be interesting to track the evolution of range, charge times, and if the market moves to swappable batteries in future versions of this review paper.

Reduction in battery cost has also driven an increase in sales of BEVs (and vice-versa). As shown in Fig. 13 [92], the average battery cost has dropped about 89% since 2010, to \$137/kWh in 2020. This cost reduction is due to sales growth, reduced manufacturing costs, new battery pack designs, and reduced cost of cathode materials [93]. Many believe that we will need to reach \$100/kWh before BEVs can really compete with the cost of conventional vehicles on a large scale [94]. However the definition of comparable ICE vs BEV is subjective. An ICCT report suggested a BEV pack price of \$104/kWh by 2025 and \$74/kWh by 2030 in the US. They propose that by 2025 \$104/kWh will be price parity for a 200-mile-range BEV to a car. However a 200-mile-range BEV will not reach price parity until 2027 and a 250 mile-range BEV will be comparable in 2028. Extrapolating this to a 400 mile-range-SUV (commonly available in ICE form today, although not commonly utilized) would not occur until 2031 where the pack price is closer to \$69/kWh [95].

Another key aspect for the mass adoption of BEVs is infrastructure. Home charging is an option, however even with a Level 2 system it can take 10–12 h to charge a Bolt or a LEAF. Clearly, a public infrastructure is needed if BEVs are going to make up a significant portion of the fleet.

This infrastructure is definitely growing. In just the last five years (since 2015), the number of charging outlets has roughly quadrupled in the European Union, with nearly 25,000 fast chargers (greater than 22 kW charge power) and just under 200,000 normal chargers (less than 22 kW charge power) [95].

In the US, there were roughly 25,000 public Level 2 charging stations, with more than 75,000 outlets in 2020. There were about 4000 public DC fast charging stations, with more than 16,000 outlets [96]. Globally there were more than 2000 Tesla Supercharger stations with over 20,000 chargers as of November 2020 [97].

How do these numbers compare to conventional gas stations? There are around 115,000 gas stations in the USA [98]. Assuming an average

of eight gas pumps per station, theoretically one million cars could all refill at the same time, versus around 90,000 Level 2 and DC fast public charge connectors. Of course Level 1 charging is available in private homes, the rate of Level 1 charging depends on grid voltage. The US standard voltage is 110 V, while in Europe it is 220 V and up. An EV will charge at a rate of 3,4 miles/hour in the US compared to 8–10 miles/hour at the higher 220 V. Therefore home charging, without upgrading home electrical systems, remains challenging. While the electric infrastructure has not yet reached the required level to meet future BEV sales, it is growing rapidly.

Of course, new battery chemistries and cell technologies are the focus of many startups, much venture capital, and a growing amount of government funding. For example, the United States Department of Energy Vehicles Technology Office has the goal to [102]:

“...identify new battery chemistry and cell technologies with the potential to reduce the cost of electric vehicle battery packs by more than half, to less than \$100/kWh (ultimate goal is \$60/kWh battery cell cost), increase range to 300 miles, and decrease charge time to 15 min or less by 2028.”

The funded projects include “next generation lithium-ion battery technologies” (e.g., advanced anodes such as silicon, advanced cathodes, no-cobalt/low-cobalt cathodes, graphene), as well as “beyond lithium-ion battery technologies” (e.g., metallic lithium, solid-state, lithium sulfur, lithium-air, and sodium-ion). These technologies are being explored by manufacturers as well but are all at an early stage of development.

In addition, Tesla recently revealed its plans to revolutionize the battery, with the ultimate goal of producing a \$25,000 vehicle in just three years. The announcement came on “Battery Day”, held after Tesla’s annual stockholders meeting on September 22, 2020. Included in Tesla’s plans is a switch from cobalt to nickel cathodes and a redesign of their battery cells.

