

Indirect Emissions from Electric Vehicles: Emissions from Electricity Generation

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Carbon dioxide (CO₂) emissions from passenger cars represent an important and growing contributor to climate change. Increasing the proportion of electric vehicles (EVs) in passenger car fleets could help to reduce these emissions, but their ability to do this depends on the fuel mix used in generating the electricity that energises EVs. This study analyzes the indirect well-to-wheels CO₂ emissions from EVs when run in the US, the UK, and France and compares these to well-to-wheels emissions data for a selection of internal combustion engine vehicles (ICEVs) and hybrid electric vehicles (HEVs). The study also compares the well-to-wheels emissions of the existing passenger car fleet in each country to a hypothetical EV fleet with the average electricity generation requirements of the three EVs considered in this analysis.

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Transport is one of the largest and fastest-growing contributors to increased greenhouse gas concentrations and the associated climate change^{1,2}. Globally, passenger cars alone emit more than 6 percent of anthropogenic carbon dioxide (CO₂)², the most abundant anthropogenic greenhouse gas³. Electric vehicles (EVs) – vehicles which have onboard batteries that are charged with grid electricity and which have no tailpipe emissions – have received significant attention in the past two decades as a means of helping to further reduce localised vehicle emissions and mitigate the associated health concerns. Consequently, policies to increase the number of EVs on the roads have become increasingly common in industrialised countries in recent years⁴⁻⁶.

Upstream emissions from power plants that energise EVs, however, are often neglected, and only recently studies by Jacobson⁷ and Arar⁸ have addressed this issue. These studies conclude that an instantaneous conversion of the US vehicle fleet to battery power could bring a CO₂ emission reduction of up to 58 percent, and even greater reductions are possible if electricity generated entirely from renewable sources such as hydro, solar, wind, or nuclear power is used⁹. The potential of EVs to reduce greenhouse gas emissions depends on the fuel mix used in the electricity generation that charges the vehicles' batteries, which can vary widely from country to country, and within countries. Consequently, the emissions from electricity generation, and thus the

indirect CO₂ emissions from EV use, also vary widely across and within nations.

This study focuses on CO₂, the most important contributor to anthropogenic climate change³. It examines these indirect emissions from electric car usage from well to wheels, comparing across three major industrialised countries in which the national electricity grid is fed by different mixes of renewable and fossil fuel sources: the US, where coal has the largest share; the UK, where natural gas has a share nearly equal to coal; and France, where nuclear power predominates. The paper calculates the amount of electricity required to run electric cars and the CO₂ emissions that result from generating this electricity in the US, the UK, and France in order to establish a sensitivity analysis of indirect emissions and electricity carbon footprint. Moreover, this study compares these indirect emissions to the well-to-wheels CO₂ emissions of some of the most efficient ICEVs and HEVs – that is, emissions from primary fuel extraction to delivery to the vehicle fuel tank (well-to-tank) and emissions from combustion of the fuel (tank-to-wheels).

The study also considers the increase in net electricity consumption that could occur if the entire passenger car* fleet in each country was replaced with EVs.

* "Passenger cars" does not include light-duty trucks: SUVs, pickup trucks, and minivans with a gross weight of up to 8500 pounds (3.9 metric tons) in the US and 3.5 tons in the UK and France (refs. 13, 25, 28). This study omits light-duty trucks as there were, at the time of writing (April 2010), no commercially-available battery electric options.

Electric power generators do not operate at full capacity all the time. The average capacity factor, or plant load factor, of electricity generation – that is, the ratio of net electricity generation in a given period to the amount of electricity that would be generated in that period if operating at full nameplate capacity – is 48 percent in the US ^{10, 11}, 52 percent in the UK ^{11, 12}, and 55 percent in France ^{11, 13, 14}. Net electricity generation is less than the nominal capacity of the grid – in the US and UK it is about 70 percent of annual peak demand ^{10, 12} – because power stations must be shut down periodically for maintenance and because electricity demand is not constant over the course of a day or year. The effect a large-scale introduction of EVs might have on net electricity consumption, and the ability of the grid to supply this, is considered below.

