The Introduction of Plug-In Hybrid Electric Vehicles and the Evolution of the Electrical Network Towards the Hydrogen Economy

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Abstract

A successful approach to the twin problems of peak oil and the need to reduce emissions of carbon dioxide to the atmosphere from the fossil fuels should also include a way of dealing with vehicles, particularly as their numbers increase rapidly in large developing countries such as Brazil, China and India. The Plug-In Hybrid Vehicle (PHEV) is an important option because over 90% of the energy needs of the transportation sector come from oil, because something approaching 70% of the oil used in a developed country is consumed for transportation purposes, because world oil consumption accounted for 41.3% of the world carbon dioxide emissions from the fossil fuels in 2006, and because it has been found that some 78% of the commuters in the U.S.A. drive 64.5 km. (40 miles) or less to work. This paper examines the impact of a major option of this kind on the electrical network, on the means of generating the necessary extra power needed, and on the smooth linkage to a future hydrogen economy.

The main conclusions of this paper are that the deployment of up to one million PHEVs (or even more) can be supported by the electrical network now with only minor modifications needed in most parts of Canada, and that this approach depends critically upon the success of the current efforts to improve the lithium-ion battery system. It is also clear that a continuing and stable electrical network remains essential since distributed generation (generation in the home, etc.) will not supply the needed extra energy, particularly at night when most of the vehicles will be recharged. It is also likely two quite different coal-using processes will be needed for the further expansion of this option in the future to keep the network in balance - one based upon combustion and the other gasification – with both equipped for the capture and sequestering of carbon dioxide. It is difficult to envision the PHEV option becoming the main path to the future for cars without the expansion of nuclear generation, particularly in Ontario. It is also shown that the widespread adoption of PHEVs leads to a seamless path to the ultimate hydrogen economy.

Introduction

The Plug-In Hybrid Vehicle (PHEV) is a technological response to both the need to cope with the approaching peak in the world production of conventional oil within the next decade or so and the need to reduce emissions of carbon dioxide from the fossil fuels to combat global climate change. The reasons for the present interest in this option may be summarized as arising from the following four statistical facts:

- Over 90% of the energy requirements of the transportation sector are derived from oil;

- Developed economies tend to devote something approaching 70% of their total requirement for oil to the transportation sector;

- World oil consumption accounted for 41.3% of the emissions of carbon dioxide from the fossil fuels in 2006; and

- Most cars are used much of the time for short trips, and this effect is typically quoted in terms such as 78% of the commuters in the U.S.A. drive 64.5 KM (40 miles) or less to work.

The successful development of a superior battery is required to make this and its cousin option – the all-electric vehicle - possible. At the present time, it appears likely the lithium hydride battery systems now under intense investigation will become available within the next few years with sufficient storage capacity, the ability to tolerate an acceptable number of charging and discharging cycles, good safety, and reasonable cost to permit the PHEV option to deploy widely. Success is by no means certain since there are many hurdles still to be overcome in the manufacturing process. There are, however, other battery systems that could find a role in cars of the PHEV type, as might the development of superior capacitors used either alone or in conjunction with batteries. The first PHEVs are now appearing as third party conversions of production models of hybrid cars. The Toyoto Company has announced that a production version based upon its well known *Prius* model will be tested in street service in Japan in the coming year. Equipped with the more limited Nickel/Metal Hydride batteries, the all-electric range is announced as 13 kilometres (8 miles). General Motors Corporation has announced its Chevrolet 'Volt' model (all-electric drive design with on board motor-generator back-up) will become available for testing in 2008 with serial production scheduled for late 2010. Its all-electric range is announced as 64.5 km (40 miles) based upon a new type of lithium-ion hydride battery. Other auto manufacturers are in various stages of the development of plug-in vehicles.

The PHEV option is also supported by some other factors. Cars of this class might be sold the same way as personal computers where a certain basic minimum memory capacity is provided that may be augmented as required by users. For those with only a short commute, the basic battery provided might be all that is necessary, while those who must travel further on their daily activities could opt for additional costly (and heavier) storage capacity. The battery system itself may be leased rather than sold to reduce the first cost of the vehicle, and to provide the purchaser with some additional protection in case of premature failure of this the most vulnerable part of the vehicle.

There is also in effect an automatic subsidy for this option in the early stages of its widespread deployment since the electrical supply does not attract road tax at present. This tax substantially increases the price of gasoline at the pump; this discriminatory tax situation could well continue for some years as a matter of policy.

