

Calculation of Breakeven Points for EV Superiority Over Gasoline Vehicles

by Ed Innes, MScEE, BScEE, CET

September 10, 2012

(with appreciation to colleagues and peers)

In 1903, the president of the Michigan Savings Bank told Henry Ford's lawyer that the horse was here to stay, and the automobile was only a novelty – a fad. We know how that worked out. Ford sold 1,750 Model A cars that first year. In 2010, Ford sold 4,988,031 vehicles. In 1997, the first year of the Prius, Toyota sold 3,000 units. Critics claimed the car was a failure. The Toyota Prius now stands as the world's third best-selling car model, with 247,230 vehicles sold in the first quarter of 2012, coming behind only the Toyota Corolla (300,800) and Ford Focus (277,000). In 2011, its first year, GM sold 7,671 Volt plug-in cars. Similarly, Nissan sold over 20,000 Leaf electric vehicles (EVs) in its first year. Collectively, first year plug-in sales are ten times that of the Prius. These sales took place during a global economic depression, which has almost caused the financial collapse of lending institutions and countries, and it still threatens to do so. Once again old-fashioned critics with no real background to speak of in these technologies are claiming these new cars to be failures. Consumer Reports gives the Volt a 93% satisfaction score – the highest rating ever for a car. Fear of change is a poor indicator of progress.

EVs are coming. EVs already cost much less to operate and have superior performance. In fact, several automotive journalists have raved about the superior performance of current generation EVs. This is known to EV owners as 'the EV grin'. Race car driver Marco Andretti (grandson of Mario) describes electric drive as the future of racing. Many EVs, but not all, have a higher upfront cost, but battery technology trends point directly toward this cost becoming competitive in the near future. Cost conscious companies such as FedEx and Frito-Lay have already determined that future is right now, and are increasing their fleets because the savings offset any higher purchase cost. This future is not influenced by old-fashioned thinking and baseless criticisms. It is created by sharper minds that can innovate around problems. EVs failed in the 1970s because they still used lead batteries, just as they did when they failed in the early 20th century. Change the battery and the reason for failure goes away. Change the battery sufficiently, and it becomes a clear winner. The winning batteries are not theoretical. They have already been tested and measured. Numerous chemistries under development in the laboratory are even better.

The following is a calculation of factors to determine the various breakeven points for electric vehicles (EVs) compared to gasoline vehicles. Because electric traction motors inherently perform better than internal combustion engines as traction devices (due to a superior torque curve), there are in fact very few parameters within which EVs need to catch up. And as will be shown below, it is not necessary in all cases to completely catch up to produce an effectively equivalent or superior vehicle. The remaining factors with which EVs still lag gasoline vehicles are: 1) battery energy mass density, 2) battery energy volumetric density (which is closely tied to mass density), and most importantly, 3) vehicle cost (which is also closely tied to battery mass density, although it also depends significantly on vehicle design and component optimization). A fourth factor, charge time could be mentioned as a potential issue for some existing EVs, but commercial batteries and chargers already exist that are as fast as gasoline refuelling, faster devices have been demonstrated in the lab (less than 1 minute), and EV owners actually prefer the slower home charging method to using a public fuelling station.

This analysis was requested in order to justify through the application of scientific and engineering means that EVs are or will become competitive or superior to gasoline vehicles. From an intellectual perspective, the implied assumption that gasoline vehicles are superior is not based on any similar analytic approach whatsoever. Instead, the assumption is conjectural and anecdotal in structure, and as such is encumbered with multiple superstitious

attributes. Thus, the onus of proof is asymmetrical, with very little in the way of logic or evidence to justify this bias. One example of this asymmetry is the assumed expectation that an EV must be capable of summertime levels of performance in winter, even though it is commonly known that gasoline vehicles are not capable of this level of performance. Another example is the false concept of lithium shortages, which is a recyclable or renewable material and the 25th most common element in the Earth's crust, while ignoring the very real effects that oil markets are currently experiencing, as demonstrated by seven years of stagnating petroleum production despite near record prices – which is the classic supply-and-demand description of a sustained shortage. Fossil fuels are non-recyclable, far rarer than lithium, and disappear forever after just one use. Batteries are both rechargeable and recyclable. Such a lop-sided illogical debate, based on groundless false theories and untested assumptions is unprofessional. This analysis is an attempt to restore some objective professionalism.

The approach taken below is one of first principles calculations in order to make the process as transparent, and the conclusions as indisputable, as possible. It is possible to produce slightly different results, but by and large these differences amount to quibbling. Different approaches and different what-if assumptions are encouraged. Basic proficiency in the scientific method at the high school level is assumed.

A. Calculating the physical breakeven point for electric cars and conventional gasoline cars:

1) Calculation of the energy density a battery requires in an electric vehicle in order to match the energy density of gasoline in a gasoline vehicle, and produce an electric vehicle that matches (or exceeds) gasoline vehicle weight, size, range, and performance in every physical way:

- gasoline energy density: 12,200Wh/kg
- mass of gasoline on board: 35kg
- gasoline drivetrain efficiency: 20%
- effective gasoline energy delivered to wheels: $12,200\text{Wh/kg} \times 35\text{kg} \times 20\% = \underline{85,400\text{Wh}}$
- effective electric energy delivered to wheels must also be: 85,400Wh
- mass of gasoline drivetrain (fuel tank, engine, transmission, fluids, exhaust, emissions): 315kg
- mass of gasoline & drivetrain: $35\text{kg} + 315\text{kg} = 350\text{kg}$
- mass of battery & drivetrain must also be: 350kg
- mass of electric drivetrain (motor, inverter): 70kg
- mass of battery: $350\text{kg} - 70\text{kg} = 280\text{kg}$
- electric drivetrain efficiency: 90%
- battery energy density: $85,400\text{Wh} / 90\% / 280\text{kg} = 339\text{Wh/kg}$, or about 340Wh/kg
- $385\text{mi} / (340\text{Wh/kg} \times 280\text{kg}) = \underline{4.0\text{mi/kWh}}$, a value that has significant room for improvement as vehicle designs and components become optimized for EVs
- Note as a sanity check that a Nissan Leaf with about 80Wh/kg, has about ¼ the range of a similar size 385mi range gasoline car.
Leaf effective electric energy delivered to wheels: $80\text{Wh/kg} \times 280\text{kg} \times 90\% = \underline{20,160\text{Wh}}$, about ¼ that required

2) In comparison, the energy density of typical batteries in typical electric vehicles in the 1970s was:

- gasoline energy density: 12,200Wh/kg
- these were lead batteries, typically: 30 to 40Wh/kg
- efficiency was also low, about: 20% - 80%, typically 70%

- they were heavy, and at approximately twice the battery mass were: 500kg
- effective electric energy delivered to wheels: $35\text{Wh/kg} \times 500\text{kg} \times 70\% = \underline{12,250\text{Wh}}$, about 1/7 that required (1/14th for the same battery weight) as in (1) above
- This is why these lead battery cars behaved like slow, short range, heavy golf carts.
- It is impossible to make a proper car out of lead batteries; now, then, or in the future.
- They also typically only retain about 55% of capacity at -20°C, 42% at -30°C, and 30% at -40°C, greatly reducing range in winter.
- Lead acid battery cycle life is less than 200, meaning they wear out in only a year or two in an EV, and much sooner in hot climates.
- Note: Some descriptions of Li-ion performance are remarkably naive, and incorrectly similar to lead acid battery performance. The fact that detractors resort to this is indicative of how weak their position is.

3) State-of-the-art of the best energy density battery available today:

- trick question, best commercial battery, about: 600Wh/kg, but it is very expensive and only used in highly specific aerospace applications
- Tesla Model S laptop batteries, 252Wh/kg (3.1Ah cells), a 44% increase over the cells in the Roadster (2007).
- Tesla Model S battery pack about: 170Wh/kg
- as mentioned, most large-cell EV packs are about: 80Wh/kg
- Boston-Power prismatic battery: 207Wh/kg, temp: -40°C to 70°C, 1000+ cycles at 100% DOD; 2000+ cycles at 90% DOD; 3500+ cycles at 75% DOD (in commercial production)
- US Navy has measured Envia battery: 400Wh/kg (will take about 5 years to commercialize, although Envia claims 2 or 3 years)
- lithium sulphur, currently about: 450Wh/kg (will likely not be commercialized until it reaches 550 to 600Wh/kg)
- at the research level: 1,350Wh/kg (but currently has only 100 cycle life and needs further materials development)

4) Timeline for when a physically superior electric vehicle (using a 340Wh/kg battery or better) is likely:

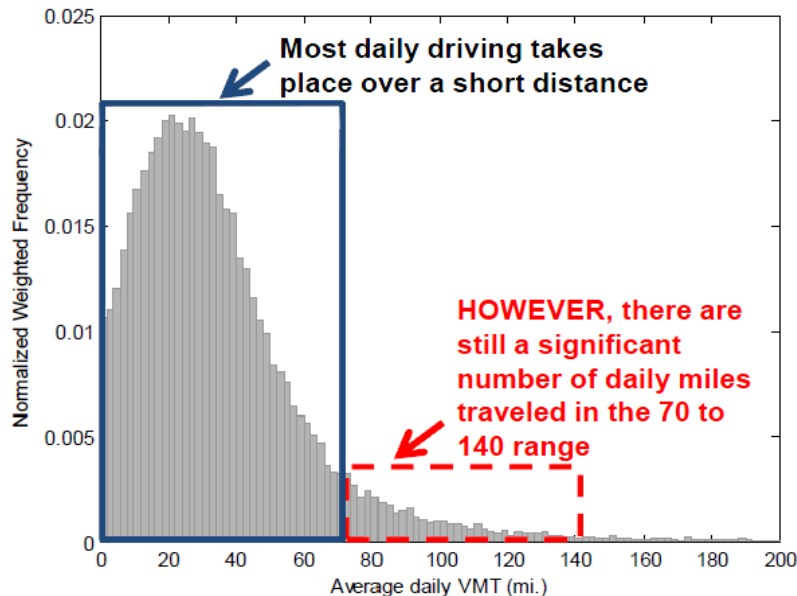
- At a conservative development rate, about 5 years for the battery and about 10 years (another 5 years) for the EV, essentially using one of the many Si-anode or Li-S batteries under development, but such an EV could arrive earlier.