A number of recent studies have looked at emissions associated with plug-in hybrid-electric vehicles (PHEVs) ¹⁵⁻¹⁷. Most studies on the potential of EVs to reduce greenhouse gas emissions compared to conventional vehicle technologies are at least a decade old ¹⁸⁻²¹. As previously mentioned, two exceptions are Jacobson ⁷ and Arar ⁸. In a review of options for powering EVs and fuel cell vehicles, Jacobson states that “The US could theoretically replace all 2007 on-road vehicles with BEVs (battery electric vehicles) powered by 73 000-144 000 5-MW wind turbines, less than the 300 000 airplanes the US produced during World War II,” resulting in a 33 percent reduction in US CO₂ emissions. Jacobson assumes that wind-generated electricity is over 99 percent carbon-free and that the plug-to-wheels efficiency of BEVs (75-86 percent) is much greater than the average tank-to-wheels efficiency of fossil-fuel vehicles (17 percent). Arar, using 2006 figures, finds that an instantaneous conversion of the US fleet of passenger cars and light-duty trucks to battery power could bring a CO₂ emission reduction of 58 percent. Arar also attempts to estimate fleet emissions for 2020 assuming a 10 percent uptake in EVs per year from 2011 to 2020 but using the present fuel mix. He finds that the 2020 fleet would emit 36 percent less CO₂ than if the conversion to EVs had not taken place.

The present study looks specifically at the electricity usage and associated well-to-wheels CO₂ emissions for three battery EVs which, at the time of writing (April 2010), were the only multi-passenger EVs available for sale in more than a single country: the Tesla Roadster; the THINK City; and the REVAi (marketed in the UK as the G-Wiz i). The Tesla Roadster, from Tesla Motors of San Carlos, California, has been available for purchase in the US since 2008 and from stores in Europe and Canada since 2009 ¹¹. The THINK City, from Think of Aurskog, Norway, has been available in Norway since 2008, with plans for sales

elsewhere in Europe in 2009 and in the US from 2010 [‡]. The REVAi, from REVA Electric Car Company of Bangalore, India, has been available since 2008 in India and several European countries [§]. Unlike previous US-focused studies ^{7, 8}, the present study focuses on the US, the UK, and France. Moreover, by calculating indirect emissions from electricity generation in France, a country with relatively low-carbon grid electricity, the study explores the potential for emissions reduction through decarbonisation of the electricity sector.

Methods

Here we elaborate on the methodology used in the calculations. Data used are given in the text.

The average CO₂ emissions from electricity generation in each country (Table 3) were calculated as follows:

$$\text{Emissions (g / kWh)} = \frac{\text{CO}_2 \text{ produced (g)}}{\text{Net electricity generated (kWh)}}$$

Net electricity generation is defined here as electricity generated by major power producers – that is, companies whose main business is electricity generation – since national CO₂ emissions figures for electricity generation refer only to major power producers. The US Energy Information Administration’s *Annual Energy Review* expressly excludes plants with a generator nameplate capacity less than 1 MW ¹⁰.

The well-to-wheels CO₂ emissions for the three EVs considered in this study were calculated by summing well-to-power-plant emissions and power-plant-to-wheels emissions. Well-to-power-plant CO₂ emissions – analogous to well-to-tank for ICEVs – are defined here as emissions from primary fuel extraction (e.g., coal, oil, gas) to delivery to the power plant for use in electricity generation, including all intermediate steps (detailed in Table 6). Well-to-power-plant emissions for each EV in each country were calculated from fuel efficiency data (Table 2), the breakdown of total net electricity generation (Table 4), and the well-to-power-plant emissions for each type of fuel used in electricity generation (Table 6).

Power-plant-to-wheels CO₂ emissions – analogous to tank-to-wheels for ICEVs – are defined as emissions from generation of electricity at the power plant to delivery to the EV’s battery. Power-plant-to-wheels emissions for each EV in each country were calculated from the fuel efficiency for each EV (Table 2) and the average direct CO₂ emissions from electricity generation (Table 3).

The sum of the well-to-power-plant (WtPP) and the power-plant-to-wheels (PPtW) CO₂ emissions for each EV in each country (C) is the well-to-wheels (WtW) CO₂ emissions (Table 5):

¹¹ www.teslamotors.com/media/press_room.php: April 9, 2008, and March 3, 2009. All websites in this paper were accessed August 1, 2009.

[‡] www.think.no/think/Press-Pictures/Press-releases: March 12, March 18, and May 6, 2009

[§] www.revaindia.com/revaworldwide.htm

$$WtW_{EV} [g / km] = Eff_{EV} [MJ / km] \cdot (WtPP_C + PPtW_{EV}) [g / MJ]$$

Analogously, well-to-wheels CO₂ emissions for the ICEVs and HEVs (Table 9) are the sum of well-to-tank emissions, defined as emissions from primary fuel extraction to delivery to vehicle fuel tank, and tank-to-wheels emissions, defined as emissions from combustion of the fuel. The tank-to-wheels data are from the UK Government's Vehicle Certification Agency (VCA); the well-to-tank figures were calculated from fuel efficiency figures from the VCA and the literature value for oil in Table 6, taken to be the same for well-to-tank as for well-to-power plant. The well-to-tank emissions (75 g/kWh) are comparable to those from Silva *et al.*²², who report 51.1 g/kWh for well-to-tank greenhouse gas emissions for diesel.

