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What is the target battery cost at which Battery Electric Vehicles are socially cost competitive?

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6 November 2014

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 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.[2] Given the constraints limiting the supply of biofuels[3] 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.

There is an extensive literature on the potential CO_2 savings that BEVs might offer,[4] but almost all of the cost comparisons use market prices,[5] stressing

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[1] Email addresses dmgn@cam.ac.uk, g.strbac@imperial.ac.uk. This paper arises from work done under the FP7 Green e-Motion project.

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

[3] See IEA (2013a).

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

the financial benefits to the users of avoiding road fuel taxes, enjoying cheap fuel, and receiving substantial purchase grants.[6] Clearly 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 ecosystem of charging infrastructure, service providers, leasing agents and the like sufficient to make BEVs a credible alternative to ICVs.

Nevertheless, for these subsidies to be justified, there has to be a reasonable prospect of cost parity in the relatively near future, such as 2020-25, otherwise the substantial sums spent on subsidizing deployment (according to IEA, 2013b, some $50,000 per EV) 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.

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. This article addresses the question of 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. Its originality lies in stripping out all the various distortions that currently bedevil comparisons between BEVs and

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[5] See e.g. Aguirre et al (2012), Al-Alawi and Bradley (2013), Element Energy, 2013, fig17; EPRI (2013), Le Duigou et al (2104), Kley et al (2011), Madina et al (2012), Prud'homme and Koning (2012).

[6] 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 £1,000 on fuel costs each year."

ICVs by applying the techniques of social cost benefit analysis to the comparison.[7]

2. Decarbonizing transport

In 2012 oil accounted for 33% of total world total final energy consumption and zero-carbon energy accounted for only 13%.[8] 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.[9] While it is technically 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.

Other approaches to zero-carbon transport include biofuels (although at present these are quite carbon-intensive), or the use of hydrogen either in combustion or fuel cells.[10] Very substantial ICV 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

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[7] 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/t 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.

[8] *BP Statistical Review of World Energy 2013*

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

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

with steadily improving ICVs, although these efficiency gains will also raise the capital cost of the ICVs.

The UK is the only country to date that has legislated binding carbon targets. The *Climate Change Act* set a target to reduce UK emissions by at least 80% from 1990 levels by 2050. The Committee on Climate Change sets out periodic carbon budgets and monitors the UK's performance. The most recent (Fourth) Carbon Budget sets out a target of a 50% cut in emissions in 2025 relative to 1990 levels (32% on 2012 levels).[11] The core scenario to meet this interim target has "A 60% penetration of electric vehicles in new car sales by 2030, the majority of which were assumed to be plug-in hybrids rather than pure electric, reflecting ongoing concerns around range constraints." In defending this ambitious target the Committee claims 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).

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 will first discuss the major tax distortions for road fuels, then discuss how to project future efficient road transport fuel costs including their environmental and carbon costs, and then turn to the cost differences between ICVs and BEVs. At this point, as main cost barrier is the cost of the battery, it becomes convenient to work in terms of cost per kWh rather than per km travelled, in part because this reduces uncertainties caused by efficiency changes, but also to focus attention on the under-appreciated role of establishing the efficient cost of electricity. As future prices, costs and efficiencies are all

[11] http://www.theccc.org.uk/wp-content/uploads/2013/12/1785a-CCC_AdviceRep_Chap3.pdf

uncertain; the aim is to provide a range of values which cover a defensible range of possibilities. 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 15,000 km, with a battery life of 10 years. [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 2014 excise taxes on unleaded gasoline required to fund the transport system (and generate additional tax revenue above that) lie mainly between €600-700/1,000 litres (EC, 2014), 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/litre, a VAT rate of 20%, fuel consumption of 6 litres/100km and 14,000km/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/litre and 15,000km/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 (€72.5/1,000 litres, 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 or corrective 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% would amount to €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.

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[12] There is an issue about the appropriate discount rate to use in SCBA. For public policy decisions the public sector discount rate, equal to the return on marginal public sector investment, 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%. The UK Government uses 3.5% as its social discount rate, and at this rate the Low costs would be 8% lower. However, car owners discount at a higher rate, and leasing rates suggest rates of 8-10% (all real).

[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.

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, and also, since 2011, have diverged between the USA and Europe as a result of US shale oil production. The relative wholesale and pre-tax retail prices of gasoline to diesel and each to oil have also varied quite 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 (taking the US figures, which are higher than the European figures). 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 2.68kg 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 might be expected to decrease 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 results are gathered together in Table 1.

