

Research



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An assessment of electric vehicles: technology, infrastructure requirements, greenhouse-gas emissions, petroleum use, material use, lifetime cost, consumer acceptance and policy initiatives

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Concerns about climate change, urban air pollution and dependence on unstable and expensive supplies of foreign oil have led policy-makers and researchers to investigate alternatives to conventional petroleum-fuelled internal-combustion-engine vehicles in transportation. Because vehicles that get some or all of their power from an electric drivetrain can have low or even zero emissions of greenhouse gases (GHGs) and urban air pollutants, and can consume little or no petroleum, there is considerable interest in developing and evaluating advanced electric vehicles (EVs), including pure battery-electric vehicles, plug-in hybrid electric vehicles and hydrogen fuel-cell electric vehicles. To help researchers and policy-makers assess the potential of EVs to mitigate climate change and reduce petroleum use, this paper discusses the technology of EVs, the infrastructure needed for their development, impacts on emissions of GHGs, petroleum use, materials use, lifetime costs, consumer acceptance and policy considerations.

1. Introduction

Concerns about climate change, urban air pollution and dependence on unstable and expensive supplies of foreign oil have led policy-makers and researchers to investigate alternatives to conventional petroleum-fuelled internal-combustion-engine vehicles (ICEVs) in transportation. Because vehicles that get some or all of their power from an electric drivetrain can have low or even zero emissions of greenhouse gases (GHGs) and urban air pollutants, and can consume little or no petroleum, there is considerable interest in developing and evaluating advanced electric vehicles (EVs), including pure battery-electric vehicles (BEVs), plug-in hybrid electric vehicles (PHEVs) and hydrogen fuel-cell electric vehicles (HFCVs). We will refer to BEVs and PHEVs together as plug-in electric vehicles, or PEVs, while ‘engine’ will refer to an internal combustion engine (ICE), and ‘motor’ to an electric motor. To help researchers and policy-makers assess the potential of EVs to mitigate climate change and reduce petroleum use, this paper discusses seven facets of EVs: their technology, the infrastructure needed for their development, petroleum use and impacts on emissions of GHGs, materials use, lifetime costs, consumer acceptance and policy considerations.

2. Characteristics of plug-in electric and hydrogen fuel-cell electric vehicles

Automobile companies around the world are developing and marketing several types of electrified vehicles: BEVs powered by an electric motor and battery, typically having a range of approximately 160 km; PHEVs having an ICE, electric motor and battery; and HFCVs, which have a hydrogen storage system, a fuel cell, an electric drivetrain and possibly a peak-power battery. PHEVs can operate on electricity alone for a range of 15–60 km and as a charge-sustaining hybrid using the engine and gasoline (petrol) for extended ranges. The characteristics of a number of PEVs marketed in 2012 are shown in table 1.

All the PEVs currently being marketed use lithium-ion batteries, and most analysts expect that vehicles in the foreseeable future will use improvements of the same basic lithium-ion chemistry.

(a) Powertrains of battery-electric vehicles

As indicated in figure 1, the powertrain of a battery-powered vehicle is relatively simple, comprising an electric motor and the electronics system, or motor controller, that controls the power from the battery to the motor. (If the EV uses an alternating current (AC) motor, the controller inverts the direct current (DC) output of the battery to AC.) The output of the motor is the torque to the wheels that powers the vehicle. The efficiency of the drive system from the battery output to the wheels is very high, in the range 80–90%. The electric motor can act as a generator, which permits the recovery of energy during the braking of the vehicle. A general discussion of the design and performance of electrified vehicles is given in Burke [1].

Manufacturers are careful in the design of EVs to reduce their weight and road load compared with conventional ICE vehicles of the same size and type in order to attain maximum range for a reasonable size battery. The range of the vehicle is given by

$$\text{range (km)} = \frac{\text{kWh}_{\text{bat-usable}} \times 1000}{\text{Wh}_{\text{bat}}/\text{km}_{\text{veh}}}, \quad (2.1)$$

where $\text{Wh}_{\text{bat}}/\text{km}_{\text{veh}}$ is the energy from the battery required to operate the vehicle. The energy use of the vehicle depends on its weight, its aerodynamic drag (C_{DA}), the rolling resistance coefficient (f_r) of the tyres and the driving conditions (determined by the ‘driving cycle’). Note that the range is dependent on the *usable* energy from the battery ($\text{kWh}_{\text{bat-usable}}$), not the maximum total energy that can be stored in the battery. In most EVs, the fraction of the total stored energy that can be used is limited to less than 80%, in order to prolong the life of the battery.

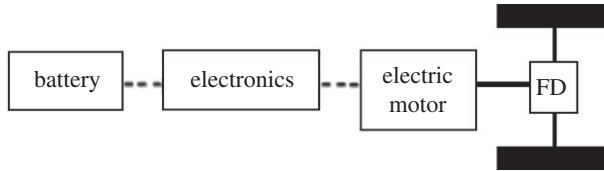


Figure 1. General schematic of battery electric vehicle. FD, final drive.

Table 1. Characteristics of selected plug-in electric vehicles marketed in 2012. NCM, nickel cobalt manganese; LTO, lithium titanate oxide.

model/manufacture	veh. type	kerb wt. (kg)	battery type (kWh)	bat. chem.	motor (kW)	range (km)
Leaf/Nissan	BEV	1530	lithium-ion/24	NCM	80	140
MiEV	BEV	1080	lithium-ion/16	NCM	47	150
EV Fit/ Honda	BEV	1480	lithium-ion/20	LTO	92	150
Smart/Mercedes	BEV	—	lithium-ion/18	—	55	109
EV Focus/Ford	BEV	1680	lithium-ion/23	NCM	107	140
Volt/GM	PHEV	1715	lithium-ion/16	NCM	111	55–65
Prius/Toyota	PHEV	1420	lithium-ion/4.4	NCM	60	18
G-Max/Ford	PHEV	1550	lithium-ion/7.6	NCM	68	34

Table 2. Characteristics of lithium-ion batteries using various chemistries. Sources: Reddy [2] and Burke & Miller [3]. Cycle life is the number of deep charge–discharge cycles, typically to 80% depth of discharge.

chemistry anode/cathode	cell voltage max/nom.	energy density (Wh kg ^{−1})	cycle life (deep)	thermal stability
graphite/NiCoMnO ₂	4.2/3.6	100–170	2000–3000	fairly stable
graphite/Mn spinel	4.0/3.6	100–120	1000	fairly stable
graphite/NiCoAlO ₂	4.2/3.6	100–150	2000–3000	least stable
graphite/iron phosphate	3.65/3.25	90–115	>3000	stable
lithium titanate/Mn spinel	2.8/2.4	60–75	>5000	most stable

The maximum total battery capacity is given by

$$\text{kWh}_{\text{bat}} = \frac{\text{kWh}_{\text{bat-usable}}}{\text{fr}_{\text{bat-usable}}} = \frac{\text{range (km)} \times \text{Wh}_{\text{bat}}/\text{km}_{\text{veh}}}{1000 \times \text{fr}_{\text{bat-usable}}}, \quad (2.2)$$

where $\text{fr}_{\text{bat-usable}}$ is the usable fraction of battery stored energy. The corresponding battery weight is given by

$$\text{weight}_{\text{bat}} = \frac{\text{kWh}_{\text{bat}} \times 1000}{(\text{Wh/kg})_{\text{bat}}}. \quad (2.3)$$

Table 2 summarizes the characteristics of lithium-ion batteries of several chemistries. Table 3 shows performance characteristics of what might be ‘typical’ BEVs as a function of weight, drag and rolling resistance, based on simulation results for the United States Federal City and Highway driving cycles. The driving range is between 100 and 150 km, and the 0–96 km h^{−1} acceleration time is between 8 and 11 s. By comparison, conventional gasoline vehicles have similar acceleration times but approximately four times the driving range.

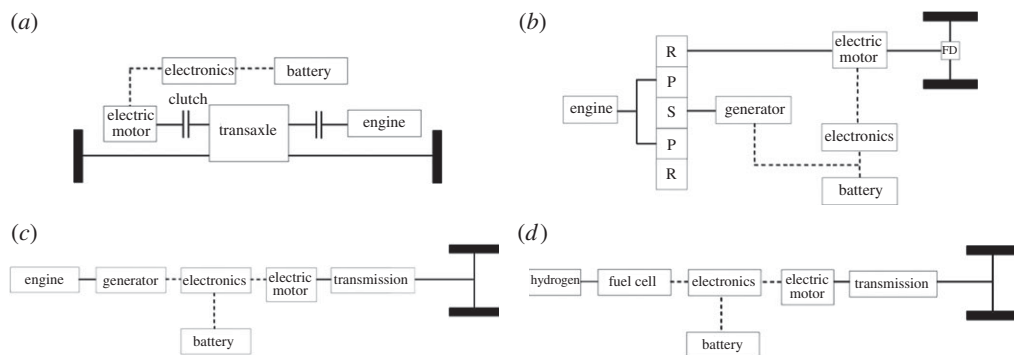


Figure 2. Driveline schematics of various electrified vehicles. (a) Parallel hybrid driveline: single-shaft design (BEV). (b) Parallel hybrid driveline: planetary shaft design (PHEV). P, planetary gear; S, sun gear; R, ring gear; FD, final drive. (c) Series hybrid driveline, engine and battery (PHEV). (d) Hybrid driveline, fuel cell and battery (HFCEV).