Other attractive features include the ability to modify PHEVs to return power to houses and other small loads for emergency use during failures of the network. Such a capability would have been very useful in the ice storm that severely affected Eastern Canada a few years ago. (There is a trial underway at the Google Company in California in which a PHEV car will be controlled through a WI-FI connection to the Web to not only drop the charging load instantly as required but signal the vehicle to begin supplying energy to the grid at times of peak demand.) Under Canadian winter conditions with no garage, electrical energy supplied to recharge the battery could also serve to preheat the vehicle prior to service. PHEV vehicles can also be easily and reversibly set to control maximum speed and distance within specified limits and so be attractive to parents of teenage drivers.

This paper examines the effect on the electrical network of a major PHEV option. It is assumed that only simple instantaneous load-dropping by such means as traditional carrier signals will be adopted as have already been employed to remotely disconnect hot water heaters and other larger energy users in houses at peak times. An important finding in the nearer term is that such a major new demand will overwhelm the concurrent growth of distributed generation and so make the preservation of the integrity of the power grid more important than ever. Another finding for the longer term is that the widespread adoption of this class of vehicle can be an important step towards a wider hydrogen option.

Concurrently with the deployment of large numbers of PHEVs, there are reasons to believe a larger share of the energy requirements for space conditioning will also fall on the electrical network. This is primarily due to the expected increase of natural gas prices which will lead in turn to much better insulated structures. At some point, the reduction in total energy requirement falls to the extent that individual householders and the like become more indifferent to the higher heating cost of electricity. The greater convenience and ease of control in both heating and cooling modes, including the adoption of heat exchange-based ventilation devices, and a lower first cost may well, in many cases, more than off-set the greater unit cost of the electricity. A very well insulated house, favourably situated to benefit from passive solar gains, may still be cheaper to heat with natural gas but this extra cost may be so small that the consumer will pay more for the greater convenience of electricity. From a policy point of view, there are also savings in obviating the need for a natural gas distribution network in new housing developments. The emergency aspect must also be considered in that if there is a failure in natural gas supply for any reason, people will inevitably turn on their small electric heaters and stoves to keep warm. The possibility of two major new markets expanding the demand for electricity in the near future concurrently – to meet the needs of a growing fleet of PHEVs and an additional fraction of space conditioning needs – makes it all the more important to examine the conditions required to both supply and maintain the stability of the electrical network with these new loads.

The Characteristics of the Canadian Electrical Supply System

The development of the electrical network in itself has been recognized by electrical engineers as one of the great technical developments of history. The network will be considered here as the linkage between the main generation located at the core of the electrical system to the many consumers located at the periphery. The centralized generation at the core may consist of hydroelectric and nuclear installations working full time in base load mode, fossil fuel units operating both in base load and shoulder load modes, and combined-cycle natural gas-based turbines operating to meet both shoulder and peak-loads. The growing component of wind generation at the core depends upon the speed of the wind and its timing. Aside from the core generation, over time, there will be increasing small scale output located at the periphery of the network derived from micro wind turbines and solar panels, from small natural gas-driven engines (either small reciprocating engines or micro gas turbines) and high temperature fuel cells which supply both power and heating/cooling service to houses and other small establishments. The effective deployment of such distributed generation depends upon the ability of the network to absorb and re-distribute power provided from such sources at certain times and load conditions. The network must also retain the ability to supply energy back to homes and other such local sources when this distributed generation is insufficient. Large-scale co-generation, usually based upon natural gas, though important, is not considered here because its adoption depends upon site-specific matching conditions for heat and power needs in oil refineries, hospitals, processing industries, large commercial establishments, and the like. In the case of Alberta, such co-generation in the oil sands context may reach very high levels as the rapid expansion of this industry continues.

According to the *Canadian Energy Overview* published by the National Energy Board in 2007, the nation's total installed capacity was 123 gigawatts (GW) at the end of 2006, an increase of only 54 MW from 2005. The corresponding generation in 2006 was 353 TWH, a minor decline from the 358 TWH supplied in 2005. The capacity to generate power from the wind more than doubled in 2006 to reach 1,460 MW at year-end. It is interesting that Alberta had established a 900 MW limit for wind generation in that Province, as compared to the present capacity of 384 MW, because of concerns related to reliability problems associated with managing expanded wind generation on its integrated power system but this limit has now been rescinded.