The well-to-wheels CO₂ emissions of the hypothetical EV fleet in each country is the average of each row in Table 5. The average well-to-wheels CO₂ emissions for the existing passenger car fleets in each country were calculated from the net calorific value of fuel consumed by the fleet, the number of vehicle kilometres driven, the literature value for oil in Table 6, and fleet tailpipe CO₂ emissions.

Results and Discussion

EVs

Table 1 compares key characteristics of each of the three EVs included in this study (see Tables and Figures). The amount of electricity generation required to run each of the three EVs in each of the three countries considered in this analysis is shown in Table 2[†].

Table 2. Amount of electricity required to run EVs (kWh/km)^a

	Tesla Roadster	THINK City	REVAi
US ¹⁰	0.21	0.18	0.15
UK ¹²	0.21	0.19	0.15
France ¹⁴	0.21	0.18	0.15

^a All vehicle data are from www.teslamotors.com, www.think.no, and www.revaindia.com, except a personal communication from M. Boxwell (REVA G-Wiz [REVAi] Owners' Club) stating that the REVAi's loss due to charging inefficiency is 13 percent.

The figures are inclusive of electricity transmission and distribution losses and battery charging inefficiency.

The average CO₂ emissions from electricity generation in the same countries are shown in Table 3 (see Methods for details on calculations).

[†] All data in this study are for 2006, the last year for which all data were available.

Table 3. Average CO₂ emissions from electricity generation (g CO₂/kWh)

	Average Emissions
US ^{10, 36}	605
UK ^{12, 37}	543
France ^{14, 38}	88

These figures can be interpreted in part through the share of electricity in each country that is generated from fossil fuels: 71 percent in the US, 77 percent in the UK, and just 10 percent in France^{10, 12, 14}. The carbon intensity of the UK's electricity generation is less than that of the US despite the UK having a greater share of its electricity generation coming from fossil fuels. This is because, as shown in Table 4, the US has a greater share of coal in its fuel mix, while the UK has a greater share of natural gas. Coal produces approximately twice as much CO₂ per kWh as natural gas¹².

Table 4. Breakdown of total net electricity generation (GWh / percent of net electricity generation)

	Coal	Oil	Natural Gas	Nuclear	RES/ Other ^a	Net Elec. Gen. ^b
US ¹⁰	1 990 900	64 400	813 000	787 200	409 500	4 065 000
	49.0	1.6	20.0	19.4	10.1	100.0
UK ^{12, c}	136 173	2 727	122 232	68 248	9 903	339 283
	40.1	0.8	36.0	20.1	2.9	100.0
France ^{14, c}	21 302	5 005	19 494	422 854	72 673	541 327
	3.9	0.9	3.6	78.1	13.4	100.0

^a "RES" refers to renewable energy sources; "Other" fuel includes other gases and non-renewable waste, amounting to less than 2 percent of net electricity generation in each country.

^b Percentages may not add to totals due to rounding.

^c Gross figures have been converted to net by removing electricity used in pumping for pumped storage.

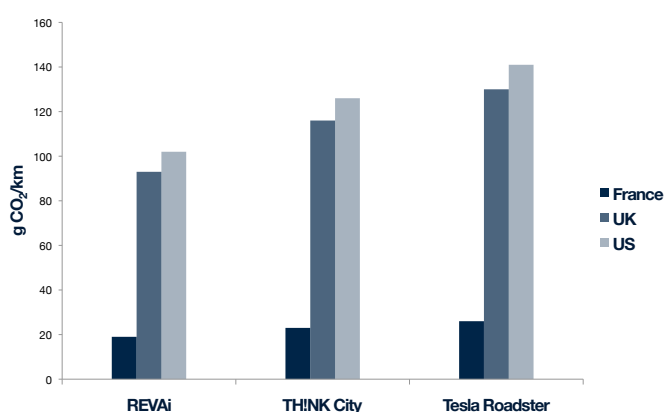
The well-to-wheels CO₂ emissions for the three EVs considered in this study are shown in Table 5.

Table 5. Average well-to-wheels CO₂ emissions for EVs (g CO₂/km)^(Tables 2, 3, 4, 5)

	Tesla Roadster	THINK City	REVAi
US	141	126	102
UK	130	116	93
France	26	23	19

As this table demonstrates, the fuel mix in the national electricity grid is the overwhelming factor in determining the indirect well-to-wheels CO₂ emissions from electric vehicles (see Figure 1).

