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Electric vehicles: A tentative economic and environmental evaluation ☆

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ABSTRACT

A simple model is developed to estimate the excess costs of an electric car, relative to a similar fuel car, for the consumer and for society, as well as the CO_2 gains it offers. These magnitudes are a function of a dozen parameters, such as the purchase cost, the battery cost, the electric efficiency, the price of electricity, the CO_2 content of electricity (for the electric car), the purchase cost, the fuel efficiency, fuel prices, local pollution costs, CO_2 emission (for the fuel car), as well as car life and mileage driven. With the likely present values of these parameters, excess costs are much above 10,000 euros per car, for very small CO_2 gains. Sensitivity analyses are conducted to test the impacts of possible changes in parameter values. In nearly all cases, they are not sufficient to eliminate excess costs or to significantly increase CO_2 gains. The electric car appears to be a huge gamble with taxpayers money.

1. Introduction

Electric vehicles are often presented as a green solution to the transport problem (Barkenbus 2009, McKinsey 2009). They offer, it is argued, the benefits of the conventional (fuel-powered) car without many of its costs. They make it possible for individuals and families to move around rapidly, comfortably, at any moment in time, which makes them more consumer friendly than public modes of transportation. Yet, unlike classical cars, they do not consume scarce and dwindling fossil fuel resources. Above all, electric cars do not reject greenhouse gases, nor local pollutants, directly at least.

The idea is not new. One century ago, the press was already asserting: the electric car "has long been recognized as the ideal solution" because it "is cleaner and quieter" and "much more economical (*The New York Times*, November 2, 1911); and: "prices of electric cars will continue to drop until they are within reach of the average family" (*The Washington Post*, Halloween 1915). For many years, however, the electric car remained a dream, or a concept, or a curiosity.

Things might be changing. At the 2010 Paris Motor Show, several automobile companies presented electric vehicles for mass sales. This makes it possible to go beyond literary and qualitative appraisals of the electric car potential. It gives us access to some of the data required to undertake a quantitative evaluation of the economic and environmental achievements of an electric car.

This paper sets out a simple methodology, which takes the form of a computerized model. This model allows an assessment of the costs and performances of an electric car relative to a fuel-powered car. In the baseline case, parameter values reflect the situation in France. But the model makes it possible to assess the impacts of changes in the value of relevant key parameters, such as energy efficiency (of both types of cars), production costs, oil and electricity prices, CO_2 content of electricity, yearly mileage, fuel taxes, etc. The conclusions drawn are therefore meaningful beyond French borders. In recent years, a number of comparisons of electric and conventional vehicles have been conducted, particularly in the USA (Lipman and Delucchi 2006, Samaras and Meisterling 2008, Thomas 2009, Michalek et al., 2011) and on Germany (Ernst et al., 2011), or at the European Union level (Thiel et al., 2010). This paper is different in several respects. First, unlike many of these studies, the paper is focussed on the socio-economic viability of electric vehicles, not primarily on their CO_2 emissions. Second, the comparison is restricted to a single pair of purely electric and conventional vehicles, whereas the studies mentioned tend to consider simultaneously various types of non-fuel powered vehicles (hybrids with different mixes of energies, electric plug-in hybrids, fuel cell batteries). Third, the emphasis is on the sensitivity analysis. The future values - and in some cases the present values - of some of the relevant parameters are often uncertain. Rather than trying to produce the "right" numbers, we prefer to use several plausible numbers, and simulate the outcomes, or, to put it otherwise, to conduct sensitivity analyses.

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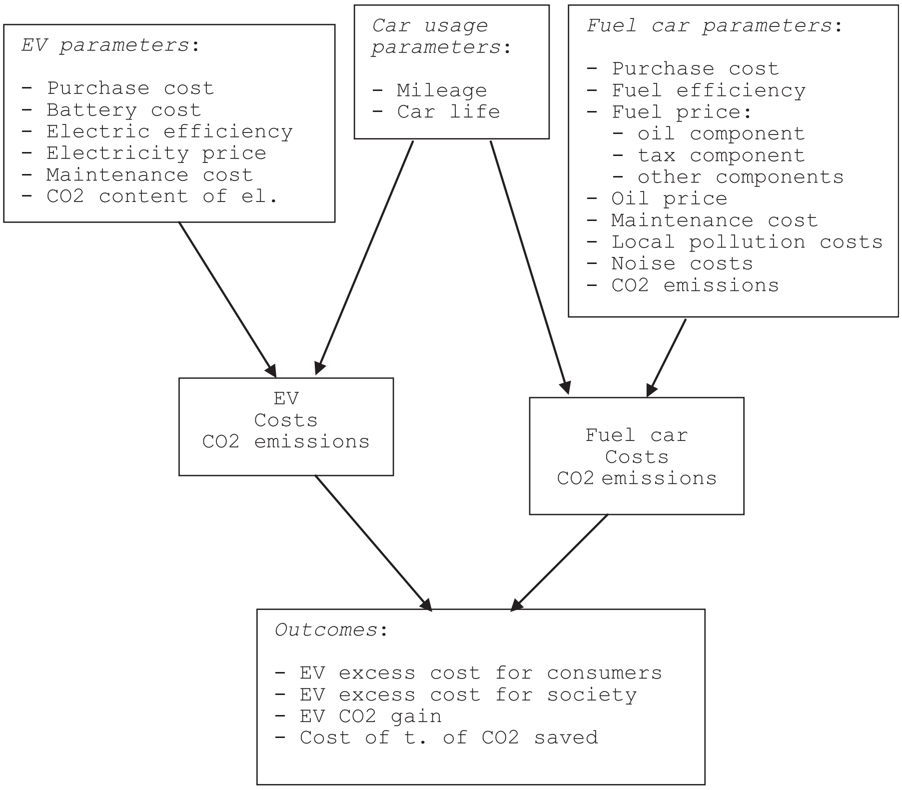

Fig. 1. Diagrammatic presentation of the model.

Fourth, the data utilized relates mostly to France, although the sensitivity analyses conducted should give some generality to the policy conclusions arrived at. The paper tries to evaluate a new technology, which, by nature, is not country-specific

The rest of the paper is organized as follows. In Section 2, we explain the structure of the model. Section 3 then presents the data used and the results obtained in a baseline case. Sections 4 and 5 report the sensitivity analyses conducted to test the robustness of the baseline case findings to present uncertainties and to possible or likely changes. Section 6 concludes.