Table 3. Simulated performance characteristics of BEVs of various weights, drag coefficients and tyre rolling resistance. All vehicles simulated with a 75 kW AC induction motor and regenerative braking, a 150 Wh kg⁻¹, 20 kWh (16 kWh usable) lithium-ion battery and a frontal area of 2 m²; hwy, highway; acc, acceleration.

test wt. (kg)	drag coefficient (C_d)	rolling resistance coefficient (f_r)	city (Wh km ⁻¹)	city (km)	hwy (Wh km ⁻¹)	hwy (km)	acc. 0–96 km h ⁻¹ (s)
1200	0.30	0.008	130	122	131	123	8.0
	0.20	0.008	124	130	113	142	7.9
	0.30	0.006	125	128	124	130	8.0
	0.20	0.006	118	136	106	152	7.9
1500	0.30	0.008	142	112	139	115	9.5
	0.20	0.008	133	118	121	133	9.4
	0.30	0.006	138	120	130	123	9.4
	0.20	0.006	125	126	111	142	9.3
1800	0.30	0.008	154	104	147	109	11.2
	0.20	0.008	145	110	129	125	11.0
	0.30	0.006	144	112	136	118	11.1
	0.20	0.006	136	117	118	136	10.9

(b) Powertrains of plug-in hybrid electric vehicles

As indicated in figure 2, the powertrains of PHEVs are more complex than those for BEVs because they have an electric motor and an engine, which can operate one at a time or simultaneously to power the vehicle. The general arrangement of the powertrain can be as either a parallel or a series hybrid (figure 2a–c). In the series configuration (figure 2c), the engine is not connected to the wheels and its output is converted to electricity via the generator. The primary disadvantages of the series arrangement are that a generator of comparable power to the engine is required and there are significant losses in the generator. This results in a higher cost of the series arrangement and for highway driving a lower efficiency than for the parallel arrangement, in which the engine is directly connected to the wheels. The primary advantage of the series arrangement is that it can be implemented rather simply to extend the range of a BEV.

Most of the plug-in hybrids being developed are based on parallel designs (an exception is the GM Volt, which is based on a series design). In a plug-in design, the battery is sized (in kWh) based on the desired battery-only driving range of the vehicle using equations (2.1)–(2.3). When the battery is depleted as a result of operating the vehicle only on electricity, the vehicle is operated as a charge-sustaining hybrid. In this charge-sustaining operating mode [4,5], the engine and the electric motor power the vehicle and the electric motor acting as a generator powered by the engine maintains the battery at a constant state of charge near its minimum depleted state. The battery then is fully recharged by plugging it into a wall plug when extended charge times are available. In this system, a PHEV uses electricity for short trips and primarily gasoline for longer trips. The fuel economy of the PHEV for the long trips can be expected to be close to that of charge-sustaining (non-plug-in) hybrids like the non-plug-in version of the Toyota Prius.

(c) Powertrains of hydrogen fuel-cell electric vehicles

While BEVs and PHEVs store electricity and (in the case of PHEVs) a liquid fuel on-board the vehicle to power the vehicle, an HFCV uses a fuel cell to convert hydrogen stored on-board the vehicle into electricity and then operates as an EV (figure 2*d*). HFCVs also generally will have peak-power devices such as high-power batteries or ultracapacitors. The design and performance of HFCVs are discussed in detail in [1,6,7].

Fuel-cell passenger cars and sport utility vehicles (also called four-wheel drives, off-road vehicles and four-by-fours outside of North America) are being developed by a number of automobile companies around the world (including Honda, Toyota, General Motors, Mercedes-Benz, Nissan and Hyundai), with limited production and marketing planned starting in 2015. In these vehicles, the hydrogen is stored in high-pressure (350–700 atm) tanks. The range of the production vehicles will be 400–500 km and their fuel economy (gasoline energy equivalent) will be about 2.5 times that of a conventional engine-powered vehicle of the same size.

3. Infrastructure for battery and hydrogen fuel-cell electric vehicles

HFCVs and PEVs require a new energy infrastructure to be deployed. HFCVs probably will be refuelled primarily by a widespread public network of refuelling stations that will be analogous to the current gasoline refuelling network. HFCVs can be refuelled in a few minutes, and given the improvements in the HFCV range over the last decade, these HFCVs probably will refuel about as quickly and frequently as conventional gasoline vehicles do now (every 250–350 miles (400–550 km)).

By contrast, the PEV charging infrastructure and PEV charging patterns will be quite different from the current liquid-fuel infrastructure and ICEV refuelling. Most significantly, PEVs can be charged conveniently at home. When PEVs need to be recharged away from home, they could be charged at workplaces, retail establishments, commercial parking garages and even large multi-vehicle fast-charge facilities that function like an electric-vehicle analogue of a gasoline station.

This section discusses the fuel infrastructure for electric-drive vehicles. The fuel infrastructure is defined to be all of the facilities and equipment associated with fuel production, distribution and dispensing with either hydrogen or electricity.

(a) Hydrogen infrastructure

The hydrogen infrastructure includes hydrogen production, delivery and refuelling stations. This infrastructure can take several different forms because hydrogen is an energy carrier, like electricity, that can be made in many different ways, from a number of different primary energy resources. There are two general infrastructure configurations (figure 3): (i) hydrogen energy feedstocks (water, electricity, natural gas) are delivered to local fuel production and refuelling sites, where hydrogen is produced and dispensed on site; or (ii) hydrogen is made from a number

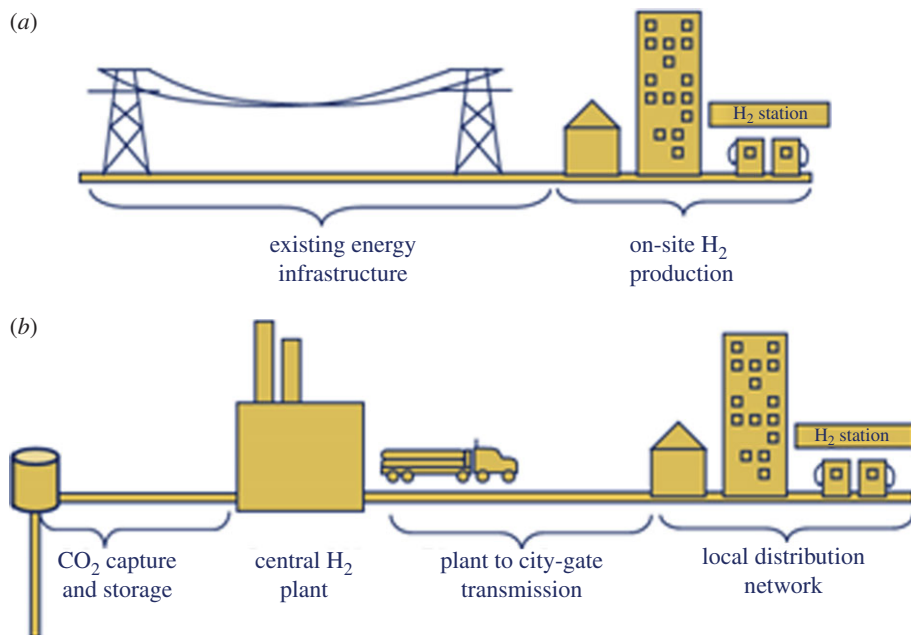


Figure 3. Two broad categories of hydrogen infrastructure, (a) onsite and (b) central H₂ production. (Online version in colour.)

of energy feedstocks (water, natural gas, electricity, biomass, coal), in large centralized facilities, and then delivered via pipeline or truck to refuelling stations.

Centralized hydrogen production can be accomplished by thermochemical conversion of hydrocarbon fuels (coal, natural gas, petroleum products or biomass), electrolytic water splitting (using electricity) or thermochemical water splitting using high-temperature nuclear or concentrated solar heat. Hydrogen produced in large centralized facilities can be transported to the refuelling station as a gas in pipelines, as a compressed gas via tube trailer trucks or in a cryogenic liquid form using insulated tanker trucks. Large-scale production from hydrocarbons also offers the potential for capturing most of the CO₂ contained in the hydrocarbon fuels.

Small-scale hydrogen production (also called ‘on-site’ or ‘distributed production’) can take place directly at the refuelling station site using commonly distributed energy products, such as electricity and natural gas. Worldwide, 100–200 of these stations have been built and operated. In several regions in Europe, Japan and North America, there are plans to build early networks of 10–20 stations, in support of early commercial roll-out of HFCVs.

Several studies have investigated how a hydrogen infrastructure might grow over time, typically starting with hydrogen at a few ‘clustered’ stations and expanding to a widespread infrastructure composed of numerous central plants connected via a pipeline network to a series of hydrogen refuelling stations [8–11]. Two of the key issues in these studies are the cost of the refuelling infrastructure and the staging of the roll-out of vehicles and stations.

The earliest hydrogen stations are likely to be built in a limited number of metropolitan areas, so-called ‘lighthouse’ cities, along with a coordinated roll-out of HFCVs. Stations presumably will be located in relatively dense metropolitan areas to maximize the number of potential HFCV owners within reasonable distance of each station [12,13]. If early stations and vehicles are co-located in clusters, consumers can have reasonable access to fuel, even with a sparse initial network of stations.