6. Conclusions

This paper has reviewed the current powertrain technology landscape in terms of emissions regulations, vehicle sales, powertrain architecture market share (as well as some forecasting), and research directions. The major findings of the paper are summarized as follows:

- Established tailpipe CO₂ limits will require a reduction of 3,4% per year in major markets throughout this decade.
- US gas emission limits are the tightest in the world, while the European PN limits have driven a broader adoption of filters, including for gasoline vehicles.
- Future regulations such as Euro 7 in Europe and LEV IV in the USA will tighten the emissions targets focusing on further reductions in NO_x and PN limits, also including new species and new procedures to emphasize the cold start contribution.
- RDE norms have been successful in fulfilling that modern Euro 6d compliant vehicles emit NO_x emissions well below the laboratory limits even when tested on the road.
- Despite these reductions in ICE emissions, several countries have announced targets for eliminating the internal combustion engine by 2025–2040.
- Although global sales of light-duty passenger and light commercial vehicles dropped during the first quarters of 2019 caused by COVID-19, a strong recovery is predicted in the coming years with sales expected to reach an all-time record high by 2024.
- Internal combustion engine manufacturers are focusing efforts in different areas (materials, fuel-air mixing, air path, exhaust energy recovery, friction reduction through lubricants, engine control...) to push for a 50% BTE target, which will favor the near-future scenario in which hybrid powertrains will prevail.

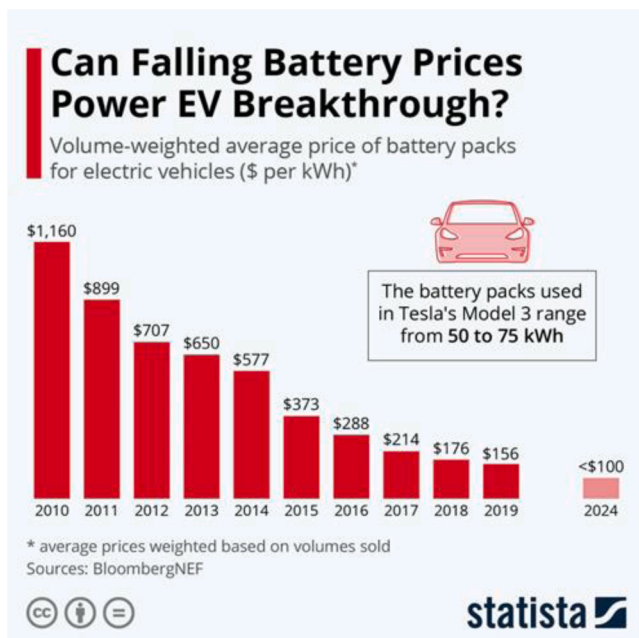


Fig. 13. Average electric car battery price from 2010 to 2019. Also shown is a projected cost in 2024 [92].

- Global sales of BEVs are expected to continue growing exponentially as the battery-pack cost reduces and charging infrastructure increases. If we apply the current growth rate scenario, the 50% BEV adoption point would occur globally around 2040. Other studies see this point arriving sooner. We will continue to track this trend and adjust these scenarios in future review papers.
- The \$100/kWh target battery cost that is believed necessary for BEVs to compete with the cost of small conventional vehicles which an acceptable sub 200 mile range is expected to arrive by 2024 at the latest, compared to \$137/kWh in 2020. This will be followed with an exponential growth of the related infrastructure. Larger vehicles and longer-range vehicles will require significantly lower pack costs before parity is reached.

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.

Acknowledgments

None.