2. Methodology

Fig. 1 presents in a diagrammatic fashion the structure of the model. The evaluation is comparative. It compares an electric car with a fuel-powered car providing about the same level of service during a similar period of time. It does it from three important viewpoints: consumer costs, socio-economic costs and CO_2 emissions.

Consumer costs are what consumers pay to use the two types of cars. Socio-economic costs are consumer costs minus specific taxes (which are not an economic cost, but a transfer) plus externalities. The externalities considered here are those caused by fuel car usage (Parry et al., 2007) and include externalities related to local pollutants (SO2, NOx, PM10) and to the noise produced by the fuel-powered car.[1] We ignore road maintenance and accidents costs, which are common to both the fuel car and the electric car and would cancel each other in the comparison.

CO_2 emissions are an externality, of course, but one which is difficult to price. The officially reported values are usually based on political targets of emissions reductions. Capped market prices mostly reflect the bounded scarcity of resources, not the future and uncertain damages caused by global warming (see Tol 2005). For that reason, we prefer to evaluate the difference in CO_2 emissions and relate it to the difference in socio-economic costs to find out the marginal cost of a ton of CO_2 saved thanks to an electric car.[2] Our model is not purely lifecycle as Michalek et al., (2011), Samaras and Meisterling (2008) or Patterson et al., (2011). We only consider "tank-to-wheel" CO_2 emissions of fuel-powered cars and do not measure those linked to the production and disposal of oil, vehicles and batteries.

There are three main outcomes of the exercise. The first is the difference between the consumer cost for the electric vehicle (CEC) and the consumer cost for the fuel vehicle (CFC). We assume that CEC > CFC and call it the consumer excess cost (CS) of the electric car:

$$CS = CEC - CFC$$

For the electric car to have a market, CS must be reduced to zero by some form of public subsidy.

The second outcome is the difference between the socio-economic electric cost (SEC) and the socio-economic fuel cost (SFC). We call it the socio-economic excess cost (SS) of the electric car:

$$SS = SEC - SFC$$

The third outcome is the difference (G, as in greenhouse gas) between the CO_2 emissions of the fuel car (GF) and those of the electric car (GE), or rather of the electricity consumed by it ("displaced emissions"). We assume that GF > GE and call G the CO_2 gain of the electric car:

$$G = GF - GE$$

[1] We do not account for the monetary effects related to the reduced "oil dependency" of countries, as done in the US case by Michalek and al. (2011).

[2] The abatement cost can then be compared to the marginal damages induced by an additional ton of CO2 in the atmosphere as estimated in academic works, or to the values indicated in official reports (see Section 3).

A fourth outcome of interest is the ratio of the socio-economic excess cost (SS) to the CO_2 gain of the electric car (G). It is the unit (or marginal) cost of a ton of CO_2 saved (g):

$$g = SS/G$$

Car usage is characterized by k, the number of km driven per year, and by n the lifetime of the car. These parameters are identical for both types of cars.

Cost is defined as present value, calculated with a social rate of discount r, of all costs incurred during the lifetime of the cars. With a flow of costs y_t over the 1 to n time period, the present value Y of this flow is:

$$Y = \sum_t y_t (1/(1+r)^t$$

The fuel car is characterized by its fuel efficiency (xf), which is the number of km driven per unit of fuel consumed (km/litre). The electric car by its electricity efficiency (xe), that is the number of km driven per unit of electricity consumed (km/kWh). Just one word on these units. Efficiency and productivity are generally defined as an output/input ratio, and increases in productivity or efficiency are considered desirable. This is in conflict with the European fashion of measuring the performance of a car in litre/100 km or in kWh/100 km (but not with the US fashion of measuring it in miles/gallon). Our definition of efficiency is therefore the inverse of the definition commonly used in Europe.

The cost of the electric car usage consists of the initial construction cost Ie, plus the battery cost B, plus the electricity consumption cost E. The battery cost is expressed in cost per year, because several car companies intend to rent batteries on a monthly or annual basis.[3] E is the present value of the flow of yearly expenditures e_t. e_t is the quantity of electricity consumed (itself a function of the electric efficiency xe and of the distance driven k) multiplied by the price of electricity in year t pe_t:

$$e_t = k^*(1/xe)^* pe_t$$

The cost of the fuel car usage (If) consists of the initial construction cost plus the fuel consumption cost (F), which is the present value of the flow of yearly expenditures (f_t). It is useful for the analysis to decompose f_t into three components: an oil cost, a specific tax cost, and other costs.

The oil cost for a given year t is a function of the quantity of oil consumed (itself a function of k the number of km driven), of the fuel efficiency (xf) of the car, of the price of oil (po) on international markets expressed in US dollars per barrel, and of a coefficient λ:

$$Oilcost_t = k*(1/xf)*\lambda*po_t$$

The tax cost for year t is simply the quantity of fuel consumed yearly multiplied by the unit tax t_t, expressed in euros per litre.

$$Taxcost_t = k*(1/xf)*t_t$$

The other costs (oil transport, refining and distribution) are assumed to be constant over time. They are also the product of unit costs z by quantities of fuel consumed yearly.

"Tank-to-wheel" CO_2 emissions of the fuel car (for a given year t) are defined as the product of the number of km driven (k) by the quantity of fuel consumed multiplied by the CO_2 content of a litre of fuel (gf). As a first approximation, we take the damages caused by CO_2 to be a function of the total quantity of CO_2 emitted during the 15 years of the life of the vehicle, irrespective of the years of emission. These emissions will be an addition to the world stock of CO_2 in 2027, which is what contributes to global warming damages. In so doing, we take into account the damages that will occur in the 2027–2100 period, and ignore those that will occur in the coming 15 years, which are much less important. Yearly emissions are not discounted. The CO_2 emissions over the life of the car (GF) are therefore:

$$GF = k*n*gf*(1/xf)$$

Similarly, the CO_2 emissions associated with the electric car (GE) over the lifetime of the car are the number of km driven (k) multiplied by the number of years considered (n), multiplied by the electric efficiency (xe), multiplied by the CO_2 content (c) of the electricity consumed:

$$GE = k*n*(1/xe)*c$$

CE and CF do not include all car usage costs. They ignore insurance costs, repair and parking costs. As done by Thiel et al. (2010) for example, these costs are assumed to be equal for the two types of cars, and therefore not to influence the excess cost; they can be ignored. We do not account for the charging stations needed by electric vehicles. According to Depoorter & Assimon (2011) one such station costs about 3,000 €, but can service several cars.