Fig. 1. Average well-to-wheels CO₂ emissions for EVs (g CO₂/km) plotted from the data in Table 5



In the US and the UK, the emissions for the THINK City and the Tesla Roadster are not appreciably lower than those of the most efficient small diesel cars, as shown below. France, however, with 78 percent of its electricity coming from nuclear (Table 4), would find substantial emissions reductions from passenger cars if it were to replace a large part of its fleet with EVs. The well-to-power-plant CO₂ emissions associated with nuclear power generation are less than half the average of coal, oil, and natural gas (Table 6), and the generation of electricity from nuclear fission produces no CO₂ emissions.

Table 6. Well-to-power-plant CO₂ emissions by type of fuel used in electricity generation (g CO₂/kWh)^a

	Coal ^{39, b}	Oil ^{40, c}	Natural Gas ^{39, d}	Nuclear ^{7, e}
Range	85-135	40-110	48-100	9-70
Mean ^f	110	75	74	40

^a The well-to-power-plant CO₂ emissions for hydro power (1.9 g CO₂/kWh)⁴¹ are negligible and have been excluded. This figure does not include methane emissions, which may occur in a flooded reservoir from the anaerobic decomposition of biomass⁴⁰.

^b For coal, this includes mining and transport.

^c For oil, this includes exploration, extraction, transportation, and refinement.

^d For natural gas, this includes gas processing, venting wells, pipeline operation (mainly compression), and system leakage in transportation and handling⁴⁰.

^e For nuclear, this consists of fuel conversion, enrichment, and fabrication. Enrichment produces up to 95 percent of the CO₂ emissions from nuclear fuel processing. Emissions can vary greatly depending on the specific enrichment process employed.

^f Used in all calculations

ICEVs and HEVs

The figures from Table 5 can be compared to well-to-wheels CO₂ emissions data for a selection of ICEVs and HEVs, as shown in the overall comparison, Table 9 (EV data are shaded; ICEV and HEV data are unshaded).

Table 9 underlines the importance of comparing the vehicles on a well-to-wheels basis. By simply looking at tank-to-wheels or the analogous power-plant-to-wheels,

the lowest-emitting car besides the EVs running in France and the REVAi running in the UK, would be the Smart fortwo cdi at 88 g CO₂/km[†]. The next six ICEVs and HEVs in Table 9 would all come ahead of the Tesla Roadster running in the US. A well-to-wheels analysis, however, demonstrates that EVs generally produce less CO₂ emissions than comparable ICEVs or HEVs. The Tesla Roadster fares well against comparable ICEVs such as the Lotus Elise and the Porsche Boxster, both of which have well-to-wheels emissions approximately double those of the Tesla Roadster in the US.

The well-to-tank CO₂ emissions for the ICEVs and HEVs in Table 9 range from 25 to 64 g/km. The analogous well-to-power-plant emissions for the three EVs ranges from just 6 to 17 g/km, due to their superior fuel efficiency. Even though the average efficiency of electricity generation and supply to end users in the US, the UK, and France is only 30 percent, 34 percent, and 37 percent, respectively^{10, 12, 23} – about the same as an efficient diesel engine²⁴ – these EVs' lower use of fuel means their emissions are lower than comparable ICEVs or HEVs. The next section examines a hypothetical move to replace the current ICEV fleet in each country with EVs.

Fleets

The three EVs under analysis differ in size and power, and the average of their emissions can be used to represent those of a hypothetical EV fleet. If all passenger cars in each country^{**} were replaced with EVs with the average electricity generation requirements of the Tesla Roadster, THINK City, and REVAi (the three EVs considered in this analysis), the fleet well-to-wheels CO₂ emissions for each country would be as found in Table 7. (The results are based on the average CO₂ emissions from electricity generation from Table 3, which may change by the time electric vehicles reach significant fleet penetration.)

Table 7. Average well-to-wheels CO₂ emissions for hypothetical EV fleets (Table 5) and existing passenger car fleets (g CO₂/km).

	Hypothetical EV fleet ^a	Existing fleet ^b
US	123	301 10, 27-29, 40
UK	113	223 12, 25, 37, 40
France	23	229 12, 13, 38, 40, 42

^a The figures for the hypothetical EV fleets are the average of the well-to-wheels CO₂ emissions of the Tesla Roadster, THINK City, and REVAi.

^b Existing fleet figures are calculated from the net calorific value of fuel consumed by the fleet, the number of vehicle kilometres driven, the literature value for oil in Table 6, and fleet tailpipe CO₂ emissions.