There are striking differences in the way electricity is generated in various regions of the country. Overall, hydropower, thermal, and nuclear facilities accounted for some 60, 24, and 16 percent respectively of total Canadian generation in 2006. But this break down gives a misleading indication of the regional situation obtaining in any one province. British Columbia and Quebec rely heavily on hydropower; Alberta, Saskatchewan, and parts of the Atlantic Provinces rely to varying extents on the fossil fuels; and Ontario is supplied from a mix of hydropower, nuclear reactors and generation from coal though this latter source is being phased-out over time as a matter of policy. Another distinguishing feature of the Canadian electrical system is the tendency for close integration with the very large electrical systems to the south in the U.S.A. as opposed to linkages across the county although these are being strengthened.

Other relevant developments include the deployment of *Smart Meters* in some provinces to allow consumers to shift their consumption of energy to less costly periods of the day. These metering devices will eventually provide the means for returning distributed generation from small home sources – mini wind turbines and solar panels, etc. - to the network for credit against overall power consumption in an effective way.

For the early stages of the deployment of PHEVs, regardless of the generation mix in any one province, there appears to be sufficient off-peak capacity at present to support a large number of such vehicles – as many as one million or even more - although the extra energy required would have to come from somewhere. At margin outside of B.C. and Quebec, the new requirement would tend to come increasingly from fossil fuel sources given that the hydro and nuclear capacity is generally operated continuously in base load mode.

The Supply of Electricity for PHEVs in the Early Stages of Their Deployment

The early stage of deployment will be considered here as the period before there are one million vehicles capable of connection to the network. A conservative household power recharge rate of 1 KW per vehicle will be assumed for the network as it now stands. A re-charging period of ten hours would seem possible for many of these vehicles overnight. With a million vehicles, the maximum total connected load would then be of the order of 1 GW and the off-peak energy consumption would then be increased by 10 GWH each night or 3650 GWH on the year. This amounts to about one per cent of the generation in 2006. Thus such a new load would seem manageable given a local distribution of PHEVs approximately proportional to the population in the regions of Canada. It is also possible some recharging could be done during the more expensive shoulder period during the day for a period of about four hours in total without impinging on the peak itself. Cold cities such as Edmonton already make provision for plug-in vehicles equipped with traditional block heaters although the power requirement for these devices is usually less than 1 KW per car.

To transfer 10 KWH to the battery overnight is to supply the car with the energy equivalent contained in about one litre of gasoline on a First Law basis. This energy is in the form of electricity that may be fed directly to the motor in contrast to gasoline which must be converted through a heat cycle to obtain mechanical work. Even after compensating for the losses associated with changing voltage, AC/DC conversion, and the charging and discharging of the battery, it will be equivalent on a Second Law basis to at least two litres of gasoline. Under this assumption, the 10 KWH charged overnight should allow the car to be driven at least twice the distance in electrical mode as this energy equivalent in the form of gasoline supplied to the usual heat engine cycle. For most PHEVs under development at present, this suggests a typical maximum driving distance of between 15 and 30 kilometres under all-electric operation. Greater distances will require more battery capacity and faster charging procedures which in turn will require upgrades to the electrical supply for most houses. Nevertheless, there is an option for a major PHEV option before this major investment becomes necessary.

The Effect of a Major PHEV Option on the Distributed Generation Option

Simply stated, the main problem is that the timing of the need for recharging the batteries in the vehicles does not match the prospects for distributed local electrical generation in houses, etc. very well. With micro wind turbines, the generation depends upon the state of the wind. In the case of solar panels, without expensive storage facilities for generation during the day, the contribution at night will be negligible. Even in the case of mini co-generation based on natural gas-fired engines of one kind or another, or even high-temperature fuel cells, the peak heating requirement for houses is rarely at night. This fundamental mismatch means the electrical network will be increasingly needed to play a balancing role with greatly expanded distributed generation. In short, the network will be needed more than ever with many PHEVs in service.