Finally, in the calculation of the socio-economic cost, one must take into consideration the local pollution costs associated with the fuel car and the noise emitted by the combustion engine.

It appears that SC and SS depend on about a dozen variables: Ie, If, B, xf, pe_t, xf, pb_t, x, t_t, z, r, n, k. For cars to be purchased in 2011, most of these variables are known with a fair degree of certainty, although three (those with a subscript t) might change over the period considered: electricity prices, oil prices and oil taxes. For cars to be purchased in subsequent years, several of the parameters, such as electricity and fuel efficiency, purchase prices, battery costs, are also susceptible to change over time, as discussed in sections 4 and 5.

3. Baseline case

What values should be attributed to our variables in order to determine the excess cost and the gain caused by the replacement of a fuel car by an electric car? We constructed a baseline case by comparing an electric car presented by Renault under the name of Zoe at the October 2010 Paris World Motor Show with a Renault Clio diesel car. The two cars seem to be roughly comparable in size and comfort. In our baseline case, we shall assume they are used mostly for daily commuting purposes, for 15 years ($n=15$), and are driven 10,000 km per year ($k=10{,}000$), two generous estimates. It is assumed that both types of cars will be scrapped at the end of this period. We use a 4% social rate of discount.

The sale price of the Clio diesel car (If) is reported to be "from 11,700 €" on the official Renault site (www.renault.fr); we retained 12,000 €. The sales value of the electric car (Ie) is reported to be 20,000 €, before a 5,000 € French government subsidy.[4] These numbers are sales values, when we are interested in cost values. Can they differ much? Most probably not. The automobile industry is extremely competitive, with very small profit margins,[5] and sales prices (before subsidies) are probably a fair reflection of economic costs.[6]

[3] Thanks to these rental schemes, we do not have to deal with the potential shortest lifetime of the batteries compared to the one of the vehicles (see Lipman and Delucchi 2006). More generally, we ignore the "battery problem" (see Axsen and al. 2010, Werber et al., 2009).

[4] Renault has provided commercial information on Zoe cars in March 2012, during the revision of the paper. The information confirms our baseline figures: purchase cost will reach 20,700 € (before a public subsidy of 5,000 €).

[5] In their analysis on the retail costs of non conventional vehicles, Lipman and Delucchi (2006) assume a 3% profit margin on the invoice price.

[6] This result holds if one rejects "cross-vehicles subsidies" by the constructors, as distortions on the sub-markets (disposal and final sell of vehicles).

Concerning the cost of the Zoe batteries (Lithium-ion, 22 kWh), Renault offers batteries on a rental basis, at 75 € per month, or 900 € per year. This makes it possible to calculate B, the present value of battery usage, at 10,000 €. What was just said in the preceding paragraph about the cost representativeness of sales for vehicles applies probably to batteries.

The fuel car considered is reported to consume ‘‘less than 5 l of diesel per 100 km’’; this is a fuel efficiency of 20 km/litre ($xf=20$). Based on the New European Driving Cycle, this kind of commercial information is known not to represent very accurately the ‘‘real’’ energy consumption of vehicles, the latter being probably 15–25% higher (Zachariadis 2006, Patterson et al., 2011). Our 20 km/litre figure may therefore underestimate the true quantity of fuel consumed by the conventional cars.[7]

To price fuel, we started with a June 4, 2010 estimate of UFIP (Union Française de l'Industrie Pétrolière), a reliable industry source, that presents the structure of diesel oil prices.

The price in Table 1 corresponds to a crude oil price of 75 US$ per barrel. Over the course of time, it will be equal to 0.448*po/75. This assumes, for the sake of simplicity, a constant dollar/euro exchange rate, an hypothesis that could easily be abandoned. In the baseline case, we shall assume a 6% per year increase in the price of crude oil, which means oil at 170 $ a barrel in year 15 (2025).[8]

The specific tax to be considered in France is obviously the TIPP[9], the rate of which is expressed in euros per litre. The VAT (19.6% in France) assessed on the TIPP, a tax on the specific tax, should also be treated as a specific tax. The tax is therefore 0.542 €/litre, and the possibility of an increase can be considered.

Other costs, i.e. refining and distribution costs, at 0.193, including VAT, are assumed to be constant over time.

It is not easy to find explicit and reliable estimates of the electricity efficiency of the electric car. Producers usually do not communicate it in the abundant publicity they make about their products. The US Energy Policy Information Center[10] evaluated in 2010 the consumption of a midsize plug-in electric vehicle, similar to the Renault Zoe studied here, to be 27.5 kWh/100 km, a 3.64 (km/kWh) efficiency. This number includes a 7% transmission loss and a 10% charging loss. Thiel et al. (2010) use a lower value of 13.5 kWh/100 km, a 7 (km/kWh) efficiency. A recent French official report on electric cars states that electric car efficiency ranges from 15 kWh/100 km to 25 kWh/100 km, depending essentially on traffic speed (Conseil d'Analyse Stratégique 2011). These figures are in line with those retained by Ernst et al. (2011) or Axsen et al. (2010) for hybrid electric vehicles. We shall use in our baseline case 20 kWh/100 km, i.e. an electric efficiency of 5 km/kWh driven ($xe=5$), which is also the figure retained in Depoorter & Assimon (2011), then test the impact of higher values in our sensitivity analyses.[11]

The price of electricity retained for year 1 (2011) is the retail price of electricity in France: 0.11 €/kWh ($pe=0.11$). This is a low price, lower or much lower than in most other European countries, thanks to the high nuclear content of electricity in France. This assumes that the heavy investments required to offer electric cars an easy access to the grid would not be reflected in higher prices. With this low price, the present value of the electricity cost of the electric car is about 2,400 €.

Table 1
Diesel Oil Price Structure, France, 2010.
Source: UFIP (www.ufip.fr).

	Before VAT	VAT	After tax
Crude oil (at 75 $/barrel)	0.375	0.073	448
Specific tax (TIPP)	0.428	0.084	0.512
Other (refining, distribution)	0.162	0.031	0.193
Pump price			1.153

Regarding local pollution costs (SO2, NOx, PM10), we use a French official commission report, known as the Boiteux report (because it was chaired by Marcel Boiteux, a respected economist, the father of Ramsey-Boiteux pricing), the findings of which were endorsed in 2004 by the minister of Transport in an official ‘‘directive’’ (Commissariat Général du Plan, 2001; Ministère de l'Equipement, des Transports, 2004). For private cars, in non-dense urban areas (as opposed to dense urban areas and rural areas), the local pollution cost to be utilized in cost-benefit analysis was 0.01 €/vehicle-km in 2000. To take into account the rapid decrease in car emissions per km driven, this value was to decline by about 4.5% per year over the 2000–2020 period. This means 0.006 €/veh-km in 2011. We retain this value, and this decline rate for the 15 years period studied.