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[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).

Table 1 Calculation of social cost of road fuels excluding taxes, US(2012) $/L

Date	Scenario	Oil price $/bbl	CO_2 cost $/tonne	retail pre-tax prices US$/L G	D	CO_2 cost US$/L G	D	Pollution US$/L G	D	Total US$/L G	D
2015	Low	$91	$0	$0.70	$0.72	$0.00	$0.00	$0.03	$0.08	$0.73	$0.81
	Central	$110	$9	$0.91	$0.89	$0.02	$0.02	$0.04	$0.11	$0.97	$1.03
	High	$130	$21	$1.11	$1.06	$0.05	$0.06	$0.05	$0.14	$1.21	$1.26
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

Sources: DECC (2012, 2013), Newbery (2005) updated to 2012 prices, exchange rate $1.60=£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 9.7kWh/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 102bhp (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 (107kW) 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). Table 2 summarizes these assumptions and for projection purposes, the simplest assumption is that efficiencies in 2015 are all Low, in 2020 range from Low to Medium and in 2030 range from Medium to High.

Table 2 Assumed conversion efficiencies and multipliers for road fuel relative to EVs

	assumed efficiencies			multipliers	
	Diesel	Gasoline	Battery	Diesel	Gasoline
Low	30%	20%	70%	2.33	3.50
Medium	35%	30%	75%	2.14	2.50
High	41%	37%	80%	1.95	2.16

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

The first difference is that different vehicles have different drive train costs set out in Appendix B. The base case is taken as a gasoline ICV, and the extra €1,900 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. The lower drive train cost of a BEV compared to the gasoline ICV is then deducted from the battery cost. 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.[15] More anecdotal

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

evidence[16] 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.[17] suggests somewhat lower maintenance costs for gasoline vehicles of 4.6 US¢/mile (2.2€¢/km) for a small sedan (e.g. Ford Focus) and 4.92 US¢/mile (2.4€¢/km) for a medium sedan (e.g. Honda Accord). The Vincentic *2013 Diesel Analysis*[18] 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 150,000km the maintenance cost penalty for a gasoline ICV might therefore be €2,400-3,300 and for a diesel ICV €2,700-3,750, which represent considerable, although delayed, reductions to the Total Cost of Ownership.[19]

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 €1,900 capital penalty of a diesel ICV compared to gasoline ICV is amortized over its lifetime (with a high cost assuming 10% discount rate and 150,000km and a low cost estimate assuming 5% discount and 170,000km), as explained in Appendix B. the final column of Table 3 then gives the target range of prices for BEV "fuel" cost (battery plus electricity, both expressed in €¢/kWh).

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

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

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

[19] This is comparable to the figure of €3,000 lower O&M costs for a BEV from Tecnalia (2014) table 16.

Table 3 Deriving the equivalent BEV target "fuel" cost, €¢(2012)/kWh

		total fuel energy content €¢/kWh		battery energy equivalent €¢/kWh		operating cost penalty €¢/kWh		total €¢/kWh	
Date	Scenario	G	D	G	D	G	D	G	D
2015	Low	6.4	6.4	22.5	14.9	8.0	16.2	31	31
	Central	8.5	8.2	29.7	19.0	9.5	19.5	39	39
	High	10.6	10.0	37.1	23.3	11.0	22.8	48	46
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

Source: Tables 1 and 2, and own calculations (exchange rate \$1.3 = €1)

Thus in 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 €¢22.4/kWh compared with the cheaper gasoline ICV, (€¢29.1/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 €¢48.3/kWh for the cheaper diesel (but €¢52.5/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**

Although current battery costs are high, they are anticipated to fall, and Appendix B reviews projections for battery costs as well as the credit for lower BEV drive train costs. The range of battery pack costs depends on source, discount rate and distance travelled, even assuming that all batteries last 10 years and can deliver 170,000 km.[20] The results from Element Energy's conservative

[20] 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

and optimistic estimates (which cover the range of the other estimates given in Appendix B) are summarized in the top part of Table 4. In addition to the battery cost there is the cost of the home charger, shown in the central part of Table 4. The other correction to make in the other direction is the credit for the lower drive train cost of BEVs compared to the reference gasoline ICV, taken as rising to €1,430 by 2020 (and €1,500 by 2030) (see Appendix B).