References

- [1] P.K. Senecal, F. Leach, Diversity in transportation: Why a mix of propulsion technologies is the way forward for the future fleet, *Results Eng.* 4 (2019), 100060, <https://doi.org/10.1016/j.rineng.2019.100060>. Volume ISSN 2590-1230.
- [2] Our World in Data, "Emissions by sector", accessed on April 2nd, 2021 [online]. Available: <https://ourworldindata.org/emissions-by-sector#annual-co2-emissions-by-sector>.
- [3] European Commission, [Online], Available: https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en.
- [4] European Commission, "Communication from the commission to the European Parliament, the council, the European economic and social committee and the committee of the regions" [Online], Available: https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf.
- [5] National Highway Traffic Safety Administration, United States Department of Transportation. [Online], Available: <https://www.nhtsa.gov/laws-regulations/corporate-average-fuel-economy>.
- [6] China Society of Automotive Engineers. Website: <http://en.sae-china.org/a3967.html>.
- [7] Giechaskiel B., Valverde V., Clairotte M., "Real Driving Emissions (RDE): 2020 assessment of Portable Emissions Measurement Systems (PEMS) measurement uncertainty", EUR 30591 EN, Luxembourg: Publications Office of the European Union, 2021, ISBN 978-92-76-30230-8 (online), doi:10.2760/440720, JRC124017.
- [8] California Air Resources Board, Website: <https://ww2.arb.ca.gov/sites/default/files/202009/ACC%20H%20Sept%202020%20Workshop%20Presentation%20%28Updated%29.pdf>.
- [9] European Environment Agency, "Average CO2 emissions from newly registered motor vehicles in Europe". [Online], Available: <https://www.eea.europa.eu/data-and-maps/indicators/average-co2-emissions-from-motor-vehicles/assessment-2>.
- [10] United States Environmental Protection Agency, Website: <https://www.epa.gov/automotive-trends/download-automotive-trends-report>.
- [11] United States Environmental Protection Agency, Website: <https://www.epa.gov/sites/production/files/2021-01/documents/420r21003.pdf>.
- [12] Joshi, A., "Review of Vehicle Engine Efficiency and Emissions", SAE international 2021-01-0575. ISSN: 0148-7191.
- [13] J. Park, M. Shin, J. Lee, J. Lee, Estimating the effectiveness of vehicle emission regulations for reducing NOx from light-duty vehicles in Korea using on-road measurements, *Sci. Total Environ.* 767 (2021), 144250, <https://doi.org/10.1016/j.scitotenv.2020.144250>.
- [14] N. Molden, J. Hobday, R. Lofthouse, Managing reputation and emissions compliance through independent testing, in: *Proceedings of the 41st International Vienna Motor Symposium, 2020 presented at the*.
- [15] The International Council on Clean Transportation, website: <https://theicct.org/blog/staff/global-ice-phaseout-nov2020>.
- [16] U.S. Department of Labor Bureau of Labor Statistics, *The Employment Situation - February 2021*, U.S. Department of Labor, Washington D.C., 2021.
- [17] Bureau of Economic Analysis, U.S. department of Commerce, "Gross Domestic Product, 4th Quarter and Year 2020", 28 January 2021. [Online]. Available: <https://www.bea.gov/news/2021/gross-domestic-product-4th-quarter-and-year-2020-advance-estimate>. [Accessed 19 March 2021].
- [18] IHS Markit, "Navigating a New Reality," IHS Markit, London, United Kingdom, 2020.
- [19] S. Wappelhorst, D. Hall, M. Nicholas, N. Lutsey, *Analyzing Policies to Grow the Electric Vehicle Market in European Cities*, International Council on Clean Transportation, 2020. Washington D.C.
- [20] International Council on Clean Transportation, *China Announced 2020-2022 Subsidies for New Energy Vehicles*, International Council on Clean Transportation, 2020. Washington, D.C.
- [21] C. Zhuge, B. Wei, C. Shao, Y. & D. Shan, The role of license plate lottery policy in the adoption of Electric Vehicles: a case study of Beijing, *Energy Policy* 139 (2020), 111328, <https://doi.org/10.1016/j.enpol.2020.111328>. April 2020.
- [22] Deloitte, "2020 global automotive consumer study: is consumer interest in advanced automotive technologies on the move?," Deloitte, London, United Kingdom, 2020.
- [23] Stafford, E. and Dorian, D., "Best New EVs and Hybrids of 2021," *Car and Driver*, 18 February 2021. [Online]. Available: <https://www.caranddriver.com/features/g27271118/best-hybrid-electric-cars/>. [Accessed 18 March 2021].
- [24] United States Environmental Protection Agency, *The EPA Automotive Trends Report*, US EPA, 2020. Washington D.C.
- [25] C. Morris, Proposed Legislation Would Restore Federal EV Tax Credit to GM and Tesla, *Charged Electric Vehicles Magazine*, 2021, 14 February [Online]. Available: <https://chargedevs.com/news/proposed-legislation-would-restore-federal-ev-tax-credit-to-gm-and-tesla/> [Accessed 18 March 2021].