For the noise externality, it is difficult to use the values provided by the Boiteux report. The monetary equivalents for noise disturbances are expressed as a decline rate in housing prices varying with the decibel emitted, not in €/veh-km. For that reason, we prefer the value proposed by the European Commission in the *Handbook on Estimation of External Costs in the Transport Sector* (Malibach et al., 2008): 0.001 €/veh-km.

Tables 2 and 3 sum up the value of the various parameters used in the baseline case.

Table 4 compares, in present value terms, the consumer cost of the two types of vehicle, for a similar usage. With the values given to the relevant variables in this baseline case - that seem to reflect to-day's reality - the electric car is not competitive. For a given service (10,000 km per year during 15 years), it costs the consumer an additional 13,000 euros to use an electric car instead of a fuel car. This result is in line with a number of studies highlighting that the current technological state of electric cars still implies a significant financial burden for households compared to conventional cars, but also to hybrid vehicles (Thiel et al., 2010, Michalek et al., 2011, Thomas 2009, Lipman and Delucchi 2006).

The level of service provided by the electric car is inferior to the level of service provided by the standard fuel car in at least one respect. With its 22 kWh battery, the Zoe electric car can only be used for tips less than 150 km. Unlike the fuel car, it cannot be used for most vacation trips. The willingness to pay for the greater degree of liberty offered by the fuel car is difficult (although not impossible) to estimate, and most probably reaches several thousands euros.

This additional 13,000 € is the excess cost for the consumer. From a socio-economic viewpoint, however, one should take into account the specific taxes paid by the fuel car. These taxes are a transfer, not an economic cost, not a consumption of scarce resources. Table 2 shows that such taxes amount to about 2,800 €. This should be deducted from the socio-economic cost of the fuel car, and increase the excess cost. Conversely, one should subtract the externalities due to local pollution and noise

[7] This is particularly true if conventional vehicles replace electric cars in congested cities, with low traffic speeds and frequent stop and go sequences.

[8] It might be the case that oil-related costs are not proportional to crude oil prices. This would be due to non linearities in changes in the demand for the various coproducts extracted from crude oil, or in the refining costs of these coproducts (that depend themselves on the type of crude). For the sake of simplicity, we ignore this possibility.

[9] Taxe Intérieure sur les Produits Pétroliers.

[10] A project of an apparently reliable think tank committed to reducing ‘‘oil dependency’’ entitled ‘‘Securing America's Future Energy’’ (http://energypolicyinfo.com).

[11] The commercial information provided by Renault (see footnote 9) states that the 22 kWh battery of the Zoe allows an autonomy of 260 km. However, the same source recognizes that under ‘‘real’’ driving conditions, this autonomy decreases to 100–150 km, depending on the outside temperature and humidity rate. This corresponds to a 4.5–6.7 km/kWh.

Table 2
Present Value of Fuel Consumption, Fuel Car, Years 1–15.

	€	%
Oil cost O	3,704	51
Oil taxes T	2,846	37
Other costs Z (refining, distribution)	1,073	14
Total	7,623	100

Note: calculated on the basis of a 6% per year increase in the price of crude oil, with a price of 170 $ a barrel in 2025.

Table 3
Value of parameters used in the baseline case.

Number of years (n)	15
Car usage (k), in km/year	10,000
Social rate of discount	4%
Fuel car:	
Purchase cost (If), in €	12,000
Fuel efficiency (xf), in km/liter	20
Oil price (po) in year 1, in $/barrel	75
Yearly change in oil price (%)	6%
Fuel taxes (t), in €/l	0.512
Other fuel costs (z), in €/l	0.193
CO_2 emissions (gf), in kg/l	2.6
Local pollution costs in year 2011 (€/km)	0.006
Yearly change in local pollution costs (%)	4.5%
Noise costs in €/km	0.001
Electric car:	
Purchase cost (Ie), in €	20,000
Battery cost present value (B), in €	10,007
Electricity efficiency (xe), in km/kWh	5
Electricity price (pe), in €/kWh	0.11
Yearly change in electricity price (%)	0%
CO_2 content of electricity (c), in g/kWh	90

Table 4
Present value of fuel and electric car usage, for consumers over a 15 years period, baseline case.
Source: See text and Table 3 for the values given to the various parameters. *Note*: The total cost is not quite total since it does not include costs common to the two types of cars, such as parking, insurance or repair.

(In €)	Fuel car	Electric car	Difference
Purchase cost	12,000	20,000	+8,000
Battery cost	–	10,007	+10,007
Fuel or electricity cost	7,623	2,446	−5,177
Total cost	19,623	32,453	+12,889

costs saved with electric cars (respectively 520 and 111 € over 15 years, a modest amount compared to the costs of ownership and to the taxes). The economic differential, what society loses by utilizing an electric car, is finally about 15,000 €.

In terms of market penetration, what matters is the consumer excess cost. Except for a handful of consumers who want to show they are very rich and very green, there is not much of a market for the electric car as it is presently.[12] Sales require average subsidies of around 13,000 € per car, more than twice those currently proposed in France. Such subsidies might take the form of compulsory purchases by government or quasi government bodies. This will take place at a high cost in terms of public finance. If next year, 10% of car sales in France (2.3 million cars) were to be electric cars, this would imply a subsidy of 3 billion euros,[13] as well as a tax loss of 0.7 billion euros, that is an increase in tax or in debt of 3.7 billion euros.

Can this drain on economic resources and on public finance be justified by the gain in CO_2 emissions likely to be generated by the electric car?

It is easy to figure out the "tank-to-wheel" CO_2 emissions of our reference fuel car that will be saved. As mentioned above, they are equal to $gf*(1/xf)*k*n$. The CO_2 content of a litre of diesel oil (gf) is 2.6 kg. With a fuel efficiency (xf) of 5 km/litre, and 10,000 km/year, the fuel car will reject 1.3 t of CO_2 per year (about half what is rejected by a cow in the form of methane), and 19.5 *t* over its lifetime.