Although it is natural to express the costs per km driven, for our purposes the more useful cost is per kWh, as the aim is to compute the full "fuel" cost of BEVs, which include the battery costs and also the electricity used. The lower part of Table 4 therefore translates the costs per km into a cost per kWh, based on 5km/kWh, so the numbers in the top part are multiplied by 5 to give the cost per kWh. 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.

As BEVs become more efficient the km/kWh may increase and may already be approaching 7km/kWh, but 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.

Table 4 Battery cost (in €¢(2012) per km and per kWh)

Battery lifetime 10 years	2012	2015 *Total battery cost €¢(2012)/ km*	2020	2030
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	€1,600	€1,200	€800	€400
Credit for low drive train cost (rel to gasoline)	€0	€750	€1,430	€1,500
		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

Sources: see Appendix B

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.

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. If power pricing is competitive and undistorted, and if electricity is nodally priced,[21] the wholesale spot price (and particularly the intra-day and/or balancing price) should reflect this social cost. To this must be added the cost of distribution to the charging point.

As the share of low cost plant on the system rises (wind, PV, nuclear) so the System Marginal Cost and nodal price at the export nodes could fall to near zero. That does not imply zero nodal prices at all nodes, particularly if there is adequate transmission to points of higher scarcity value, but export constraints will surely bind in many periods (otherwise transmission has been over-built), and then keep local prices low.

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 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, wholesale 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 intermittent supply.

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 signaled in advance (as with some current French tariff plans). More likely is the option of controllable demand where the right to allow some control over some appliances, including BEVs, will lead to a discount on the standing charge and on the power taken by such controllable devices. Contracts will either be for

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[21] 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.

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.

It seems reasonable to assume that EV charging points will be required to have smart metering and one or two-way communications facilities, and by the time BEVs have more than marginal penetration, that the distribution networks (DNs) will also be adequately instrumented to monitor power flows and voltages at a sufficiently granular level to assess the capability of the network to accommodate more power flows (and their attendant marginal losses). As with the transmission grid, efficient distribution network (DN) pricing requires that each connection pays variable charges equal to the marginal system losses, plus any local DN scarcity price, plus a fixed tariff (relating to peak demand or maximum load), that recovers any shortfall in allowed revenue.

As a result EV charging points may offer two options – instantaneous charging at the appropriate locational spot price (nodal energy price at the Grid Supply Point plus the spot DN charge) 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 DN element in 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). Appendix C gives quantified estimates of peak and off-peak electricity appropriate to the EU.

The figures for off-peak and peak electricity are given in the middle part of Table 5 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 5. The highlighted numbers show cases in which these costs are no higher than some of the fuel cost cases highlighted.

Table 5 Range of costs per kWh for battery and electricity €¢/kWh excl VAT

	2011	2015	2020	2030
Net battery + charger (10yr life)	*cost €¢(2012) per kWh*			
Low at 5%, 17,000 km/yr	64	38	22	13
High: 10%, 15,000 km/yr	92	57	36	22
Electricity off-peak	5	4	4	4
peak	25	30	37	43
Total cost	*cost €¢(2012) per kWh*			
Low + off-peak	69	42	26	17
High + peak	117	87	73	65
90% off-peak, 10% peak	74	47	31	22
comparable ICV fuel costs				
Gasoline Low	29	31	23	22
Gasoline High	29	48	53	56
Diesel Low	31	31	29	29
Diesel High	31	46	48	58

Source: Table 4 and Appendix C

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 5 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.

Figure 1 shows the results visually, taking the Low and High fuel costs for the ICVs and the Low and High battery costs in Table 5. 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). 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.