The Effect of a Major PHEV Option on Core Generation Requirements

The extra load on the electrical network arising from the first million or so of PHEVs to enter service causes the existing installed central generation facilities to be operated for longer periods. The higher rate of utilization is generally attractive to utilities because increased revenue may be obtained from essentially the same capital investment. There is additional operating risk because there will be less down time to conduct basic maintenance activities. It is generally more difficult to expand the base load components of the total installed capacity (due mainly to the higher unit capital cost for hydro and nuclear facilities) than the shoulder and peak load generation facilities. Consequently, another result of an increased off-peak load is to bring these latter facilities into service for a disproportionately longer time. This means that outside B.C. and Quebec, more of this extra load will be generated from the fossil fuels. The result is the reduction of carbon dioxide emissions from the PHEV option may not be as great as when the extra energy can be supplied from essentially the same average overall mix of generation. The expansion of the wind and some other variable renewable generation options complicates the situation greatly. It would be ideal if the wind blew hard at night, but unfortunately, in many cases, the wind speed tends to moderate in those hours.

A major PHEV option with its increasing night time load will lead to a need for generation facilities of moderate capital cost but with low emissions of carbon dioxide. The expansion of hydro and nuclear generation is expected to lag the new demand once the deployment of these vehicles has started in a serious way. It would also be helpful, at least in the early stage, if this new capacity could be added quickly in manageably small yet efficient increments until the full extent of the need was clearly understood.

The emerging oxy-coal combustion option may prove attractive for this purpose. Coal is combusted in oxygen with the flame temperature reduced to manageable levels by re-cycling part of the cooled product flue gas. The advantage of this process is that the flue gas produced has only two major constituents – carbon dioxide and steam - from which the carbon dioxide may be readily separated for subsequent sequestering. The main disadvantage of this approach is that expensive oxygen is required for the combustion stage. It seems possible a process of this kind would meet the moderate capital cost requirement for smaller-sized units that could be added to the generation mix within a reasonable period of time. If there were to be an application for the captured carbon dioxide, as may be the case in Alberta and Saskatchewan for the enhanced recovery of oil (and possibly to facilitate the extraction of methane gas from coal seams in the future), the economics of this combustion option are much improved. Unfortunately, this market is rarely profitable enough to make the new combustion systems self-supporting under current conditions unless encouraged by financial measures implemented to combat carbon dioxide emissions. Despite the added complications arising from flue gas recirculation and carbon dioxide capture, the time to dispatch electrical energy from such installations should be no greater than from conventional air-blown powdered coal installations. The oxygen plant might be equipped with enough storage capacity to permit most of its production at off peak times to aid load levelling.

The Relationship Between a Major PHEV Option and the Hydrogen Economy

At a later time, given success, the growing PHEV option might well coincide with the early stages of the deployment hydrogen energy economy. At present, the conventional reforming of natural gas is the cheapest source of hydrogen except for certain special cases such as the limited supply available now from some oil refineries and the hydrogen that could be separated from the coke oven gas (about 50% hydrogen by volume) produced in the steel industry as it has in the past. It is ironic that one of the cheapest potential sources of hydrogen in Ontario (though limited in quantity) is already produced from coal but in the longer-term, large quantities could be produced from this fuel in dedicated processes. It is also possible that municipal solid waste could be processed by thermal means such as by using the plasma heating techniques now in pilot operations in Ottawa and Montreal to produce a fuel gas from which hydrogen may be separated. The higher prices for natural gas expected in the future would be an impetus to the supply of hydrogen from these more unconventional sources.

Only small changes are necessary to the conventional natural gas reforming process to capture about two-thirds of the carbon entering with the natural gas as the dioxide. Aside from the flue gas resulting from the underfiring, there are two gases produced in the process – hydrogen and carbon dioxide – and these are presently separated as a routine step in the many industrial-scale units in operation around the world. Only relatively minor modifications are needed to capture this fraction of the carbon dioxide for sequestering. A steam of hydrogen may thus be produced from natural gas with substantially less carbon dioxide released to the atmosphere. The hydrogen may be used to power gas turbines that could be operated in the usual combined-cycle configuration. This class of process has been proposed in Norway, Scotland, and the U.S.A. in conjunction with the provision of carbon dioxide to enhanced oil recovery operations. Doubts about the operation of large gas turbines consuming hydrogen as the fuel have evidently been largely resolved. There is no reason why the dispatch times with turbines fired with hydrogen should be any different from their conventional cousins fired with natural gas. Information filed with the National Energy Board from agreements with pipeline companies indicates this time is of the order of five minutes.

