

A Historic Perspective on the Future Cost of Off-Peak Electricity for EVs

Alistair I. Millerⁱ
Senior Scientific Associate, Office of the Principal Scientist
Atomic Energy of Canada Limited
Chalk River, ON
millera@aecl.ca

Vehicles powered by electricity (EVs) or by a combination of electricity and hydrocarbons (PHEVs) can take advantage of off-peak storage of electricity. This allows cheaper power and avoids increasing peak consumption. While this approach offers less capacity and flexibility for off-peak storage than converting electricity to hydrogen – where storage can encompass many days of average consumption – using off-peak power directly avoids most of the substantial energy losses of interconversion between electricity and hydrogen and so the fuel cost is substantially less.

Two Canadian provinces (Ontario and Alberta) have market-driven wholesale pricing for electricity. Analysis of Ontario data indicates that the appropriate cost to use for off-peak electricity would be around 50-60% of the average if equal amounts of electricity were to be stored daily based on low-cost overnight power. Data for 2005, with an overall average cost of 6.85 ¢/kW.h, are likely most representative of future electricity costs in Ontario and are also consistent with current cost estimates of generation from new nuclear capacity using ACR=1000TM reactors.

Alberta electricity costs have tended to be higher than in Ontario but 2005 had a very similar average (7.04 ¢/kW.h). However, Alberta costs are consistently more variable than Ontario's and the average two-hour daily minimum is only around 33% of the overall average.

If electricity were to provide 90% of the energy output of a typical PHEV, the 2005 wholesale cost of off-peak electricity would translate into approximately 120 \$/a (Alberta) and 140 \$/a (Ontario) for a typical Canadian traveling 20 000-km/a in a light vehicle using electricity for 90% of its propulsion. Electrical grid distribution costs would also have to be added, though one can argue that these should be fairly small since electricity is only being used at times of lowest demand.

Ontario's existing coal-fired generation capacity is used intermittently. In contrast, because of their capital-intensiveness, nuclear plants are best operated continuously. We show that replacing Ontario's existing coal-fired plants with new nuclear plants operated continuously would easily create enough off-peak electricity to supply electricity for over one-third of the Ontario light-vehicle fleet if these were PHEVs or EVs in 2015. Annual CO₂ emissions would be reduced by over 6 million tonnes.

ⁱ millera@aecl.ca

Introduction

Stabilizing atmospheric levels of carbon dioxide (CO₂) is now widely accepted as the major environmental challenges of the 21st Century. To do so will require a worldwide decrease of more than 50% in emissions of CO₂ while at the same time accommodating rapidly increasing energy usage by emerging economies, such as China and India. Conservation and increased energy efficiency can slow the rate of CO₂ increase but cannot alone come anywhere close to stabilizing atmospheric CO₂. For stabilization, changes will be needed in every sector of the global energy economy. Transportation, which presently accounts for between one-quarter and one-third of global energy usage and 30% of the GHG emissions, requires a major shift away from conventional usage of hydrocarbon fuels. Some governments (e.g. California) and industries (e.g. US Oil and Gas¹) are already beginning to call for substantially improved conversion efficiencies (i.e. tighter CAFE standards) for hydrocarbons but this is, at best, an interim measure in the face of the underlying growth in transportation. Three possible non-emitting, long-term strategies are also being championed as alternate energy sources for vehicles: (1) fuels based on biomass; (2) hydrocarbon-based fuel cycles where CO₂ is captured; and (3) propulsion based on non-emitting electrical energy. .

For the first approach, availability of land appears to preclude major reliance on the biomass approach, quite apart from the questionable efficacy of CO₂-emissions avoidance yielded by some routes, such as converting corn starch to ethanol. If efficient conversion technologies are developed, biomass may make a modest contribution to reducing net CO₂ emissions but that is as much as can be expected.

For the second approach, using carbon-based fuels but either recycling or capturing and sequestering the CO₂ produced, no highly promising cycles based on CO₂ capture have yet emerged. Carbon Capture and Sequestration (CCS) technologies for large-scale, stationary sources are being developed but application to the widely dispersed and mobile sources for transportation is at best a distant and uncertain possibility. Further, it is an approach hampered by obvious inefficiencies based on complexity and uncertainty over the ability to capture and sequester the preponderance of the CO₂ generated.