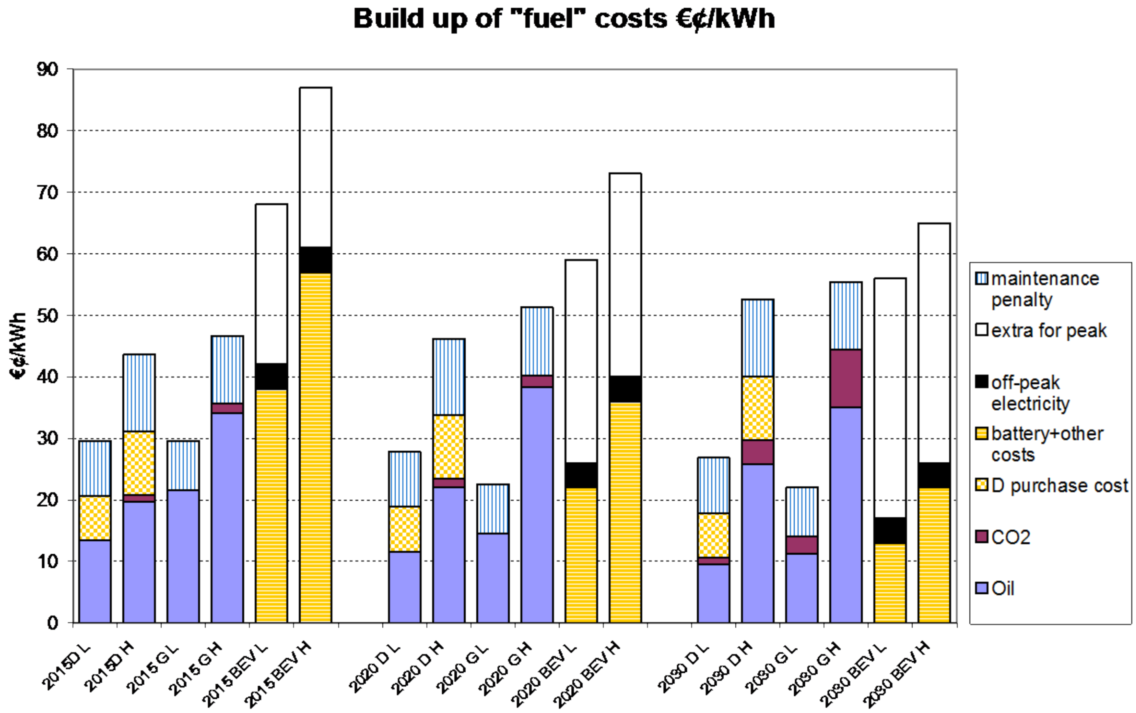

Figure 1 Cost ranges for ICVs and BEVs, in equivalent €¢(2012)/kWh for BEV
Source Table 5

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 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.

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. 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 and battery costs.

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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. Since 1986 the gasoline spread (i.e. the difference between the gasoline and oil price) fluctuated around $(2012)10/bbl (€¢5/L) while the diesel spread appeared to be trending upwards and was negative until 2005, but since then has been positive but volatile. The (averaged) US spot 3:2:1 crack spread has fluctuated between $5-10/bbl or roughly €¢5/litre since 2000 and in July 2014 was just under $8/bbl (EIA, 2014). The European crack spreads are shown in Fig A.1. The 3:2:1 spread averaged $(2012) 11/bbl (monthly CV = 29%) and the crack spreads for gasoline was $10/bbl (€¢5/L, CV 45%) and for gasoil was $14/bbl ((€¢7/L, CV 32%).