The estimated cost of hydrogen from the first refuelling stations will be relatively high, probably exceeding \$10 per kg [13], because early stations will be small, serving dozens of cars instead of hundreds or thousands, and underused, and thus will not benefit from economies of scale. As the technology matures, the HFCV fleet size grows and larger stations are built, the cost of hydrogen will decrease to under \$8 per kg (figure 4). If the km per kJ efficiency of HFCVs is 2 to

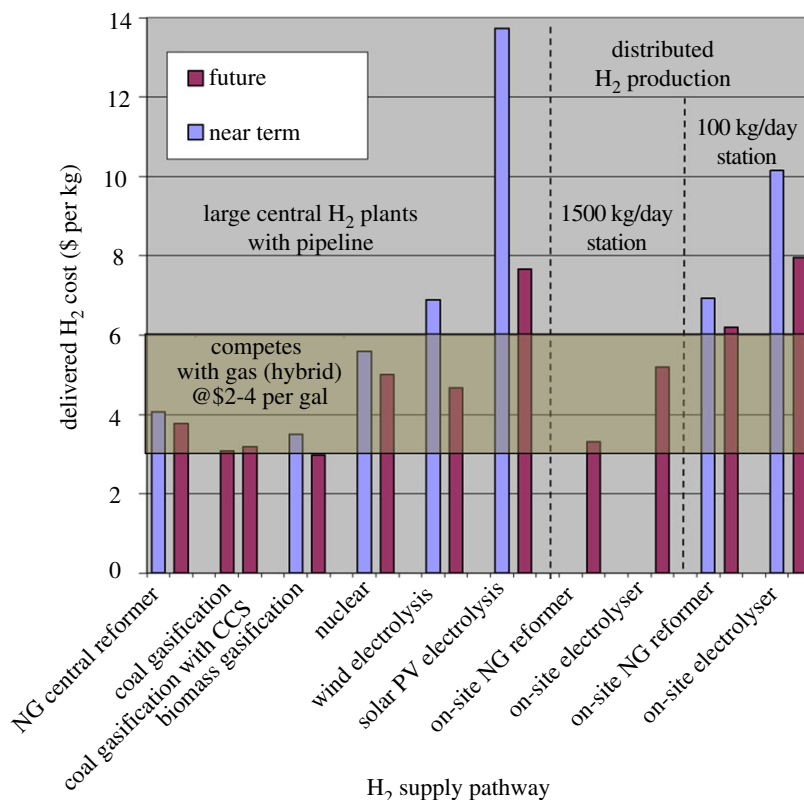


Figure 4. Delivered cost of hydrogen fuel for various supply pathways and station sizes [14]. Cost comparison with gasoline assumes hybrid gasoline vehicle. (Online version in colour.)

2.5 times that of conventional gasoline vehicles, then hydrogen at \$8 per kg and gasoline at \$3.20 to \$4 per gallon result in the same fuel cost per km (based on [14]).¹ If the km per kJ efficiency of HFCVs is 1.5 times that of *hybrid* gasoline vehicles, then hydrogen at \$8 per kg and gasoline at about \$5.30 per gallon result in the same fuel cost per km (based on [14]).

Figure 4 compares the projected delivered cost of hydrogen transportation fuel produced via different pathways for ‘near term’ (scaled-up infrastructure with current technology) and ‘future’ systems (full-scale infrastructure with advanced technologies beyond 2015). We find that costs are likely to come down as technology advances, and that production from hydrocarbons generally costs less than electrolytic hydrogen production. All centralized generation alternatives assume that hydrogen is deployed at a massive scale. On-site generation alternatives assume that in the long term stations deliver either 1500 kg of H₂ per day, which would supply about as many cars per day as do current gasoline stations, or 100 kg of H₂ per day, which would be typical of near-term demonstration H₂ stations serving a relatively small number of early HFCVs. These small stations are estimated to have significantly higher hydrogen cost because they would not benefit from economies of scale.

Figure 4 also shows the range for hydrogen fuel costs to compete with gasoline on a dollar-fuel-cost-per-mile basis, based on a gasoline *hybrid* vehicle competing with an HFCV. If H₂ costs \$3–6

¹For comparison, the retail prices of premium gasoline for the week of 22 April 2013 [15]:

	Belgium	France	Germany	Italy	Netherlands	UK	USA
excl. taxes (\$ per gallon)	3.30	3.28	3.42	3.44	3.31	3.18	3.45
incl. taxes (\$ per gallon)	7.66	7.54	7.92	8.52	8.52	7.84	3.84

per kg, the fuel cost per mile for an HFCV would be about the same as for an efficient gasoline hybrid using gasoline at \$2–4 per gallon, given an assumed HFCV fuel economy that is 1.5 times higher than a comparable gasoline hybrid vehicle. As figure 4 shows, most hydrogen production systems are estimated to deliver hydrogen for less than \$6 per kg in the long run. The cost of H₂ would thus be competitive with gasoline (in hybrid vehicles) on a fuel-cost-per-mile basis in the USA, Europe and Japan.

There also have been some analyses of home- and neighbourhood-based hydrogen refuelling, which would likely be accomplished via steam reforming of natural gas and atmospheric venting of CO₂. The costs for home and neighbourhood refuelling are in the range \$7–9 per kg H₂, which would be competitive on a cost-per-mile basis with gasoline (in hybrid vehicles) at around \$5 per gallon [16].

Finally, we note that total hydrogen infrastructure capital investment costs have been estimated to be around \$38 billion to serve a fleet of 20 million cars in the USA, approximately 9% of today's USA light-duty vehicle (LDV) fleet or approximately \$2000/HFCV served [8,17].

(b) Electric charging infrastructure

The PEV charging infrastructure consists of electricity generation, transmission and distribution, and PEV charging equipment and stations (also called electric vehicle service equipment (EVSE)). The first three elements (generation, transmission and distribution) constitute the traditional electricity grid, are part of electricity supply for all demands and are not specific to PEV charging. If vehicles are charged off-peak when large numbers of plants are underused, then existing or currently planned generation capacity will be sufficient in most places in the USA to meet the demands from large numbers of vehicles (millions) [18]. However, it is possible that parts of the distribution systems (e.g. distribution transformers) may need to be upgraded if PEVs are concentrated in certain neighbourhoods, which can be the case with hybrid vehicles [19]. Distribution transformers (which have an installed cost of approx. \$3000) typically serve less than 5–10 homes in a neighbourhood and the addition of several EVs, each of which can add demands approximately equivalent to an additional home, may require the installation of additional transformer capacity.

It is expected that most charging will occur overnight when the PEV is at home in a dedicated parking space. In the USA, there are approximately 54 million garage spaces for 250 million cars (21%) [20]. However, the percentage of cars with garage space is lower in dense cities, where many people live in multi-unit residential buildings or single-family homes without dedicated off-street parking. For vehicles without a garage or dedicated off-street parking, recharging options include non-dedicated residential off-street parking lots and garages (e.g. in apartment complexes), private commercial parking garages, workplace charging and even public charging in residential and commercial areas. Workplace charging may prove to be popular, because the workplace is a frequent destination, the distance between home and work is fixed, and there is the potential for a dedicated parking spot next to a charger. Public recharging, which can occur at retail locations, rest stops and other public locations, might help curb what has been called 'range anxiety' among PEV drivers and encourage greater PEV driving [21]. Because there is little real-world, mass market experience with PEVs, more research is needed to assess the potential impact of the availability of home- and non-home-based charging options on the adoption and utility of PEVs.

The EVSE in the home can be a conventional circuit and receptacle (120 V and about 20 A in the USA, and 240 V and about 15 A in Europe) that provide 2–3 kW of power (this has been designated 'Level 1' charging), or a higher-voltage (240 V or higher), higher-amperage (30 A plus) circuit and special recharging equipment that provide 6 to 12 kW or more of power (sometimes called 'Level 2' charging). Level 1 charging is inexpensive, because virtually all homes have Level 1 circuits and most current PEVs have equipment on-board to manage Level 1 recharging, but it is relatively slow: at 2 kW one obtains approximately 6 miles (9 km) of driving range per hour of charging,

and at 3 kW this goes up to 9 miles (14 km) of driving range per hour.² Level 2 recharging is much faster—at 10 kW, a PEV would obtain approximately 30 miles (47 km) of driving range per hour of charging—but also more costly: EVSEs with Level 2 capabilities can cost \$1000–2000 excluding installation and potential electrical upgrades in order to provide the appropriate outlet near the EV parking spot (i.e. garage or driveway) [22].

Higher-power charging stations, informally dubbed ‘fast-charge’ or ‘super-fast-charge’ stations, have been proposed for high-traffic public/retail/parking and highway rest areas. DC ‘fast charge’ can provide power up to 60 kW, which can charge a PEV battery in 15–30 min, depending on battery chemistry and size. DC fast-charge EVSEs cost \$10 000–\$40 000 [22]. In addition, the relatively high power will probably necessitate extensive electrical work for service connections. The total connection/installation cost may be \$67 000 for two adjacent DC fast-charge stations [23]. ‘Super-fast-charge’ public stations can provide even higher power, albeit also at a higher cost. The total capital cost (station EVSE, plus grid reinforcement costs, plus transformer) may be 115 000 Euro (approx. \$150 000) for a large, ‘super-fast’ (250 kW) DC public station capable of serving 288 EV per day at 20 kWh each [24].