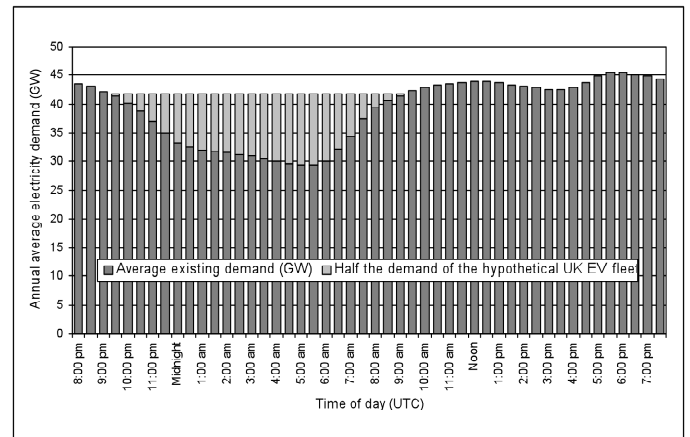
[†] www.vcacarfueldata.org.uk (UK Government's Vehicle Certification Agency)

^{**} That is, the number of passenger cars registered in each country in 2006, the last year for which all study data were available.

Table 7 also shows the average well-to-wheels CO₂ emissions for the existing passenger car fleets in each country. Compared to the existing fleets, the hypothetical EV fleets would produce 59 percent less CO₂ emissions in the US, 49 percent less in the UK, and 90 percent less in France. The UK and French fleet figures are lower than that of the US in part because of their greater use of diesel vehicles, whose engines are more efficient than petrol engines; the higher use of manual transmissions compared to automatic; the smaller average car size; and the traditionally stricter fuel efficiency standards^{13, 25, 26}. Even considering the 2006 model year only, the US well-to-wheels CO₂ emissions would still be higher, at 234 g/km, than those of the entire fleets in the UK and France^{10, 27-29}. The difference would be even more marked if light-duty trucks were included. Light-duty trucks, many of which are used as passenger cars and include SUVs, pickup trucks, and minivans, make up 42 percent of all light-duty vehicles in the US, while accounting for only 10 percent in the UK and 16 percent in France^{13, 25, 28}.

Moving a large part of the ICEV fleet to EVs would require a number of considerations. First, it may be difficult to get consumers to move to smaller cars such as the TH!NK City, and REVAi, particularly in the US, where, as mentioned above, SUVs, pickup trucks, and minivans make up two-fifths of the light-duty vehicle fleet. Second, EVs are still more expensive than comparable ICEVs, despite tax credits and other incentives (Table 1). Third, the average vehicle lifetime in the US (for example) is about 15 years³⁰, meaning that major fleet penetration, under the best circumstances, would take many years⁸. Fourth, emissions reductions from taking ICEVs off the roads would be partially offset by increased emissions from power plants, although controlling emissions from a few thousand power plants may be easier than controlling emissions from millions of tailpipes. Fifth, a charging infrastructure and concomitant government policies would be required. Finally, if the entire fleet in each country (see footnote **) were replaced with EVs with the average electricity demand of the Tesla Roadster, TH!NK City, and REVAi, the increase in net electricity consumption that would occur in each country would be 12 percent in the US^{10, 28}, 20 percent in the UK^{12, 25}, and 15 percent in France^{13, 14}. However, since EVs are usually charged at night when demand is lower, and most EVs would not have to be charged, or charged fully, every night for average daily usage, the increase in demand could potentially be met in part by maintaining daytime electricity production levels overnight. In the UK, for example, where charging the hypothetical EV fleet would see a greater relative increase in electricity demand than in the US or France, half of the additional demand could potentially be met in this way, as shown in Figure 2, without the need for additional electricity generation infrastructure.

Fig. 2. Average electricity demand in the UK in 2006 (www.nationalgrid.com/uk/Electricity/Data), with half the demand the full hypothetical UK EV fleet would bring.



Furthermore, charging EVs in large numbers in this way, in off-peak hours, could lead to improved load shapes, reducing daily variability in electricity demand^{15, 31}. The extent of this improvement may increase with the flexibility offered by intelligent electricity grids³² and the introduction of EV batteries with shorter charging times. EVs could also potentially return to the grid excess electricity stored in their batteries during times of peak load and replace it with electricity in off-peak hours³³. Under the status quo, meeting the demand of the full hypothetical EV fleet along with existing demand would require using approximately 66 percent of installed capacity^{11, 12, 25, ††} instead of the current 52 percent^{11, 12}. But an increase in demand for charging EVs, if it happens, would come gradually, over many years, and extra capacity could be added over time.

