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What is needed for battery electric vehicles to become socially cost competitive? ☆

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ABSTRACT

Battery electric vehicles (BEVs) could be key to decarbonizing transport, but are heavily subsidized. Most assessments of BEVs use highly taxed road fuel prices and ignore efficient pricing of electricity. We use efficient prices for transport fuels and electricity, to judge what battery costs would make BEVs cost competitive. High mileage, low discount rates and high oil prices could make BEVs cost competitive by 2020, and by 2030 fuel costs are comparable over a wider range. Its contribution lies in careful derivation of efficient fuel and electricity prices and the concept of a target battery cost.

1. Introduction

There is growing agreement that if the world is to avoid damaging climate change then fossil fuel consumption will need to be drastically cut. Road transport currently accounts for 17–18% of global carbon dioxide (CO_2) emissions and the IEA estimates that CO_2 emissions from vehicles will double by 2050, at which point they might account for one-third of total emissions.[1] Given the constraints limiting the supply of biofuels[2] and the relative ease of decarbonizing the electricity supply industry, battery electric vehicles (BEVs) could provide a mass scale low carbon option for road transport. The key question is how, when, and at what scale to support the transition from Internal Combustion Vehicles (ICVs), primarily using diesel and gasoline, to BEVs.

The economics of BEVs depend on future oil, carbon and delivered electricity prices as well as, crucially, the cost and performance of the battery and drive train, all of which are uncertain, and many of which are overlain with price distortions. While there is an extensive literature on the potential CO_2 savings that BEVs might offer,[3] almost all of the cost comparisons use market prices and make comparisons in terms of cost per km or the total cost of private ownership,[4] stressing the financial benefits to the users of avoiding road fuel taxes, enjoying cheap fuel, and receiving substantial purchase grants.[5]

This article proposes a different approach to examining the economics of BEVs, working in terms of the full social cost of delivered energy to the wheels, comparing electricity, gasoline and diesel. This has several advantages. First, much of the remainder of the vehicle can be held constant across fuel choices. The only differences that need to be compared are the engine, drive train, fuel tank/battery, and pollution abatement equipment. Second, it forces one to consider likely technical improvements in all these components, not just in the battery. Third, it directs attention to the market distortions in the delivery of these energy vectors. For gasoline and diesel these are primarily the heavy excise duties and the lack of separately identified carbon and emissions taxes, but for electricity, the issues are more subtle and benefit from greater clarity than is normally afforded in more transport-oriented studies. It therefore aims at a greater degree of cross-subject integration, between transport and electrical engineers unfamiliar

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[1] See e.g. *The Global Fuel Economy Initiative* at http://www.unep.org/transport/gfei/autotool/understanding_the_problem/Trends_and_scenarios.asp.

[2] See IEA (2013a).

[3] E.g. Andress et al. (2011), EPRI (2007), Liu and Santos (2014), HM Treasury (2007), Neubauer et al. (2012), Pasaoglu et al. (2012), Prudhomme and Koning (2012), Thiel et al. (2010), Zhang et al. (2013).

[4] See e.g. Aguirre et al. (2012), Al-Alawi and Bradley (2013), Element Energy (2013, Fig. 17), EPRI (2013), Le Duigou et al. (2014), Lin et al. (2013), Kley et al. (2011), Madina et al. (2012), Prudhomme and Koning (2012).

[5] Thus the UK Deputy Prime Minister issued a press release on 30 Jan 2014 (at https://www.gov.uk/government/news/nick-cleggs-drive-to-make-uk-world-leader-in-electric-cars) stating "Electric car owners do not have to pay car tax or congestion charges and many chargepoints are free to use. The cars cost from just 2p a mile, which means a family that drives an electric vehicle 10,000 miles in a year would save around £1000 on fuel costs each year."

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with the techniques of social cost-benefit analysis, [6] and transport economists unfamiliar with the determinants of the efficient pricing of the different energy vectors and the economics of learning-by-doing. It reports results of a recently completed and very significant EU Framework 7 project Green E-motion (GeM, 4 years, 40 partners, €40 million) on which the authors were engaged. The project evidence is extensive, somewhat diffuse, and often at a high level of aggregation. This paper starts from the bottom up to clarify the key determinants of the relative social costs of ICVs and BEVs. In addition, while many studies, including GeM, use complex simulation models, we break the problem down into readily scrutinized steps to clarify the sources of the inherent uncertainties.

One of the benefits of concentrating on the efficient cost of delivered energy is that it requires monetizing the environmental costs, and particularly the social cost of greenhouse gas emissions, measured by carbon dioxide equivalents (CO_2e). These costs are uncertain, and certainly underpriced in the (early 2015) EU Emissions Trading System (which in any case does not apply to road transport). This paper therefore considers a plausible range of future values for the social cost of CO_2. The carbon content of fossil fuels is well-defined, but identifying that of electricity is far harder. Since BEVs add to electricity demand, if marginal electricity is generated from fossil fuels (even with a largely decarbonized electricity sector), is the claimed CO_2 benefit of BEVs almost completely offset by increased CO_2 emissions from the electricity sector? Liu and Santos (2014) use the GREET[7] model for the US to estimate lifecycle emissions in CO_2e gm/km for passenger cars in the US in 2020 and find that BEV's have a surprisingly high 60% CO_2e/km of ICVs, despite zero tailpipe emissions, because of the carbon intensity of electricity generated. Most such lifecycle studies use the average country-specific carbon intensity of electricity, not the relevant marginal intensity, nor the difference in the endogenous evolution of the electricity system with and without BEVs, which is the approach adopted here.

Our approach is to identify what would need to happen to battery and electricity costs for cost parity to be the case at some future date, given various oil and carbon price projections and the likely evolution of the European electricity system. Its originality lies in stripping out all the various distortions that currently bedevil comparisons between BEVs and ICVs by applying the techniques of social cost benefit analysis to the comparison and integrating this with careful modelling of electricity supply.

BEVs are heavily subsidized, for the defensible reason that mass deployment is needed to drive down costs, create a market to induce battery and motor manufacturers to innovate and reap economies of scale, and to support the development of an eco-system of charging infrastructure, service providers, leasing agents and the like sufficient to make BEVs a credible alternative to ICVs. The most recent and thorough estimate of the learning rate for the cost of the BEV battery pack suggests that costs per kWh fall at 6% for each doubling of the installed battery volume (Nykvist and Nilsson, 2015). The 2014 stock of BEVs was 410,000, and had been doubling each year for some time. Thus subsidies that increased the number of battery packs sold by 410,000 in 2014 would lower all future costs by 6% and advance the date at which BEVs yielded a net unsubsidized social surplus by one year.

The UK Committee on Climate Change claimed that "Electric vehicles are projected to become cost-effective during the 2020s, and deployment during this decade also has a market development benefit, enabling greater uptake in the 2030s and early 2040s. Over the period to 2050, the benefit relative to the delayed scenario has a net present value of £27 billion under central assumptions" (CCC 2013, box 3.6, p. 57). This is the benefit to the UK alone (Ling, 2012, Fig. 16), based on the UK Government's CO_2 price in 2030 of £74/tonne rising to £212/tonne in 2050, and is predicated on the benefits of early rather than late action. The assumption is that technology reaches maturity by 2030 and that after 2050 there is no difference between early and late action.[8] As the UK has less than 3% of the global number of cars, if these figures are scaled up for car numbers ($\times$35) but scaled back from lower average global income per head benefits (33% of UK), the global benefit could be £300 (€360) billion. Discounting at the UK social discount rate of 3.5% p.a., advancing the date at which this value were reached by one year would be worth £11 billion, or £27,000 (€32,000, $40,000)/BEV for each of these extra 410,000 BEVs. To put this in perspective, substantial sums have already been spent on subsidizing deployment (according to IEA, 2013b, some $50,000 per EV). As each doubling of the stock of batteries halves the gain in social value of the subsidy per BEV, these earlier subsidies can be justified if indeed the date of economic penetration is advanced and the subsequent carbon and other gains realized (Ling, 2012, assumed 40% new cars were zero-emitting by 2025 and 100% by 2030). Weiss et al. (2012), working with a slightly higher learning rate of 7%, estimated that "Our forecasts suggest that BEVs may require learning investments of around €100 billion and €150 billion before reaching price breakeven with HEVs and conventional ICE vehicles." This is below the €360 billion estimated above, and, less relevantly, less than the 2009 worldwide €226 billion in fossil fuel consumption subsidies (IEA, 2010).

Nevertheless, for these subsidies to be justified, there has to be a reasonable prospect of cost parity in the relatively near future, such as 2025, otherwise the substantial sums spent on subsidizing deployment might better be allocated to R&D with mass roll-out delayed until the technology has improved enough. Cost parity means at the very least that the "fuel" cost of the BEV is no higher than that of comparable ICVs, where the "fuel" cost includes not only the electricity cost but also the interest and depreciation of the battery, as that is an essential but additional part of EV power delivery. This is clearly a minimal requirement as there are additional hurdles that BEVs would need to overcome; of which limited range and slow charging rates are the most obvious. Other barriers are discussed in Newbery and Strbac (2015).