Battery swapping (‘rotatable’ battery systems) is an alternative option to DC fast charge for taking BEVs on longer trips. The idea is that a BEV’s depleted batteries could be removed and replaced with freshly charged batteries in about the same amount of time as it takes to fill up a tank of gas (i.e. a few minutes). An important benefit is that batteries can be leased, which lowers the initial cost of purchasing a BEV, and can be upgraded by the battery-swap companies as better technologies become available.

Finally, EVs are not only an electricity consumer on the grid, they can also help manage and improve grid operation. Smart-grid technologies can be used to intelligently manage charging of vehicles to minimize adding charging demands to existing peaks, shifting demand towards off-peak, baseload generation [25]. With the addition of vehicle-to-grid power (where power can flow from the vehicle’s batteries to other loads on the grid), EVs can potentially provide frequency regulation, spinning reserves or immediate response backup of intermittent renewable generation [26–28].

4. Greenhouse-gas emissions impacts and oil use of electric vehicles

This section summarizes what is known about the relative emissions of GHGs from battery, fuel-cell and plug-in hybrid EVs versus conventional ICEVs (adapted from [29]). Although battery electric vehicles (BEVs) and fuel-cell vehicles (FCVs) are often called zero-emission vehicles, and although most BEV and HFCV fuel options do entail significant reductions in GHG and urban air-pollutant emissions compared with conventional gasoline vehicles, this is not always the case; for example, if coal without carbon capture is the sole feedstock for the electricity for BEV charging. A comprehensive analysis therefore should consider all sources of emissions throughout the ‘life cycle’ of fuels and vehicles, from the production of raw materials and feedstocks to end-use by vehicles, and even disposal. Here, the ‘life cycle of fuels’, also called the ‘fuel cycle’, includes emissions from the ‘upstream’ production and transport of fuels and feedstocks plus ‘end-use’ or ‘tailpipe’ emissions from vehicle operation. The ‘life cycle of vehicles’ includes emissions related to the production, transport and disposal of vehicles and the materials in vehicles.

(a) Background

GHGs are a number of different gases and aerosols that have climatic impacts. For EVs of various types that are fuelled with electricity and/or hydrogen, the GHGs of greatest interest are carbon dioxide (CO₂), methane (CH₄), nitrous oxide (N₂O), nitrogen oxides (NO_x), the latest automotive refrigerants (HFC-134a, HFO-1234yf and so on), ozone (O₃), and direct and secondary particulates from power production. Some other gases with apparently lesser significance (due in part to their

²These estimates assume a vehicle (such as the Nissan Leaf) that uses 0.34 kWh per mile (0.21 kWh km^{−1}).

relatively weak global warming potentials) but that also contribute are carbon monoxide and various non-methane hydrocarbons (NMHCs).

Research on GHG emissions from fuel cycles related to EV use dates back to at least the early 1990s, when the introduction of BEVs by major automobile manufacturers and growing concern about climate change spurred interest. At that point, most studies focused on criteria (i.e. regulated) air pollutants (carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter and sulfur dioxide), but some GHGs were occasionally included.

Emissions of GHGs from conventional gasoline ICEVs are a combination of ‘upstream’ emissions from fuel production and distribution, emissions from fuel use during vehicle operation (also called ‘end use’ or ‘tailpipe’ emissions) and emissions from the vehicle production and disposal life cycle. GHG emissions from the life cycle of fuels for BEVs and HFCVs are only upstream emissions related to the production of electricity or hydrogen; there are no ‘tailpipe’ emissions from the vehicles themselves (except for water vapour in the case of HFCVs). The upstream emissions from these vehicles are dependent on the manner in which the electricity and/or hydrogen is produced, along with the energy efficiency of the vehicle (typically expressed in watt hours per mile or kilometre for BEVs, and miles or kilometres per kilogram for hydrogen-powered vehicles). For PHEVs fuel-cycle emissions are a complex combination of upstream and end-use (tailpipe) emissions since these vehicles use a combination of grid electrical power and another fuel that is combusted (or potentially converted with a fuel cell) on-board the vehicle. There can be significant tailpipe emissions depending on travel patterns and the type of plug-in hybrid, along with any strategies to prevent criteria pollutant emissions from the catalyst-based control system when it is periodically starting up from low temperatures.

For all EVs there are emissions related to the vehicle production and disposal life cycle; these vehicle life-cycle emissions differ from vehicle life-cycle emissions for gasoline vehicles mainly (but not entirely) because of emissions from battery manufacture.

(b) Upstream fuel-cycle emissions

The emissions associated with fuel production, or upstream emissions, dominate the fuel-cycles associated with BEVs and HFCVs. For BEVs, upstream emissions consist of emissions from the production and delivery of electricity for vehicle charging. These emissions vary regionally based on the fuels and types of power plants used to generate electricity. For HFCVs, upstream emissions are from the production, delivery and dispensing of gaseous or liquid hydrogen. For PHEVs, total emissions consist of a mix of upstream emissions from electricity generation (proportional to the extent that the vehicle is recharged with electricity) and both upstream and in-use emissions from fuel combustion from the vehicle engine (or potentially conversion in a fuel cell).

(c) Comparison of greenhouse-gas emission reductions from the fuel life cycle for various electric vehicle types

Figure 5 compares fuel-cycle GHG emission-reduction studies for BEVs and HFCVs. BEVs have the potential to reduce fuel-cycle GHG emissions by about 55–60% using either natural gas power plants or the California grid mix (which is heavily dependent on natural gas). Using coal-based power, BEVs may reduce fuel-cycle emissions by about 20% or slightly increase them (model results vary somewhat), and using the US grid mix (which is about half coal-based) emission reductions of the order of 25–40% appear possible. For HFCVs using hydrogen produced from natural gas steam reformation, fuel-cycle GHG emissions can be reduced by 30–55% according to the various studies. When entirely or almost entirely powered by completely renewable fuels such as wind, solar and hydroelectricity, fuel-cycle GHG emissions from both BEVs and HFCVs can be almost 100% eliminated.

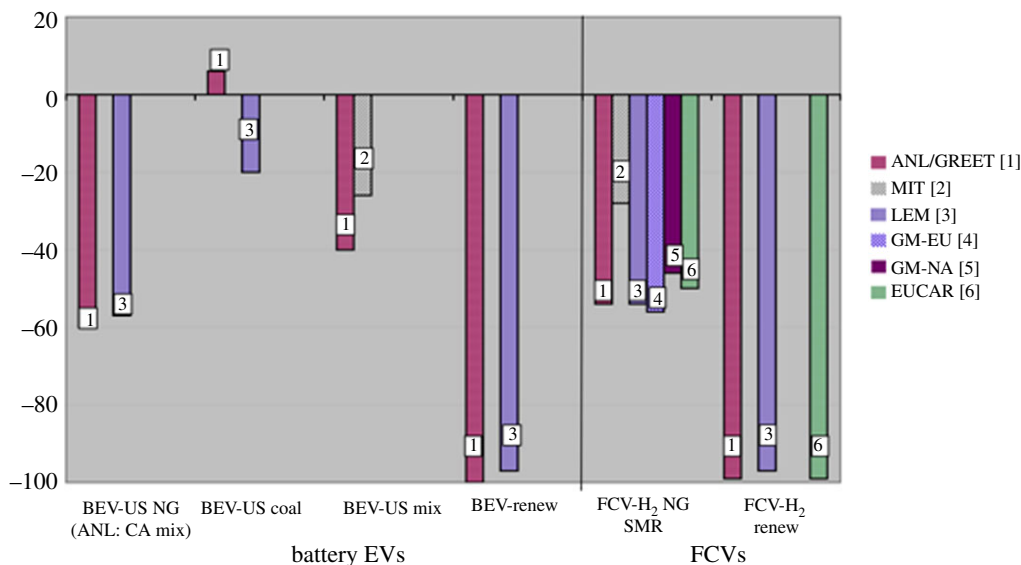


Figure 5. Comparison of fuel-cycle GHG emission-reduction estimates for BEVs and FCVs. Sources: 1, [30,34]; 2, [36]; 3, [46]; 4, [31]; 5, [32]; 6, [33]. (Online version in colour.)

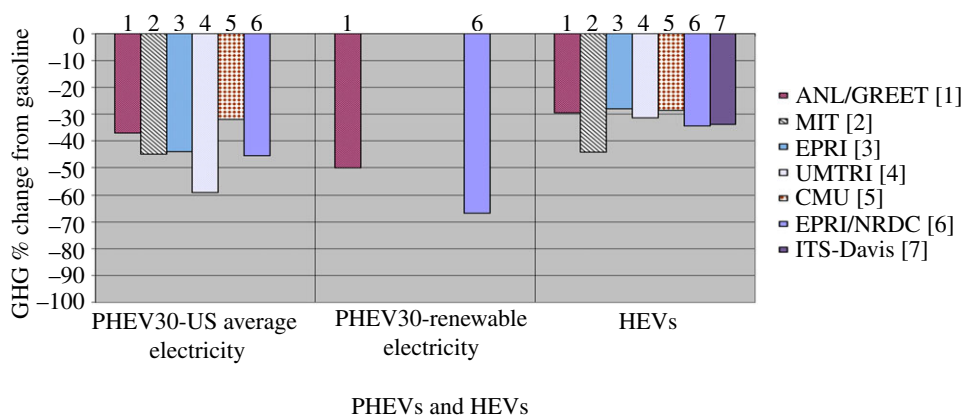


Figure 6. Comparison of fuel-cycle GHG emission-reduction estimates for PHEVs and HEVs. PHEV30 = PHEV with a 30-mile range. Sources: 1, [34,35]; 2, [36]; 3, [37]; 4, [38]; 5, [39]; 6, [40]; 7, [6]. (Online version in colour.)