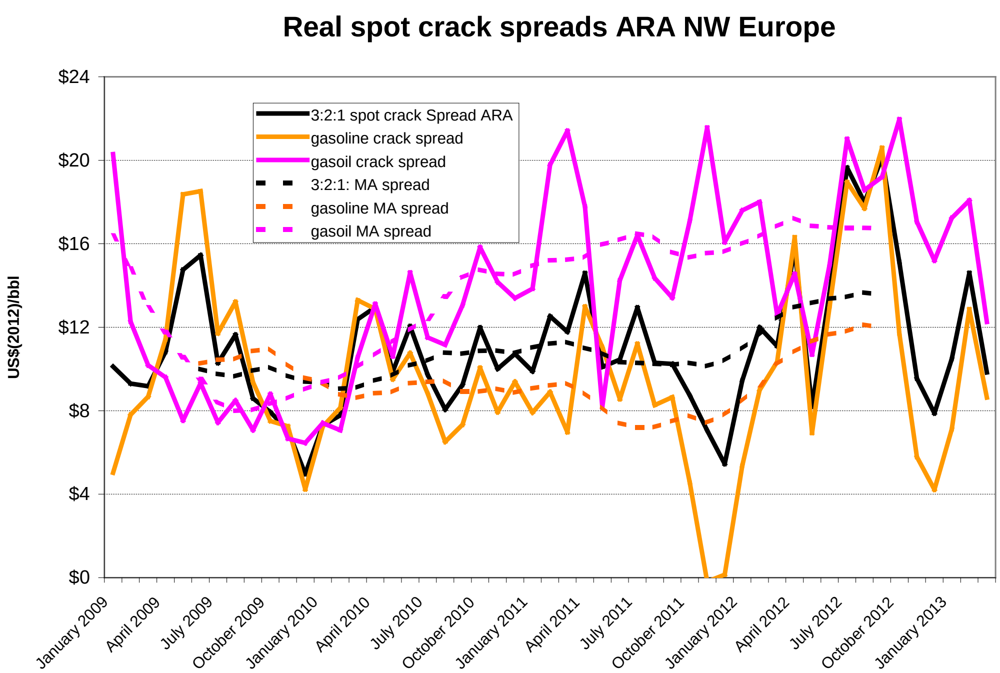

Figure A.1 ARA spot crack spreads
Source: calculated from IEA (2013c)

In the US the fob New York prices per litre of heating oil and gasoline are on average close (heating oil is 102% (CV 11%) of the price of gasoline from 1986-

2014). From 2009 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.

The other problem is that US oil price data, which is readily and publicly available from the EIA, has recently diverged from international prices as a result of the shale oil revolution. The WTI marker prices of crude in the US was virtually identical to the Brent marker price until Jan 2011, since when Brent has been on average 15% higher than WTI. 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 (EIA, 2014). 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 and for gasoline as 1.11, which are not so different allowing for the higher gasoline:diesel price ratio in the US).

Appendix B Battery and vehicle purchase costs

Vehicle cost differences

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 advantage of BEVs compared to ICVs is 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 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)3,860 and for the gasoline vehicle as €(2012)1,941.[22]

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 75kW BEV the cost would be €2,050. 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 €1,900 more expensive.

More recent cost estimates are provided by Contestabile et al (2011), but looking forward to 2030.Their central cost estimate for the 80kW gasoline ICV in 2030 for the engine and mechanical transmission (gearbox) is $(2010)3480 + $425 for the fuel tank and pollution control (or €2,930), with considerably enhanced performance. At that date the central cost estimate for an electric motor and power electronics for a BEV is $2,000 (€1,500), a cost advantage (ignoring the battery) of €1,430. Using their pessimistic cost estimates (that would be closer to a 2010 cost base) the differential advantage would fall to €1,160. 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

[22] 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.

electric drive trains. That suggests taking the 2030 case favourable to BEVs as enjoying a cost advantage of €1,430 and in 2015 as €1,000, but assuming no difference in costs in the unfavourable case.

Battery costs

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 $2,600/kWh to $240/kWh between 1999-2011, 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, p16). 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.

For these larger cells, Element Energy (2012, p23) estimated the cost for BEVs at $400/kWh in 2012, to which has to be added the battery management system, power electronics, connections, cell support, housing, and temperature control $5,227) to give a raw cost of a 22kWh battery of $638/kWh. After adding overheads, margin and warranty costs the final cost is estimated at roughly $800/kWh for the pack. The cost for a mid-sized car with a battery of 22kWh would be $17,500 with a range of 120km. Projections to 2020 with a shift to high capacity (layered) cathodes give an estimated cell cost falling to $200/kWh and the cost of the other elements falling to $120/kWh for a 30kWh battery, so that by 2020 the battery pack could fall to $320/kWh or $9,600 for the pack, and to $215/kWh by 2030 ($6,500). Costs are higher for PHEVs as they have smaller batteries and higher power densities, so by 2020 a 12kWh battery pack might cost $523/kWh or 6,276 for the pack.

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. Thus Ecologic Institute (2011) provides an earlier battery cost projection for the unsubsidized cost to the OEMs. To summarize: "we estimate battery cost in 2012 (unsubsidized) to be € 620 per kWh, but there are some small fixed costs for the battery like safety fuses and current leak detection that do not scale with battery size, so that an add on cost of € 200 per battery is utilized that is independent of kWh storage capacity." That would imply that a 24 kWh battery would cost €15,080 or $18,850, almost the same as the Element Energy's (2012) estimate (although these are stated to be costs, not retail prices, and so might need an additional margin added). They also concur in battery life estimates: "In the EU, the more moderate temperatures may allow real world battery life to be around ten years on average, and we anticipate continued improvement to 2020 by which time, expectations are that average life may be in the thirteen to fifteen year range."