2. Decarbonizing transport

In 2012 oil accounted for 33% of total world total final energy consumption and zero-carbon energy accounted for only 13%.[9] Of this oil consumption, 69% was light and middle distillate primarily used for transport. In Europe, road transport is responsible for 17.5% of overall greenhouse gas emissions and its emissions increased by 23% between 1990 and 2009.[10] While it is technically

[6] There is a small number of social cost benefit studies of EVs that remove taxes and add environmental costs, including an early one by Carlsson and Johansson-Stenman (2003) and one examining the 2010 case in Denmark (Christensen and Christensen, 2011), but they are concerned just to judge whether the example chosen is socially attractive, not what would be required for this to be the case in future. Liu and Santos (2014) exclude all taxes and subsidies and include external costs (for CO_2 at $27/tonne in 2020) but only consider the US case, where they find that BEVs are 25% more costly than the reference gasoline ICV. If retail pre-tax oil prices were twice as high then hybrids become competitive at low discount rates, but not BEVs.

[7] Greenhouse Gas, Regulated Emissions and Energy Use in Transport at https://greet.es.anl.gov/.

[8] Personal communication from E Ling, Committee on Climate Change.

[9] BP Statistical Review of World Energy 2013.

[10] European Environment Agency at http://www.eea.europa.eu/highlights/most-carmakers-must-further-improve/key-message/percentage-of-emissions-coming-from

relatively simple to decarbonize electricity generation, finding zero-carbon transport fuels is considerably more challenging. Interest centres on developing competitive BEVs, together with transitional or partial electrification via Hybrid EVs (HEVs) and Plug-in Hybrid EVs (PHEVs), which have both an Internal Combustion Engine (ICE) and an electric motor with battery. Extended range BEVs have a smaller ICE that can top-up the battery, overcoming range anxiety but also incurring the cost of two motors. Natural gas can be used in ICVs and has a lower carbon intensity per km than conventional ICVs, perhaps only 75% by 2020 in the US (Liu and Santos, 2014), but are therefore still carbon-intensive.

Other approaches to low-carbon transport include biofuels (although at present these are quite carbon-intensive), or the use of hydrogen either in combustion or fuel cells.[11] Very substantial fuel efficiency improvements are possible by reducing vehicle weight and improving the efficiency of the ICE (US DOE, 2011), and alternative transport fuels and designs will have to compete with steadily improving ICVs, although these efficiency gains will also raise the capital cost of the ICVs.

3. Social cost benefit analysis of BEVs

Social cost benefit analysis (SCBA) differs from a financial or commercial evaluation in valuing all inputs and outputs at efficiency, not market prices. The difference is that efficient prices are corrected for all external costs and benefits (such as pollution and CO_2 emissions from fossil fuels), but do not include any distorting taxes needed to collect revenue. In the absence of external costs or benefits, and in a competitive market with an efficient tax system, the efficient prices would be producer prices, which would be subject to VAT to give consumer prices (Diamond and Mirrlees, 1971).

This section first discusses the major tax distortions for road fuels, then how to project future efficient road fuel costs including environmental costs, before examining cost differences between ICVs and BEVs. As noted above, there are several advantages in working in terms of the delivered energy cost per kWh. The main cost difference is the battery cost, which is measured in $ or €/kWh. It also focuses attention on the under-appreciated role of establishing the efficient cost of electricity, including its carbon cost, and also reduces uncertainties caused by efficiency changes. As future prices, costs and efficiencies are all uncertain, the aim is to provide a range of plausible values. As BEVs are considerably more capital intensive than ICVs, there are two additional factors that will influence the comparisons: the rate of discount and the annual utilization rates. The range here will be from a low cost assuming a low (real) discount rate of 5% and high annual distance travelled of 17,000 km and the high cost end assuming a high discount rate of 10% and low annual distance of 12,000 km, both with a battery life of 170,000 km.[12]

Working at efficient rather than tax-inclusive market prices makes a huge difference to the relative costs of ICVs and BEVs, as there are massive differences between the efficient price of road fuel and its retail price. Looking across the core EU countries, the 2015 excise taxes on unleaded gasoline required to fund the transport system (and generate additional tax revenue above that) lie mainly between €600 and 700/1000 l (EC, 2015), on top of which the fuel and excise tax bear VAT at rates typically around 20%. Taking a rather low average excise tax of €0.6/l, a VAT rate of 20%, fuel consumption of 6 l/100 km and 14,000 km/yr (the average in the UK and also for BEVs there) the loss of tax revenue under the current road tax regime of replacing an ICV by a BEV would be €600/BEV/yr. At €0.7/l and 15,000 km/yr the lost fuel duty would be €760/BEV/yr. Part of the excise tax on road fuel can be justified as an efficient carbon tax, and part for the social cost of other pollutants. Adding on a carbon cost of €30/tonne CO_2 (€72.5/1000 l, kL) and the rather high (2000) figures for air and water pollution costs from gasoline of €49/kl (Newbery, 2005, but three times higher for diesel) would give an efficient environmental charge of about €120/kl, so that the excess tax (or road charge) would be (taking the lower figure) €600–120=€480, which, including VAT at 20% is €580/kl in distortionary tax.[13] The first and most important correction to make in identifying cost-parity is thus to correct the fuel prices.

3.1. Projecting efficient road fuel prices

The natural way to project future transport fuel prices is to start with the future price of oil in US$/barrel, then add on refining and retailing margins to arrive at a pre-tax fuel cost at the pump. This is not simple as gasoline and diesel are joint products and their relative price depends on relative demand. In addition, oil prices have been both volatile across time, dramatically so since 2003. The relative wholesale and pre-tax retail prices of gasoline to diesel and each to oil have varied widely across countries, as discussed in Appendix A.

It is therefore not simple to move from forecasts of oil prices (given in US$/bbl) to wholesale product prices and instead we take a range. For the low price projection, the prices per litre, l, of diesel and gasoline are taken as equal, with a 3:2:1 crack spread (see Appendix A) of $8/bbl (US¢5/l, €¢4/l, i.e. adding this amount to the crude price in US¢/l). For the high oil price projection, the wholesale gasoline price multiplier is taken as 1.26 (for regular non-oxygenated gasoline) and the diesel price is 1.18, both times the crude price per litre. The central projection, where given, is a simple average of these extremes. These wholesale prices are adjusted to the pre-tax retail price by adding the retail margin of roughly US (2012) ¢8/l for gasoline, ¢10/l for diesel.[14]

The next adjustment is to add on carbon costs based on the DECC (2012) assumed traded values, noting that the carbon content of fuels is 2.68 kg CO_2/l for diesel and 2.36 kg CO_2/l for gasoline. The final adjustment is to add predicted pollution costs. These are derived from Newbery (2005), and at 2012 prices they would add US¢6/l to gasoline and US¢18/l to diesel fuel. These should fall over time with rising standards, and are assumed to have fallen to 60% of these values by 2015 in the central case, to 50% by 2020 and to 40% by 2030, in each case with the low value at 0.75 and the high value 1.25 times the central value. The central oil price for 2015 is the average from Jan–Jun 2015, the high and

[11] MacKay (2013) argues that hydrogen fuelled cars are ten times more energy intensive than the Tesla EV (which claims 15 kWh/100 km) while the Honda fuel-cell car, the FCX Clarity, consumes 69 kWh/100 km but energy is needed to generate the hydrogen. See Chapter 20 in http://www.withouthotair.com/download.html.

[12] There is an issue about the appropriate discount rate to use in SCBA. For public policy decisions the public sector discount rate should be used, and this ought to be the same as the pre-tax private sector rate (Diamond and Mirrlees, 1971), arguably closer to 5% than 10%. Car owners appear to discount at a higher rate, and leasing rates suggest rates of 8–10% (all real). The 2012 UK Travel Survey shows company cars drive 31,000 km/yr and private owners 12,500 km/yr. While BEVs remain more expensive, they are likely to be driven above average distances.

[13] These are at 2012 prices. Pollution costs should have fallen since 2000 as standards have risen and are gradually included as new vehicles replace older models. Note that VAT is included as BEVs displace cars for private use.

[14] US margins for gasoline are readily available at http://energyalmanac.ca.gov/gasoline/margins/index.php and are about 6–8 US¢/l but diesel margins are harder to find and may be somewhat higher (see e.g. http://www.forecourttrader.co.uk/news/fullstory.php/aid/8496/Diesel_3_pence_per_litre_more_than_it_should_be_says_AA.html). UK gross margins are higher at 12 US¢/l (http://www.ukpia.com/files/pdf/ukpia-briefing-paper-understanding-pump-price.pdf).

low reflect the residual uncertainty for the year as a whole. The results are gathered together in Table 1.

3.2. Converting fuel costs to electricity equivalents

As we are interested in comparing the fuel costs of ICVs and BEVs, and as the latter are measured in kWh, it is convenient to translate ICV fuels from volume to energy units, given that the energy density of gasoline is 8.76 kWh/l and of diesel is 9.7 kWh/l. The first column in Table 3 takes the final column of Table 1 and converts from cost/l in US$ to cost/kWh in €¢ as the cost of the "fuel energy content".