When we compare estimates of the fuel-cycle GHG reductions (from gasoline) to be expected from PHEVs and HEVs (figure 6), we see that findings vary by study. For a PHEV that has a 30 mile (50 km) electric range, fuel-cycle GHG emission reductions compared with a conventional vehicle are estimated to be 30–60% using the US grid mix. PHEVs running on renewables-based electricity offer greater reductions, in the range of 50% to almost 70%. For HEVs, most studies typically estimate reductions of approximately 30%, although one study estimates a reduction of approximately 45%.

(d) Vehicle life-cycle emissions

Note that the estimates in figures 5 and 6 are of *fuel-cycle* GHG emission reductions; that is, they do not include emissions from the vehicle-material life cycle, which generally comprises the assembly, shipment and recycling of the vehicle and the complete life cycle of the materials

in the vehicle. Because EV batteries are massive and relatively energy-intensive to manufacture, GHG emissions from the EV vehicle-material life cycle generally will be higher than from the ICEV vehicle-material life cycle. Published life-cycle analyses indicate that GHG emissions from the production of lithium-ion batteries are of the order of 5–15% of the fuel-cycle emissions from gasoline ICEVs, depending mainly on assumptions about the composition, manufacturing process, size, performance, lifetime and recyclability of lithium-ion batteries, and the amount and kind of energy used in battery manufacturing [41–43]. It is important to note, however, that in a world powered entirely by renewable energy [44], vehicle life-cycle emissions for EV will be essentially zero.

(e) Oil use of electric vehicles

For two reasons, BEVs and HFCVs use virtually no oil directly in their energy life cycles: worldwide, very little oil is used to generate electricity (around 5% of the total today, projected to decline to 2% by 2035 [45]), and ‘upstream’ use of oil in the life cycle of non-petroleum energy feedstocks is almost zero (based on our use analysis using the Lifecycle Emissions Model [46]). Direct life-cycle oil use by PHEVs depends on the size and use of the battery, and the fuel efficiency of the ICE, and so cannot be easily predicted accurately, but it probably is reasonable to assume that people will not buy PHEVs unless they greatly value the electric-drive option, in which case PHEVs probably will use *much* less oil than do conventional gasoline vehicles. Indeed, the estimates of fuel-cycle GHG reductions with PHEVs using renewable energy, in figure 6, give a first approximation of the reduction in oil use in the range 50–65%.

Note that in theory the use of EVs will have indirect economic effects on the use of petroleum. Theoretically, an initial reduction in oil use will tend to cause the price of oil to fall, which then will tend to cause a ‘rebound’ increase in the use of petroleum products. However, supply and price dynamics in the world oil market are complex, and to our knowledge no-one has estimated this ‘rebound’ effect in the context of substituting electric-drive for ICE vehicles.

5. Material-use impacts of electric vehicles

In an electric transportation system, the key new technologies will be electric motors and controllers, batteries and fuel cells. An important question is whether any of these technologies use materials that are either scarce or else concentrated in a few countries and hence subject to price and supply manipulation, in which case the need for such materials might become a barrier to development. Here, we focus on rare-earth elements (REEs), particularly neodymium, for electric motors, lithium and other metals for lithium-ion batteries, and platinum for fuel cells.

(a) Neodymium for electric motors (adapted from [44])

Some permanent-magnet AC motors can use significant amounts of REEs. For example, the motor in the Toyota Prius uses 1 kg of neodymium (Nd) or 16 kg MW^{-1} . In a worldwide fleet of EVs with permanent-magnet motors, the total demand for Nd might be large enough to be of concern, especially because permanent-magnet motors with Nd are also used in generators for wind-power turbines. A highly electrified world in which 50% of global electricity was provided by wind turbines and two-thirds of LDVs had electric motors could require up to 200 000 tonnes of Nd oxide per year. This rate of consumption would exhaust known global Nd oxide reserves in less than 100 years and would exhaust the more speculative potential resource base in perhaps a few hundred years. Therefore, it seems probable that a rapid global expansion of wind power and EVs eventually will require generators and motors that do not use Nd or other REEs. However, this is not likely to be a serious constraint, because there are alternatives to Nd for use in motors and generators [44].

Table 4. Metal weight percentage of the active materials for the cathode, anode and electrolyte of lithium-ion batteries. Source: Gaines & Nelson [47]; el. = electrolyte.

metal	cathode					anode	el.
	LiCoO ₂	LiNiCoAl	LiNiCoMn	LiMn ₂ O ₄	LiFePO ₄	Li ₄ Ti ₅ O ₁₂	LPF ₆
lithium	7.1	7.3	7.3	3.9	4.4	6.1	4.6
cobalt	60.2	9.3	9.8				
nickel		48.7	25.8				
aluminium		1.6					
manganese			24.0	60.8			
titanium						52.0	
iron					35.4		
phosphorus					19.6		20.4
fluorine							75.0

(b) Lithium and other metals for batteries

As mentioned above, EVs are expected to use lithium-ion batteries for the foreseeable future. Table 4 shows the metal weight percentage of active materials for the cathode of lithium-ion batteries of various chemistries, along with the percentages for a lithium titanate anode and an LPF₆ electrolyte. With the metal weight fractions of table 4 and data on metal resources and prices (top part of table 5), we estimate the cost of the lithium, cobalt, manganese, nickel, phosphorus or titanium in a 200 kg battery, and the time period over which annual production of 20 million EVs would consume current reserves of the metal (bottom part of table 5). (We do not include iron or aluminium because we assume *prima facie* that the additional use of these materials in EV batteries would be very small compared with other uses.)

The simple analysis in table 5 illustrates the potential impact of a large global EV fleet on the demand for and cost of key materials, and thus helps us understand the long-run economics of different lithium-ion battery chemistries. Two results are of particular interest: the cost of battery materials at current prices, and the number of years that current reserves would last assuming the production of 20 million EVs per year. The latter gives us a sense of how material prices, and hence the cost of materials for a battery, might develop in a large EV market.

LiCoO₂ and LiNiCoAl batteries have relatively high materials costs at current prices (table 5). Moreover, the production of large numbers of these batteries could rapidly deplete known reserves (see reserves/EV demand ratio in table 5), which could increase cobalt and nickel prices and make the batteries even more costly in the future. Note that for cobalt and nickel the ratio of resources to EV demand would be about twice as much as the reserves/EV demand ratio. For these reasons, LiCoO₂ and LiNiCoAl may not be economic cathode materials for the sustained production of large numbers of EV batteries.

LiNiCoMn batteries also use costly nickel and cobalt, albeit less than do LiCoO₂ and LiNiCoAl batteries. At current prices, the nickel and cobalt cost about \$500 per battery (table 5). And again, EV demand for both is likely to increase prices, perhaps considerably. The demand for cobalt for the production of 20 million batteries per year would be about equal to current world mine production of cobalt, and would deplete current cobalt reserves in less than 60 years (and deplete cobalt resources in about 120 years) (table 5). The demand for nickel to make 20 million EV batteries per year would be two orders of magnitude larger than current world mine production.

Although Li₄Ti₅O₁₂ anodes use expensive titanium metal, the total materials cost at current titanium prices is modest, and the total cost per kilogram of a Li₄Ti₅O₁₂ anode is less than that of the more widely used graphite anode [50]. However, the impact on titanium price of increased

Table 5. Supply and cost of lithium, cobalt, nickel, manganese, phosphorus and titanium for EV batteries.

	Li	Co	Mn	Ni	P	Ti
data on metals, <i>ca</i> 2012 ^a						
world reserves (10 ⁹ kg)	13	7.5	630	75	9600	420
identified resources (10 ⁹ kg)	40	15	large	> 130	> 43 000	> 1200
major countries	Bolivia, Chile, Argentina	Congo, Australia	South Africa, Ukraine	Australia, New Caledonia	Morocco, western Sahara, China	China, Australia
recycled percentage of consumption	tiny but growing	25	unknown, but probably small	43	none for phosphate rock	unknown, but probably very small
world mine production (10 ⁹ kg yr ⁻¹)	0.037	0.11	0.016	0.002	30	0.004
price (\$/kg)	25	30.9	0.0074	17.6	0.68	5.0
calculated supply and cost ^b						
battery chemistry	all	LiCoO ₂ / LiNiCoMn	LiMn ₂ O ₄	LiNiCoAl/ LiNiCoMn	LiFePO ₄	Li ₄ Ti ₅ O ₁₂
material per battery (kg)	3.1	40/6.5	40	32/17	13	22
material cost per battery (2012 price) (\$)	78	1228/200	0	566/300	9	109
EV demand, 20 × 10 ⁶ batteries per year (10 ⁹ kg yr ⁻¹)	0.06	0.79/0.13	0.80	0.64/0.34	0.26	0.44
reserves/EV demand (years)	210	9/58	780	120/220	37 000	960

^aFrom [48] except as noted. *Reserves* are currently economically extractable. *Identified resources* are currently or potentially economically extractable and known or estimated based on specific geological evidence. *Co*, price is USGS-reported spot market price for cathodes. *Li*, in 2012, lithium carbonate (Li₂CO₃) sold for about \$5 per kg, and lithium hydroxide (LiOH) sold for about \$7 per kg, prices that correspond to about \$25 per kg Li. *P*, USGS data are for phosphate rock [48]; we convert to P basis assuming 0.6 kg P per 4.2 kg phosphate rock [49]. *Ti*, USGS data are for TiO₂ [48]; we convert to Ti-only basis. USGS-based TiO₂ price calculated by dividing USGS-reported \$3.9 billion value of production by USGS-reported 1.3 billion kg production.