- [26] Yekikian, N., "Here is Every Electric Car You Can Buy in 2021," *Motortrend*, 26 October 2020. [Online]. Available: <https://www.motortrend.com/features-collections/every-electric-car-you-can-buy/>. [Accessed 16 March 2021].
- [27] A. Mersky, F. Sprei, C. & Q. Samaras, Effectiveness of incentives on electric vehicles adoption in Norway, *Transp. Res. Part D* 46 (2016) 56–68, <https://doi.org/10.1016/j.trd.2016.03.011>.
- [28] Kvalo, S., "Volkswagen Golf in Norway - from diesel to electric," *Norsk elbilforening*, 21 September 2020. [Online]. Available: <https://elbil.no/volkswagen-golf-in-norway-from-diesel-to-electric/>. [Accessed 15 March 2021].
- [29] Motor India, "SIAM Annual convention 2017 - Gadkari urges Indian auto sector to gear up to meet global challenges," *Motor India*, 08 September 2017. [Online]. Available: <https://www.motorindiaonline.in/events/gadkari-urges-indias-auto-sector-to-gear-up-to-meet-global-challenges-at-siam-annual-convention/>. [Accessed 14 March 2021].
- [30] Shah, R., "Government finally wakes up: Sets a realistic goal of 30% electric vehicles by 2030 from existing 100% target," *Express Drives*, 08 March 2018. [Online]. Available: <https://www.financialexpress.com/auto/car-news/government-finally-wakes-up-sets-a-realistic-goal-of-30-electric-vehicles-by-2030-from-existing-100-target/1091075/>. [Accessed 17 March 2021].
- [31] Harrabin, R., "Ban on new petrol and diesel cars in UK from 2030 under PM's green plan," *BBC*, 18 November 2020. [Online]. Available: <https://www.bbc.com/news/science-environment-54981425>. [Accessed 14 March 2021].
- [32] McKerracher, C., Izadi-Najafabadi, A. and O'Donovan, A., "Electric Vehicle Outlook 2020," *BloombergNEF*, London, United Kingdom, 2020.
- [33] Brown, A., Lommele, S. and Schayowitz, A. & K., "Electric vehicle charging infrastructure trends from the alternative fueling station locator: first quarter 2020," *NREL*, Golden CO, 2020.
- [34] Shell, "Shell accelerates drive for net-zero emissions with customer-first strategy," *Shell*, 11 February 2021. [Online]. Available: <https://www.shell.com/media/news-and-media-releases/2021/shell-accelerates-drive-for-net-zero-emissions-with-customer-first-strategy.html>. [Accessed 17 March 2021].
- [35] Markets and Markets, "Electric Vehicle Charging Station Market by Level of Charging (Level 1, Level 2 & Level 3, By Charging Infrastructure (Normal Charge, Type-2, CCS, CHAdeMO and Tesla Supercharger), DC fast Charging (Fast & Ultra-fast) - Global Forecast to 2027," *Markets and Markets*, 2021.
- [36] The Tesla Team, "Model S Long Range Plus: Building the First 400-Mile Electric vehicle," *Tesla*, 15 June 2020. [Online]. Available: <https://www.tesla.com/blog/model-s-long-range-plus-building-first-400-mile-electric-vehicle>. [Accessed 19 March 2021].
- [37] Edmunds, "2020 Toyota Camry Hybrid Specs & Features," *edmunds*, 2021. [Online]. Available: <https://www.edmunds.com/toyota/camry-hybrid/2020/features-specs/>. [Accessed 18 March 2021].
- [38] "38 FR 1255, Jan. 10, 1973, as amended at 39 FR 16125, May 17, 1974; 39 FR 43283, Dec. 12, 1974; 48 FR 4287, Jan. 31, 1983; 56 FR 13768, Apr. 4, 1991; 58 FR 16019, Mar. 24, 1993; 61 FR 3837, Feb. 2, 1996; 61 FR 33039, June 26, 1996," [Online].
- [39] T. Oki, European fuel economy policy for new passenger cars: a historical comparative analysis of discourses and change factors, *Int. Environ. Agreem.* (2020), <https://doi.org/10.1007/s10784-020-09510-7>.
- [40] SMMT, "British engine production falls -27.0% in 2020 as pandemic hits output". Accessed 27 April 2021. <https://www.smm.co.uk/2021/01/british-engine-production-falls-27-0-in-2020-as-pandemic-hits-output/>.
- [41] SMMT, "UK car production down -29.3% as coronavirus slams brakes on sector". Accessed 27 April 2021. <https://www.smm.co.uk/2021/01/uk-car-production-down-29-3-as-coronavirus-slams-brakes-on-sector>.
- [42] Financial Times, "UK carmakers braced for more job losses after worst year since 1984". Accessed 27 April 2021. <https://www.ft.com/content/b7136bae-66cb-490-d-ba04-36754b4e393e>.
- [43] F. Leach, G. Kalghatgi, R. Stone, P. Miles, The scope for improving the efficiency and environmental impact of internal combustion engines, *Transp. Eng.* (1) (2020), 100005, <https://doi.org/10.1016/j.treng.2020.100005>. ISSN 2666-691X.
- [44] Javier Serrano, Peter Senecal, Numerical simulations of reacting and non-reacting flows, *Transp. Eng.* (2020) (Open access) December 2020.
- [45] L. Fang, N. Papaioannou, F. Leach, M.H. Davy, On the application of artificial neural networks for the prediction of NOx emissions from a high-speed direct