It is much more difficult to evaluate the CO_2 emissions associated with the electricity consumed by the electric car, defined as $GE = ge*(1/xe)*k*n$. The reason is that ge, the CO_2 content of a kWh of electricity, varies greatly from place to place and from moment to moment (Peterson et al., 2011, Samaras and Meisterling 2008), from about zero to 1,000 g of CO_2 per kWh. Rather than a number, it is better to offer a function:

$$GE = 0.030*ge(\text{with}\,xe = 5)GE = 0.021*ge(\text{with}\,xe = 6.5)$$

Fig. 2 represents this function. The break-even point appears to be a CO_2 content of electricity of about 650 g/kWh, with an electric efficiency of 5 km/kWh. Beyond this limit, the electric car emits more CO_2 than the reference fuel car. Before this limit, the electric car performs better, in terms of CO_2, than the fuel car. For a greater electric efficiency, the break-even point is higher.

Table 5 presents 2007 estimates of the *average* CO_2 content of electricity for a selection of European countries.[14] The average for Euro-15 countries is reported to be 330 g. It is lower than 100 g in Sweden and in France, because of a high share of nuclear and hydro in the electricity-mix. But it is higher than 400 g in Germany, the UK, the Netherlands or Denmark, not to mention most of Eastern European countries.[15]

What counts, however, is the *marginal* CO_2 content of the electricity used to recharge the electric car batteries. It varies greatly. It can be very low. In France, if electric cars were only recharged at night, when electricity is mostly produced by nuclear power plants emitting next to zero CO_2, the gain would be close to 19 *t* per car. But if the cars were recharged at times when a larger share of electricity is produced by fuel or gas powered plants, the gain would be much reduced.

Somewhat arbitrarily, we assumed the electricity demand for recharging the vehicles to be representative of the actual all-purposes electricity demand. We can thus retain 90 g/kWh for the marginal CO_2 content of electricity, i.e. the average number for France in Table 5.[16] This produces a CO_2 gain of 16.8 *t* per car over the 15 years of the car life. It represents, in the French electricity context, an impressive 85% decline. This important advantage, however, is more apparent than real. First, it cannot hold for all cars used in France. As mentioned, the 100% electric car is expected to remain a niche market, servicing at best 10% of the car market. Second, it is obtained at a high cost: the economic excess cost of 15,000 € previously calculated puts the abatement cost at 895 € per ton of CO_2 eliminated.

[12] Caulfield et al. (2010) use "stated preferences" to investigate the willingness to pay for the electric car. They highlight that customers currently give more importance to the costs they bear than to the environmental benefits they could create.

[13] One could even apply a 30–50% coefficient to these subsidies to account for the opportunity cost of public funds.

[14] Eurostat does not provide these statistics. Neither does WRI. The IAE does, but sells them.

[15] Peterson et al. (2011), among others, report such heterogeneity in the case of the US, where the states strongly differ concerning the energy used for the production of electricity.

[16] A direct calculation dividing the 2008 CO2 emissions produced by electricity generation (29 M tons, according to the authoritative CITEPA report entitled *Inventaire des émissions de gaz à effet de serre en France*, and dated April 2010) by the 2008 electricity production (575 TWh), one obtains 50 g/kwh.

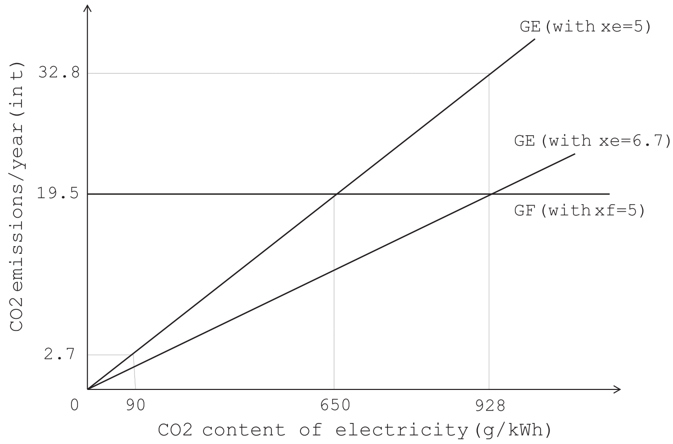

Fig. 2. CO_2 Emissions of fuel and electric cars, as a function of the CO_2 content of electricity.

Table 5
Average CO_2 content of electricity, selected European countries, 2003.
Source: Ministère de l'Ecologie. 2010. *Chiffres-clés du climat France et Monde*, quoting IEA.

(In g of CO_2 per kWh)	
Sweden	40
France	90
Belgium	290
Italy	388
Spain	390
Netherland	405
Germany	427
UK	500
Czech Republic	558
Poland	668
Average Europe-15	330
Average Europe 27	362

This number deserves some comments. First, it is about 10–15 times higher than most estimates of "CO_2 prices". The meta-analysis of Tol (2005) reviews more than 100 estimates of the marginal costs generated by a ton of CO_2. The average of all estimates is 66 € (93 $) per ton. If one limits the sample to the studies that use standard hypothesis on costs aggregation and preference for the present, notes Tol (2005), a number of 36 € (50 $) per ton of CO_2 appears to be on the high side. A basic tenet of environmental economics is that an optimal environmental policy equalizes marginal abatement costs over sectors, and countries. Electric vehicles cannot be considered a step in that direction.

Second, the abatement cost of 895 € per ton of CO_2 has been calculated in the favorable French case. For most other countries in Europe, the unit cost would be much higher. For the UK - assuming the same vehicles, prices and taxes characteristics - a gain of 3.1 *t* (-15% per car CO_2 emissions) would be obtained at a unit cost of 4,800 €.[17]

The CO_2 gains associated with the electric vehicle appear to be relatively unimportant and/or extremely costly, and unable to counterbalance the consumer and socio-economic excess costs associated with it.

Could a full life cycle analysis invalidate this conclusion? It is true that the production of a combustion vehicle, as well as fuel transportation and refining, produce CO_2. But so does the production of an electric vehicle and of its batteries (See Samaras and Meisterling 2008 or Patterson et al., 2011), not to mention the construction of power plants and grids. The additional CO_2 emissions associated with the two types of vehicles are likely to cancel each other.