^bCalculated from the data in the first part of this table, the data in table 4, and other sources, as follows. *Material per battery*: equal to the electrode metal weight fractions shown in table 4, multiplied by electrode/battery weight ratios of 0.33 for the cathode or 0.21 for the anode [41]; these fractions will vary with battery chemistry, but we ignore this variation here, and multiplied by an assumed 200 kg per battery (roughly 20 kWh or 100 km range at 5 km per kWh). We assume that lithium (in the electrolyte as well as the electrode) is 1.6% of the entire battery mass (average value over a range of lithium-ion battery chemistries [47]). *EV demand* is the metal required to produce 20 million 200 kg batteries per year—about 30% of the current 63 million vehicles per year world production (<http://oica.net/category/production-statistics/>).

titanium demand due to the production of large numbers of EV batteries is not clear. On the one hand, even a large EV programme would not exhaust current reserves for about 1000 years, but on the other hand, the additional annual titanium demand of a large EV programme would be two orders of magnitude larger than current world production (table 5).

LiMn_2O_4 and LiFePO_4 batteries do not use costly or potentially scarce materials. Manganese, iron and phosphorus are relatively inexpensive and abundant, and likely to remain so even if large amounts of EV batteries are produced.

Finally, we consider lithium. Several recent analyses indicate that if the global lithium industry can be expanded smoothly, and if known lithium resources can be extracted economically, and if lithium-ion batteries can be recycled economically, then currently identified lithium resources can support the economic development of a very large global EV fleet (50% or more of new vehicle production—larger than the 30% assumed in table 5) lasting for a century or so [44,51,52].

Presently, the cost of lithium is only a small, albeit non-trivial, fraction of the total cost of a battery. Given that lithium-ion batteries contain approximately 100–300 g lithium per kWh of battery [52], a battery in an EV with a relatively long range (say 20–30 kWh) would contain 2–9 kg lithium (in table 5, we estimate 3 kg). At the 2012 price of about \$25 per kg Li (table 5), this amount of lithium would contribute \$50 to \$225 to the manufacturing cost of a vehicle battery (in table 5, we estimate about \$80).

However, if it turns out to be costly to expand lithium production and recycle lithium, lithium prices could rise substantially. On the one hand, most of the world's identified lithium resources are in Bolivia and Chile [53], and both countries recognize the importance of lithium to battery and car makers and are hoping to extract as much value from their lithium resources as possible. On the other hand, dramatic increases in demand for lithium will spur the search for new sources and more economic production methods, and may eventually lead to the economic extraction of lithium from the ocean, which for all practical purposes has an infinite (albeit currently quite costly) resource [54]. Similarly, although lithium-battery recycling presently is not economic, and the long-term costs of large-scale recycling of lithium batteries is not known, the industry is still nascent, and it is not unreasonable to assume that in a couple of decades economic recycling will be developed (see [41,52] for discussions of recycling.)

In conclusion, it appears that there are at least two lithium-ion battery chemistries, LiMn_2O_4 and LiFePO_4 , that do not use scarce or expensive materials, assuming that the lithium production and recycling industries develop as might be expected. The implications of this for evaluating the cost and desirability of battery technologies is discussed in §6.

(c) Platinum for fuel cells (adapted from [55])

The production of 20 million 50 kW fuel-cell vehicles annually might require of the order of 250 000 kg of platinum (Pt)—more than the total current world annual production. How long this output can be sustained, and at what platinum prices, depends on at least three factors: (i) the technological, economic and institutional ability of the major supply countries to respond to changes in demand; (ii) the ratio of recoverable reserves to total production; and (iii) the cost of recycling as a function of quantity recycled.

The effect of recycling on platinum price depends on the extent of recycling. It seems probable that a 90% recycling rate or better will keep platinum prices significantly lower than will a 50% recycling rate. We cannot predict when and to what extent a successful recycling system will be developed. Nevertheless, we believe that enough platinum will be recycled to supply a large HFCV market and moderate increases in the price of platinum, until new, less costly, more abundant catalysts or fuel-cell technologies are found. Indeed, catalysts based on inexpensive, abundant materials may be available relatively soon; research on iron-based catalysts suggests that a worldwide FCV market will not have to rely on precious-metal catalysts indefinitely [56].

Work by Sun *et al.* [57] supports this conclusion that platinum recycling will moderate the cost of platinum for HFCVs. They developed an integrated model of HFCV production, platinum loading per HFCV (a function of HFCV production), platinum demand (a function of HFCV

production, platinum loading and other factors) and platinum prices (a function of platinum demand and recycling), and found that, in a scenario in which HFCV production was increased to 40% of new LDV output globally in the year 2050, the average platinum cost per HFCV was \$500, or about 13% of the cost of the fuel-cell system.

6. Lifetime costs of electric vehicles

In this section, we present the results of a recent comprehensive review of studies of the full social lifetime cost of BEVs, PHEVs and fuel-cell electric vehicles (FCEVs) [58]. The full social lifetime cost of a vehicle comprises all of the initial and periodic costs of owning and operating a vehicle, including ‘external’ costs such as air pollution, climate change and oil dependence.

Analyses of the lifetime cost of EVs are relevant because, although there are no technical barriers to developing EVs that perform as well as do petroleum ICEVs, it is not clear from current market conditions whether advanced EVs eventually will be economic compared with gasoline vehicles. No manufacturer is producing advanced EVs in large quantities, and the prices for commercial vehicles produced in small quantities tell us little about long-run manufacturing costs at high production volumes. Moreover, the manufacturing cost is not the only relevant cost metric: vehicles that have higher initial costs might have lower operating and maintenance costs and as a result might have lower total costs over their lifetime. And even if advanced EVs have higher lifetime *consumer* costs than do comparable ICEVs, they still might have lower lifetime *social* costs, on account of having lower ‘external’ (non-market) costs such as the value of air-pollution damages, climate-change impacts, and oil-use and energy-security costs.

A comprehensive review and analysis of the lifetime cost of EVs draws the following conclusions [58, p. 57–58]:

Compared with conventional gasoline ICEVs, advanced EVs—BEVs, PHEVs and FCEVs—have higher initial costs, lower fuel costs, lower external costs, possibly higher insurance costs and possibly lower maintenance and repair costs. It thus is not immediately obvious how the full social lifetime cost of advanced EVs compares with the full social lifetime cost of gasoline ICEVs.

The formal estimation of the full social lifetime cost depends on a number of uncertain analytical details, including:

- the size of key components for EVs (batteries, fuel cells, hydrogen pressure vessels, electric motors), which depends on the desired performance and driving range and the energy efficiency of the vehicle;
- the cost of key materials for EV components, including for example lithium for batteries, platinum and membranes for fuel cells and carbon fibre for pressure vessels;
- the lifetime of key components (for example, cycles for batteries and pressure vessels, hours of operation for fuel cells);
- how manufacturing costs change with increasing production due to technological learning and economies of scale;
- the energy use of the EV, which depends on the technology and design of the powertrain, the drivecycle, the weight of the EV, the desired performance and other factors;
- the cost of energy for the EV, which depends on feedstock costs, fuel production costs, fuel distribution costs and fuel dispensing/delivery costs, which in turn depend upon the type of fuel and the desired fuel delivery method (e.g. compressed versus liquefied hydrogen; slow overnight battery charging versus fast commercial battery charging);
- the relationship between insurance costs and vehicle value;
- the maintenance and repair requirements of advanced EV components and drivetrains;
- the magnitude of the changes in oil use and emissions of air pollutants and GHGs, and the dollar value of these changes, which in turn depend on assumptions and methods

used to address a range of difficult-to-model problems, such as the costs of catastrophic climate change or the macroeconomic costs of oil-supply disruptions;

- the treatment of non-cost transfers, such as producer surplus and taxes and fees; and
- the cost and performance of advanced batteries and fuel cells (for recent work see [50,59]).