- injection diesel engine, *Int. J. Engine Res.* (2020), <https://doi.org/10.1177/1468087420929768>. June.
- [46] N. Papaioannou, X. Fang, F. Leach, MH. Davy, Prediction of NOx emissions for a range of engine hardware configurations using artificial neural networks, in: *Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference*, ASME 2020 Internal Combustion Engine Division Fall Technical Conference, 2020, <https://doi.org/10.1115/ICEF2020-2911>. Virtual, Online. November 4–6 V001T06A001ASME.
- [47] Mack Trucks, 'Next Generation Mack® MP8® Engine Boosts Fuel Efficiency by up to 3 Percent'. Accessed 27 April 2021. <https://www.macktrucks.com/mack-news/2020/next-generation-mack-mp8-engine-boosts-fuel-efficiency-by-up-to-3-percent/>.
- [48] J.V. Pastor, A. García, C. Micó, F. Lewiski, A. Vassallo, F. Concetto Pesce, Effect of a novel piston geometry on the combustion process of a light-duty compression ignition engine: an optical analysis, *Energy* 221 (2021), 119764, <https://doi.org/10.1016/j.energy.2021.119764>. ISSN 0360-5442.
- [49] The Engineer, 'Weichai Group launches the world's first commercial diesel engine with a brake thermal efficiency over 50 per cent'. Accessed 27 April 2021. <https://www.theengineer.co.uk/promoted-content/weichai-group-launches-the-worlds-first-commercial-diesel-engine-with-a-brake-thermal-efficiency-over-50-per-cent/>.
- [50] Dieselnet, 'SuperTruck II 2020 program update'. Accessed 27 April 2021. <https://dieselnet.com/news/2020/07supertruck.php>.
- [51] US DoE, 'Energy Department Announces \$137 Million Investment in Commercial and Passenger Vehicle Efficiency'. Accessed 27 April 2021. <https://www.energy.gov/articles/energy-department-announces-137-million-investment-commercial-and-passenger-vehicle>.
- [52] J. Dornotte, P. Najt, R. Durrett, Downsized-Boosted Gasoline Engine with Exhaust Compound and Dilute Advanced Combustion, *SAE Int. J. Adv. Curr. Pract. Mobil.* 2 (5) (2020) 2665–2680, <https://doi.org/10.4271/2020-01-0795>.
- [53] B. Hong, SK. Mahendar, J. Hyvönen, A. Cronhjort, AC. Erlandsson, Quantification of losses and irreversibilities in a marine engine for gas and diesel fuelled operation using an exergy analysis approach, in: *Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference*, ASME 2020 Internal Combustion Engine Division Fall Technical Conference, ASME, 2020. Virtual, Online. November 4–6, V001T01A00510.1115.
- [54] Conway, G., Chambon, P., and Alger, T., 'Opportunities for electrified internal combustion engines,' *SAE Technical Paper* 2020-01-0281, 2020, 10.4271/2020-01-0281.
- [55] F. Leach, R. Ismail, M. Davy, A. Weall, B. Cooper, The effect of a stepped lip piston design on performance and emissions from a high-speed diesel engine, *Appl. Energy* 215 (2018) 679–689, <https://doi.org/10.1016/j.apenergy.2018.02.076>. PagesISSN 0306-2619.
- [56] N. Papaioannou, X. Fang, F. Leach, MH. Davy, Prediction of NOx emissions for a range of engine hardware configurations using artificial neural networks, in: *Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference*, ASME 2020 Internal Combustion Engine Division Fall Technical Conference, 2020, <https://doi.org/10.1115/ICEF2020-2911>. Virtual, Online. November 4–6, V001T06A001ASME.
- [57] F. Leach, V. Shankar, M. Davy, M. Peckham, The influence of cycle-to-cycle hydrocarbon emissions on cyclic NO:NO₂ ratio from a HSDI diesel engine, in: *Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference*, ASME 2020 Internal Combustion Engine Division Fall Technical Conference, 2020, <https://doi.org/10.1115/ICEF2020-2904>. Virtual, Online. November 4–6, V001T04A001ASME.