4. Short term sensitivity analysis

Some of our parameters values are very well established; others are much less certain. It is important to see if, why, and by how much, our outcomes are modified by changes in the value of these questionable parameters, in order to test the robustness of the analysis, and to identify the variables that could most affect outcomes. Table 6 presents how for the present batch of vehicles the consumer excess cost, the economic excess cost, and the CO_2 gain are modified as a result of such changes.

4.1. Rate of discount

A first question is: are our findings, which are expressed in present value terms, very sensitive to the rate of discount chosen (4% in the baseline case)? Not really: they change by about 500–600 €. One could have expected the electric car, which is supposed to be more costly at the time of purchase and less costly in yearly fuel/electricity consumption, to be favoured by a low rate of discount. Actually, the opposite is true. The reason is that in our model (as in most cases in reality), battery costs are yearly costs, and yearly costs of the electric car are higher than the yearly costs of the fuel car.

4.2. Oil prices

A second question is: would a rapid increase in the price of oil in the next 15 years drastically change the picture? In the baseline case, we assumed a 6% per year increase, already a substantial increase. A 12% per year increase (implying a price of 370 US$ in year 15, considered very unlikely by most experts) would decrease our two excess costs by about 2,000 euros.

4.3. Fuel taxes

A third question relates to fuel taxes. We simulated the impact of a doubling of the present fuel taxes in year 1, a radical (and unlikely) measure. It obviously does not affect the economic excess cost, which remains around 15,000 €. It only lowers the consumer excess cost by about 3,000 €, to 10,000 €, which remains high enough to prevent mass purchases of the vehicle.

4.4. Electricity price

Fourthly, the electricity price used in the baseline case (0.11 €/kWh), the present price paid by households in France, is low by European standards. It is much lower than the cost of solar electricity, which is presently in France sold to the network at about 0.45 €. We simulated the impact of an electricity price increase of 10% per year, implying a price of 0.41 €/kWh in year 15 (below the present cost of solar electricity). This results in an increase of both excess costs of more than 2,300 €.[18] The marriage of electric cars and solar electricity would not be a happy one.

[17] Countries like Germany or Spain would have intermediary positions, with approximately 6 *t* of CO2 saved (per car emissions reduction of 30%) and an abatement cost of 2,500 €.

[18] If the electricity used were, beginning in 2011, entirely photovoltaic electricity sold at its cost – an unrealistic hypothesis indeed - the electricity cost

Table 6
Outcome changes generated by possible changes in the value of key parameters.

	Consumer excess costexcess (€)	Economic cost (€)	CO_2 gain (Tons)	Cost of CO_2 gain (€/ton)
Baseline case	12,900	15,000	16.8	895
Rate of discount: 2%[a]	13,500	16,100	16.8	956
Rate of discount: 6%[a]	12,300	14,200	16.8	846
(a) Fuel taxes: +100%[b]	10,000	15,000	16.8	895
Oil prices: +12%/year[c]	10,800	13,000	16.8	776
Electricity prices: +10%/year[d]	15,200	17,400	16.8	1,038
(b) Electr. efficiency: +30%[f]	12,300	14,500	17.4	832
(c) Yearly mileage: +30%[e]	11,300	14,100	21.8	649
(a)+(b)+(c)+changes car prices[h]	3,300	9,900	22.7	438

Notes: All cost numbers have been rounded to the nearest 100, to facilitate the reading of the results.
[g] 13,000 km/year instead of 10,000.
[a] As opposed to 4% in the baseline case.
[b] From 0.512 to 1.024 €/litre.
[c] from 75 $/barrel in year 1 to 285 $/barrel in year 15.
[d] From 0.11 €/kWh in year 1 to 0.42 in year 15.
[e] 400 g/kWh as opposed to 90 in the baseline case.
[f] 6.5 km/kWh instead of 5.
[h] Lower electric car price (19,500 instead of 20,000) and higher fuel car price (15,000 instead of 12,000).

4.5. Electric efficiency

A fifth issue concerns the electric efficiency of the electric car. The one assumed in the baseline case is 5 km/kWh (20 kWh/100 km). We simulated the impact of a 30% more electric efficient car (6.5 km per kWh, or 14 kWh/100 km). It reduces the excess costs by only about 500 €, not a radical change in the overall picture. It also improves the CO_2 gain, by only about 1 t over the 15 years period.

4.6. Car mileage

A sixth question relates to the mileage driven annually. The base line case assumes a yearly car usage of 10,000 km. Were this number to be increased by 30%, to 13,000 km, the excess costs would decrease, by about 800 €, the CO_2 gains would increase by 5 t, and the cost of a ton of CO_2 saved decreases to about 650 €.

This raises an important issue. The advantage of an electric car (relative to a fuel car) varies significantly with the number of km driven. The more kilometers are driven per year, the more attractive it is. Yet, because of their short range, electric cars are only suited for short daily trips. Is there a contradiction here? In average terms, yes; in market terms, no.

The average number of km per year driven on daily trips is low. In France, a 2008 nation-wide transport survey gives the number of local trips (of less than 80 km) per week, as well as the average distance of each trip.[19] Since we know the number of cars, we can calculate the *average* yearly mileage of each car on local trips: 2,000 km. Many cars (for instance the second car in a number of households) are not used every day, or only on very short distances. For electric cars, this is a double-edged sword. On the one hand, it does reduce the negative impact of the range constraint. But on the other hand, it increases the unit cost of the electric car, which is characterized by high investment costs and low operating expenditures.

The electric car, however, does not target the average car, nor the entire market. It focuses only on those cars which are driven many kilometers in the form of short-range trips. Industry believes that cars driving at least 13,000 km per year on such short trips represent about 10% of the market. It is therefore legitimate to consider the advantages of the electric car for this particular segment of the demand only. It means that the electric car market is and should be presently considered as a *niche market*, not as an alternative to the fuel car in general.

4.7. Five simultaneous changes

All of the above changes have been considered parameter by parameter. We can also conduct the sensitivity analysis for sets of changes. We discussed an earlier draft of this paper with Renault officials. While they endorse the methodology, they suggested that the *simultaneous* introduction of five changes (relative to our baseline case) would, in their view, better reflect reality: (a) a 100% higher fuel tax, (b) a 30% greater electricity efficiency; (c) a 30% higher mileage; (d) a slightly lower sales price for the electric car (19,500 € instead of 20,000 €); and (e) a significantly higher price of the fuel car (15,000 € instead of 12,000).