Overall comparison

The well-to-wheels CO₂ emissions for EVs, a selection of ICEVs and HEVs, and the hypothetical EV and existing national fleets are compared in Table 9. This table demonstrates that EVs generally emit less CO₂ than comparable ICEVs. The data also underline the importance of the fuel mix in the electricity grid: *the more electricity generation from nuclear and renewable sources, the lower the CO₂ emissions associated with EV use.*

The data hide regional differences within each country, however. In the US, for example, in twelve states more than 70 percent of in-state electricity generation comes from the combustion of coal, while in four states more than 70 percent comes from nuclear and renewable sources^{††, †††}. At one extreme is North Dakota, where 94 percent of in-

†† www.nationalgrid.com/uk/Electricity/Data

††† www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls

††† These figures are indicative only, as electricity in much of the US is generated and transmitted on a regional basis, in regions that may span several states and may not follow state boundaries.

state electricity generation comes from coal, and where emissions from in-state electricity generation average 1012 g CO₂/kWh ^{§§}. At the other extreme are states like Idaho, which generates 84 percent of its in-state electricity from hydroelectric, resulting in in-state electricity generation emissions of just 65 g CO₂/kWh ^{2§§}. In the UK, 96 percent of electricity generated by major power producers in Northern Ireland comes from fossil fuels, while 37 percent in Scotland is from nuclear and renewable sources ¹². In France, 99 percent of electricity generation in the region of Île de France is from conventional thermal combustion, while in eight other regions more than 95 percent of generation is from nuclear and renewable sources ¹⁴.

If the EVs in this study were to run in states or regions where one fuel predominates, the results would be similar to Table 8, which shows CO₂ emissions for the three EVs if running on just one fuel.

Table 8. Average well-to-wheels CO₂ emissions for EVs (g CO₂/km) if using electricity generated from a single fuel (Tables 2, 4, 5), a

	Tesla Roadster	THINK City	REVAi	Hypothetical EV fleet
Coal	212	189	153	185
Oil	155	138	111	135
Natural gas	101	90	73	88
Nuclear	8	7	6	7

^a Using CO₂ emissions estimates for electricity generation in the UK ¹²: 912 g/kWh for coal, 670 g/kWh for oil, and 412 g/kWh for natural gas.

These figures compare to well-to-wheels CO₂ emissions of 234 g/km for passenger cars from the 2006 model year in the US (see above, under Fleets). Thus, even though the EVs may be running on electricity generated entirely from coal, and even though the efficiency of electricity generation and supply to end users in the US, the UK, and France averages only 34 percent (see above), the EVs' superior efficiency means they have lower well-to-wheels emissions than the average ICEV. The EVs considered here require 37 to 55 percent less energy per kilometre than the most efficient ICEV or HEV in Table 9.

Obtaining maximum environmental benefits from EVs, however, requires decarbonising the electricity sector. Changing the fuel mix is difficult due to long lead times from planning to operation, combined with plant lifetimes of up to 50 years. Jacobson suggests that nuclear, tidal, wave, and hydroelectric may not be the best options because their long lead times produce "opportunity cost emissions" compared to technologies with the least delay: solar-photovoltaics, concentrated solar, and wind, closely followed by geothermal ⁷.

Despite the environmental advantages mentioned above,

the number of EVs on the road remains small, most likely due to cost and limited vehicle range. As of 2007, there were approximately 4200 battery electric passenger cars running in the US ³⁴ and 1200 in the UK (P. Syron, UK Department for Transport, personal communication). Vehicle cost remains high at these low production volumes, although those who cannot yet afford an EV would do well to drive a fuel-efficient ICEV or HEV like those shown in Table 9. Continued improvement in ICEV technology is essential, as ICEVs will continue to dominate vehicle sales for the foreseeable future.

Conclusions

Analyzing the indirect well-to-wheels CO₂ emissions from three production EVs has shown that EVs can reduce well-to-wheels CO₂ emissions over the existing fleet by more than 90 percent. This suggests that EVs should be particularly promoted where electricity generation is the least carbon-intensive – as has been done, for example, in California and France ⁴ – as the potential for EVs to reduce CO₂ emissions depends on the fuel mix used in generating the electricity that powers them. The electricity grid must be decarbonised if EVs' full potential to reduce CO₂ emissions is to be realised: Decarbonisation of electricity production should go hand-in-hand with the introduction of EVs. Decisions on building new electricity generation capacity in the coming years will affect the carbon intensity level of the grid for decades to come and affect the potential for EVs to greatly reduce CO₂ emissions. In order to create a comprehensive picture of the environmental benefits of different vehicles and drivetrains, however, the cradle-to-grave emissions of the vehicles themselves have to be taken into account. The authors' research group is currently investigating these embedded emissions.