B. Calculating the range required for an EV (or any other vehicle):

- 1) Miles of range a vehicle needs in order to meet daily driving needs for every day except one (364/365), in a year of average driving:
 - for one day in a year: 195 miles
 - for one day in 2 years: 220 miles
 - for one day in 5 years: 250 miles
 - for one day in 10 years: 270 miles

- for one day in 20 years: 295 miles

Distribution of odometer average daily VMT across vehicles



- This will be important in determining the number and type of fast chargers required.
 - These estimates are based on averages derived from US and Canadian driving data. They are generally shorter than what most people falsely imagine their driving requirements to be. Averages include all driving, and do not exclude occasional cross-country trips.
 - The average person drives about 12,000mi/year = 33mi/day. Being an average, this means that for every day a driver exceeds 180mi, they or someone else will compensate by driving 0.4mi/day less the rest of the year.
 - The average driving profile can be modelled by an exponential function, with the average person driving 25 miles per day, 50% of the time.
 - 90% of all daily driving is less than 75mi, thus an EV in a 2-car family can have significantly shorter range and still accomplish the majority of all driving. This is what the EV industry is temporarily providing for early adopters right now.
 - Nissan is reporting that Leaf owners are driving approximately 2mi/day further than with the vehicle it replaced due to the EV becoming their preferred primary vehicle.
- 2) Energy densities of batteries needed to achieve those ranges in an EV that is otherwise equivalent to a gasoline car:
- 1 in 1 year: 195 miles: 170Wh/kg
 - 1 in 2 years: 220 miles: 195Wh/kg
 - 1 in 5 years: 250 miles: 220Wh/kg
 - 1 in 10 years: 270 miles: 240Wh/kg
 - 1 in 20 years: 295 miles: 260Wh/kg

- 90% of all daily driving: 75 miles: 70Wh/kg
- 3) Procedure on the rare occasion when the range is exceeded:
- Charge the battery, preferably at Level II or III.
- 4) Evidence that a 200mi range car is practical for cross-country trips:
- Two UBC students crossed Canada in 14 days in 2010 with a 200mi range homemade VW Beetle electric conversion and became the first EV to cross Canada. There was no support team other than they brought their pet dog along for the ride. They used existing charging infrastructure. Charging infrastructure is an issue in that it is not as available as gasoline in some ways (no visible stations specifically for that purpose) and far more available in others (plugs, including 50A, 240V Level II plugs, are fairly ubiquitous). For example, Californians have been using RV park plugs for cross-state EV treks for years.
 - More charging infrastructure is definitely desirable, but it is not critical. Putting in Level II and III charging is a convenience that will spur increased use, not a limiting factor that might prevent driving.
- 5) When a physically adequate (170Wh/kg to 240Wh/kg) electric vehicle is likely (as opposed to a physically equivalent, 340Wh/kg EV):
- This is more difficult question to determine than gasoline equivalency because it is somewhat subjective.
 - Technologically, it only depends on existing lithium-ion batteries and incremental improvements.
 - For exotic high-end sports cars, such as the Tesla Roadster (250mi range), it was several years ago.
 - For luxury cars, such as the Tesla Model S (160-300mi range), it arrived June 2012.
 - For small cars, it will likely arrive with the higher density lithium chemistries, simply because the tendency of the auto industry is to build small cars as economy models as much as possible.

C. Results of cold weather performance testing:

1) Results of Manitoba Hydro PHEV testing:

- electrical performance degradation at -20°C: not measurable
- electrical performance degradation at -30°C: not measurable
- In comparison, gasoline performance degradation at -20°C: gasoline fuel economy fell by about half
- The vehicle does not have an electric heater, so it is impossible for cabin heating to reduce range.

2) Results of CanmetENERGY testing for the same type of Hymotion PHEVs across Canada:

- Measured electrical consumption per km decrease at -18°C: 25% less electricity compared to +22°C
- Loss in battery capacity at -18°C: 15%
- Net gain in electrical range at -18°C: **12% more range**
- The increase in electrical efficiency due to cold temperature is approximately twice the minimal temporary loss in battery capacity due to cold temperature.

- There is enough increase in range to accommodate electric interior heating.
- **The notion that electric range must go down in winter is proven to be pure myth.**
- A123, the Hymotion battery manufacturer, has since released an extreme temperature version of this battery, with better temperature performance.

3) Results of CAA Manitoba testing of two EVs:

- Winter of 2011-12.
- CAA Manitoba concluded that perception that EVs can't operate at -30°C was wrong.
- A slight increase in charging time was the only issue encountered.

4) Results of Hydro Quebec testing of EVs:

Preliminary results: Boucherville pilot project – May 2012

Observations:

In winter:

- No starting issues
- No performance problems: 80 km range achieved in cold weather (down to - 15°C)
- No charging complications due to cold weather
- In winter, the majority of trips (60 km or less) can be made with just one charge at home.

Other observations:

- User satisfaction rating is 8.9 on a scale of 10.
- Nearly 60% of charging done from user's residence.



5) Is it possible to select a lithium battery that performs poorly in winter?

- Yes, of course. But what would be the point in doing that?

6) Is it possible to select an EV interior electric heater that performs poorly and reduces mileage significantly in winter?

- Yes, of course. But what would be the point in doing that?
- A good design would include a Power Smart approach, such as adding insulation. Nissan is improving efficiency for 2013 by using a heat pump.
- Electric heat is instant, a significant advantage over waiting several minutes for a frozen engine block to warm up.
- Future batteries will make this issue irrelevant anyway.

D. Potentially limiting materials:

1) Lithium Supplies:

- Lithium is the 25th most abundant element in the Earth's crust. The notion that it is running out is ridiculous.
- Lithium is so plentiful that until recently, mines often closed when newer higher grade deposits were found. For example, North American mines closed when the Salars were discovered in South America.
- Recently some North American mines have reopened in anticipation of higher demand for EVs.
- Lithium itself represents a minor cost item in battery manufacture.
- Lithium is recyclable, unlike petroleum. It is not consumed as a fuel. As such, it is not subject to a Peak Oil phenomenon.
- Current lithium battery recycling recovers 98% of the lithium, but is generally uneconomic due to the low cost of mining. Economics depends on other materials used in the batteries.

2) Rare earth elements:

- Not necessary for EV development.
- For example, the Tesla Model S EV does not use any, neither in its motor nor in its battery.
- The current 'shortage' of rare earth elements has more to do with mines previously closing due to lower cost deposits in China than it has to do with an unusual concentration there.

E. Calculating the relative fuel cost of electricity vs gasoline:

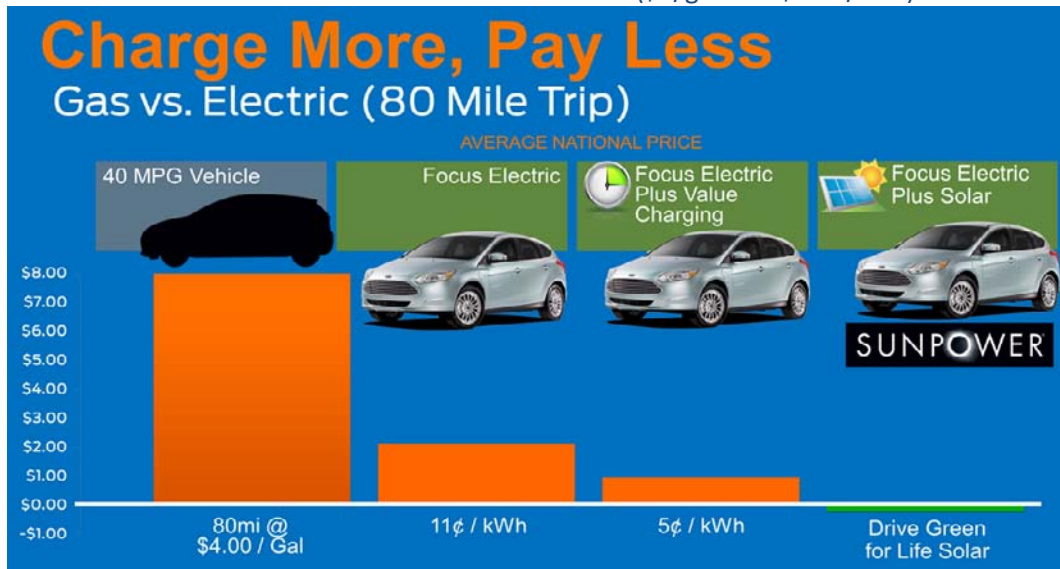
1) Calculating the equivalent gasoline price to 6.9¢/kWh electricity used in an EV:

- $6.9\text{¢/kWh} \times 30\text{mpgUS} / 90\% / 4\text{mi/kWh} / 3.785412\text{ litre/galUS} = \underline{\underline{15\text{¢/litre}}}$
- Manitoba EV Association members have independently determined electricity is one eighth the cost of gasoline for their vehicles.
- CAA Manitoba concluded about 12¢/litre equivalent for their two EVs tested.
- Driving on electricity is like paying 15¢/litre for gasoline.
- This is one eighth the current retail cost of gasoline (121.9¢/litre).
- This is because EVs are about 4 times as energy efficient as gasoline cars, and 121.9¢/litre gasoline is the same as 13.9¢/kWh of chemical energy, about twice the cost of electricity.