The first three changes have already been examined individually. What happens when these five changes are jointly introduced? In this case, the excess cost for the consumer is significantly reduced to 3,300 € (-23% compared to the baseline case). Therefore, a 5,000 € subsidy would be more than enough to compensate and create a market. The socio-economic excess cost, however, remains high, at 9,900 €. Even in the most "optimistic" scenario, the electric car remains a bad deal for society and presents a CO_2 abatement cost above 400 € per ton.

5. Longer term sensitivity analyses

The preceding sensitivity analyses apply to the present batch of cars. Things might be different in the future, for two obvious reasons: economies of scale and technological improvements.

Economies of scale are particularly important in the automobile industry (Lipman & Deluchi 2006; Thomas 2009; Thiel et al., 2010). The production cost of a car, or of parts of a car, can be cut by as much as 50% when production volumes increase from 10–20,000 units a year to 500,000 units a year. Such volumes are current for the standard fuel cars. Production costs of electric cars and of batteries presently given probably assume volumes sufficiently high to reap part of the potential scale economies. But it can be hypothesized that more remains to be reaped, and that increased volumes would mean lower costs. Technological improvement might be even more important to cut costs for a relatively novel technology like that of electric cars. Over the course of time, the curve representing production costs as a function of volume will go down.

Fig. 3 illustrates the possible future of the electric car. AA' is the production cost curve for a fuel car. It is flat, because economies of scale have already been obtained. BB' is the present production cost curve for an electric car. We do not know exactly where we are presently on this curve. DD' is the potential demand curve for an electric car, low for a high price, high for a low price. The effective demand curve, however, is doubly bounded. First, it only begins in L, because of the existence of a fuel car substitute at a lower price (prices are assumed to be equal to production costs). Second, it is limited by the number of car owners that drive

(*footnote continued*)
of the electric car would be above 11,200 €, much greater than the fuel cost of the fuel car, and the economic excess cost would jump above 23,000 €.

[19] See ENTD (enquête nationale sur les transports et déplacements), at www.statistiques.developpement-durable.gouv.fr.

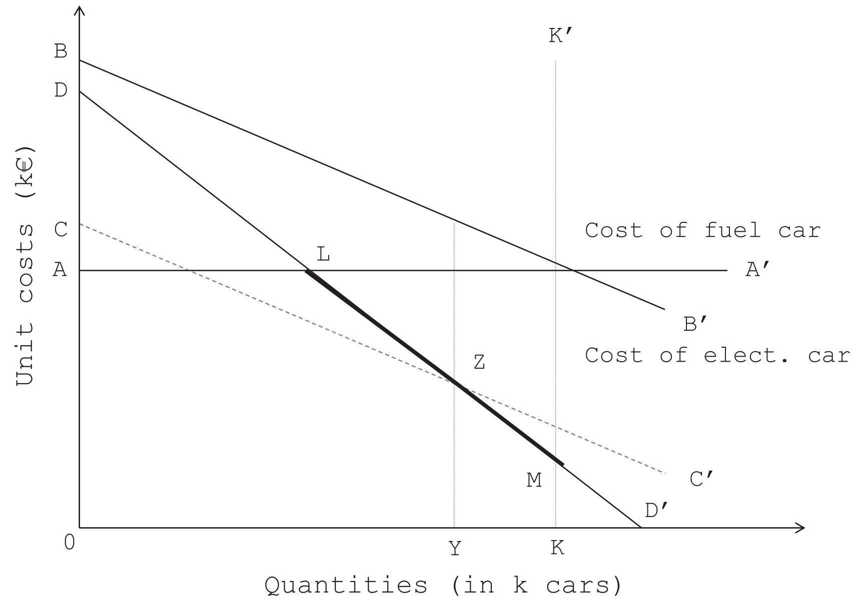

Fig. 3. Costs as a function of volumes.

sufficiently (for instance at least 13,000 km/year) in the form of short trips (for instance less than 150 km/day). This limit is figured by line KK'. M is the intersection of DD' and KK'. The demand for electric cars is therefore figured by the segment LM.

As appears on Fig. 3, the present production cost curve of an electric car (BB') does not intersect the demand curve (LM), and there is no market for electric cars. For a market to be created, a subsidy that will lower BB' to, for instance, CC' is necessary. An equilibrium will be reached in Z, with Y cars sold—at a cost to public finance equal to BWZC. For this to be sustainable, the subsidy must be replaced, over the course of time, by a reduction of the electric car cost at least equal to the subsidy. Can such a cost reduction be expected?

A reduction of the usage cost of electric vehicles could come from three improvements: a reduction of the construction cost (or sales price before subsidy) of the car, a reduction in the cost of batteries, and an increase in the electric efficiency of the car. We simulated the impact of such changes individually, then jointly, on the electric car excess costs. For construction costs, we consider a 30% reduction, from 20,000 € to 14,000 €. For batteries cost, we also consider a 30% reduction, from 900 €/year to 630 €/yr. For electric efficiency, we consider a 100% improvement, from 5 to 10 km/kWh (from 20 to 10 kWh/100 km). Each of these improvements would be a significant industrial achievement. Results are presented in Table 7.

Taken individually, the impacts of these changes are not impressive. Excess costs are reduced, but remain substantial: in the 7,000–12,000 € range for the consumer excess cost, in the 9,000–14,000 € range for the socio-economic excess cost. The CO_2 abatement cost of the electric car lies in between 500–600 € per ton, still above the alternative CO_2 values presented in Section 3.

If they were to happen simultaneously—which would represent a remarkable industrial achievement—these changes would reduce the electric car excess costs to much lower levels: 2,600 € for the consumer (-60% compared to the baseline case), and 4,800 € for society (-70%). However, they would not suffice to create a non-subsidized market for the electric car, and electric cars would continue to be operated at a high social cost. In order to eliminate the consumer excess cost, one has to add to these three technological changes a rather high (14%/year) increase in oil prices, that would raise the price of oil to 470 $ per barrel in

Table 7
Outcomes generated by improved electric vehicles.

	Consumer excess costexcess (€)	Economic cost (€)	CO_2 gain (t)	CO_2 gain (€/t)
Present vehicles (baseline case)	12,900	15,000	16.8	895
Future vehicles:				
(A) Initial cost: −30%	6,800	9,000	16.8	536
(B) Battery cost: −30%	9900	12,000	16.8	715
(C) Electricity efficiency: +50%	11,600	13,800	18.2	757
(D) (A)+(B)+(C) together	2,600	4,800	18.2	263
(E) (D) + Oil prices: =14%/year	−300	1,800	18.2	102

Notes: Numbers have been rounded to the nearest 100 to facilitate reading. In the baseline case, the initial cost is 20,000 €, the battery cost is 900 €/year, the electric efficiency is 5 km/kWh (20 kWh/100 km), and the oil price is 75 $/barrel. A 14% per year increase in the oil price means 470 $/barrel in year 15.