The third approach of routes based on electricity as the primary energy source currently seem to hold the greatest promise. Electricity can be used directly for trains or streetcars and, is indeed, quite common, though less so than formerly as a consequence of cheap oil. Direct use of grid electricity is a useful technology but unlikely ever to make a major contribution to CO₂-abatement because (a) it is expensive to install and so only cost-effective on very heavily traveled routes²; (b) it is unsuited to free-roaming vehicles; and (c) it cannot take advantage of off-peak power.

All of these alternative routes are prone to causing emissions shifting in the form of collateral emissions elsewhere in the chain of energy generation.

The routes that hold real promise for moving significant off-carbon all involve intermediate storage in some chemical form followed by re-conversion to electricity.

Many of them involve only evolution of existing technology and infrastructure and any associated emissions are well understood. The final step of conversion to electricity for the actual drive introduces an element of commonality, which extends also to hybrid drives relying on intermediate electrical storage.

For several decades, batteries and hydrogen have vied to be the preferred replacement for oil-based liquid fuels to power transportation. Hydrogen was usually envisaged as being re-converted to electricity by a fuel cell, really also acting as an atypical battery. Both routes have made substantial progress and it appears likely that they will be complements rather than competitors. Vehicles utilizing fuel cells for primary propulsion will surely be hybrids, reliant on battery technology to handle peaks of demand and to recover braking energy.

Apart from issues with fuel cell performance of efficiency, longevity and cost, hydrogen must overcome two large obstacles: (1) losses in conversion and (2) low density of energy storage. Batteries are clearly superior in conversion efficiency but their density of energy storage is again low and, unlike hydrogen in gaseous form, weight is a significant factor. (Even though the weight of hydrogen containers is significantly greater than of the stored hydrogen, the whole storage system is likely to be lighter than battery storage.)

Developments of both technological approaches are somewhat cloaked by secrecy for commercial and marketing advantage, but it is obvious that neither has yet overcome all of the major obstacles. Ballard – a leading developer of fuel cells – appears optimistic that it will meet its targets of cost, lifetime, and cold-start for light vehicles – by about 2010. GM has announced a similar deployment timeframe. On the other hand, recent statements from Toyota³ indicate that launch of their next generation of hybrid vehicles has been delayed by problems over the safety of lithium-ion batteries, which had been expected to provide the next major advance in hybrid and battery-electric powertrains. Nonetheless, such setbacks are to be expected with any new technology and the difficulties are likely to be surmounted.

Regardless of advances in the technologies, advanced batteries seem unsuited to emerge as totally dominant technologies within transportation: storage batteries will not provide the primary fuel for either ships or aircraft or probably for the heavy-duty end of land-based transportation (trains and heavy trucks). However, improvements in batteries will likely lead to lighter hybrid vehicles that rely on grid electricity, either substantially as with deeply pluggable hybrid-electric vehicles (PHEVs) or completely for electric vehicles (EVs). The better batteries become, the larger will be the proportion of energy that can be supplied by stored electricity.

AECL has previously examined the free-market patterns of electricity prices that operate in Ontario and Alberta for plausible patterns of pricing for hydrogen based on off-peak pricing. In this paper, we examine this same price information in the context of battery storage of off-peak electricity.

Hydrogen and fuel cells versus EVs

Molinski has compared the overall efficiencies of using electricity to drive vehicles with and without the intermediate step of conversion to hydrogen⁴. He calculates an overall efficiency for propulsion using EVs of 77% of the input electricity and of only 22% using hydrogen and fuel cellsⁱⁱ. If EVs can be competitive in other respects, there is clearly a huge attraction of superior energy efficiency. We note, however, that hydrogen storage can be more flexible than storing electricity in vehicle batteries. Cavern storage of hydrogen – akin to storage of natural gas and subject to the availability of suitable underground salt strata – is a low-cost bulk option able to smooth electricity usage over weeks and even seasons. On-vehicle battery storage is likely limited to approximately a daily cycle and so with an order of magnitude less storage capacity but it would be utilizing a storage medium that already existed. This paper attempts to understand the latter type of storage, based on price fluctuations within any day.

Options for Electricity Production to Supply EVs

In locations such as Manitoba and Quebec that are rich in large rivers or with untapped hydroelectric resources, it is possible to contemplate generation of electricity with low greenhouse-gas emissions. But, intrinsically, large-scale hydraulic stations operate as required and they do not produce surplus, off-peak power of discounted value. It is in jurisdictions with limited hydraulic resources that off-peak pricing naturally emerges, as data for both Ontario and Alberta show. This paper considers exploitation of off-peak pricing, focusing particularly on Ontario.