2) Calculating the equivalent electricity price to \$1.00/litre gasoline used in a conventional car (also \$1.20/litre, \$1.40/litre):

- $100\text{¢/litre} \times 3.785412\text{ litre/galUS} \times 90\% \times 4\text{mi/kWh} / 30\text{mpgUS} = 45\text{¢/kWh}$
- $120\text{¢/litre} \times 3.785412\text{ litre/galUS} \times 90\% \times 4\text{mi/kWh} / 30\text{mpgUS} = \underline{\underline{55\text{¢/kWh}}}$
- $140\text{¢/litre} \times 3.785412\text{ litre/galUS} \times 90\% \times 4\text{mi/kWh} / 30\text{mpgUS} = 64\text{¢/kWh}$
- Driving on gasoline is like paying 55¢/kWh for electricity.

- Note similar results for Focus EV from Ford in the US (\$4/galUS = \$1.06/litre):



Also note the cheapest option is solar PV, but this includes a subsidy.

- According to Ford, driving on 5¢/kWh electricity is like paying 50¢/galUS for gasoline.
- Also similar results from Hydro Quebec (stated as cost over 8.6 months):

Preliminary results: Boucherville pilot project – May 2012
Project includes: 20 EVs with European specifications and 10 SNA EVs

	Base	Distance (km)	Energy (MWh)	(kWh / EV)	Electricity cost * / EV
Actual – Dec. 2010 / March 2012	30 EVs – 8.6 months	283,221	49	1,633	\$ 125.74

* Based on average electricity price including taxes on April 1st, 2012 for a domestic customer using 1 000 kWh / month (\$ 0.077 / kWh)

Comparison with gas for the same distance

	Consumption per 100 km	Distance (Km per vehicle)	Consumption per vehicle	Cost *
Internal combustion vehicle	8.2 liters (equivalent to 28.6MPG)	9441	774.16 liters	\$ 1,014.15

* Average regular gas price in Montreal for Dec. 2010 to March 2012 \$ 1.31 / liter (equivalent to \$4.95/gallon)

- According to Hydro Quebec, driving on 7.7¢/kWh electricity is like paying 16.2¢/litre for gasoline.
- 3) Calculating the cost of providing a household plug for an EV:
- \$0 in most circumstances, unless a specific case can be made for one.

- From the above discussion of driving patterns, energy consumption, and charging, it should be obvious that an ordinary 120V, 15A household electrical outlet is sufficient for replacing charge used in day to day driving, averaging about 25 miles (about 6 to 7kWh).
- This can easily be replaced while plugged in overnight on half the capacity of an ordinary household 120V circuit, about the same as a block heater load. (A vehicle that is twice as large would require an entire circuit.)
- Obviously, an EV eliminates the need for a block heater, freeing up half of such a circuit.
- Occasional long-range usage can still be adequately served by an ordinary outlet, over more than one night if need be, without interfering with average EV use. The average vehicle spends 23 hours parked out of every day.
- This is consistent with experiences of several early adopters, such as members of the Manitoba EV Association.
- EV manufacturers tend to recommend installing a dedicated charging station out of hand, not because it is necessary, but because they wish to guarantee customer satisfaction under all conceivable scenarios.
- The current installed cost of home charging stations (Level II) is about \$2,000, and while noticeable, it does not substantially alter the economics if one is included. As an EV is used more, such as for longer trips, the fuel savings increase significantly. The majority of the cost is the station itself, which is more complicated than an outlet.
- Electrician rates for installing an ordinary (Level I) dedicated circuit approximately \$100 to \$300. Rates for 20A or 240V outlets are not appreciably different.
- These chargers and circuits are permanent installations that do not need to be replaced when the car eventually is.
- In order to avoid an unnecessary charger station installation, actual driving history should be analyzed for an extreme usage pattern before deciding whether one is actually necessary or not.
- There is a strong human tendency to over-imagine extreme usage patterns.
- Availability of workplace charging, retail store charging, and public charging significantly reduces the potential need for a home charging station, whether or not it is capable of rapid charging (Level III).

4) Calculating the savings for using electricity instead of gasoline for driving 12,000mi (20,000km) per year:

- Annual cost of gasoline for a small (30mpg) car:
- $100\text{¢/litre} \times 3.785412 \text{ litre/galUS} \times 12,000\text{mi} / 30\text{mpgUS} = \$1,510$
- $120\text{¢/litre} \times 3.785412 \text{ litre/galUS} \times 12,000\text{mi} / 30\text{mpgUS} = \underline{\$1,820}$
- $140\text{¢/litre} \times 3.785412 \text{ litre/galUS} \times 12,000\text{mi} / 30\text{mpgUS} = \$2,120$
- Annual cost of electricity for an equivalent size small EV:
- $6.9\text{¢/kWh} \times 12,000\text{mi} / 90\% / 4\text{mi/kWh} = \underline{\$230}$
- Annual cost saving of electricity instead of gasoline for a small (30mpg car):
- $100\text{¢/litre}: \$1,510 - \$230 = \$1,280$
- $120\text{¢/litre}: \$1,820 - \$230 = \underline{\$1,590}$
- $140\text{¢/litre}: \$2,120 - \$230 = \$1,890$
- Note that the savings increase linearly with higher mileage: 18,000mi/year at \$1.20/litre, would save $1.5 \times \$1,590 = \$2,385$

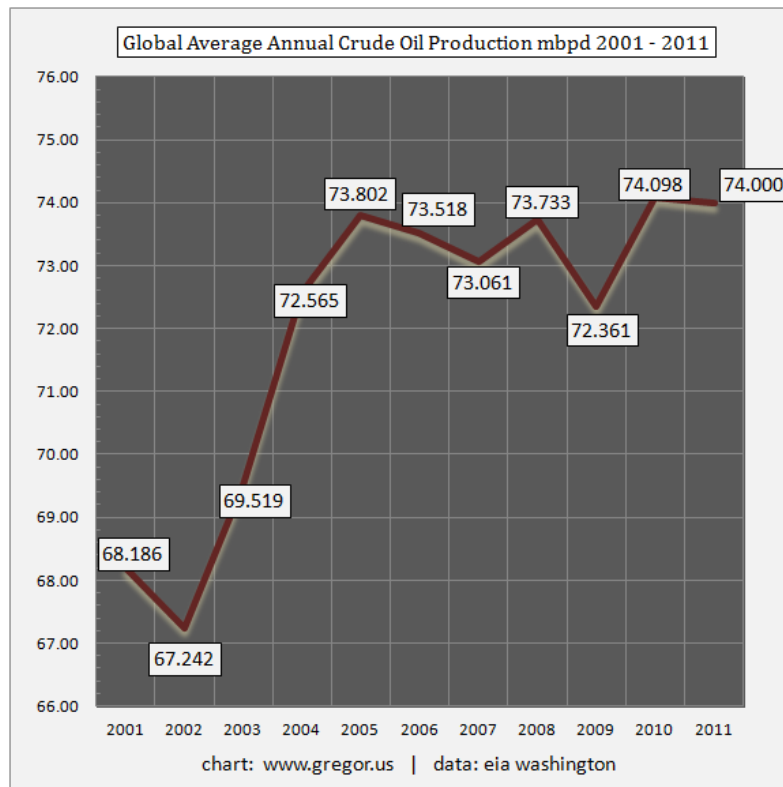
5) Calculating the present value savings over $n = 10$ years at $i = 6\%$ discount (if gasoline does not increase):

- 100¢/litre, $A = \$1,280$: $P(A, n, i) = \$9,420$
- 120¢/litre, $A = \$1,590$: $P(A, n, i) = \underline{\$11,700}$
- 140¢/litre, $A = \$1,890$: $P(A, n, i) = \$13,910$
- (Remember: this is the saving due to driving an EV, total gasoline expenditures are higher: $A = \$230$ in electricity adds $P(A, n, i) = \underline{\$1,700}$ to each of these present values)