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Notes and references

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^{§§} www.eia.doe.gov/cneaf/electricity/epa/generation_state.xls and emission_state.xls

- 1 B. Metz, O. Davidson, P. Bosch, R. Dave and L. Meyer (eds.), Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK, 2007, pp. 99-116.
- 2 N. Stern, *The Economics of Climate Change: The Stern Review*, Cambridge University Press, Cambridge, UK, 2006, Postscript Annex 7.c.
- 3 S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L. Miller (eds.), Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge UK, 2007, pp. 95-127.
- 4 D. Calef and R. Goble, *Policy Sci.*, 2007, **40**, 1.
- 5 M. Åhman, *Energ. Policy*, 2006, **34**, 433.
- 6 UK Department of Energy and Climate Change, *The UK Low Carbon Transition Plan: National Strategy for Climate and Energy*, TSO, Norwich, UK, 2009.
- 7 M.Z. Jacobson, *Energ. Envir. Sci.*, 2009, **2**, 148.
- 8 J.I. Arar, *Atmos. Envir.*, 2010, **44**, 733.
- 9 S. Campanari, G. Manzolinia and F. Garcia de la Iglesi, *J. Power Sources*, 2009, **186**, 464.
- 10 Energy Information Administration, *Annual Energy Review 2007*, US Department of Energy, Washington, DC, 2008.
- 11 Energy Information Administration, *International Energy Annual 2006*, US Department of Energy, Washington, DC, 2008.
- 12 UK Department of Energy and Climate Change, *Digest of United Kingdom Energy Statistics 2009*, TSO, Norwich, UK, 2009.
- 13 French Ministry of Ecology, Energy, Sustainable Development, and Planning, *Transportation Accounts in 2006* (Translated from French), Paris, 2007.
- 14 French Ministry of Ecology, Energy, Sustainable Development, and Planning, *Power Production and Distribution in France and in the Regions in 2005 and 2006* (Translated from French), Paris, 2008.
- 15 R. Sioshansi and P. Denholm, *Envir. Sci. Tech.*, 2009, **43**, 1199.
- 16 C. Samaras and K. Meisterling, *Envir. Sci. Tech.*, 2008, **42**, 3170.
- 17 C. Stephan and J. Sullivan, *Envir. Sci. Tech.*, 2008, **42**, 1185.
- 18 J. Lindly and T. Haskew, *Adv. Environ. Res.*, 2002, **6**, 291.
- 19 O. Kobayashi, S. Tange, T. Takeishi, H. Ishitani, R. Matsuhashi and Y. Yoshida, SAE Global Vehicle Development Conference (SAE Technical Paper 952793), Dearborn, MI, December 1995.
- 20 Q. Wang and D. Santini, Magnitude and Value of Electric Vehicle Emissions Reductions for Six Driving Cycles in Four U.S. Cities with Varying Air Quality Problems, Argonne National Laboratory, Argonne, IL, 1993.
- 21 J. Bentley, P. Teagan, D. Walls, E. Balles and T. Parish, *The Impact of Electric Vehicles on CO₂ Emissions: Final Report*, Arthur D. Little, Cambridge, MA, 1992.
- 22 C. Silva, G. Gonçalves, T. Farias and J. Mendes-Lopes, *Sci. Total Environ.*, 2006, **367**, 441.
- 23 French Ministry of Ecology, Energy, Sustainable Development, and Planning, *Benchmarks: Key Energy Figures, 2009 Edition* (Translated from French), Paris, 2009.
- 24 D. Pimentel, M. Herz, M. Glickstein, M. Zimmerman, R. Allen, K. Becker, J. Evans, B. Hussain, R. Sarsfield, A. Grosfeld and T. Siedel, *BioScience*, 2002, **52**, 1111.
- 25 UK Department for Transport, *Transport Statistics Great Britain*, TSO, Norwich, UK, 2008.
- 26 A. Schäfer, J. Heywood, H. Jacoby and I. Waitz, *Transportation in a Climate-Constrained World*, The MIT Press, Cambridge, MA, 2009.
- 27 *Code of Federal Regulations*, 40 § 600.113-78: Fuel economy calculations, US Office of the Federal Register, Washington, DC, 2008.
- 28 Bureau of Transportation Statistics, *National Transportation Statistics 2009*, US Department of Transportation, Washington, DC, 2009.
- 29 US Environmental Protection Agency, *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2006*, Washington, DC, 2008.
- 30 J. Heywood, SAE World Congress & Exhibition (proceedings: *Fuel Cell Power for Transportation 2004*), Detroit, 2004.
- 31 A. Ford, *Energ. Buildings*, 1995, **22**, 207.
- 32 D. Coll-Mayor, M. Paget and E. Lightner, *Energ. Policy*, 2007, **35**, 2453.
- 33 J. Tomić and W. Kempton, *J. Power Sources*, 2007, **168**, 459.
- 34 Energy Information Administration, *Alternatives to Traditional Transportation Fuels 2007*, US Department of Energy, Washington, DC, 2009.
- 35 European Parliament and Council Directive 2002/24/EC, 2002.
- 36 Energy Information Administration, *Electric Power Annual 2007*, US Department of Energy, Washington, DC, 2009.
- 37 UK Department for Environment, Food, and Rural Affairs, *UK Emissions of Air Pollutants 1970 to 2006*, AEA, Didcot, UK, 2008.
- 38 French Interprofessional Technical Centre for Air Pollution Studies (CITEPA), *Inventory of Greenhouse Gas Emissions in France under the United Nations Framework Convention on Climate Change* (Translated from French), CITEPA, Paris, 2009.
- 39 R. Dones, T. Heck and S. Hirschberg, *Encyclopedia of Energy*, 2004, **3**, 77-95.
- 40 D. Weisser, *Energ.*, 2007, **32**, 1543.
- 41 H. Hondo, *Energ.*, 2004, **30**, 2042.
- 42 French Ministry of Ecology, Energy, Sustainable Development, and Planning, *Transport Figures, 2009 Edition* (Translated from French), Paris, 2009.