Other estimates suggest a rapidly changing view even for current and near future costs. Thus "In April (2012), Bloomberg New Energy Finance estimated battery costs at $689 per kilowatt hour, down from $800 a year earlier."[23] But "It wasn't clear from the report if that cost is for cells, all components and software—or a total installed cost. Any quoted price per kilowatt-hour can be partial and hide costs that produce a misleading figure in either direction."[24]

However, the extent to which future cost may fall may depend on both the choice of chemistry and the future cost of material. To cite a recent comment:[25]

> "Allan Paterson, electrochemical engineer at Axeon, says: "The battery is the biggest cost in a BEV. 60% of that cost is the cells; and 60% of cell cost is the materials needed for the cathode." This means that although battery technology has halved in the past three years as cheaper elements have been utilized, even high volume production will not completely mitigate the price of the chemicals needed. "We will see cell costs halve in the next five to 10 years, but the price will struggle to come down further," says Paterson. "Currently costs run to $600/kWh and the target is to bring them down to $300. But that will be a struggle."

More recent data is provided by PWC (2013), which reports on a battery cost study looking forward to 2016. They found reasonable consistency in the various bottom-up cost modelling and surveying OEMs with a target cell cost of $280/kWh, to which must be added other elements to give a target battery cost for a 24kWh EV of $425/kWh (i.e. total cost $10,200 and the same as Element Energy's optimistic 2015 cost) and $570/kWh for a 16kWh PHEV (i.e. total cost of $9,120).[26] These targets are roughly 70% of the 2012 costs of $15,000 for a BEV and $13,000 for the PHEV (of the same sizes). Their study concluded that the

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[23] http://green.autoblog.com/2012/06/21/battery-costs-will-fall-to-250-kilowatt-hour-by-2015/ accessed 1/5/13

[24] http://www.plugincars.com/elusive-real-battery-costs-120698.html accessed 1/5/13

[25] At http://www.fleetnews.co.uk/fleet-management/electric-vehicles-battery-technology/41776/page/1/ accessed 2/5/13

[26] Note that the battery of the PHEV is considerably larger than normal range of sizes of 5-12 kWh

industry was on course for a $300/kWh battery pack by 2020 consistent with some of the estimates given above.

Battery user cost depends on life expectancy, which depends on the Depth of Discharge (DoD) and might improve to 12 years and 1,000 cycles with 100% DoD. With 0.15kWh/km that would give a theoretical 200 km range per cycle or 200,000 km at about 17,000km/yr. In practice life can be extended by reducing the DoD to 80%, allowing 1,500 cycles to give 240,000 km or 20,000km/yr (in temperate conditions). 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.

If the user drives the car at a (high) annual average of 17,000 km for 10 years, then the average cost per km can be determined. The user cost also depends on their discount rates, and if these are high, buyers would probably be attracted by a battery leasing scheme.[27] A realistic interest cost for leasing can be deduced from current battery rental rates. The Renault Fluence ZE will rent the 22kWh battery with full recovery in event of breakdown for £104/month for a 36 month lease and 12,000 miles (19,000km) 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%.

[27] 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, 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/

Appendix C Estimating the social cost of electricity

The social cost of electricity depends critically on when and where the power for charging is taken. Figure 2 shows an engineering estimate (looking forward to an optimized 2030 system) of the ***additional*** system cost of discretionary (convenience) charging for an extra vehicle. That estimate is higher at low levels of controllable charging (0% smart EV), and decreases with the level of smart charging (interestingly the costs are more sensitive to the share of smart charging than the level of EV penetration has reached very high levels). Note that extra grid costs are negligible and generation opex and capex are the major part – €150 per year with zero smart charging, with the DN charge only about €30 per year. If we assume 18,000 km/yr or 3,600kWh, the additional energy component amounts to 4.1€¢/kWh or 0.8€¢/km, which seems modest, perhaps not likely to deter those who value convenience. The difference between 0% and 100% smart charging is even less. Of course, this is an average over the year, and in some hours the price would be substantially higher, so that users might prefer to buy spot power unless the price exceeded some pre-set limit.