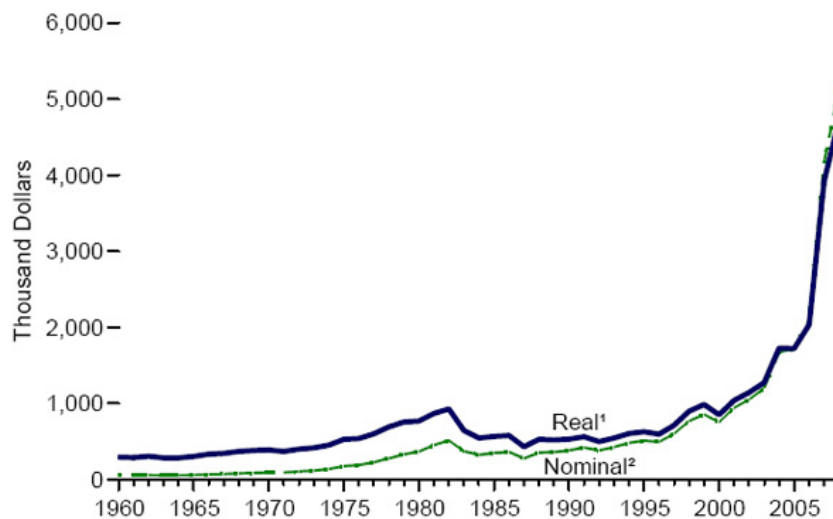
6) The historical rate at which petroleum costs have been rising over the last decade:

- average 17% per annum for Brent (world price).
- average 15% per annum for WTI (landlocked North American interior price, ie in Manitoba).
- WTI has been trading at a 20% discount over the last several years, which is expected to end with various pipeline options that will connect the stranded WTI price to the globally traded Brent price.
- average 14% per annum for gasoline (US commodity price).
- average global oil & gas capex increase for 2012 over 2011 is 13.4%
(<http://www.globaldata.com/PressReleaseDetails.aspx?PRID=333&Type=Industry&Title=Oil%20%26%20Gas>)
- average North American oil & gas capex increase for 2012 over 2011 is 15.7% (higher primarily due to unconventional oil and gas activities, especially shale and tar sands; same ref.)
- Notes on future oil supplies:
 - Global conventional petroleum production has stopped growing and has levelled off at 73 to 74 million bbl per day (bpd) since 2004-2005.
 - The 14 million bpd gap between 74 million bpd of petroleum production and 88 million bpd of consumption is being met with unconventional supplies such as natural gas liquids and tar sands extracts.
 - Oil well drilling costs have increased 15%pa (4-fold) over last decade (USA, source: <http://www.eia.gov/totalenergy/data/annual/pdf/sec4.pdf>).
 - Expenditures per bbl of oil reserve additions (before drilling) have increased 15%pa over last decade.
 - Per bbl cost of production of new 'unconventional' oil is: \$45 to \$65 for pre-salt (extremely deep, >16,000ft) deepwater; \$50 for tight oil (shale oil); \$50 to \$75 for tar sands (bitumen), and over \$100 for both arctic offshore and oil shale (kerogen). These costs are also rising at 15% per annum.
 - Pre-salt oil requires drilling through nearly 2 miles of water and "post-salt" rock and then through over a mile of salt, eg, offshore Brazil.
 - Approximately 4% to 6% of existing global oil supply (produced at \$10 to \$20 per bbl) is being exhausted and replaced by higher priced supplies every year, which are increasingly 'unconventional'.
 - It is highly unlikely that 'speculators' are hiding significant quantities of \$10 to \$20 per bbl oil from a Brent market price currently over \$110 per bbl. This is the time to cash in.
 - As a general rule, newer supplies require more drilling, more energy, more water, and more processing, all of which incur additional cost. They also tend to be shorter lived and lower quality, which reduces return on investment. The industry naturally went after the most economically efficient resources first.

- It is uncertain how long petroleum prices can continue to increase at this rate. Rapid petroleum price increases are historically associated with economic depression, which in turn reduces demand and price, which in turn reduces supply. What is certain is that the cost of new petroleum supply is rapidly becoming more expensive because it is becoming less and less conventional all the time. It is also certain that petroleum will not be produced unless it is at a profit. There is no historical precedent for this evolving situation. Reduced demand in the US and Europe since 2008 is quickly being replaced by China and India, which both appear to be more tolerant of higher petroleum pricing.



Costs per Well, All Wells, 1960-2008



- Notes on Peak Oil:
 - Peak Oil is the point at which petroleum production reaches its all time maximum flow rate.
 - There are numerous examples of Peak Oil occurring in individual oil fields, oil provinces, and oil producing countries. United States production peaked in 1970, and currently is at about half of the peak rate.
 - It is relatively easy to prove mathematically that Peak Oil will eventually occur globally, using introductory calculus. The proof is essentially the definition of an integral.
 - The important question is when global Peak Oil will occur, and this cannot be definitively established until after it occurs. Several estimating techniques exist, but this lengthy topic is beyond the scope of this document. The current plateau is cause for concern, but it is neither proof that it has arrived, nor proof that it has not arrived.
 - **Peak Oil is not necessary for EV adoption**, although it would obviously be a strong incentive.
 - While there is no historical example of global Peak Oil (it only happens once), after the production peaked in the US, and the country lost the control that it once held over world oil markets through the Texas Railroad Commission, this set the stage for the 1973 Arab Oil Embargo. The Embargo, while only curtailing about 5% of supply, caused serious gasoline shortages in the US, despite a 43% gasoline price increase and a federally imposed 55mph speed limit. It led to a run-up in world oil prices from \$3 per bbl to \$12 per bbl within the first year, a 300% annual increase. Despite the Embargo ending, within 8 years, the price had increased by 1,200%, a 38% annual increase. Conditions were desperate enough that lead battery powered cars were reintroduced, even though they were known to be unsuitable. These are the cars EV critics tend to fixate on.

They are no longer relevant.



- The following gasoline escalations conservatively assume Peak Oil does not occur.

7) Calculating the present value savings over $n = 10$ years at $i = 6\%$ discount (if gasoline continues rising at $g = 15\%$ pa):

- PV cost of electricity over $n = 10$ years for an equivalent size small EV (if electricity rises at $g = 3\%$ pa):
- From $6.9\text{¢}/\text{kWh}$, $A' = \$230/\text{y}$ becomes a PV of: $P(A', n, i, g) = \$1,900$
- PV saving of electricity instead of gasoline for a small (30mpg car):
- From $100\text{¢}/\text{litre}$, $A' = \$1,510$: $P(A', n, i, g) - \$1,900 = \$21,100 - \$1,900 = \$19,200$
- From $120\text{¢}/\text{litre}$, $A' = \$1,820$: $P(A', n, i, g) - \$1,900 = \underline{\$25,500} - \$1,900 = \underline{\$23,500}$
- From $140\text{¢}/\text{litre}$, $A' = \$2,120$: $P(A', n, i, g) - \$1,900 = \$29,700 - \$1,900 = \$27,700$

8) If the vehicle is twice as big, say an SUV:

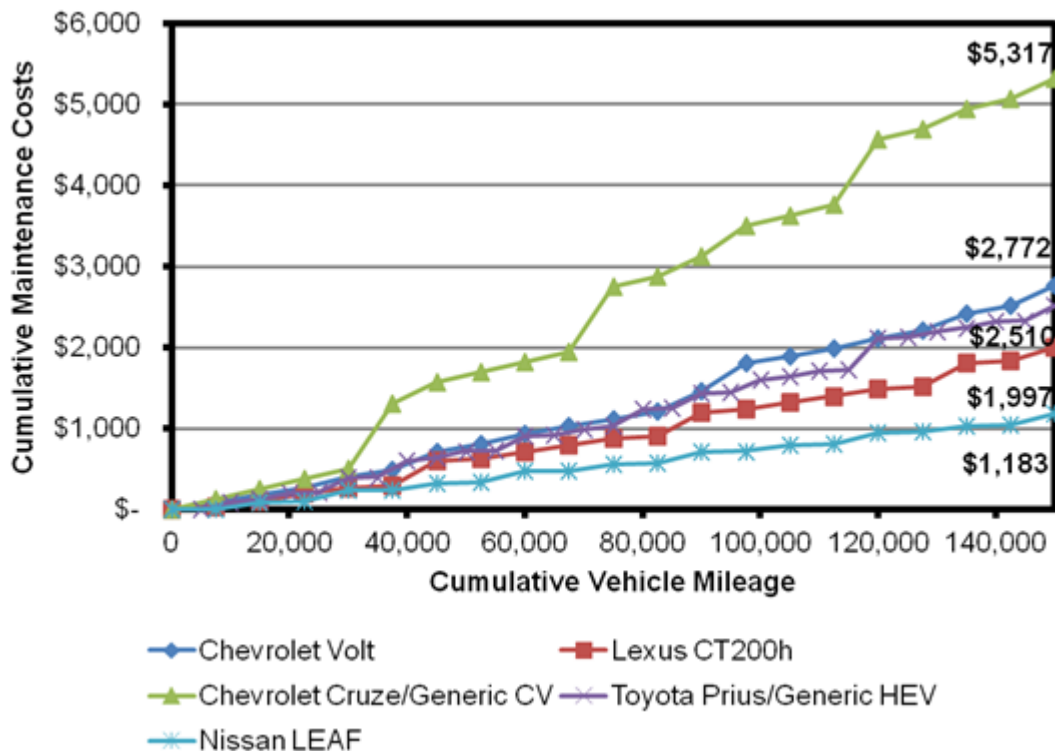
- Then twice the savings occur, because both the gasoline and EV savings are linearly scalable.