Tables and figures

Table 1. EV characteristics ^a

	Tesla Roadster	THINK City	REVAi
Driving range, combined city/highway (km)	~354	175	80 (city only)
Top speed (km/h)	201	100	80
Peak power (kW)	185	30	13
Battery type	Lithium-ion	Lithium-ion or sodium	Lead acid
Battery capacity (kWh)	~53	28.3	9.6
Battery charging time (h), 0-100% state of charge	3.5-48 ^b	13	8
Battery weight (kg)	450	245-260	~250
Total curb weight (kg)	1238	1397	650 ^c
Base price (US\$) ^d	109 000	~34 000	~14 000

^a All data are from www.teslamotors.com, www.think.no, and www.revaindia.com, except where noted.

^b The charging time is 3.5 hours using Tesla's High Power Connector; 8 hours using its 240-V Mobile Connector, the highest-power portable charging option; and 37-48 hours using its 120-V Mobile Connector.

^c The REVAi is classified as a quadricycle rather than a passenger car under European Parliament and Council Directive 2002/24/EC ³⁵

^d Base price in the US (Tesla Roadster), Norway (THINK City: NOK 212 500), and the UK (REVAi: £8495; www.goinggreen.co.uk/store/pick_new [UK REVA retailer]); converted to US dollars on August 1, 2009, at www.xe.com/ucc.

Table 9. Comparison of well-to-wheels CO₂ emissions for EVs, hypothetical EV and existing fleets by country, and a selection of current ICEVs and HEVs ^a.

COUNTRY					
EV Model ^b	gCO₂/km				
HEV/ICEV Model ^b	gCO₂/km				
FRANCE					
REVAi	19	UK		US	
THINK City	23	REVAi	93	REVAi	102
<i>EV Fleet</i> ^d	23	Smart fortwo (diesel)	112	Smart fortwo (diesel)	112
Tesla Roadster	27	<i>EV Fleet</i>	114	Toyota Prius T3	118
Smart fortwo (diesel) ^e	112	Toyota Prius T3	118	THINK City	123
Toyota Prius T3 ^d	118	THINK City	118	<i>EV Fleet</i>	123
Seat Ibiza ^e	126	Seat Ibiza	126	Seat Ibiza	126
Volkswagen Polo ^e	127	Volkswagen Polo	127	Volkswagen Polo	127
Toyota iQ ^f	128	Toyota iQ	128	Toyota iQ	128
Smart fortwo (gasoline) ^f	133	Tesla Roadster	131	Smart fortwo (gasoline)	133
Honda Civic Hybrid ^d	140	Smart fortwo (gasoline)	133	Honda Civic Hybrid	140
Mini Cooper Clubman ^f	166	Honda Civic Hybrid	140	Tesla Roadster	143
Lotus Elise ^f	208	Mini Cooper Clubman	166	Mini Cooper Clubman	166
<i>Existing Fleet</i>	228	Lotus Elise	208	Lotus Elise	208
Porsche Boxster ^f	284	<i>Existing Fleet</i>	221	Porsche Boxster	284
		Porsche Boxster	284	<i>Existing Fleet</i>	361

^a www.vcacarfueldata.org.uk (UK Government's Vehicle Certification Agency)

^b The 2009 model year is used for all. Except where noted, the fuel is gasoline and the gearbox is automatic.

^c The figure for the hypothetical EV fleets is the average of the fuel efficiency figures of the Tesla Roadster, THINK city, and REVAi.

^d HEV

^e ICEV Diesel

^f ICEV Gasoline