15 years. Even in this extreme case, the electric car would be operated at a cost (a socio-economic excess cost) to society.

While the abatement cost may fall to 100 € per ton of CO_2 saved in that case, a value close to some estimates of the marginal CO_2 damages (Tol 2005), the CO_2 gains generated by more efficient electric cars are not much affected by these technological changes (+8% compared to the baseline case). Note that the numbers of Table 7 have been calculated with the French average CO_2 content of electricity. In most other European countries, the abatement cost of CO_2 would be higher, even much higher. Moreover, we assumed no progress in CO_2 emissions of fuel car, a strong hypothesis with respect to recent changes in car technologies (Zachariadis 2006). A constant price (i.e. cost) of electricity was also considered. A more realistic long-term scenario would abandon this assumption, and this would increase excess costs.

6. Conclusion

The conclusions of this analysis are not encouraging for the success of the purely electric car. On the basis of available information on costs and performances, it appears that the present 100% electric car fares much less well than a standard conventional fuel car. Over the lifetime of a car, it will cost some 12,000 euros more to the consumer, and 15,000 euros more to society. These numbers take into account the cost of local pollution and of the noise caused by fuel cars.

It is hard to justify such enormous excess costs by the CO_2 gains that will be produced. Over the 15 years of car usage, these gains will range from zero in a country like Poland to a maximum of 19 t in a country like Sweden or France provided batteries are recharged at night when the CO_2 content of electricity is close to zero. Assuming the average European Union CO_2 content of electricity, the CO_2 gain of an electric car operating 10,000 km during 15 years will be about 8 t. The implied cost of saving one ton of CO_2 ranges from about 900 euros to infinity (in extreme cases, the electric car would increase CO_2 emissions), with an average of 2,500 euros. This is a particularly costly way of reducing CO_2 emissions.

There are serious uncertainties about several of the parameter values used, for the present, and even more so for the future. We conducted sensitivity analyses to evaluate the impact of alternative values of these parameters upon our conclusions. We considered different rates of discount, important increases in fuel taxes, in crude oil prices, in electricity efficiency (of electric cars), in mileage driven, in the carbon content of the electricity utilized, and important decreases in the cost of electric cars and of batteries.

All of these changes do impact the excess costs and the CO_2 gains. But not much. Taken individually, they typically reduce excess costs by 1,000 or 2,000 euros. In that sense, our model turns out to be quite robust. It is only when several of these changes are introduced jointly that excess costs are reduced significantly. A 30% decline in electric car cost and in battery cost, plus a 100% increase in electric efficiency, plus a 14% per year increase in the price of oil eliminate the consumer excess cost but not the socio-economic cost. The probability that all these changes occur together is not zero, but it is very low.

Even in the most "optimistic" scenarios, CO_2 gains remain low: they are increased by a few tons over the lifetime of the car by a better (or much better) electricity efficiency, and decreased by an increase in the carbon content of the electricity used.

Late in 2011, the OECD issued a study, explicitly based on our methodology, that replicates our analysis, and extends it to the comparison of three pairs of electric/non electric similar vehicles (OECD, 2011). This study basically reaches the same conclusions.

Table A1

For reference					
Value of parameters:					
Number of years (n)	15	15	1	2	3
Social rate of discount	4%	4%			
Car usage (k/yr)	10000	10000			
Fuel car:					
Purchase cost (If) in €	12000	12000			
Fuel efficiency (xf) in lm/litre	20	20			
Oil price (po- in $/barrel)	75	75			
Change in oil price (%)	6%	6%	75	80	84
Fuel taxes (t) in €/lit	0.512	0.512			
Change in fuel tax rate (%)	0%	0%	0.512	0.512	0.512
Other fuel costs (z) in €/lit	0.193	0.193			
Change in local emission costs (%/yr)	−4%	−4%			
Local pollution costs (€/km)	0.006	0.006	0.006	0.0058	0.0055
CO_2 emissions (gf), in kg/lit	2.6	2.6			
Noise costs (€/km), in kg	0.001	0.001			
Change in noise costs (%/year)	0%	0%	0.001	0.001	0.001
Electric car:					
Purchase cost (Ie), in €	20000	20000			
Battery renting (B) in €/yr	900	900			
Electricity efficiency (xe) in km/kWh	5	5			
Electricity price (pe), in€/kWh	0.11	0.11			
Change in elect price	0%	0%	0.11	0.11	0.11
CO_2 content of electricity (c) in g/kWh	90	90			
Usage cost of fuel car (in €):					
Purchase cost		12000			
Oil cost of fuel		3 704	224	237	252
Fuel taxes		2 846	256	256	256
Other fuel costs		1 073	96.5	96.5	96.5
(Subtotal: fuel costs)		7 623			
Total		19623			
Local pollution costs		524	60	57.6	55
Noise costs		111	10	10	10
Usage cost of electric car, in €:					
Purchase cost		20000			
Battery cost		10 007	900	900	900
Electricity cost		2 446	220	220	220
Total usage cost		32 453 €			
Results:					
Excess cost (consumer), in €		12 889			
Excess cost (economy), in €		15 040			
CO_2 gain, in tons		16.8			
Cost/ton of CO_2, in €/t		895			

One parameter deserves a particular attention: mileage. The more km per year an electric car is driven, the more economic (or more precisely the least uneconomic) it is. But mileage is constrained by the limited range (150 km) of electric cars. This means that the electric car market can, if anything, only target cars driven many km per year in the form of small trips. This is only a fraction (about 10% according to industry estimates) of the automobile market. The idea that the electric car could be a general substitute to the fuel car is not acceptable. It can only, at best, be a niche market.

Let us repeat that this paper did not examine the reality and prospects of hybrid cars, which are likely to be rather different.

The 100% electric car appears as a gamble on the part of producers and governments. Until massive cost and efficiency improvements are achieved, it will require enormous subsidies. If they are achieved, and achieved rapidly, this gamble might pay. If not, a lot of resources will have been wasted. In this case, a fraction of these resources would have made it possible to reduce CO_2 by much larger amounts.

Appendix A. Spreadsheet used for calculations

See (Table A1).

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