F. Calculating the maintenance costs:

1) Maintenance savings for an EV vs an ICEV:

- About \$200 per year (intentionally conservative). There are no tune-ups, oil changes, etc. Brakes are electric, not mechanical.
- From University of Minnesota: about \$253/year

- From EPRI, about \$330/year:



2) Calculating the present value savings over $n = 10$ years at $i = 6\%$ discount:

- $A = \$200/y$; $P(A, n, i) = \underline{\$1,470}$

G. Calculating the total O&M costs:

1) Total EV savings over 10 years at 6% discount, adding fuel and maintenance savings:

- If gasoline stops rising: $\$11,700 + \$1,470 = \$13,170$, or about **\$13,200**.
- If gasoline continues rising: $\$23,500 + \$1,470 = \$24,970$, or about **\$25,000**.

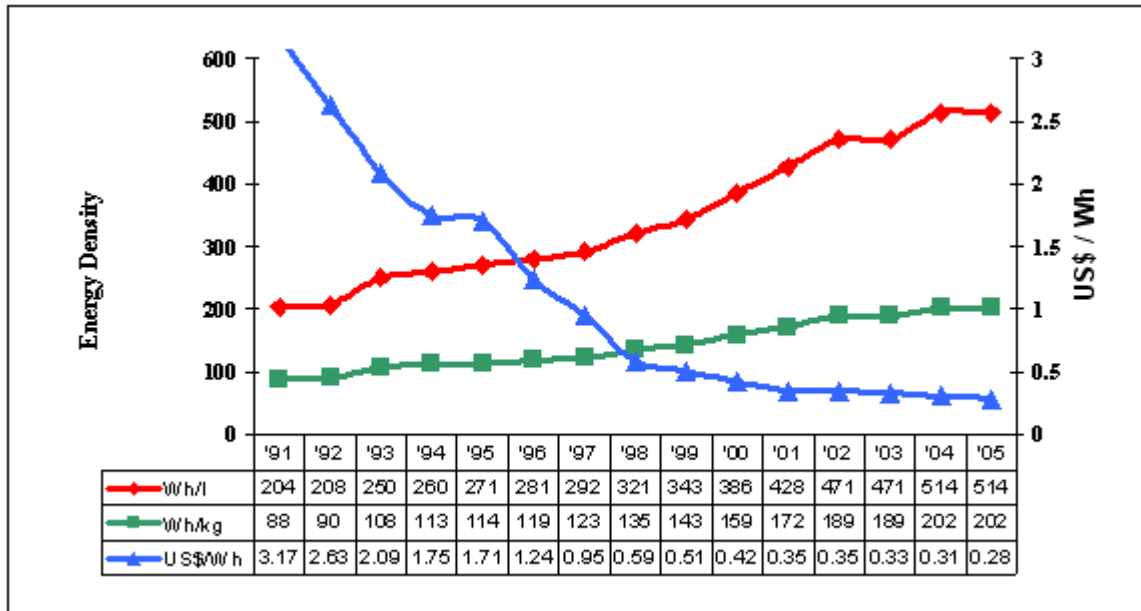
H. Calculating future battery cost reductions:

1) Current costs of EV batteries:

- Tesla Model S: \$300/kWh (Tesla charges \$700/kWh for additional battery size in finished vehicle, source: Tesla)
- Nissan: \$450/kWh (was \$700/kWh when Leaf was designed and US price of vehicle set at \$35,200, source: Nissan)
- Ford: \$520 to \$650/kWh (source: Ford)
- Thundersky: \$375/kWh (used by home mechanics for EV conversions, retail cell price = \$107.50 for 0.36kWh, or \$300/kWh for cells, source: <http://alliancerenewableenergy.com/Thunder-Sky->

2) Historical rate at which lithium battery costs are falling:

- Varies from 8% to 14% per annum for Li-ion:



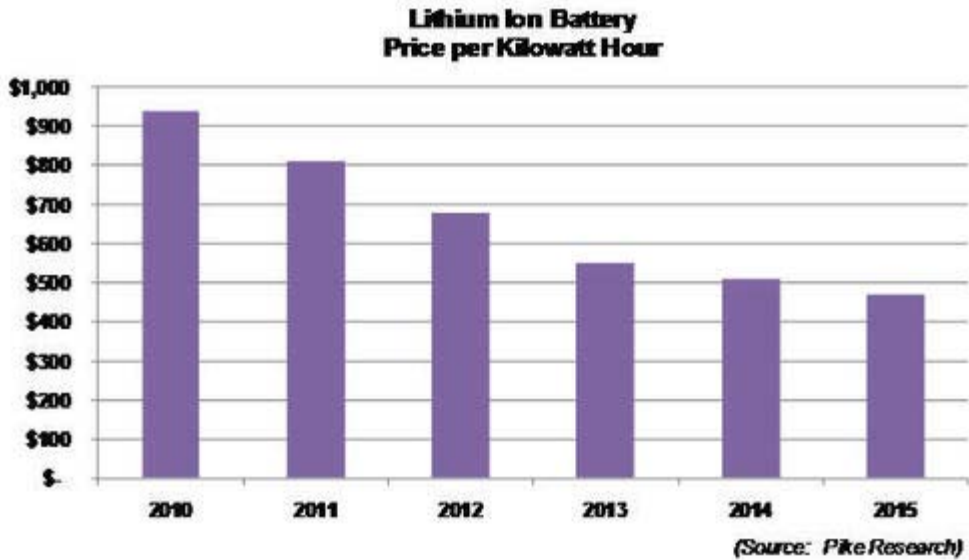
- This is accompanied by a similar increase in energy density.
- From 1999 to 2011, Li-ion 18650 laptop cells fell from \$2,600 to \$240/kWh, or about 18%pa (Tesla uses a higher cost premium cell)

3) Average cost of a typical EV battery for current contracts with a 2015 delivery:

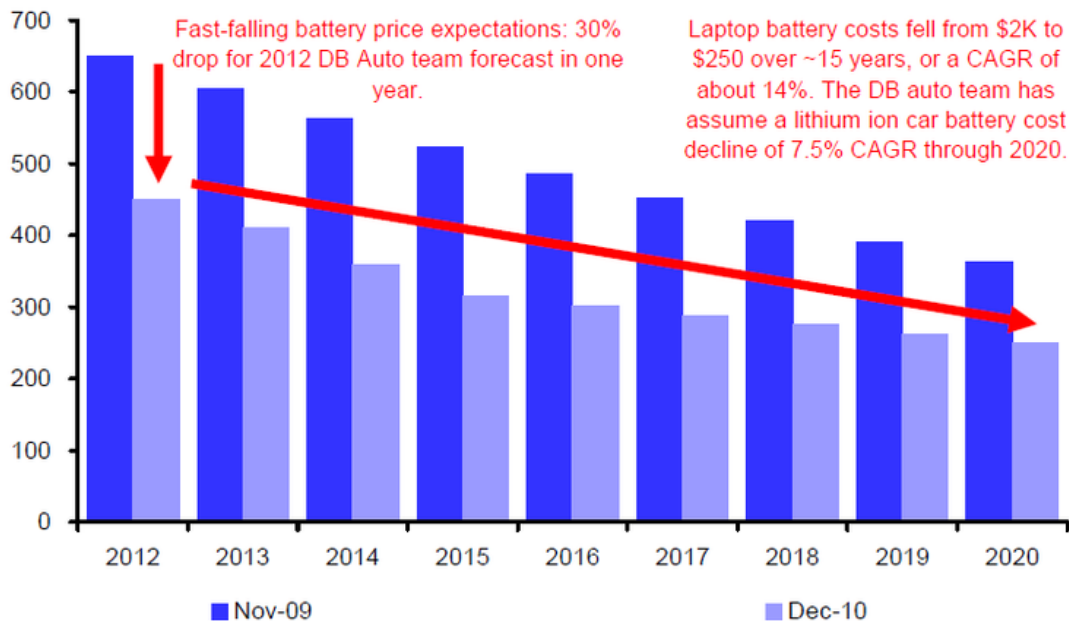
- Will be at about \$250 (€180-€200) per kilowatt hour in Japan and Korea. Raw materials account for 60%; labour, utilities, and depreciation 33% (Munich-based Roland Berger Strategy Consultants). (Tesla uses a laptop format battery and does not use this EV type of battery.)
- This represents an 18%pa decrease for Nissan.
- This represents a 25%pa decrease for Ford.