The next adjustment is to move from the cost of the raw energy in the fuel to the cost of delivered power on the road, for which we need estimates of the efficiency of the ICE and of the comparable BEV power train. As an example of current ICV technology, the Škoda Octavia has a combined Euro rating for the 102 bhp (76 kW) gasoline engine of 6.2 l/100 km (16 km/l, or 0.55 kWh/km). For the 105 bhp (78 kW) diesel engine, the combined rating is 4.4 l/100 km (54 mpg, 23 km/l or 0.42 kWh/km). It is not immediately obvious what the correct comparator might be. Thus the Ford Focus EV has a similar size and suitable additional power (107 kW) and does 0.2 kWh/km, which seems typical of several vehicles (e.g. the 80 kW 2013 Nissan Leaf, according to users, although Nissan claims 0.15 kWh/km on the EU test cycle).

These efficiencies are current good practice but in future the efficiency of ICVs is likely to improve (under pressure of various performance standards and also in response to higher fuel prices). Thus diesel engines can have up to 41% efficiency, although their typical efficiency is 30%, while petrol engines can achieve 37.3% but are more typically 20% (US DoE, www.fueleconomy.gov). In contrast electric motors convert 75% of the energy supplied into the batteries to power the wheels. In addition BEVs can recover half their kinetic energy by regenerative braking thus improving their city efficiency, although this is of less benefit for longer journeys (where in any case range limitations make them less suitable). While the carbon intensities of fossil fuels are well known, for electricity it will depend on the plant supplying the power. Modern coal-fired plant has an intensity of 850 g/kWh and modern gas plant 380 g/kWh but average losses in transmission and distribution of 6% raise these to 900 and 400 g/kWh. Appendix B explains in detail how future electricity costs and their carbon cost are estimated and projected for "off-peak" (smart charging) and "peak" (convenience charging).

Table 2 summarizes these assumptions and compares the energy and carbon intensity relative to the *input* of 1 kWh taken by the BEV (rather than the energy needed to deliver 1 kWh to the wheels).

Thus if BEVs are supplied from coal-fired generation, their carbon intensity will actually be higher than fossil fuels under most efficiency assumptions, and it would need gas-fired generation to improve on this. The Low BEV carbon intensity figures apply to 2015, Medium to 2020 and High to 2030. The assumed efficiencies in 2015 are all Low, in 2020 range from Low to Medium and in 2030 range from Medium to High. These data allow an estimate of the equivalent ICV fuel costs expressed per kWh of the power taken by the BEV battery, and these figures are given in the second column of Table 3 labelled "battery energy equivalent". In addition, there are operating cost differences between ICVs and BEVs that need to be included to establish a target cost for the battery needed to deliver a comparable lifetime cost of use.

3.3. Adjusting for operating cost differences

Vehicles differ in the drive train costs and their associated maintenance costs. The evidence on these cost differences is set out below, taking as the base case a gasoline ICV. The extra capital penalty of a diesel ICV compared to gasoline ICV is then amortized over the life of the vehicle to give an equivalent increase in operating costs. BEVs differ from ICVs in having a higher cost for the "fuel tank" – the battery – but a lower cost for the drive train.

Data on the differential drive train cost advantages of BEVs compared to ICVs are available from a number of sources. ANL (2009) sets out a methodology to make realistic comparisons between different vehicles, including fuel cell, hydrogen combustion, and varying range PHEV (but unfortunately, not pure BEVs). It starts from specifying performance in acceleration, top speed, and sustained speed on a grade, and then deduces the power needed for different sized vehicles. The reference vehicle is a 2007 gasoline ICV, and it makes projections to 2045. In contrast, a diesel ICV

Table 1
Calculation of social cost of road fuels excluding taxes, US(2012) $/l.Sources: DECC (2012, 2013), Newbery (2005) updated to 2012 prices, exchange rate $1.60 = £1.

Date	Scenario	Oil price $/bbl	CO_2 cost $/tonne	Retail pre-tax prices US$/L		CO_2 cost US$/L		Pollution US$/L		Total US$/L	
				G	D	G	D	G	D	G	D
2015	Low	$40	$0	$0.38	$0.40	$0.00	$0.00	$0.03	$0.08	$0.41	$0.48
	Central	$50	$9	$0.51	$0.51	$0.02	$0.02	$0.04	$0.11	$0.57	$0.65
	High	$70	$21	$0.63	$0.62	$0.05	$0.06	$0.05	$0.14	$0.73	$0.81
2020	Low	$85	$0	$0.66	$0.68	$0.00	$0.00	$0.02	$0.07	$0.69	$0.75
	Central	$117	$14	$0.95	$0.94	$0.03	$0.04	$0.03	$0.09	$1.02	$1.07
	High	$147	$28	$1.25	$1.19	$0.07	$0.07	$0.04	$0.11	$1.35	$1.38
2030	Low	$74	$61	$0.60	$0.62	$0.14	$0.16	$0.02	$0.06	$0.76	$0.83
	Central	$132	$121	$1.09	$1.07	$0.29	$0.32	$0.03	$0.07	$1.41	$1.46
	High	$191	$182	$1.59	$1.52	$0.43	$0.49	$0.03	$0.09	$2.05	$2.10

Table 2
Assumed conversion efficiencies and multipliers for road fuel relative to EVs.Source for electricity carbon intensity: ICL (2014, Fig. 3.27).

	Assumed efficiencies (%)			Energy input multipliers relative to BEVs		CO_2 intensity g/kWh into battery			
	Diesel	Gasoline	Battery	Diesel	Gasoline	Diesel	Gasoline	BEV peak	BEV off-peak
Low	30	20	70	2.33	3.50	645	943	800	450
Medium	35	30	75	2.14	2.50	592	674	450	200
High	41	37	80	1.95	2.16	539	583	150	60

Table 3
Deriving the equivalent BEV target "fuel" cost, €¢(2012)/kWh.Source: Tables 1 and 2, and own calculations (exchange rate $1.3=€1).

Date	Scenario	Total fuel energy content €¢/kWh		Battery energy equivalent €¢/kWh		Operating cost penalty €¢/kWh		Total €¢/kWh	
		G	D	G	D	G	D	G	D
2015	Low	3.6	3.8	12.6	9.0	8.0	16.2	20.6	25.2
	Central	5.0	5.1	17.4	11.9	9.5	19.5	26.9	31.4
	High	6.4	6.5	22.5	15.1	11.0	22.8	33.5	37.9
2020	Low	6.0	6.0	15.1	12.8	8.0	16.2	23	29
	Central	8.9	8.5	26.8	18.9	9.5	19.5	36	38
	High	11.9	10.9	41.5	25.5	11.0	22.8	53	48
2030	Low	6.7	6.6	14.4	12.9	8.0	16.2	22	29
	Central	12.3	11.6	28.8	23.8	9.5	19.5	38	43
	High	18.0	16.6	45.1	35.6	11.0	22.8	56	58

is both more costly but more fuel efficient. ANL (2009, Table 3-11a) gives the estimated 2015 costs for the reference diesel motor plus additional exhaust costs as €(2012)3860 and for the gasoline vehicle as €(2012)1941.[15]

The crucial vehicle cost differences apart from the battery are the motor and its associated control equipment. Delft (2011) breaks down these costs for BEVs as the sum of the motor, the inverter, the converter, the converter for other electrical equipment, and the regenerative brakes. The 2012 cost is estimated at €475+21 kW, so for a 75 kW BEV the cost would be €2050. Very roughly it would seem that a BEV has the same motor cost as a gasoline ICV, and that a diesel ICV would be perhaps €1900 more expensive.

More recent cost estimates are provided by Contestabile et al. (2011), but looking forward to 2030.Their central cost estimate for the 80 kW gasoline ICV in 2030 for the engine and mechanical transmission (gearbox) is $(2010)3480+$425 for the fuel tank and pollution control (or €2930), with considerably enhanced performance. At that date the central cost estimate for an electric motor and power electronics for a BEV is $2000 (€1500), a cost advantage (ignoring the battery) of €1430. Using their pessimistic cost estimates (that would be closer to a 2010 cost base) the differential advantage would fall to €1160. This is about the cost of the gearbox for an ICV, and it is not clear whether ANL includes the gearbox costs, which might explain the apparent cost parity of gasoline and electric drive trains. That suggests taking the 2030 case favourable to BEVs as enjoying a cost advantage of €1430 and in 2015 as €1000, but assuming no difference in costs in the unfavourable case.

In addition to these drive train cost differences, BEVs should have lower maintenance costs. Evidence on BEV maintenance costs is hard to find and somewhat anecdotal, but that for ICVs is well documented. The cost of tyres should be the same for all vehicles. The UK AA gives the service and labour costs as follows: Gasoline: €¢3.3/km; Diesel: €¢3.6/km or 8% more.[16] More anecdotal evidence[17] suggests that servicing the electric motor (but not the battery) might be one-third this cost, or only €¢1.1/km. That implies a cost penalty of 2.2€¢/km for gasoline vehicles and 2.5€¢/km for diesel.