- [58] KL. Wallace, JA. Caton, TJ. Jacobs, Use of a thermodynamic cycle simulation to identify fundamental thermodynamic factors of NOx formation in a natural gas engine, in: *Proceedings of the ASME 2020 Internal Combustion Engine Division Fall Technical Conference*, ASME 2020 Internal Combustion Engine Division Fall Technical Conference, 2020, <https://doi.org/10.1115/ICEF2020-2928>. Virtual, Online. November 4–6 V001T01A003ASME.
- [59] Dorscheidt, F., Sterlepper, S., Görgen, M., Nijs, M. et al., "Gasoline particulate filter characterization focusing on the filtration efficiency of nano-particulates down to 10nm," *SAE Technical Paper* 2020-01-2212, 2020, 10.4271/2020-01-2212.
- [60] Leach, F., Lewis, A., Akehurst, S., Turner, J. et al., "Sub-23nm particulate emissions from a highly boosted GDI engine," *SAE Technical Paper* 2019-24-0153, 2019, 10.4271/2019-24-0153.
- [61] Giechaskiel, B., Woodburn, J., Szczotka, A., and Bielaczyc, P., "Particulate matter (PM) emissions of Euro 5 and Euro 6 vehicles using systems with evaporation tube or catalytic stripper and 23nm or 10nm counters," *SAE Technical Paper* 2020-01-2203, 2020, 10.4271/2020-01-2203.
- [62] V. Valverde, B. Giechaskiel, Assessment of gaseous and particulate emissions of a Euro 6d-Temp diesel vehicle driven >1300km including six diesel particulate filter regenerations, *Atmosphere* 11 (6) (2020) 645, <https://doi.org/10.3390/atmos11060645>.
- [63] Thakral, N., Premnath, V., Khalek, I., and Eakle, S., "Development of a burner-based test system to produce controllable particulate emissions for evaluation of gasoline particulate filters," *SAE Technical Paper* 2020-01-0389, 2020, 10.4271/2020-01-0389.
- [64] US DoE, 'Annual merit review'. 2020. Accessed 27 April 2021. <https://www.energy.gov/eere/vehicles/vehicle-technologies-annual-merit-review>.
- [65] Mc Grane, L., Douglas, R., Irwin, K., Stewart, J. et al., "A study of the effect of light-off temperatures and light-off curve shape on the cumulative emissions performance of 3-way catalytic converters," *SAE Technical Paper* 2021-01-0594, 2021.
- [66] M. Masoudi, J. Hensel, E. Tegeler, A review of the 2018 U.S. DOE CLEERS conference: trends and deeper insights in reduction of NOx and particulate in diesel and gasoline engines and advances in catalyst materials, mechanisms, and emission control technologies, *Emiss. Control Sci. Technol.* 6 (2020) 113–125, <https://doi.org/10.1007/s40825-019-00134-1>.
- [67] K. Lehtoranta, P. Koponen, H. Vesala, K. Kallinen, T. Maunula, Performance and regeneration of methane oxidation catalyst for LNG ships, *J. Mar. Sci. Eng.* 9 (2) (2021) 111, <https://doi.org/10.3390/jmse9020111>.
- [68] J. Anderson, Final Report to T&E of Emissions Determination from RDE Regeneration Testing, Ricardo, 2019. https://www.transportenvironment.org/sites/te/files/publications/2020_01_Ricardo_testing_for_New_diesels_new_problems.pdf.
- [69] SwRI Pressroom, 'SwRI Engineers develop near-zero emissions engine technology'. Accessed 27 April 2021. <https://www.swri.org/press-release/near-zero-emissions-diesel-engine-technology>.
- [70] Valverde Morales, V., Clairrotte, M., Pavlovic, J., Giechaskiel, B. et al., "On-road emissions of euro 6d-TEMP vehicles: consequences of the entry into force of the rde regulation in Europe," *SAE Technical Paper* 2020-01-2219, 2020, 10.4271/2020-01-2219.
- [71] Manufacturers of Emission Controls Association, Technology feasibility for heavy-duty diesel trucks in achieving 90% lower NOx standards in 2027. 2020, http://www.meca.org/resources/MECA_2027_Low_NOx_White_Paper_FINAL.pdf.
- [72] FCP, Leach, MS. Peckham, MJ. Hammond, Identifying NOx hotspots in transient urban driving of two diesel buses and a diesel car, *Atmosphere* 11 (4) (2020) 355, <https://doi.org/10.3390/atmos11040355>.