4) Future battery price projections:

- Pike research was \$200/kWh more pessimistic in Jan 2010, projecting a price for 2015 that became the 2012 price:

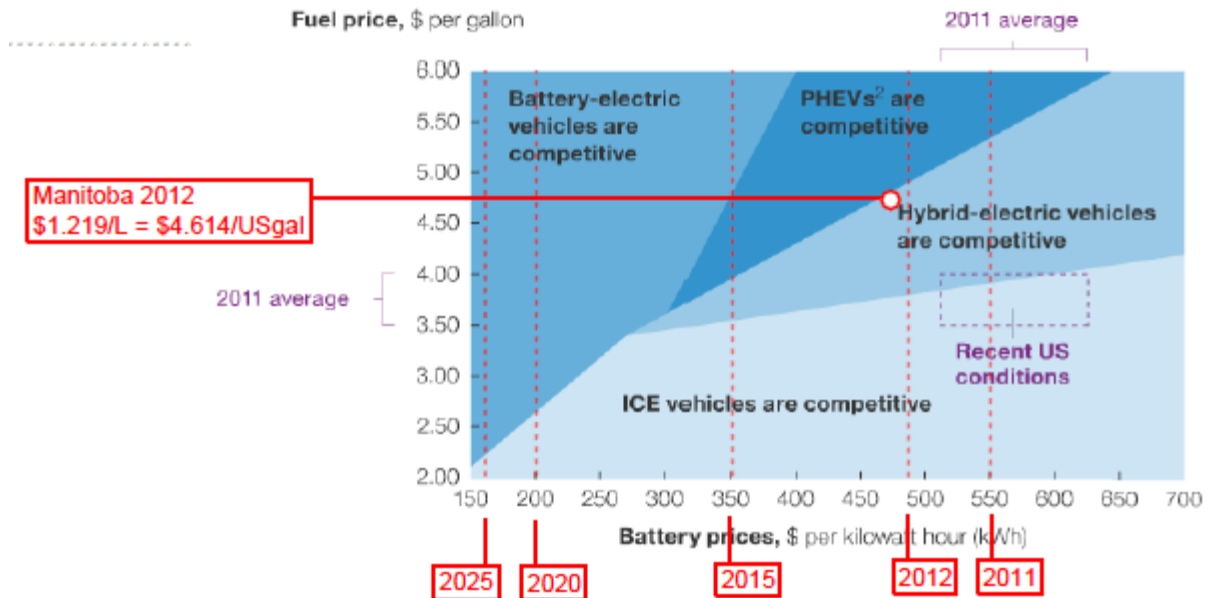


- Deutsche Bank had to lower its similar projections by 30%, 11 months later in Dec 2010, to reflect actual market price:



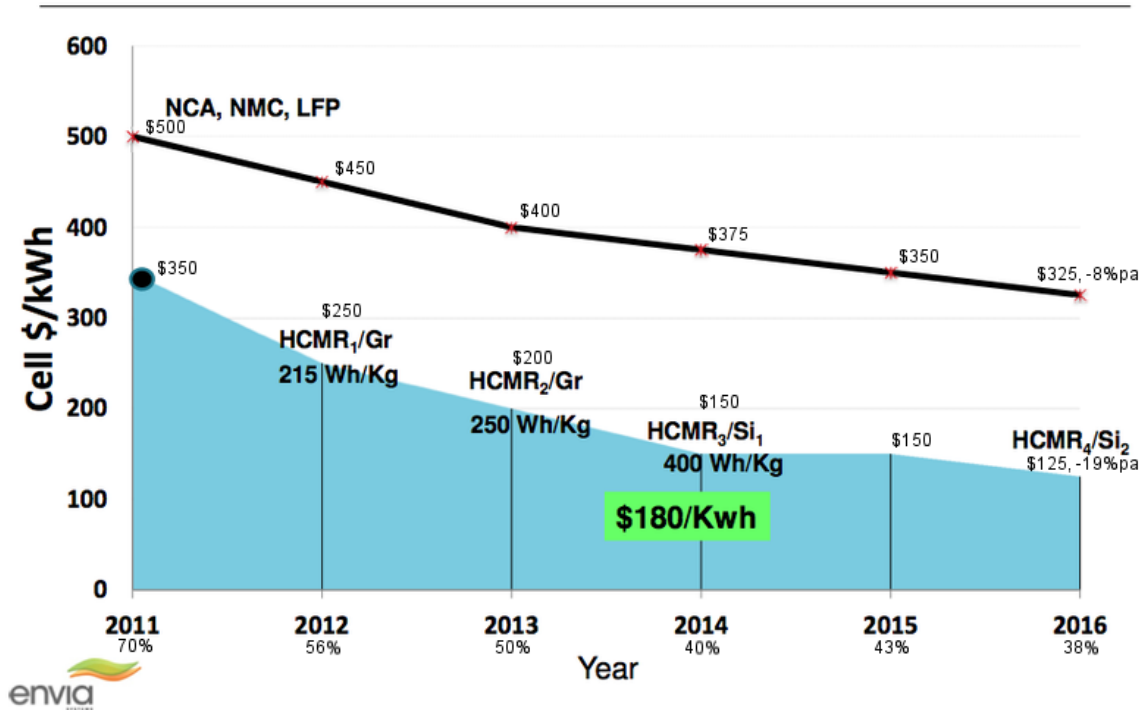
Source: DB Auto team, industry discussions and private interviews, Deutsche Bank

- Note the historical price decline is still expected to continue (https://www.mckinseyquarterly.com/Battery_technology_charges_ahead_2997, July 2012) and make EVs lower cost at almost any gasoline price:



- Envia is projecting its 400Wh/kg battery will lower these cost projections further (Feb 2012), based on materials costs:

Envia vs. industry cost roadmap

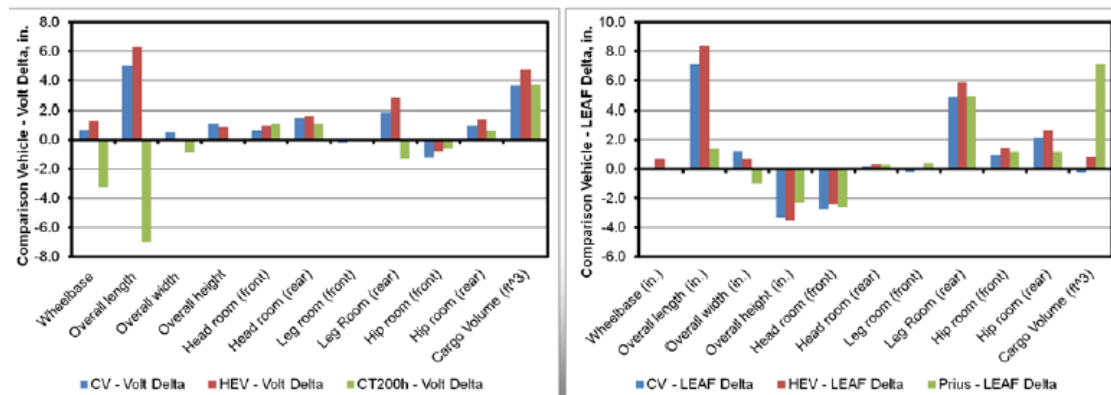


Note: this is a proponent graph. Abbreviations refer to specific chemistries.

- These price declines can continue for several decades as there are several alternative chemistries, such as lithium-sulphur and lithium-air, under development that promise much higher energy densities (as discussed in A3 above).
- 5) Calculation of present day conditions to determine when the cost of an EV battery will enable an EV that is equivalent-to-gasoline:
- First, as the manufacturers all point out; there is no equivalent gasoline model available that is equivalent to an existing PEV. The PEVs are intentionally not marketed as the economy cars they are often mistakenly compared to. Furthermore, there is significant room for improvement that will lower costs as vehicle designs and components become optimized for EVs. A properly designed & optimized EV is not simply a converted gasoline vehicle. Neither is a properly designed & optimized gasoline vehicle simply a converted EV.
 - The budget-oriented Versa is smaller than the Leaf and not at the same trim level.
 - The Cruze is not available in the same trim level as the Volt.
 - The gasoline Focus is not available in the same trim level as the Focus EV. According to Ford, the low-volume \$40,000 Focus EV is equivalent to a high-volume \$25,000 gasoline car.
 - The Tesla Model S has a flat passenger floor with the battery underneath that dramatically improves vehicle weight distribution and handling over gasoline vehicles, allows for a second trunk up front, and it does not allow for a gasoline driveshaft underneath.
 - The first three cars are roughly appointed as if they are \$25,000 gasoline cars of the same size. They are not the same as sub-\$20,000 cars.
 - Their purchase costs at \$35,000 to \$40,000 are roughly \$10,000 to \$15,000 more than this.
 - EPRI illustration of difficulty in choosing an equivalent comparison vehicle:

Picking the Right Comparison Car

- **Selections are based on vehicle size and features, and not the cheapest comparison**
- **Blend of current CVs (\$25,000) and HEVs (\$31,000) on the road now from varying auto manufacturers**



- Cost of 24kWh Leaf or Focus battery: \$11,000 to \$15,000

- Cost of EV minus battery: $\$35,000$ to $\$40,000$ - $\$11,000$ to $\$15,000$ = $\$24,000$ to $\$25,000$
- Thus, if the cost of the battery can be recouped in fuel savings, then the cost of the battery is not an issue, just the capacity of battery that is available at that cost.
- Present value operating savings (at 6% over 10y) are (from F(1) above):
 - If gasoline stops rising: **\$13,200**
 - If gasoline continues rising: **\$25,000**
- Cost of EV that is equivalent to gasoline:
 - If gasoline stops rising: $\$13,200 + \$25,000 = \underline{\$38,200}$, in other words EVs currently already break even over 10 years, but the vehicle range is less.
 - If gasoline continues rising: $\$25,000 + \$25,000 = \underline{\$50,000}$, in other words EVs currently already break even over 7 years, and can afford nearly double the range.
- Thus, if gasoline continues to go up at the current average rate, then batteries can go up substantially in price and still produce a somewhat functionally equivalent EV.