Additional information from the U.S.[18] suggests somewhat lower maintenance costs for gasoline vehicles of 4.6US¢/mile (2.2€¢/km) for a small sedan (e.g. Ford Focus) and 4.92US¢/mile (2.4€¢/km) for a medium sedan (e.g. Honda Accord). The Vincentic *2013 Diesel Analysis*[19] shows that diesels typically have slightly higher insurance, repair and maintenance costs than gasoline vehicles. If they amounted to the extra 8% in the UK, that would give a cost of 2.6€¢/km, implying a cost penalty of 1.6€¢/km for gasoline vehicles and 1.8€¢/km for diesel. Over 150,000 km the maintenance cost penalty for a gasoline ICV might therefore be €2400–3300 and for a diesel ICV €2700–3750, which represent considerable, although delayed, reductions to the Total Cost of Ownership.[20]

Paired column 3 of Table 3 shows the additional operating cost (maintenance of ICV drive train) penalties. The Low figures are based on U.S. data (€¢1.8/km for gasoline, G and €¢2.3/km for diesel, D) while the High figures are based on UK data (€¢2.2/km, G; €¢2.5/km, D). In addition the extra €1900 capital penalty of a diesel ICV compared to gasoline ICV is amortized over its lifetime (with a high cost assuming 10% discount rate and 150,000 km and a low cost estimate assuming 5% discount and 170,000 km). The final column of Table 3 then gives the target range of prices for BEV "fuel" cost (battery plus electricity, both expressed in €¢/kWh).

Thus in the 2030 Low scenario, the oil price is $74/bbl, the CO_2 price is €61/tonne (Table 1, 2030 L), gasoline efficiency is 37%, diesel efficiency is 41%, battery efficiency is 80% (Table 2 H), then the target EV "fuel" cost is €¢22/kWh compared with the cheaper gasoline ICV, (€¢29/kWh for diesel) as shown Table 3 (2030 L, right hand columns). In the 2020 High scenario the oil price is $147/bbl, the CO_2 price is €27.7/tonne, gasoline efficiency is 20%, diesel efficiency is 30%, battery efficiency is 70% (the same assumptions for all the 2015 scenarios), and the target EV "fuel" cost is €¢48/kWh for the cheaper diesel (but €¢53/kWh compared with a gasoline ICV) as shown 2020 High line of Table 3.

The final column of Table 3 shows that unless oil and carbon costs are high, the extra capital cost (in the maintenance column) makes diesel ICVs more costly per kWh delivered in power for travel (as opposed to power contained in the fuel shown in the first two columns) when compared to gasoline ICVs.

4. The cost of the battery

Battery Lithium-Ion (Li-ion) costs have fallen dramatically as their use in mobile phones and laptops has expanded. Costs for the small cells used in such appliances fell from $2600/kWh to $240/kWh between 1999 and 2011, or to less than 10% as sales rose by a factor of 14, although engineering process improvements had reached their limit by 2005 (Element Energy, 2012, p. 16). Given the difficulties of translating small cell processes to the larger cells needed for BEVs, and the long lags in developing new chemistries (10–15 years), there is unlikely to be any significant changes before 2020. Nevertheless, R&D, scale economies and learning-by-doing have been impressive, as Weiss et al. (2012) and Nykvist and Nilsson (2015) document and need to be taken into account in projecting future costs.

For these larger cells, Element Energy (2012, p. 23) estimated the raw cost for a 22 kWh BEV battery pack at $638/kWh. After adding overheads, margin and warranty costs the final cost is estimated at roughly $800/kWh for the pack. Projections to 2020 with a shift to high capacity (layered) cathodes estimate costs

[15] The conversion from US$(2007) to €(2012) Euros is problematic as the exchange rates changed considerably over the period. The conversion from $ to £ in 2007 was £0.57=$1, the price inflation in £ from 2007 to 2012 was by a factor of 1.19 and £(2012)=€1.2. The conversion from $2009 would be 24% higher.

[16] At https://www.theaa.com/motoring_advice/running_costs/.

[17] At http://auto.howstuffworks.com/will-electric-cars-require-more-maintenance.htm.

[18] At http://newsroom.aaa.com/wp-content/uploads/2013/04/YourDrivingCosts2013.PDF.

[19] At http://vincentric.com/Home/IndustryReports/DieselAnalysisNovember2013.aspx.

[20] This is comparable to the figure of €3000 lower O&M costs for a BEV from Tecnalia (2014, Table 16).

Table 4
Cost data for 24 kWh battery pack, charger and drive train credit.Source: Element Energy (2012, Tables 8-15, 8-16), Nykvist and Nilsson (2015).

Costs	2015	2020 Cons	2020 Opt	2030 Cons	2030 Opt
Pack cost (2012) $/kWh	$375	$375	$275	$290	$210
Total 24 kWh pack (2012)€	€7200	€7200	€5280	€5568	€4032
Home charger €	€1200	€800	€800	€400	€400
Credit for low drive train €	−€750	−€1430	−€1430	−€1500	−€1500
Total (2012)€	€7650	€6570	€4650	€4468	€2932

falling by 40–60% and continuing to fall to 2030 as shown in Table 4. Costs are higher for PHEVs as they have smaller batteries and higher power densities.

Element Energy (2012) is a useful reference as it is one of the more recent surveys of the state of knowledge, but there are other estimates available. Ecologic Institute (2011) provided an earlier battery cost projection for the unsubsidized cost to the OEMs which is almost the same as the Element Energy's (2012). They also concur in battery life estimates. PWC (2013) found reasonable consistency in the various bottom-up cost modelling and surveying OEMs, projecting a 2016 battery pack cost for a 24 kWh EV of $425/kWh (Element Energy's optimistic 2015 cost). Their study concluded that the industry was on course for a $300/kWh battery pack by 2020 consistent with some of the estimates given above.

Nykvist and Nilsson (2015) give the most recent and most systematic review of battery pack costs. They estimate that the costs for 2014 could be already as low as $(2014)300–310/kWh and by 2017–2018 for the industry leaders could be as low as $230/kWh. If these needed to be uplifted by a 25% margin (as in Element Energy's calculations) and adjusted to 2012 prices, these amount to $(2012) 400/kWh in 2014 and $300/kWh in 2018–2019. The estimated learning rate for industry leaders of 6% would reduce this to $375/kWh in 2015 if the BEV stock again doubled, and to $280/kWh by 2020 if the installed base doubled again between 2017–2018 and 2020. This is only slightly above Element Energy's optimistic figure of $275/kWh, consistent with Nykvist and Nilsson's, (2015) claim that "costs are probably much lower than previously reported." Table 4 summarizes these cost projections adjusted to a 24 kWh battery and rounded. The optimistic costs decline by 24% between 2020 and 2030, which if the learning rate of 6% continues, would require a further 16 fold increase in the cumulative stock of batteries, or a cumulative rate of growth of the stock of 32% p.a. (compared to the current 100% p.a.).

In addition to the battery cost there is the cost of the home charger but offsetting that is the credit for the lower drive train cost of BEVs compared to the reference gasoline ICV, taken as rising to €1430 by 2020 (and €1500 by 2030) as set out in Section 3.3. These data are collected in Table 4.

Battery user cost depends on life expectancy, which depends on the Depth of Discharge (DoD). The US Advanced Battery Consortium goals (presumably not yet achieved) are for 10 years life and a projected total range of 170,000 km, allowing a reasonably high annual average of 17,000 km for 10 years. Car manufacturers are now willing to offer battery guarantees typically for eight years or 160,000 km, so these targets may be realistic for current BEVs.

The user cost also depends on their discount rates, and if these are high, buyers would probably be attracted by a battery leasing scheme.[21] A realistic interest cost for leasing can be deduced from current battery rental rates. The Renault Fluence ZE will rent the 22 kWh battery with full recovery in event of breakdown for £104/month for a 36 month lease and 12,000 miles (19,000 km) per year, equivalent to €¢7.8/km. If the battery cost had fallen from the 2012 estimate of $800/kWh to $600 (€480)/kWh this would be equivalent to discounting at 10%, and a higher battery cost would reduce the effective interest rate, so 8% might be a reasonable lease interest rate (which also has to cover warranty, management and call-out costs). The cost estimates in this paper assume a high of 10% (real) and a low of 5% and that the battery lasts 10 years and can deliver 170,000 km.[22]

The cost data from Table 4 is translated into a cost per km and then assuming 5 km/kWh by multiplying by 5 to give the cost per kWh. As BEVs become more efficient the km/kWh may increase and may already be approaching 7 km/kWh but frontal area and speed impose absolute limits – at 110 kph, 0.25 kWh/km is the minimum (MacKay, 2013, p. 256). As efficiency rises, so the size and hence cost of the battery needed for the desired range can be reduced. Increasing efficiency increases the multiplier but lowering costs lowers it, so the two effects should roughly cancel out. The Low (L) figures take a 2:1 weighting of optimistic and conservative values for each year of the top line, and the High (H) figures take a 1:2 weighting of optimistic and conservative values for each year of the top line.