As regards the last issue, the cost and performance of advanced batteries, in §5 we concluded that there are at least two lithium-ion battery chemistries, LiMn_2O_4 and LiFePO_4 , that do not use scarce or expensive materials. However, the cost metric of interest to society is not the initial manufacturing cost, but the overall social lifetime cost per mile, which is based on the performance and lifetime of the battery as well as the initial manufacturing cost. LiNiCoMn batteries use cobalt and nickel and hence may become relatively costly if large numbers of batteries are produced, but LiNiCoMn batteries have a higher cycle life and energy density than do LiMn_2O_4 batteries, and a higher energy density than do LiFePO_4 batteries (table 2), and hence may have a lower lifetime cost. In principle, the ‘best’ battery is the one that provides the greatest present value of net social benefits over a wide range of plausible EV development scenarios. A recently developed, detailed battery cost model [50] provides the best available estimates of the manufacturing cost of advanced lithium-ion batteries, but more work is needed to develop overall social lifetime cost estimates for batteries.

Overall, most analyses suggest that, with reasonably anticipatable technological progress, the social lifetime cost (including external cost such as climate change and oil dependence) of advanced EVs can be close to the social lifetime cost of gasoline ICEVs [58]. More work is needed in the areas listed above for more definitive conclusions, particularly as new advanced EV designs and concepts continue to emerge.

7. Electric vehicle markets: understanding how people will adapt to and take advantage of the special attributes of electric vehicles

Like all automobiles, EVs provide important functions, such as mobility, but also have symbolic meaning and can engender strong emotional attachments [60,61]. All three of these—functional mobility services, symbolic meanings and affective emotional responses—have been found to influence how people respond to use PEVs in North American and European markets [62,63]. Both the direct experience of early EV buyers and the mediated experience of their social networks as these buyers start to tell stories of their experience are essential to the formation of valuations of functions, symbols and emotions. Among a sample of PEV drivers in Berlin, ‘before vehicle handover, the majority of participants expected to be constrained by the limited range of the EV. Survey data after 3 months of [B]EV use indicate that for more than 94% of users a range of 140–160 km is sufficient for everyday needs’ [64]. Experience with a BEV improved measures of functional performance by drivers in the UK, including initial acceleration, noise, smoothness, responsiveness and driving pleasure [65]. HFCVs have similar meanings and values for consumers, but because there is much less consumer experience with them, we focus on PEVs here.

Thus, when we consider the potential market for EVs, we should focus not only on the lifetime cost of the vehicles and the ostensibly disadvantageous ‘functional’ attributes, such as a recharging time longer than a gasoline refuelling time, but also on the *enhanced and new values* provided by the functional, symbolic and emotional attributes of EVs.

(a) Systems of enhanced and new values

Compared to ICEVs, EVs have three sources of enhanced and new values: (i) the electric drivetrain, (ii) the charging system for PEVs and possibilities for new refuelling networks, especially home refuelling, for HFCVs, and (iii) new identity expressions. With these three sources

of enhanced and new value, individuals and their households create new lifestyle sectors in which these new values are derived and enacted. For example, a household may reorganize their activities (especially those requiring travel) around the new ensemble of performance capabilities represented by EVs and especially around the combination of an EV and a conventional (or hybrid) vehicle in multi-vehicle households.

(i) Values from electric drivetrains

The values to be derived from the electric drivetrain are the most immediate and the most within the control of the vehicle designer and manufacturer. For example, electric motors reach maximum torque almost instantaneously, which results in more rapid low-speed acceleration compared with ICEVs. Consumers can experience this enhanced value of EVs in a matter of a few seconds—the time it takes to accelerate from a stop to 100 km h^{-1} . People who had leased the electric version of the Mini frequently commented on that BEV's acceleration capabilities; those who had driven both the electric and gasoline variants routinely preferred the performance of the electric drivetrain [66]. One Nissan Leaf EV owner interviewed by one of us in April 2012 described his satisfaction at beating any other car across an intersection from a standing start on the change of the traffic signal from red to green. Whether such aggressive driving is to be encouraged is problematic, but the examples stand out precisely because they dispel these drivers' apprehension that BEVs might be underpowered and slow—thus overcoming a potential functional disadvantage that can spark a negative emotional response [63].

Another positive attribute of electric (and hybrid) drivetrains not available in conventional drivetrains is regenerative braking, which provides functional, symbolic and emotional values, such as higher efficiency and lower operating cost, the satisfaction of contributing to important social goals to conserve energy and high-tech cachet. Prior to the introduction of hybrid vehicles into the North American market in the late 1990s, 'high fuel economy' was seen as an attribute of small, cheap, under-powered cars, i.e. 'econo-boxes' [67]. Hybrid drivetrains transformed this meaning, so that hybrids came to be seen as high-quality and high-technology, 'efficient' rather than 'economical', and as the first 'green' automobile [60].

(ii) New values derived from the electric energy and charging system

Sources of new values to be derived from charging a PEV from the electrical grid rather than refuelling at a station dispensing petroleum-based fuels include a sense of independence from oil, the satisfaction of using a relatively clean source of energy, avoiding inconvenient trips to refuelling stations, avoiding exposure to toxic gasoline vapours, being assured of always having fuel readily available and (currently) stable electricity prices compared with fluctuating gasoline prices [66]. For most consumers, all of these values, including the value of stable electricity prices in comparison to gasoline prices, are apparent relatively quickly, within a few days.

In general, PEV drivers who have at least one month of experience with home charging begin to appreciate that charging at home is a convenience. A similar value might be formed by drivers of HFCVs—if home refuelling appliances are available. Parallel experience with the early marketing of PEVs and their charging appliances—known in the technical literature as EVSE—indicates that early HFCV markets may also be limited to home owners who control viable parking in the vicinity of a location to install a refuelling appliance. Concomitant development of both home and away-from-home hydrogen refuelling [68] may broaden the population of potential early HFCV buyers and facilitate the formation of some of the same new values as PEV drivers are now doing around home recharging.

(iii) New identity expressions

In-depth, long-term research reveals that, after weeks of experimentation, learning, adaptation and social interaction, households driving PHEVs and EVs create new household activity patterns, new assignments of vehicles to accomplish those patterns, as well as new personal and

social values regarding PEVs [64,66,69,70]. Because EVs have markedly different functional and emotional attributes than do conventional vehicles, households do not merely substitute new EVs into their pre-existing, unmodified transportation and activity patterns, but rather recreate their living and travel patterns both to adjust to the constraints provided by electric transportation and to take advantage of the new possibilities that are offered. In the short term, they may reorganize their travel and refuelling patterns. In the medium term, they may change the mix of vehicles they own, to allow greater specialization by trip purpose, and then may further reorganize travel and energy use. In the long term, they may change where and how they live, to take advantage of the new possibilities in a world with electric transportation integrated into the energy system, and then again readjust their ownership and usage of vehicles and their daily activities.

These changes in travel and living patterns are accompanied and reinforced by changes in social and personal identity. Over time, EV-adapted households may present themselves as socially and economically innovative and adaptable, technologically sophisticated, environmentally sensitive and generally concerned about long-term, global issues [60,66].

(b) Conclusions

EVs are not simply replacements for conventional vehicles—they provide access to revised and wholly new values. Because of this, the potential market for EVs, i.e. PEVs and HFCVs, cannot be estimated with conventional consumer-choice models specified with traditional choice attributes, such as simple metrics of cost and performance. Even the handful of more sophisticated choice models, which include refuelling time, cargo space and other ‘amenity’ values [71–73], and those that address specific body styles and brands [74] do not account for all the systems of new values discussed here. It is probable that the processes of experimenting, learning and adaptation, as described above, will lead to much larger roles for PEVs than conventional analyses assume. When this is considered along with the possibility of using HFCVs for trips that PEVs cannot easily perform, there are no limitations to the markets for EVs broadly defined.

8. Electric vehicle policy development

PEV sales and use could soar—or stagnate—from today’s entry market levels. A limited number of manufacturers are making major investments in PEVs and consumers appear to be slowly adjusting their vehicle purchase behaviour, but because EVs provide societal benefits (e.g. reduced GHG emissions and reduced dependence on oil) that are not valued in the private sector, the marketplace by itself will not yield socially ‘optimal’ numbers of EVs. To help realize the societal benefits of EVs, governments can craft and strengthen policies that bolster emerging markets, facilitate PEV ownership and use, and boost public confidence in new, electrified transportation. Here, we discuss three important robust policy approaches that the US Government and others could follow to support and stimulate the adoption of PEVs, namely: motivate PEV manufacturers, target specific regions and local PEV clusters, and restructure and streamline regulation of PEV charging [75].³ Variations of these approaches will also be appropriate to other national jurisdictions.⁴

(a) Motivate plug-in electric vehicle manufacturers

Policy intervention is needed so that automakers do not slow down or abandon their commercialization plans as they confront market challenges. Without new policies, the future

³Mass marketing of HFCVs has not yet begun, although most major automakers have announced plans to begin selling in the tens of thousands later in this decade—depending in part on supportive policies and especially upon guarantees that hydrogen stations will be in place. Policy challenges are similar for PEVs and HFCVs in a generic sense, but the details can vary dramatically, especially related to charging and fuelling. (PEVs can be charged at home. HFCVs cannot.) In this policy discussion, we focus on PEVs, with the understanding that HFCVs require policy to assure the early installation of hydrogen fuel stations wherever automakers plan to market HFCVs.