- [73] Power Achaters, 'Achaters opposed-piston 3-cylinder 10.6L diesel emissions meet 2027 EPA, CA requirements'. Accessed 27 April 2021. <https://achatespower.com/achates-opposed-piston-3-cylinder-10-6l-diesel-emissions-meet-2027-epa-ca-requirements/>.
- [74] Green Car Congress, 'ARPA-E funds Ricardo-Achaters partnership for improving efficiency and reducing emissions in full-size pickups; GCI engine, 48V'. Accessed 27 April 2021. <https://www.greencarcongress.com/2020/09/20200911-api.html>.
- [75] Cracknell, R., Bastaert, D., Houille, S., Châtelain, J. et al., "Assessing the efficiency of a new gasoline compression ignition (GCI) concept," *SAE Technical Paper* 2020-01-2068, 2020, 10.4271/2020-01-2068.
- [76] Green Car Congress, 'Nissan reaches 50% thermal efficiency with next-generation e-POWER system; STARC'. Accessed 27 April 2021. <https://www.greencarcongress.com/2021/02/20210226-nissanpower.html>.
- [77] J. Benajes, A. García, J. Monsalve-Serrano, S. Martínez-Boggio, Potential of using OME_x as substitute of diesel in the dual-fuel combustion mode to reduce the global CO₂ emissions, *Transp. Eng.* 1 (2020), 100001, <https://doi.org/10.1016/j.treng.2020.01.001>. ISSN 2666-691X.
- [78] FEV Magazine, 'Carbon-neutral transport, the role of synthetic fuel'. Accessed 27 April 2021. <https://magazine.fev.com/en/carbon-neutral-transport-the-role-of-synthetic-fuel/>.
- [79] Rothbart, M., "e-Fuel Production via Renewables and the Impact on the In-Use CO₂ Performance," *SAE Technical Paper* 2020-01-2139, 2020, 10.4271/2020-01-2139.
- [80] Cameron, I., 'AVL moves ahead with hydrogen engine'. Accessed 27 April 2021. <https://www.newpowerprogress.com/news/AVL-moves-ahead-with-hydrogen-engine/8010310.article>.
- [81] D. MacFarlane, P. Cherepanov, J. Choi, B. Suryanto, R. Hodgetts, J. Bakker, F. Ferrero Vallana, A. Simonov, A roadmap to the ammonia economy, *Joule* 4 (6) (2020) 1186–1205, <https://doi.org/10.1016/j.joule.2020.04.004>. PagesISSN 2542-4351.
- [82] Wärtsilä Corporation, 'World's first full scale ammonia engine test - an important step towards carbon free shipping'. Accessed 27 April 2021. <https://www.wartsila.com/media/news/30-06-2020-world-s-first-full-scale-ammonia-engine-test-an-important-step-towards-carbon-free-shipping-2737809>.
- [83] Gear Brain, "Which electric car has the most EPA range? These EVs can drive the furthest in 2020", November 24 2020, [Online], Available: <https://www.gearbrain.com/longest-range-electric-cars-2637390927.html>.
- [84] Evadoptation, "Price Parity is Not the Key to EV Adoption in the US", March 29 2021, [Online], Available: <https://evadoptation.com/price-parity-is-not-the-key-to-ev-adoption-in-the-us/>.
- [85] Chevrolet Pressroom, 'Chevrolet Bolt EV - 2020'. Accessed 7 December 2020. <https://media.gm.com/media/us/en/chevrolet/vehicles/bolt-ev/2020.tab1.html>.
- [86] Tesla, website: <https://www.tesla.com/support/charging>.
- [87] Tesla, website: <https://www.tesla.com/support/supercharging>.
- [88] Isabel Kershner, Israeli Venture Meant to Serve Electric Cars Is Ending Its Run (Published 2013), *The New York Times*, 2013, 26 Maysec. Business, <https://www.nytimes.com/2013/05/27/business/global/israeli-electric-car-company-films-for-liquidation.html>.
- [89] Todd Woody, Another Clean-Tech Startup Goes Down: Better Place is bankrupt, *The Atlantic*, 2013, 26 May, <https://www.theatlantic.com/technology/archive/2013/05/another-clean-tech-startup-goes-down-better-place-is-bankrupt/276257/>.
- [90] 'A Brief History of Battery Swapping'. NIO, 29 June 2020. <https://www.nio.com/blog/brief-history-battery-swapping>.
- [91] Baldwin, Roberto, 'China's Nio lets EV drivers swap batteries in 5 minutes, hit the road'. *Car and Driver*, 21 August 2020. <https://www.caranddriver.com/news/a33670482/nio-swappable-batteries-lease/>.