5. The cost of electricity

While it may be thought that the cost of electricity is easier to estimate and even forecast, that is misleading. The social cost of electricity depends critically on when and where the power for charging is taken. The social cost varies with time as the short-run marginal cost depends on which plant is at the margin (and its fuel cost), which in turn depends on the level of demand, the volume of variable renewable generation, and the size of the unconstrained delivery area. While there may be spare zero-carbon generation somewhere in the potential market (in Europe, the whole EU plus Switzerland and Norway), transmission limits their delivery outside their price zone. The efficient electricity price will include the CO_2 cost of the marginal generation plant (zero for zero-carbon plant, on average 400–500 g/kWh for combined cycle gas turbines, 800–1000 g/kWh for coal, 500–700 g/kWh for peaking gas plant, but higher if running on distillate). The social cost should also include the risk of loss of load by adding a capacity term equal to the Loss of Load probability times the value of lost load (which will be almost zero except in a small number of hours per year). If power pricing is competitive, carbon priced at its social cost, and if electricity is nodally priced,[23] the wholesale spot price (and particularly the intra-day and/or balancing price)

[21] Apparently 80% of US car buyers prefer to lease but in the UK a 2013 survey suggested that only 53% would wish to lease an BEV car+battery or just the battery, (*footnote continued*) and 47% would wish to buy outright (see http://www.thegreencarwebsite.co.uk/blog/index.php/2013/05/21/brits-not-sold-on-battery-leasing-for-electric-cars/).

[22] Neubauer et al. (2012) use the National Renewable Energy Laboratory's Battery Ownership Model to deduce when, given the pattern of daily use and charging, the battery will need replacement, on the assumption that the vehicle has a life of 15 years, and compare the Total Cost of Ownership (including all taxes and subsidies) of the BEV with an ICV over that time horizon. Their optimal time to replace the battery compares the cost of using alternatives for trips now not viable with the existing battery with that of replacing the battery; which varies with trip distributions and whether the user has access to a second car or has to rent a Zip car.

[23] The EU Target Electricity Model envisages zonal pricing, with quite large price zones to facilitate trading, although nodal pricing is the efficient solution and the U.S. Standard Market Design now employed for more than half U.S. electricity consumption. Nodal pricing gives potentially different spot prices at each node or Grid Supply Point.

should reflect this social cost. To this must be added the cost of distribution to the charging point.

As the share of zero-carbon and low variable cost plant on the system rises (wind, PV, nuclear) so the efficient nodal price at these generating nodes could fall to near zero in many hours. If the charging points are within an area that is then exporting, prices will be very low unless distribution constraints bind, but conversely higher if porting.

Several consequences follow from such granular pricing (by moment and location). First, generation will become more like transmission and distribution in that its cost will be increasingly dominated by fixed costs. Their efficient recovery is to load them onto residual (i.e. net of intermittent generation like wind and PV) peak periods. Second, nodal spot prices will become both very volatile (either near zero or at rationing levels) and unpredictable (renewables are highly weather dependent). Interconnection and storage will become more valuable and will mitigate both volatility and unpredictability, but transmission constraints will still be important in many places and for many hours, keeping prices either low or high depending on conditions. Very smart charging would take advantage of low prices and charge controlled and connected BEVs, but convenience charging (likely to be at peak hours) would be considerably more expensive. Appendix B explains how "peak" and "off-peak" costs have been estimated.

Third, in consequence, most consumers will be hedged with contracts that will offer various options (just as there are many plans for mobile phones). The simplest and least suitable for BEVs will be a flat tariff equal to the (consumer's) demand-weighted average cost, but with smart metering some form of peak/off-peak pricing will surely become more prevalent, possibly with some super peak hours signalled in advance (as with some current French tariff plans). Trials in the UK showed that 72% of users delayed charging until the off-peak tariff (after 9 p.m.) (TRL, 2013). Looking further ahead controlled charging will lead to a discount on the standing charge and power taken. Contracts will either be for a fixed number of kWh/month with variable charges applying to deviations from those, or for all consumption, or for variants (all consumption except in certain pre-announced conditions). As a result some fraction of total demand in any location will face time-of-use prices and may have pre-programmed responses to such prices. Whether one describes these contracts as the standard electricity price with netting off for the benefits of controllability supplied, or just the relevant spot price, is primarily a matter of contract design and labelling.

As a result EV charging points may offer two options – instantaneous charging at the appropriate locational spot price (or a contract price sufficient to cover such volatile prices) or managed charging at a substantially lower price (in which the EV will be delivered charged at some future time such as 7 a.m. that can be predetermined, or adjusted with some penalty). In the managed charge option the distribution network (DN) part of the total charge might be near zero if charging is managed to avoid any constraints on the DN, and if as a result no extra DN investment specifically caused by the EV were precipitated. The social cost of delivering off-peak power may then be very low, while the cost of delivering power at the peak could be very high – including not only the costs of reserve power (high reserve capacity costs plus high variable and carbon costs) but also the scarcity value of constraints on the grid (likely to be small) and the DN (possibly very high).

The figures for off-peak and peak electricity are given in the middle part of Table 6, which also gives the values for the battery and charging costs. The last line in the next block gives the average of the low and high battery costs and assumes that 90% of charging is done off-peak. These BEV "fuel" costs can now be compared with the ICV fuel costs in Table 3 which are reproduced in the final block of Table 6.

Table 5
Battery cost (in €¢(2012) per km and per kWh).Sources: see text.

Battery	2012	2015	2020	2030
Lifetime 10 years	*Total battery cost €¢(2012)/ km*			
At 5%, 17,000 km/yr	11.6	6.7–8.2	4–6.2	3.1–4.2
At 10%, 15,000 km/yr	16.6	9.5–11.6	5.7–8.9	4.4–6.1
Home charger cost	€1600	€1200	€800	€400
Credit for low drive train cost (rel to gasoline)	€0	€750	€1430	€1500
	cost €¢(2012) per kWh			
L at 5%, 17,000 km/yr	64	38	22	13
H at 10%, 15,000 km/yr	92	57	36	22

Table 6
Range of costs per kWh for battery and electricity €¢/kWh excl VAT.Source: Table 5 and Appendix B.

	2015	2020	2030
Net battery+charger (10 yr life)	cost €¢(2012) per kWh		
Low at 5%, 17,000 km/yr	38	22	13
High: 10%, 15,000 km/yr	57	36	22
Electricity off-peak L	4	4	4
Peak H	30	35	37
Total cost			
Low+off-peak	42	***26***	***17***
High+peak	87	71	59
90% off-peak, 10% peak	47	***31***	***21***
Comparable ICV fuel costs			
Gasoline Low	21	23	***22***
Gasoline High	34	***52***	***56***
Diesel Low	25	29	***29***
Diesel High	38	***48***	***58***

The numbers show cases in which these BEV costs are no higher than some of the ICV fuel cost cases.

The impact of properly determining the social cost of charging BEVs is therefore critical in the overall cost of owning BEVs, as the largest range in Table 6 is between peak and off-peak power. If users only charge at peak prices 25% of the time the average electricity cost could fall to €¢12/kWh by 2020. If they could avoid peak charging for 90% of the time, which would be ambitious, given the assumed rather high annual distance driven, the average electricity cost might be as low as €¢7/kWh.

Fig. 1 shows the results visually, taking the Low and High fuel costs for the ICVs and the Low and High battery costs in Table 6 and separating out the carbon cost of the electricity (which is included in Table 6). Peak electricity carbon costs can be quite appreciable.

The wide range of electricity costs is very clear, and by 2020 the Low and High BEV costs with off-peak electricity are competitive with the both the High diesel and High gasoline ICV costs, but not before then (although in 2015 the Low BEV with off-peak power is comparable to High diesel ICV and cheaper than the High gasoline ICV) although this does depend on the remaining uncertainty in the 2015 oil price. By 2030 off-peak BEVs are competitive against even Low ICV fuel costs and can support considerably higher electricity prices against High ICV costs. Perhaps surprisingly, uncertainty about carbon costs has less impact than uncertainty about oil prices.

6. Conclusions

If the target battery costs can be achieved, and if 2020 oil and carbon prices are high ($150/bbl in 2012 prices, and €60/tonne

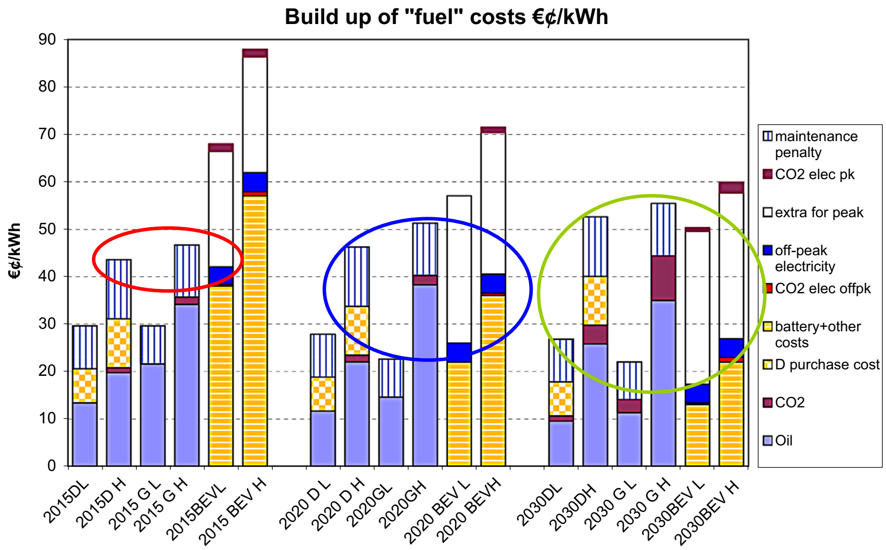

Fig. 1. Cost ranges for ICVs and BEVs, in equivalent €¢(2012)/kWh for BEV. Source: Table 6.