⁴For a review of current Federal and State policies and incentives directed at EVs, see [76].

for PEVs is uncertain: forecasts for US PEV sales range anywhere from 1% to 33% of new vehicles in the 2020–2030 time frame [77]. To support the growth of the market for PEVs, the following steps could be taken to motivate PEV manufacturers.

(i) Extend PEV policies to encourage automakers

Maintaining and growing Federal PEV grants, loans and R&D support to industry and academia is necessary to accelerate PEV deployment and commercialization. The portfolio of policies here includes grants and loans to industry, basic R&D support to academia and national laboratories, vehicle demonstration funds, support for charging infrastructure, market and other applied research, and grants for training and education, including emergency response, technician training and other supporting roles [78].

Vehicle performance standards for energy and GHGs that favour EVs are also effective. These policies are important in overcoming the large costs and barriers to early introduction. Both Europe and the USA provide special dispensation to EVs, deliberately not counting their upstream emissions in the performance standards and thus providing an incentive to automakers to produce more EVs.

Vehicle production and sales mandates are another approach to overcome startup challenges. California's Zero Emission Vehicle mandate requires automakers to produce an increasing number of PEVs and HFCVs. This mandate has been revised many times since its first adoption in 1990, with great controversy. But it has led to continuing R&D and investment in electric-drive technology over the years and slowly expanding sales. Ten other States in the USA have adopted California's mandate. The current requirement is for approximately 15% of vehicle sales to be BEVs, PHEVs or HFCVs in 2025 in those 11 States, which account for almost 30% of the US market.

(ii) Engage auto dealers

Auto dealers will play a central role in the commercialization of PEVs, as many dealers act as influential small business owners in their communities. Engaging auto dealers as PEV marketers, as supporters of local PEV initiatives, and as political proponents of PEVs can encourage PEV adoption [79].

(b) Target specific regions and local clusters

Many States in the USA have introduced their own incentive programmes to encourage the production, purchase and use of EVs. The most popular policy instrument used by States is a tax incentive aimed at reducing the incremental cost of purchasing an EV. Many States provide grants and loans to local governments to promote use of PEVs; funds are provided to electrify school buses, to purchase PEVs for municipal fleets and to install recharging infrastructure, as well as to modify utility rate structures to favour PEVs [80,81]. In this way, States play a major role in PEV deployment. PEV sales, acceptance and benefits would grow if the following geographic-specific policy strategies were pursued.

(i) Target regions with low-carbon electricity

Benchmarking and geographically targeting regions with the lowest carbon emissions can help focus policy efforts for PEV adoption. Policy (and advocacy) priorities can be based on how each region currently ranks and what policies are in place to further reduce carbon emissions from their electric grids in the future.

(ii) Compensate for lost gasoline tax revenues

Drivers of petroleum-fuelled ICEVs pay fuel taxes that, in the USA, are dedicated to road construction and maintenance. EV drivers do not pay taxes into these State and Federal trust

funds, and this potential decline in revenue can alarm transportation agencies. EV policies that include means of compensating for lost gasoline-tax revenues (such as road-user charging) might alleviate this concern of transportation agencies.

(iii) Cultivate local PEV clusters

Focusing on local PEV clusters is an important strategy for accelerating the transition to PEVs. This approach may be more effective than national strategies. It lends itself to focusing on areas with low-carbon electricity, advancing charging infrastructure where demand is highest, and providing assistance to those communities that are most supportive of EV use.

The US Department of Energy, for instance, has a Clean Cities Program with community readiness grants that support local projects for PEV deployment. In 2011, the Clean Cities Program allocated \$8.5 million for grants covering 24 cities, and the programme has compiled a series of PEV handbooks each tailored to a specific subset of stakeholders—consumers, fleet managers, public charging station hosts and electrical contractors [82,83]. Expansion of these types of programmes could help to lay the foundation for the eventual emergence of comprehensive ‘PEV ecosystems’ in selected metropolitan regions.

(c) Restructure and streamline regulation of PEV charging

US utility regulations and practices are a hotchpotch, where every State (and municipality) manages its electricity differently. Encouraging regulators to harmonize technical standards, streamline the installation of household and commercial charging stations, and use electricity tariff structures to promote charging at off-peak hours can further promote PEV adoption. Policies that advance restructured PEV recharging include the following.

(i) Reform utility ‘decoupling’ regulations

Many States have adopted electric utility regulatory regimes that decouple revenues and profits, so that utilities can earn profits without having to sell more electricity. The intent of this decoupling is to encourage investments in energy efficiency, but this has the unfortunate side effect of *discouraging* electricity sales for vehicles.

(ii) Design electricity prices for PEVs

Tariff design is a crucial tool for encouraging PEV use and managing PEV load demand growth. State regulators can play a role in encouraging utilities to adopt variable time-of-use pricing to manage the demands of PEVs on the grid.

(iii) Develop a strategy for investing in recharging infrastructure

In surveys, a majority of car owners claim that they will not buy PEVs unless there is widespread recharging infrastructure, yet early recharging evidence suggests that new PEV owners rarely seek out or use public charging [84,85]. More studies of PEV driving and recharging behaviour can help resolve this apparent contradiction and inform analyses of the most cost-effective strategies for investing in recharging infrastructure.

(iv) Reform power regulations

There is regulatory uncertainty and inconsistency regarding how utilities should be involved with PEV infrastructure investment. For example, Oregon’s Public Utilities Commission recently took a step towards opening up the EVSE market to broaden participation from utilities, but the California Public Utility Commission opted to exclude utilities from the EVSE market [86,87]. More consistency in utility regulations could help create a more certain basis for large-scale investment in EV infrastructure.

(v) Align utility incentives with energy efficiency and low-carbon goals

The 2009 American Recovery and Reinvestment Act (ARRA) conditioned a State's receipt of Energy Efficiency Program funds (approx. \$3.1 billion) on the State's adoption of policies to align utility incentives with energy efficiency goals. Similar caveats could be attached to streamlining of State regulations to future Federal disbursements for vehicle electrification.

(d) Policies outside of the USA

Tackling the major and growing global concern over transportation carbon will require an EV policy 'roadmap' that extends to other motorized and rapidly motorizing nations, including China, India, the EU, Japan, Korea and others.

The Chinese government is aggressively pursuing policy options to fund the automotive industry, with the intent of being the largest global producer of PEVs, and Japan's strong automotive manufacturing role has already led to a commanding position in hybrid vehicle and battery technology development [88]. Europe, the USA, Japan and Australia are working towards developing standards for PEVs, which may be key for global PEV adoption [88]. For countries with high fuel prices (due to either taxes or availability), such as Japan and Europe, EVs with limited acceleration and low top speeds are expected to become commercially viable [89]. Owing to higher-density cities leading to more pervasive charging infrastructure and shorter commute distance, the share of BEVs in Europe and Japan will probably surpass the USA, and if policies work to encourage the manufacture of PEVs with batteries capable of lasting the vehicle's lifetime, the prospect for deployment of vehicles in regions with higher fuel prices, including China, is greatly improved [90].

The design and adoption of these PEV-related policies in other countries face large technological, economic, political and behavioural uncertainties. However, these uncertainties create opportunities as well as challenges. Changing market dynamics and energy circumstances—including concerns for oil supply security, volatile oil prices, continuing unemployment concerns and faltering economic recovery—suggest that PEV strategies that promise jobs and energy security, as well as environmental benefits, could be particularly compelling.

9. Summary

Electric-drive vehicles based on batteries, plug-in hybrid and fuel-cell technology will greatly reduce if not eliminate direct use of oil in transportation, and will significantly reduce emissions of GHGs compared with conventional vehicles in most cases and settings studied. Under certain conditions, EVs can even have very low to zero emissions of GHGs when based on renewable fuels.

If very large numbers of EVs are manufactured for many decades, then in the long term some of the rarer materials, such as neodymium (in electric motors and generators), platinum (in fuel cells) and lithium (in batteries), will have to be recycled or eventually replaced with less-scarce materials unless additional resources are located. The cost of recycling or replacing neodymium or platinum is not likely to affect noticeably the economics of EVs, but the cost of large-scale recycling of lithium batteries is unknown.

Compared with conventional gasoline vehicles, BEVs, PHEVs and HFCVs have higher initial costs, lower fuel costs, lower external costs, possibly higher insurance costs and possibly lower maintenance and repair costs. With reasonably anticipatable technological progress and fuel-price trends, the social lifetime cost of advanced EVs can be close to the social lifetime cost of gasoline vehicles. However, as new advanced EV designs and concepts continue to emerge, more research is needed in a number of areas, especially regarding the cost, lifetime and performance of batteries, fuel cells and hydrogen storage systems.

Like all automobiles, PEVs provide important functions, such as mobility, but also have symbolic meaning and can engender strong emotional attachments. As a result, EVs do not merely replace and serve the traditional functions of conventional vehicles—they also can provide access to revised and wholly new personal and social values. As consumers experiment with, learn about and adapt to EVs, the ultimate market potential of EVs is likely to be much larger than is estimated by consumer-choice analyses based on typical conventional-vehicle attributes.

Finally, in order to fully realize the potential for PEVs, we must craft and strengthen policies that bolster emerging markets, facilitate PEV ownership and use, and boost public confidence in new, electrified transportation. Among the most important strategies are motivating PEV manufacturers, targeting specific regions and local PEV clusters, and restructuring and streamlining regulation of PEV charging.

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