6) Calculation of the difference an Envia battery would make in producing a fully cost-weight-size equivalent-to-gasoline EV:

- Projected Envia battery cost if produced in 2015: $\$150/\text{kWh}$ (based on materials and similar manufacturing equipment, source: Envia)
- battery cost to provide 385mi range: $\$150/\text{kWh} \times 85,400\text{Wh} / 90\% = \underline{\$14,200}$
- **If the Envia battery is ready by 2015**, an equivalent-to-gasoline EV could be sold if the cost of the battery can be recouped in fuel savings:
 - If gasoline stops rising: $\$13,200 - \$14,200 = -\$1,000$, a **\$1,000 premium** (roughly equivalent, a slight compromise is needed).
 - If gasoline continues rising: $\$25,000 - \$14,200 = +\$10,800$, a **\$10,800 saving**.
(Note that further savings will be realized in EVs as production volumes rise, and further component and design optimization occurs.)
- The Envia battery is likely to be ready and fully tested in a vehicle by 2022 ($n = 10$, $P = \$14,200$), so:
 - at $i = 8\%$ pa reduction, by 2022 the battery will cost: $F(P, n, i) = \$7,940$, so $\$25,000 + \$7,940 = \$32,940$ (14% less than PV of gasoline car)
 - at $i = 14\%$ pa reduction, by 2022 the battery will cost: $F(P, n, i) = \$4,950$, so $\$25,000 + \$4,950 = \$29,950$ (22% less than PV of gasoline car)
 - average: $\$31,000$
- In other words, 10 years from now, a fully gasoline-equivalent 385mi EV will cost:
 - if gasoline stops rising:
EV will cost $\$38,200 - \$31,000 = \$7,200$ less than gasoline
 - if gasoline stops rising & then resumes rising in 2022:
EV will cost $\$50,000 - \$31,000 = \$19,000$ less than gasoline
 - if gasoline continues rising through 2022:
EV will cost $\$128,000 - \$31,000 = \$97,000$ less than gasoline
- Note that a continuous 20 year price rise in petroleum at 15% from $\$1.20/\text{litre}$ in 2012, would be $\$4.85$ in 2022 and $\$19.64$ in 2032.

7) Comparison with 3rd party analysis:

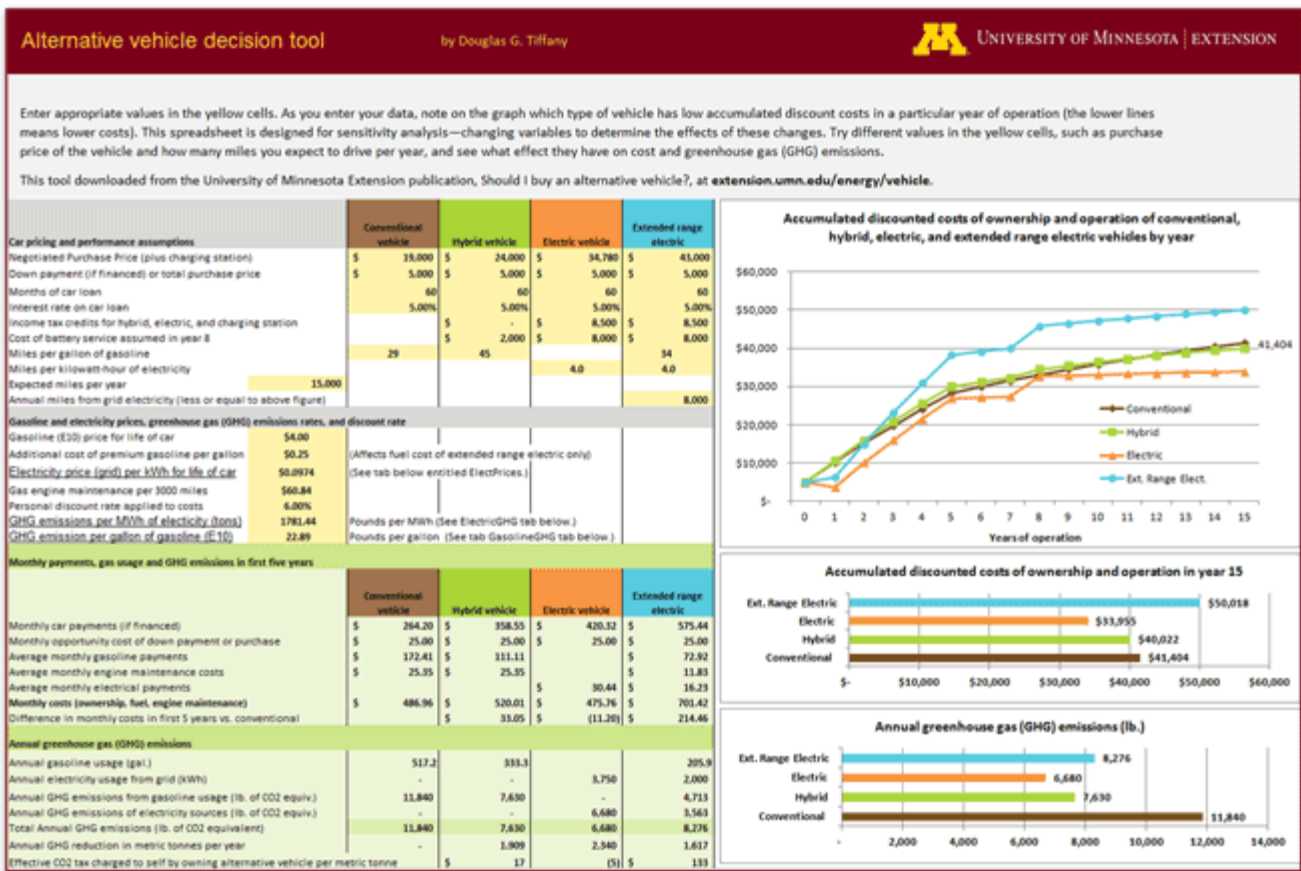
- Deutsche Bank (Dec 2010) at 10¢/kWh, fixed, and US gasoline 50¢ to 75¢ lower than 2012 actual, expected breakeven by 2012:

Figure 24: Consumer economics of pure electrics vs. ICEs as battery prices fall over the next decade

	2010		2012		2015		2020	
	No Subsidy	With Subsidy	No Subsidy	With Subsidy	No Subsidy	With Subsidy	No Subsidy	With Subsidy
Battery Cost \$/kWh	650	650	450	450	315	315	250	250
kWh	25	25	25	25	25	25	25	25
Total Battery Cost	16,250	16,250	11,250	11,250	7,875	7,875	6,250	6,250
Other Incremental Costs	2,000	2,000	2,000	2,000	1,000	1,000	0	0
Government Subsidy	0	(7,500)	0	(7,500)	0	(4,500)	0	(2,000)
Total Incremental Capital Costs	18,250	10,750	13,250	5,750	8,875	4,375	6,250	4,250
Annual Gasoline Cost Savings	1,552	1,552	1,625	1,625	1,591	1,591	1,985	1,985
Annual Electric Costs	375	375	375	375	375	375	375	375
Total Annual Fuel Savings	1,177	1,177	1,250	1,250	1,216	1,216	1,610	1,610
Payback (Years)	15.5x	9.1x	10.6x	4.6x	7.3x	3.6x	3.9x	2.6x
Assumptions								
Average Miles Traveled per Vehicle	15,000	15,000	15,000	15,000	15,000	15,000	15,000	15,000
Gasoline Price	3.00	3.00	3.25	3.25	3.50	3.50	4.50	4.50
ICE Mileage	29	29	30	30	33	33	34	34
Cost of Electricity	0.10	0.10	0.10	0.10	0.10	0.10	0.10	0.10
EV Miles Per kWh	4	4	4	4	4	4	4	4

Source: Deutsche Bank Auto Team, D/B estimates

- University of Minnesota (<http://www1.extension.umn.edu/environment/energy/vehicle/>) spreadsheet tool also shows present-day breakeven:



Includes discount rate. Also includes optimistic and pessimistic factors that cancel each other.

- A locally customized version for Manitoba is available. It is more versatile and includes independent cost escalators for more factors. It also shows a present day breakeven.

I. Example changes that simply substituting newer batteries would make to existing PEVs:

1) What are the specifications for the new 2013 GM Volt?

- Battery good to -30°C (although I have not seen a temperature performance curve yet). Also slightly higher energy density, battery capacity, electrical efficiency, and range. Physical battery size is unaltered. Envia is apparently similar to A123 batteries we tested at Manitoba Hydro, in that it has roughly equivalent winter performance at -30°C to that at room temperature. These batteries do not behave like those in laptops or cell phones. They are chemically and physically different.
- Volt battery:
 - EPA 5-cycle range = 38mi (The US EPA changed its vehicle fuel economy methodology in 2006 from an average of 2 driving cycles, urban & highway, to 5 cycles, adding aggressive driving and summer/winter cycles, lowering most vehicle fuel economies by about 15%)
 - Mass = 198.1kg
 - 16.5kWh / 198.1kg = 83Wh/kg pack density
 - 10.8kWh / 198.1kg = 55Wh/kg usable energy density
 - 10.8 / 16.5 = 65% battery depth of discharge (DOD) is used

- GM states that Volt owners have travelled more than 65 million miles. Roughly 2/3rd was on electricity and 1/3rd was on gasoline. Volt owners find a tank of gasoline lasts 900mi on average.