CO_2) and diesel performance has not improved too much, then the efficient cost per km of BEVs with a high annual mileage that are able to charge at off-peak electricity costs can be lower than the cost of a comparably powerful diesel ICV, but it does not seem likely that this would happen much before 2020. Comparisons against gasoline ICVs are more favourable, although the higher capital cost of a BEV and the very specific use in which they are competitive suggests that BEVs should aim to compete against diesel ICVs, except as one of a two-car household using the BEVs intensively for shorter journeys and the gasoline ICV for longer journeys. The number of BEVs that meet this requirement may be modest, and confined to long-distance commuters, or other intensive users who can access cheap off-peak power, and richer two-car families. By 2030 the range of costs of all ICVs and BEVs overlap, so there will be a wider range of circumstances in which BEVs are cheaper than ICVs.

Looking at it another way, if the future price of oil is $100/bbl, and the carbon cost is €50/tonne CO_2, users discount at 8% real and drive 15,000 km/yr, then on central estimates of efficiency and smart charging (90% off-peak) the target battery pack (not cell) cost (with all mark-ups to final retail) would need to be less than $300/kWh. On optimistic assumptions that is within reach by 2020, and on conservative estimates should be reached in the following decade.

These comparisons make no judgments about the non-fuel merits of BEVs and ICVs, where charging time, range, and weather sensitivity all conspire to make BEVs less attractive, except for the market segments listed above of regular lengthy commutes to a work-place with charging facilities.[24] It was for such reasons that the Committee on Climate Change scaled back its earlier projections of BEVs and replaced them with PHEVs.

In the future other developments, such as autonomous vehicles that can be summoned and used per trip may overcome these obstacles. In the meantime, some care is needed in making proper cost comparisons, given both the numerous distortions to fuel and electricity pricing, and the considerable uncertainty over future fuel prices, battery costs and relative maintenance costs.

[24] For willingness to pay and consumer attitudes to BEVs and HEVs see Axsen and Kurani, (2013), Campbell et al. (2012), and Tanaka et al. (2014).

Appendix A. Projecting the future prices of gasoline and diesel

The "3:2:1 crack spread" is the difference between the (future) value of 2 barrels (bbl) of unleaded gasoline plus 1 bbl of heating oil (essentially the same as transport diesel and almost the same price as jet fuel or kerosene) and 3 bbl of oil, suggesting that the sum of the costs of producing light and middle distillates from a barrel of crude is more stable than either one separately. This was borne out by evidence until 2000, after which it increased sharply and then fell back somewhat, indicating some disequilibrium in the refining industry associated with the recent oil price volatility and shale oil revolution. Over the last 20 years the gasoline spread (i.e. the difference between the gasoline and oil price) averaged $(2012)13/bbl (€¢6/L) with a standard deviation (SD) of $8/bbl. The diesel spread has been more volatile and trending upwards with an average of $5/bbl (SD $14/bbl). The (20 year average) US spot 3:2:1 crack spread is $10/bbl (SD $9/bbl) or roughly €¢5/l.

Fig. A.1 shows the evolution of US real oil and product prices and the ratios of gasoline and diesel to the price of crude oil, showing the sharp increase in volatility since the start of the century. It shows that the fob New York prices per litre of heating oil and gasoline are on average close (heating oil is 94% (CV 12%) of the price of gasoline from 1986 to 2015). From 2009 to 2014 the ratio of European (ARA) import gasoil: gasoline prices has been 1.04 (CV 7%). The European "pre-tax" end-use (retail) prices for diesel are 122% (CV 11%) of those in the US while for gasoline they are 104% (CV 6%) (IEA, 2013c), reflecting the relatively higher demand for diesel in Europe.

Fig. A.1 shows the US WTI marker prices of crude was virtually identical to the Brent marker price until Jan 2011, then Brent rose sharply relative to WTI but has since fallen back. Given the turbulence in the period after 2008 it seems sensible to study the US relationship between crude and wholesale product prices before that date, using EIA data for NYMEX oil and product futures prices. The ratio of gasoline to crude oil is 1.28 (SD of annual moving averages is 0.12) and for heating oil (an excellent proxy for diesel) is 1.18 (SD 0.10), both for the period Jan 1985–June 2014. Note these are fob (i.e. export and hence wholesale prices and will need adjustment to give retail prices). For the arguably more relevant sub-period Jan 2000–Dec 2010 the figures are G: 1.24, D: 1.16. We also have more recent NW European import price data, which gives from 1990 the average monthly ratio (to crude imports in the Netherlands) for gasoil as 1.26 and from Jan 2009 for gasoil as 1.15

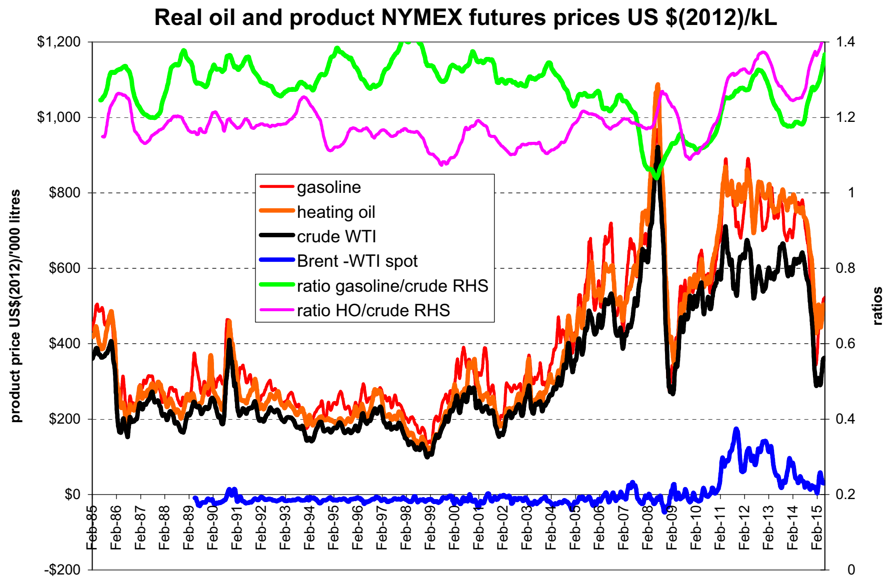

Fig. A.1. Real oil and product NYMEX futures prices 1985–2015. Source: EIA

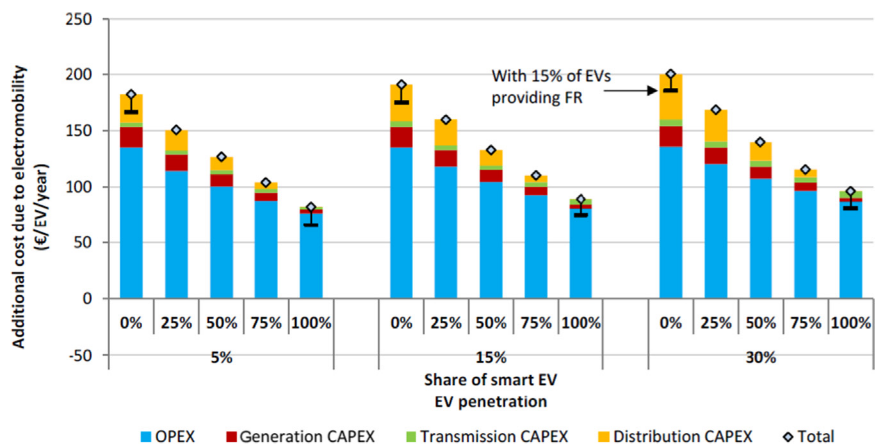

Fig. B.1. Additional system cost per EV in UK and Ireland in 2030 for 2100 kWh. Source: ICL (2014, Fig. 3.18).

and for gasoline as 1.11, which are not so different allowing for the higher gasoline:diesel price ratio in the US.