- [92] Statista, "Can falling battery prices power EV breakthrough?, Electric Mobility, September 23 2020, [Online], Available: <https://www.statista.com/chart/7713/electric-car-battery-prices/>.
- [93] BloombergNEF, "Battery Pack Prices Cited Below \$100/kWh for the First Time in 2020, While Market Average Sits at \$137/kWh", December 16 2020, [online], Available: <https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/>.
- [94] Rathi, A., "The magic number that unlocks the electric-car revolution," Bloomberg.Com, 2020.
- [95] European Alternative Fuels Observatory, "Normal and high-power public recharging points (2020)", website: <https://www.eafo.eu/alternative-fuels/electricity/charging-infra-stats#>.
- [96] Alternative fuels data center: electric vehicle charging station locations [Internet]. U.S. Department of Energy. [cited 2020 Dec 7]. Available from: https://afdc.energy.gov/fuels/electricity_locations.html.
- [97] Tesla. 'Supercharger'. Accessed 7 December 2020. <https://www.tesla.com/supercharger>.
- [98] 24/7 Wall St. How many gas stations are in U.S.? How many will there be in 10 years? [Internet]. MarketWatch. 2020 [cited 2020 Dec 7]. Available from: https://feedproxy.google.com/~r/247wallst_partners/~3/z2eL38boo94/.
- [99] Norwegian Automobile Federation (NAF). '20 popular EVs tested in Norwegian winter conditions', 12 March 2020. <https://www.naf.no/elbil/aktuelt/elbiltest/ev-winter-range-test-2020/>.
- [100] Mortimer MB. How much does climate control affect EV range? [Internet]. Car and Driver. 2020 [cited 2020 Dec 7]. Available from: <https://www.caranddriver.com/news/a31739529/how-much-does-climate-control-affect-ev-range/>.
- [101] Y. Motoaki, W. Yi, S. Salisbury, Empirical analysis of electric vehicle fast charging under cold temperatures, Energy Policy 122 (2018) 162–168 [Internet] Nov 1 [cited 2020 Dec 7] Available from, <http://www.sciencedirect.com/science/article/pii/S0301421518304828>.
- [102] Vehicle Technologies Office, "Batteries: 2019 Annual Progress Report," DOE/EE-1987, U.S. Department of Energy Vehicle Technologies Office, 2020.