2) What difference would an Envia battery make in the Volt?

- An Envia battery with 400Wh/kg would provide 400Wh/kg x 198.1kg = 79.2kWh.
- At 65% DOD, 79.2kWh x 38mi / 16.5 kWh = 182mi range.
- Increasing the PHEV DOD to typical EV 80%, increases 182mi by 80 / 65 to 225mi range.
- Increasing the PHEV DOD to Envia spec (100%), increases 182mi by 100 / 65 to 281mi range for an identical PHEV to the Volt.
- This is 81 miles more range than the UBC EV that crossed Canada in 2010 in only 14 days on existing charging infrastructure.
- With this electric range, the gasoline engine (or a midday recharge) would only be required about 0.018% of the time, about 0.06 days per year on average, using US DOT data. In other words, **the engine can simply be removed**, lowering weight, increasing range further (perhaps reducing battery size instead), and lowering cost.
- Regardless of the DOD and range, such a battery would cost (in 2015) about 79.2kWh x \$150/kWh = \$10,880, about \$3,000 more than a 16.5 kWh Volt battery with only 38 miles EPA range, and about \$1,000 less than a 24kWh Leaf battery with 73 miles EPA range. This size Envia battery should reach about **\$4,000 in about another 7 to 13 years** at current (and historical) rates of battery cost decline.

3) What difference would an Envia battery make in the Leaf?

- In a pure EV like the Nissan Leaf, simply substituting this 33% lighter battery in ten years would reduce the current US cost for the Leaf to \$27,000 (no subsidies), yet it would have almost 4 times the EPA range. This conservatively assumes there is still no mass production of the Leaf. At \$1.20/litre gasoline, it would save about \$1,590 in fuel and \$200 in maintenance per year (see above), allowing for a 4 year simple payback versus a gasoline car. But the effect of opening Nissan's 150,000 unit Tennessee plant this year (and others) will introduce further production cost savings and Yen exchange savings. **Thus, based on Volt and Leaf EPA ratings, and US Navy testing of the Envia battery, an equivalent cost (trivial or zero payback period) EV with \$1,790 annual operating savings and practical range, is entirely possible within 10 years.**

4) What would be the effect of adding more Envia battery to the Volt to turn it into an equivalent weight EV (replace gas engine, etc)?

- Going back to 65% DOD, and substituting more Envia battery for the engine, etc, would result in an extra 400Wh/kg x 150kg = 60kWh.
- At 65% DOD, 60kWh x 38mi / 16.5 kWh = 138mi, for a total of 139.2kWh and 321mi range.
- Increasing the EV DOD to typical EV 80%, increases 321mi by 80 / 65 to 395mi range, this exceeds gasoline equivalency, and even the combined range of the Volt itself.
- Increasing the EV DOD to Envia spec (100%), increases 321mi by 100 / 65 to a 494mi range for a same-size EV version of the Volt.
- With this electric range, a gasoline engine (or a midday recharge) would only be required about 0.00003% of the time, about 0.0001 days per year on average.
- (We already knew this extra 60kwh of battery was unnecessary from the first calculations.)

- Regardless of the DOD and range, such a battery would cost about $139.2\text{kWh} \times \$150/\text{kWh} = \$20,880$, and should reach about \$4,000 in about 10 to 20 years at current (and historical) rates of battery cost decline.
- This is 30% more than the combined range of the Volt. With a cycle life of 1000 cycles @100% DOD, it would result in a **494,000mi battery lifespan, about 40 years**.
- **The battery would likely still be available for repurposing in a utility station after this**, let alone at some earlier point when the car chassis wears out.

5) What difference would a lithium–air battery with a capacity of 5,000mAh/g make in the Volt?

- Replacing the 198.1kg Volt battery with this gives:
 - $10\% \times 5,000\text{Ah/kg} \times 2.7\text{V} = 1,350\text{Wh/kg}$
 - $1,350\text{Wh/kg} \times 198.1\text{kg} = 267\text{kWh}$
 - At 65% Volt DOD, $267\text{kWh} \times 38\text{mi} / 16.5\text{kWh} = \textbf{616mi range}$
 - Increasing the PHEV DOD to typical EV 80%, increases 616mi by 80 / 65 to **758mi range**.
- In other words, **the engine can be removed AND the battery can be reduced by half or two thirds** (both of which further increase range).
- This is where batteries are going after Envia. (And they are not stopping there!) Please keep in mind, however, this battery is in much earlier stages of development. Nonetheless, the technology is nowhere near its physical limits.

6) How does the Tesla Model S compare in its market segment?

- Quick cross check with larger luxury vehicles:
 - The new **Tesla S EV** varies between \$57,000 to \$77,000 (no subsidies), has 160mi to 300mi range (respective to price) on a 40kWh to 85kWh battery, 300kW (402hp) motor, 0 to 60 mph in 5.6sec (\$92,000+ Signature series is 4.4sec), top speed 125mph, seats 5 adults plus 2 children (in a third seat), 29cuft rear trunk (58 with seats folded), 8cuft front trunk, 4,647.3lb (2,108.0kg), and costs about \$207 for 12,000mi of electricity per year. Tesla can achieve positive cash flow at 8,000 units.
 - An **Audi A6** starts at \$50,000, 310hp Supercharged 3.0L V6 engine, 0 to 60 mph in 5.3sec, top speed 130mph, seats 5 adults, 14cuft rear trunk, 4,067.5lb(1,845.0kg), and costs about \$2,400 at 23mpg for 12,000mi of gas per year. 2011 sales about 10,000 units.
 - A **BMW 5-series** at \$71,000, 376hp Tri-Turbo 3.0L I6 engine, 0 to 60 mph in 4.7sec, top speed 155mph, seats 5 adults, 14cuft rear trunk, 4,199.8lb (1,905.0kg), and costs about \$1,500 at 37mpg for 12,000mi of diesel per year. 2011 sales about 50,000 units.
- While there are probably better matches, quibbling aside, **at the luxury end, it is not really necessary to wait for a better battery**. Except ... the Tesla S Signature series is sold out for this year.

- Brief comparison of special Signature Performance 85 Tesla S from Motor Trend magazine (Aug 2012):

	Base Price	Weight	Power	0-60 mph	60-0 mph	Lat grip
BMW M5	\$92,095	4384 lb	560 hp	3.7 sec	110 ft	0.94 g
Mercedes-Benz CLS63 AMG	\$96,805	4256 lb	550 hp	3.9 sec	113 ft	0.92 g
Porsche Panamera Turbo S	\$176,275	4388 lb	550 hp	3.5 sec	105 ft	1.00 g
Tesla Model S P85	\$105,400	4766 lb	416 hp	3.9 sec	105 ft	0.92 g

- “The Model S is either dominant -- or at least thoroughly competitive -- in two diametrically opposite automotive worlds. It embarrasses its high-efficiency, electric car peers with one hand, while happily trading steel-knuckle punches with Germany's mightiest warp-speed heavyweights with the other.”
- “And were we to have measured those 0-60 mph times from the first twitch of accelerator movement instead of after the standard 1-foot roll-out, the Model S would be already off and away while the gas cars were still reacting to their suddenly opened throttles. It's a startlingly instant shove into the seatback. Measured by our classical methods, the Model S P85 is now the fastest American sedan, and close to the fastest anywhere.”

400Wh/kg is overkill for an EV, and what would more likely be produced instead, is a lighter weight vehicle than a gasoline vehicle, with equivalent mileage (or perhaps less). There is considerable margin for calculation error at this energy density, while still producing a superior car to gasoline. Further energy density improvements in the battery technology are certain to happen, leaving gasoline technology even further behind.

When EVs are compared to hybrids like the standard Prius, to turbochargers, or to other higher capital cost advanced gasoline technologies, the operating savings are still over \$1,200 per year. The term ‘high efficiency’ as it is commonly applied to advanced internal combustion engine technologies, is a misnomer, referring to only a several percents worth of improvement. Even the best of these is still very poor compared to typical EV efficiency, which is about 4 times that of gasoline engines. Future optimization of EV designs will likely maintain this 4-to-1 ratio, even compared to these higher cost engine improvements. But gasoline engines face twice as high a hurdle than 4-to-1. As calculated above, the cost of gasoline is about 8 times that of electricity as a fuel; so if gasoline engine efficiency is to improve enough to compensate for price, then it must improve enough to create an engine that is almost 200% energy efficient, which is an impossible violation of the Second Law of Thermodynamics.

This future of electric drive was summed up by Bob Lutz (retired Vice Chairman at GM) in the September 7, 2012 Seattle Times: **“Electric-car technology is improving rapidly, while internal-combustion engines are as good as they’re ever going to get.”** Lutz expects that within five years, a new generation of lithium-sulphur batteries should be commercially viable. “Think of a Chevy Volt, instead of 40 miles [per charge], you’re thinking about 200 miles,” he said. “Already, engineers are working on lithium-air batteries that might deliver 400 to 450 miles between charges, if a way can be found to recharge them,” he said. **“You have to start asking yourselves, who needs a gasoline engine anymore?** For that matter, who needs a network of charging stations?”