Appendix B. Estimating the social cost of electricity

The social cost of electricity depends critically on when and where the power for charging is taken and the marginal fuel and its cost. Fig. B.1 shows an engineering cost estimate (looking forward to an optimized 2030 system) of the ***additional*** system cost of developing the electricity system to meet the demand for different penetration levels of BEVs (5–15%; the 2030 projections for the UK are 3–9%), based on 2100 kWh/EVyr.[25] The cost is higher at low levels of controllable charging (0% smart EV), and decreases with the level of smart charging (the costs are more sensitive to the share of smart charging than the level of EV penetration). Note that extra grid costs are negligible and generation opex and capex are the major part. The total cost is €190/EVyr with zero smart charging or 9€¢/kWh, with the network cost only about €30 per year. With 100% smart charging the total cost falls to €80/EVyr (3.8 €¢/kWh) and if the BEV can provide Frequency Response (FR) at no extra cost that falls to €65/EVyr (3€¢/kWh). The extra cost of unconstrained charging of 5.2€¢/kWh or about 1€¢/km seems modest, and unlikely to deter those who value convenience. As this is an optimized engineering cost estimate averaged over the year, it needs a reality check against a bottom-up approach.

The average 2013 tax-exclusive retail electricity price for medium sized households varied across the EU-15 from 10 to 20€¢/kWh (France and Ireland), with 11 of the 15 countries less than 15€¢/kWh, [26] so the average uncontrolled charging cost of 9€¢/kWh seems low, given the high capital cost of decarbonizing the electricity system to 2030. Prices also depend on fuel prices, and although oil price variations are critical for ICVs, oil is negligible in generation. Gas prices have been linked to oil prices, but that link is weakening. The approach taken here is to ignore fuel cost variations for electricity, as the range of prices arising from the peak: off-peak difference is far more significant. Including possible fuel price variations would somewhat increase the range of the electricity component with some correlation with ICV fuel costs.

[25] Assumed 2030 costs are gas:€2.6/$\mathrm{MWh_t}$, Oil \$110/bbl, coal \$120/t, CO_2 €85/t. (ICL, 2014, Table 3.2)

[26] Eurostat at http://appsso.eurostat.ec.europa.eu/nui/setupDownloads.do.

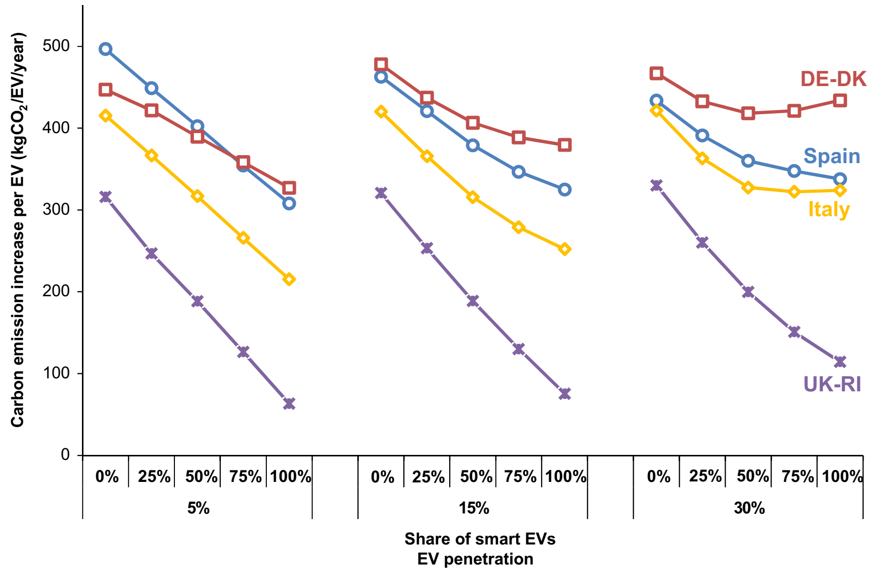

Fig. B.2. Additional annual carbon emissions per EV consuming 2100 kWh/yr. Source: ICL (2014, Fig. 3.27).

The UK 2012 retail cost of electricity for a household (3300 kWh) was £531 (€637),[27] of which 58% was the wholesale energy, supply and profit margin cost or £93 (€112)/MWh, of which the average spot energy cost was £48/MWh,[28] the rest being supply costs and margin of £45. Network and metering costs add £112 (€134) per year.

The 2012 Continental price excluding the carbon cost was closer to €42/MWh. By 2020 the average EU generation cost excluding CO_2 might increase to €48/MWh. Table 1 gives high CO_2 cost as €20/tonne. The marginal CO_2 intensity at the time of charging can be derived from Fig. B.2 and is shown in Table 2 above.

The additional benefits of FR can be found at ICL (2014, Fig. 3.29). At 75% smart charging and 10% of EVs offering FR, the additional reduction in carbon intensity is about 27 g/kWh, and comparable in the other countries. Thus the 2020 High cost of CO_2 is about €20/tonne and the carbon intensity (Table 2, Medium line) for peak carbon cost is 0.45tonnes CO_2/MWh so the CO_2 cost is 0.9€¢/kWh. The carbon costs for other dates can be similarly estimated.

The next correction to make is to account for the variation of generation cost from off-peak to peak. By 2020 and beyond the price range from peak to off-peak wholesale prices may be considerably larger than at present as a result of higher wind penetration. One way of estimating this impact is to look at the German market, which by 2012 had the same wind electricity as the UK's 2020 target. The top 25% most expensive hours in Germany were 148% of the average while the bottom 25% were 52% the average, so the 25% most costly hours might then have a pre-CO_2 wholesale energy cost of 1.48×4.8€¢/kWh$=7.1$€¢/kWh, to which should be added the marginal emissions cost of 0.9€¢/kWh to give the (average) peak energy cost of 8€¢/kWh. The off-peak energy cost might be 2.5€¢/kWh to which one might add a carbon cost of between zero and 0.5€¢/kWh, to give 2.5–3 €¢/kWh. The mark-up to move from wholesale to retail energy costs appears to be about 50% (the UK example above was closer to 100% but this is a single year snapshot) so the 2020 peak domestic energy element might be $8 \times 1.5=12$€¢/kWh and the off-peak element $2.7 \times 1.5=4$€¢/kWh.

The UK network costs (for Transmission and Distribution, T&D) in 2012 were €134 per household, but there will be considerable investment in transmission and distribution to 2020, increasing this by perhaps 50% to €200/yr for the 25% most expensive hours (spread over 825 kWh), or by 24€¢/kWh. To summarize, the 2020 peak efficient price might be $12+24=36$ €¢/kWh, while the off-peak price might be just 4€¢/kWh: a range of 9:1. This considerable range shows the importance of considering the proper allocation of various fixed and marginal costs in estimating the social cost of electricity at various times of the day or hours of the year. The more problematic part is the allocation of fixed costs, as what is needed is the cost precipitated by the increase in demand *caused* by the additional BEV. To the extent that DNs need to be reinforced to accommodate more BEVs, this will be well-defined and is included in the optimized engineering models reported in Fig. B.1 above, but some, perhaps a large part, of current T&D are just a Ramsey charge to recover past fixed costs and are not causally linked to new demand. The peak:off-peak price range thus reflects the outer limit of what it might be reasonable to attribute to these costs.

Looking into the future is always difficult, but if Europe achieves higher levels of integration, it could share balancing and reserves and thus reduce the investment needed. That should lower the cost burden on peak hours (and off-peak should fall because of access to higher levels of low variable cost low-carbon generation elsewhere in Europe). Countervailing that would be higher carbon costs which would impact at least some of the peak hour generation and changes in fuel prices. The marginal fossil fuel is likely to be gas rather than coal, given the EU commitment to decarbonization, and the assumption is that gas prices will delink from oil prices. Given the relative low weight of variations in future fossil fuel prices, the assumption is that average variable electricity cost remains constant after 2020. Table 6 gathers these estimates together.

In addition to the electricity cost there is the cost of the home charging point of perhaps €1500 (and a comparable cost to use public charging points, which offer higher charge rates at a higher fixed cost but spread over more charges). Spread over 150,000 km at 0.2 kWh/km or 30,000 kWh this would add a further €¢5/kWh. This might fall with development, as the lower projected figures in Peterson and Michalek (2012) suggest.

[27] Ofgem Updated Household energy bills explained (Feb 2013) at https://www.ofgem.gov.uk/ofgem-publications/64006/householdenergybillsexplainedudjuly2013web.pdf.

[28] The 2012 average time weighted day-ahead half-hourly price was £45 (€54)/MWh and correcting for domestic demand patterns might have increased this to £48 (€58)/MWh.

References

Axsen, J., Kurani, K.S., 2013. Hybrid, plug-in hybrid, or electric – what do car buyers want? Energy Policy 61, 532–543.

Aguirre, K., Eisenhardt, L., Lim, C., Nelson, B., Norring, A., Slowik, P., Tu, N., 2012. Lifecycle Analysis Comparison of a Battery Electric Vehicle and a Conventional Gasoline Vehicle, 〈http://www.environment.ucla.edu/media/files/BatteryElectricVehicleLCA2012-rh-ptd.pdf〉.

Al-Alawi, B.M., Bradley, T.H., 2013. Total cost of ownership, payback, and consumer preference modeling of plug-in hybrid electric vehicles. Appl. Energy 103, 488–506.

Andress, D., Nguyen, T.D., Das, S., 2011. Reducing GHG emissions in the United States transportation sector. Energy Sustain. Dev. 152, 117–136.