Typically, Ontario's electricity demand is first met by nuclear stations (providing 54% of total generated power in 2005) and run-of-the-river hydraulic stations (notably the Niagara River output of the Sir Adam Beck stations). The variable part of the demand is met by coal-fired plants, by dammed hydraulic capacity, and finally by natural-gas fired turbines.

Table 1 summarizes the capacity and generation capacity for Ontario in a typical current year, 2005⁵. The nuclear plants can provide no additional

Table 1: Ontario Generation Data for 2005

	Capacity installed (% of total)	Calc. installed cap. (MW)	Power generated (% of total)	Calc. average (MW)	Utilization average for 2005
Hydro	25.8	7740	22.3	3996	52%
Gas	16.5	4950	6.4	1147	23%
Nuclear	36.1	10830	54.1	9694	90%
Coal	21.4	6420	16	2867	45%
Misc.	0.2	60	1.2	215	
Total	100	30000		17919	

ⁱⁱ Molinski's figure is calculated using 35% efficiency for fuel cell conversion of hydrogen. This seems low since fuel cell efficiencies are usually assigned at least 50% conversion efficiency, which would give an overall percentage of 33%.

electricity since they are already operating at 90% of nominal capacity. Hydraulic power can also be presumed to be fully utilized and largely limited by total water availability. Hence, if electricity for EVs were to be produced from existing generating capacity, it would have to come from the coal-fired or gas-fired units.

Molinski contrasts the overall efficiency of a broad range of vehicle energy cycles. For hybrid vehicles, he assumes quite an ambitious efficiency of 30% of the input energy delivered as propulsive energy. For an electric vehicle using natural gas to generate the electricity, he attributes 55% efficiency to the electricity-generation step and 42% overall efficiency. So generating electricity for an EV fleet from the unused gas-fired capacity would offer so small a reduction in CO₂ emissions (less than 30%) as to be of dubious worth compared to an ICE hybrid with 30% conversion efficiency. It would also be consuming a hydrocarbon resource whose availability is dwindling (in North America at least) and whose relative value is likely to rise as it becomes more tightly linked to that of oil.

Utilizing unused coal-fired capacity would be much worse. Applying 35% efficiency to the energy-generation step – typical of Ontario’s existing coal-fired power stations – the overall figure for energy conversion to propulsive energy falls to 27%. Given that coal combustion typically produces 1.4 times as much CO₂ as burning gasoline per unit of input energy, producing fuel for EVs using this route would be counterproductive. It would appear all of the possibilities for utilizing idle capacity of existing generating units are either impractical or unattractive.

An Obvious Innovation: Utilizing New Nuclear Capacity for EVs or PHEVs

Ontario’s main political parties are both committed to phasing out coal-fired generation and to deployment of new nuclear capacity. It is the potential in this combination of political commitments that is the focus of analysis in this paper.

As we have already shown, powering EVs with electricity from existing coal-fired plants is not an acceptable option, since it would lead to an increase in CO₂ emissions. But replacing the existing 6420 MW of coal-fired generation capacity with nuclear plants would create a new problem: what to do with electricity that would now be generated during the previously idle periods of the decommissioned coal-fired plants. Costs for electricity generated by burning fossil fuels are substantially dependent on the cost of fuel and they are operated to meet the variable part of a system’s electricity demand – which is consistent with the data in Table 1. With nuclear plants, however, the fuel cost of is negligible and the cost of the initial capital dominates. So utilities always try to operate nuclear plants continuously to minimize the unit cost of electricity. Additionally, nuclear plants can only adjust their output to load-follow somewhat slowly.

The *obvious solution* would be to apply the other 48% of nuclear output currently to fueling EVs or PHEVs.

An Economic Analysis of Using Nuclear Electricity to Fuel PHEVs

Table 2 gives an overview of electricity price variation in Ontario and Alberta between 2004 and 2006. To translate these costs into costs for electricity to operate a light vehicle, we have used the Canadian average⁶ of 20 000 km/a per vehicleⁱⁱⁱ, 55% city driving at 16.8 kW.h/100 km and 45% highway driving at 21.1 kW/h/100 km^{iv} and assumed that a typical PHEV will derive 90% of its fuel in the form of electricity. This leads to an annual consumption by each vehicle averaging 3370 kW.h. The cost of that electricity is given in the rightmost half of Table 2 assuming, variously, the daily average cost and the averages for the cheapest hour, the cheapest two contiguous hours, and the cheapest three contiguous hours.