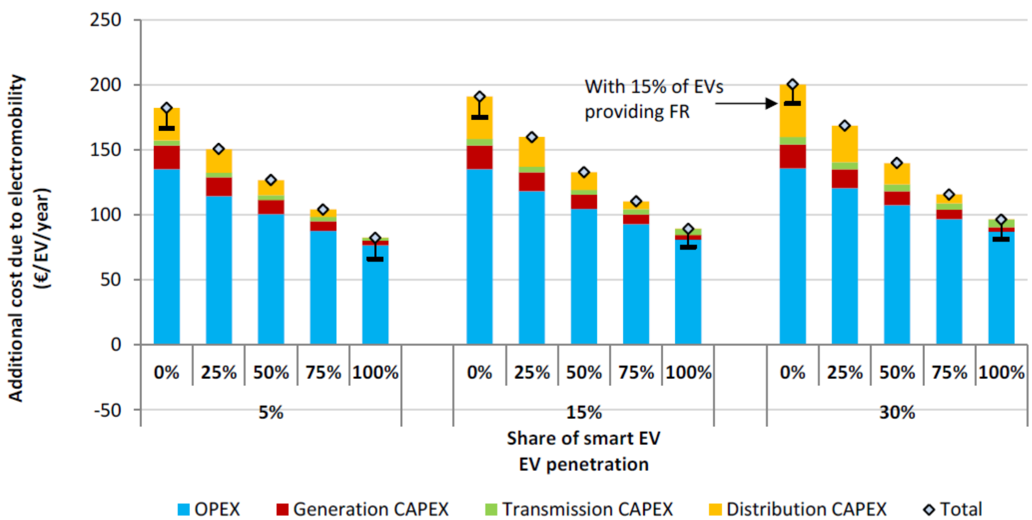

Figure 2 Additional system cost per EV in UK and Ireland in 2030
Source: Imperial College London (2014, fig 3.18)

One might also imagine simpler ways of managing the DN problem, as once there are suitable smart meters the Distribution System Operator (DSO) might temporarily disconnect those EV owners who had not opted for priority rationing – and that might be almost as effective as complex communications between the DSO and other intermediaries supplying power to the charging point. If the smart meters and two-way communications are necessitated (by mandate or for other reasons) then the extra social cost of the EV under controlled charging could be very low, and well below the average tax and levy exclusive retail cost of electricity, which in 2013 for medium sized households varied across the EU-15 from 10€¢/kWh in France to nearly 20€¢/kWh in Ireland, with 11 of the 15 countries having a price of less than 15€¢/kWh.[28]

The UK example

These engineering estimates need to be confronted with a bottom up approach to test their reliability. Thus the UK 2012 retail cost of electricity for a medium sized household (3,300kWh) was £531 (€637),[29] of which 58% was the wholesale energy, supply and profit margin cost or £93 (€112)/MWh, of which the spot energy cost might have been £48/MWh,[30] the rest being contracting and supply costs and margins of some £45). Network and metering costs add a further 25% or £112 (€134) per year. The UK has higher wholesale prices than the Continent, where the 2012 price excluding the carbon cost was closer to €42/MWh. By 2020 this might increase on average to €48/MWh, excluding carbon as the average EU generation cost. Table 1 gives as the high cost roughly €20/tonne of CO_2. What is needed is the marginal CO_2 intensity at the time of charging, which by 2020 is likely to be gas-fired combined cycle turbines (with an intensity of 420gm/kWh) or unabated coal (900gm/kWh). If coal dominates at the peak and the marginal emissions there are 800gm/kWh the carbon penalty would be 1.6€¢/kWh. With surplus nuclear or renewables, the marginal carbon cost would be zero.

The next correction to make is to account for the variation of generation cost from off-peak to peak. By 2020 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

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

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

[30] 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.

a pre- CO_2 energy cost of 1.48 x 4.8€¢/kWh = 7.1€¢/kWh, to which should be added the marginal emissions cost of 1.6€¢/kWh to give the (average) peak energy cost of 8.7€¢/kWh. The off-peak energy cost might be 2.5€¢/kWh to which one might add a carbon cost of between zero and 0.8€¢/kWh, or perhaps 0.4€¢/kWh, to give 2.9€¢/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 8.7 x 1.5 = 13€¢/kWh and the off-peak element 2.9 x 1.5 = 4€¢/kWh.

The 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 825kWh), or by 24€¢/kWh. To summarize, the 2020 peak efficient price might be 13+24 = 37€¢/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 Figure 2 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. Table 5 gathers these estimates together.

In addition to the electricity cost there is the cost of the home charging point of perhaps € 1,500 (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 150,000km 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 (2013) suggest.