ANL 2009. Multi-Path Transportation Futures Study. Vehicle Characterization and Scenario Analyses. Argonne National Laboratories. At 〈http://www.transportation.anl.gov/pdfs/TA/613.PDF〉.

Campbell, A.R., Ryley, T., Thring, R., 2012. Identifying the early adopters of alternative fuel vehicles. a case study of Birmingham, United Kingdom. Transp. Res. A Policy Pract 46 (8), 1318–1327.

Carlsson, F., Johansson-Stenman, O., 2003. Costs and benefits of electric vehicles, a 2010 perspective. J. Transp. Econ. Policy 37 (1), 1–28.

CCC 2013. The Fourth Carbon Budget Review Part 2, The Committee on Climate Change, Dec 11. At 〈http://www.theccc.org.uk/publication/fourth-carbon-budget-review/〉.

Christensen, A.S. and Christensen, E.E., 2011. A Social Cost-Benefit Analysis of an Electric Vehicle, M.Sc. in International Economic Consulting, Aarhus. At 〈http://pure.au.dk/portal-asb-student/files/39501041/Master_Thesis.pdf〉.

Contestabile, M., Offer, G.J., Slade, R., Jaegerc, F., Thoennesc, M., 2011. Battery electric vehicles, hydrogen fuel cells and biofuels. Which will be the winner? Energy Environ. Sci. 4, 3754–3772.

DECC, 2012. Updated Short-term Traded Carbon Values Used for UK Public Policy Appraisal. At 〈https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/245385/6667-update-short-term-traded-carbon-values-for-uk-publ.pdf〉.

DECC, 2013. Fossil Fuel Price Projections. At 〈https://www.gov.uk/government/publications/fossil-fuel-price-projections-2013〉.

Delft, 2011. Assessment of electric vehicle and battery technology. At 〈http://ec.europa.eu/clima/policies/transport/vehicles/docs/d2_en.pdf〉.

Diamond, P.A., Mirrlees, J.A., 1971. Optimal taxation and public production, part 1. Production efficiency. Am. Econ. Rev. 611, 8–27.

Ecologic Institute 2011. Impacts of Electric Vehicles-Deliverable 2. Assessment of electric vehicle and battery technology. At 〈http://ec.europa.eu/clima/policies/transport/vehicles/docs/d2_en.pdf〉.

EC, 2015. Excise Duty Tables Part II – Energy Products and Electricity. At 〈http://ec.europa.eu/taxation_customs/resources/documents/taxation/excise_duties/energy_products/rates/excise_duties-part_ii_energy_products_en.pdf〉.

Element Energy, 2012. Cost and performance of batteries for EVs. Final Report for Committee on Climate Change. At 〈http://www.element-energy.co.uk/wordpress/wp-content/uploads/2012/04/CCC-battery-cost_-Element-Energy-report_March2012_Public.pdf〉.

Element Energy, 2013. Pathways to high penetration of electric vehicles. Final Report for Committee on Climate Change. At 〈http://www.theccc.org.uk/wp-content/uploads/2013/12/CCC-EV-pathways_FINAL-REPORT_17-12-13-Final.pdf〉.

EPRI, 2007. Environmental assessment of plug-in hybrid electric vehicles, Electric Power Research Institute, EPRI-NRDC Rep. 1015325, vol. 1.

EPRI, 2013. Total cost of ownership model for current plug-in electric vehicles. At 〈http://www.epri.com/abstracts/Pages/ProductAbstract.aspx?ProductId=000000003002001728〉.

HM Treasury, 2007. The King Review of Low-carbon Cars: Part I. The Potential of CO_2 Reduction, 〈www.hm-treasury.gov.uk/king〉.

IEA, 2010.World Energy Outlook 2010. IEA–International Energy Agency, Paris, France.

IEA, 2013a. CO_2 Emissions From Fuel Combustion. Highlights, International Energy Agency at 〈http://www.iea.org/publications/freepublications/publication/CO2EmissionsFromFuelCombustionHighlights2013.pdf〉.

IEA, 2013b. Global EV Outlook, International Energy Agency at 〈http://www.iea.org/topics/transport/electricvehiclesinitiative/EVI_GEO_2013_FullReport.pdf〉.

IEA, 2013c. International Energy Agency. Energy Prices and Taxes Edition 2013, Quarter 2.

ICL, 2014. Economic and Environmental Impact of EV Deployment on European electRicity Systems. D9.2 Final Report 30 September. Imperial College London.

Kley, F., Lerch, C., Dallinger, D., 2011. New business models for electric cars—a holistic approach. Energy Policy 396, 3392–3403.

Le Duigou, A., Guan, Y., Amalric, Y., 2014. On the competitiveness of electric driving in France. Impact of driving patterns. Renew. Sustain. Energy Rev. 37, 348–359.

Lin, C., Wu, T., Ou, X., Zhang, Q., Zhang, Xu, Zhang, Xi, 2013. Life-cycle private costs of hybrid electric vehicles in the current Chinese market. Energy Policy 55, 501–510.

Ling, E., 2012. Decarbonising surface transport in 2050, BIEE Conference. At 〈http://www.biee.org/downloads/decarbonising-surface-transport-in-2050/〉.

Liu, J., Santos, G., 2014. Decarbonising the road transport sector. breakeven point and consequent potential consumers behaviour for the US case. Int. J. Sustain. Transp. 9 (3), 159–175.

MacKay, D., 2013. Sustainable Energy Without the Hot Air. At 〈http://www.withouthotair.com/download.html〉.

Madina, C., Coppola, G., Schumann, D., Hartung, P., Zabala, E., 2012. Business and services models for electric vehicles. In: Proceedings of the European Electric Vehicle Congress, pp. 1–12.

Neubauer, J., Brooker, A., Wood, E., 2012. Sensitivity of battery electric vehicle economics to drive patterns, vehicle range, and charge strategies. J. Power Sources 209, 269–277.

Newbery, D.M., 2005. Road user and congestion charges. In: Cnossen, S. (Ed.), Theory and Practice of Excise Taxation. OUP, Oxford, pp. 193–229 (Chapter 7).

Newbery, D.M. and G. Strbac, 2015. Barriers, Gaps, and Commercial and Regulatory Framework for Broad Rollout of e-Mobility, Final Report. At 〈http://www.greenemotion-project.eu/upload/pdf/deliverables/D9_6-Barriers-gaps-and-commercial-and-regulatory-framework-V2_1_submitted.pdf〉.

Nykvist1, B., Nilsson, M., 2015. Rapidly falling costs of battery packs for electric vehicles. Nat. Clim. Change . http://dx.doi.org/10.1038/NCLIMATE2564.

Pasaoglu, G., Honselaar, M., Thiel, C., 2012. Potential vehicle fleet CO_2 reductions and cost implications for various vehicle technology deployment scenarios in Europe. Energy Policy 401, 404–421.

Peterson, S.B., Michalek, J.J., 2012. Cost-effectiveness of plug-in hybrid electric vehicle battery capacity and charging infrastructure investment for reducing US gasoline consumption. Energy Policy. 52, 429–438.

Prudhomme, R., Koning, M., 2012. Electric vehicles. A tentative economic and environmental evaluation. Transp. Policy 23 (Sep), 60–69.

PWC, 2013. Battery Update. Can the Lithium-ion Industry Satisfy the Growing Demands of the Auto market? At 〈http://www.pwc.com/en_US/us/technology/publications/cleantech-perspectives/pdfs/pwc-cleantech-perspectives-ev-lithium-ion.pdf〉.

Tanaka, M., Ida, T., Murakami, K., Friedman, L., 2014. Consumers' willingness to pay for alternative fuel vehicles: A comparative discrete choice analysis between the US and Japan. Transportation Research Part A: Policy and Practice 70, 194–209.

Tecnalia, 2014. Business modelling analysis in the context of the European Clearing House mechanism, Interim Report 9.3.2, 28 Feb. At 〈http://www.greenemotion-project.eu/dissemination/deliverables-evaluations-demonstrations.php〉.

Thiel, C., Perujo, A., Mercier, A., 2010. Cost and CO_2 aspects of future vehicle options in Europe under new energy policy scenarios. Energy Policy 3811, 7142–7151.

TRL, 2013. Assessing the role of the Plug-in Car grant and Plugged-in Places scheme in electric vehicle take-up, PPR 668. Available at 〈http://www.trl.co.uk/trl-news-hub/transport-news/trl-press-releases/research_reveals_insights_into_the_take-up_of_electric_vehicles.htm〉.

US DOE, 2011. Potential of Technologies for Displacing Gasoline Consumption by Light-duty Vehicles Through 2045. US Department of Energy, Washington DC.

Weiss, M., Patel, M.K., Junginger, M., Perujoa, A., Bonnela, P., van Grootvelda, G., 2012. On the electrification of road transport learning rates and price forecasts for hybrid-electric and battery-electric vehicles. Energy Policy 48, 374–393.

Zhang, Q., McLellan, B.C., Tezuka, T., Ishihara, K.N., 2013. A methodology for economic and environmental analysis of electric vehicles with different operational conditions. Energy 61 (Nov), 118–127.