For comparison, the annual fuel cost for 90% of 20 000 km at \$0.668/L (before taxes)⁷ for a 25% efficient ICE achieving 6 L/100 km vehicle would be 720 \$/a. So Table 2 shows that electricity is very cost competitive. Even without using off-peak power, EVs would produce substantial savings in fuel costs – which is unsurprising given the high efficiency of the EV option compared to that of ICEs.

As Table 2 shows, the price paid for electricity in each of these two Canadian provinces is very variable from year to year. The benefit of off-peak fueling appears to be greater in Alberta than in Ontario. However, recent Alberta prices probably reflect rapid growth in energy demand in that Province and may not persist^v. Consequently, we have focused

Table 2: Prices for electricity bought by Ontario and Alberta grids

IESO averages	Lowest in each 24 hours			Annual cost \$		
	2004	2005	2006	2004	2005	2006
Ontario						
3-h	30.57	39.04	28.58	108	138	101
2-h	28.99	37.16	27.13	103	132	96
1-h	27.30	35.24	25.07	97	125	89
Average	49.95	68.49	46.38	177	242	164
AESO averages						
Alberta						
3-h	22.99	26.23	29.18	81	93	103
2-h	18.91	22.72	26.56	67	80	94
1-h	14.56	18.44	23.28	52	65	82
Average	54.59	70.36	80.79	193	249	286

ⁱⁱⁱ Molinski based his calculations of fuel usage on 15 000 miles per vehicle annually. This is too high and a figure of about 19 000 km/a (11 800 mile/a) is close to both the US and Canadian averages.

^{iv} Unlike ICEs, EVs achieve better mileage at low speeds in cities than at high speeds on highways. The figures used here are from Molinski.

^v The differences between the two provinces are unsurprising since their generating mixes are so different, with Alberta largely dependent on coal-fired generation and Ontario on nuclear and hydraulic.

on Ontario and, as a matter of judgment, on the figures for 2005, since we consider these most likely to reflect the cost pattern in ten years time when PHEVs (and/or EVs) could be becoming a significant presence. The average 2005 selling price for electricity in Ontario also matches AECL's projected costs of electricity from new nuclear reactors.

One should add a disclaimer to the cost figures in Table 2: they do not include distribution charges. So they underestimate the cost of electricity delivered to the vehicles. One can argue that this mark-up *ought* to be low since it is for a switchable load – which could displace spinning reserve capacity – and is delivered at a time of low demand but the positions of the generating and distributing utilities would need to reflect this perspective.

Examining the hourly data, the average demand in Ontario in 2005 between midnight and 3 a.m. was 15 089 MW and for the remaining 21 hours was 19 301 MW, indicating a potential for battery charging of 4212 MW or 12 636 MW.h. If one extends the charging window – not unrealistically – as from midnight to 6 a.m. – the gap in demand shrinks only slightly to an average of 4172 MW (15 093 MW and 19 265 MW) for a potential charging of 25 032 MW.h.

Using the value per PHEV of 3370 kW.h/a, previously derived, or 9.2 kW.h/d, charging over the three-hour overnight window would fuel 1.37 million PHEVs or 2.72 million PHEVs over the six-hour overnight window. The Ontario light-vehicle fleet is projected to be between 7 and 8 million in 2015⁸ so one-third of that fleet could be fueled as PHEVs or EVs.

The difference between the existing 6420 MW of coal-fired plants operating at 45% capacity and the same capacity of new nuclear plants at 90% capacity is 68 000 MW.h/d so the postulated application to PHEVs and EVs would absorb about 37% of the total surplus of generation. We tend toward viewing the apparent surplus beyond PHEV and EV application as either a cushion or an opportunity for other new, off-CO₂ applications rather than as a problem. Hydrogen production for heavy-duty transport applications is one possibility. Alternatively, if battery development fails to support PHEVs or EVs, the hydrogen-fuel cell route would require about 2.3 times as much electrical energy.

Conclusions

Replacement of Ontario's coal-fired generation capacity by new nuclear plants is more than capable of providing electrical fuel for at least one-third of Ontario's light-vehicle fleet using overnight, off-peak generating capacity. This application could absorb over one-third of the additional power that would be generated by nuclear reactors operating continuously.

Since the full lifecycle of nuclear power produces minimal CO₂ emissions, the proposed displacement of CO₂ emissions by EVs or PHEVs in Ontario (relative to hybrid vehicles using gasoline and ICEs) would exceed 6 million tonnes per annum of CO₂ emissions

avoided. And it could be accomplished with much lower fuel costs for vehicle operators and without the need for government-mandated subsidies or emission credits.

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