The hydrogen produced in this way could also be used to power vehicles equipped with either engines or fuel cells. Much depends upon the development of a successful way of bringing this hydrogen to market as well as improved means to carry the hydrogen on vehicles such as in tanks filled with the new carbon nano materials to serve as carriers of this gas.

The next stage in the gradual evolution to a hydrogen energy economy would be the installation of coal-based units for hydrogen production. The usual approach is to gasify the coal with oxygen in such a way that little methane or other higher compounds of carbon and hydrogen appear in the product gas such as by using entrained-flow partial combustion systems. The fuel gas produced will then consist essentially of some mixture of carbon monoxide, carbon dioxide, hydrogen and water vapour. After removal of sulphur and other minor impurities, the carbon monoxide is 'shifted' with additional steam in multi-stages reactors such that this gas is converted to mainly hydrogen and carbon dioxide. After separation, the carbon dioxide is then sequestered. As is the case of the conventional reforming of natural gas equipped for carbon dioxide capture, the hydrogen may be used either directly in fuel cell or compatible engine-equipped vehicles, or to generate electricity in gas turbines.

Thus it is quite possible two quite different coal processes will be used in conjunction with each other – a combustion technology and a gasification process – because one may meet shoulder electrical loads and the other peak requirements by the diversion of its steady hydrogen production to turbines as needed. In the particular process routes chosen here, both share the need for oxygen although there are other options. Unfortunately, with the current state of the development of these two quite different technologies, it is not entirely clear that the same type of coal will be an optimal feed for both. Since both capture carbon dioxide, they may share the pipeline facilities used for its delivery to the sequestering site.

An important role for nuclear energy seems inevitable to supply the additional energy required for a major plug-in vehicle option. But whatever variant of nuclear technology is used, due to its characteristically high capital cost and relatively inflexible operational requirements, there will always be the issue as to how to keep the electrical network in balance. This issue becomes more important as the unit capacity of individual reactors increases over the years. Before a large reactor enters service, the other options, especially those based upon coal, will be heavily used, only to be followed by a period of the reverse as additional increments of base load nuclear generation come on line. There are promising advances in the storage of electricity, especially in the electrochemical field (such as the new sodium/sulphur cells) that may ease this situation.

The Electrolysis Link to the Hydrogen Economy

When hydrogen is produced by the electrolysis of water, further links are possible in an electrical system already meeting the additional electrical load arising from increasing numbers of PHEVs entering service. The electrolysis approach helps overcome one of the major difficulties in supplying hydrogen to markets because the process lends itself to small-scale decentralized production without great loss in efficiency. The distribution losses in the electrical network moving energy to these local units are likely to be comparable to those arising from other methods of transporting this gas when it is produced in centralized production facilities. Small electrolysis units may be located close to users in local garages or even in individual houses. Minature compressors are now available for use in home garages if high-pressure gas is required by the on-board vehicle storage system employed. Unfortunately, with small local electrolysis units, it is unlikely the oxygen co-product can find an economic use.

Production of Hydrogen in Centralized Electrolysis Facilities

The main advantages of large centralized electrolysis processes is that the oxygen co-product may be captured for other uses. The larger quantities of hydrogen produced in such installations may be supplied to applications in industry such as chemical processes and the reduction of iron oxide in the steel industry. (One hydrogen-based process for the reduction of iron ore has operated in the past at a small but production scale; some Canadian iron ores lend themselves to the high degree of enrichment required for the best use of the reduced product in electric furnace steelmaking processes.)

The most obvious use for the oxygen co-product is in the coal-based combustion and gasification processes. In the gasification case, the coal-based unit may also be producing hydrogen off peak which would augment the total supply to justify larger pipelines or other more efficient distribution systems.

It is possible to envisage a remarkable combination of facilities at locations such as sites on the Great Lakes. Nuclear facilities need water and large fenced and patrolled areas for safety and security reasons. Coal combustion and gasification facilities require lake access for the efficient delivery of coal as well as for water. Large electrolysis units could be located close to the coal facilities to consume the oxygen co-product and share the supply system for water.

There are good reasons to consider such complexes in an Ontario context. The product is both power and hydrogen that together are needed by many industries. But another major reason is for the control of the electrical network. In such an energy complex, at peak times, the electrolysis unit may be shut down instantly (re-starting is slower) as required. The hydrogen from the coal gasification facility may be diverted to the generating turbines at dispatch times of the order of five minutes. The PHEVs plugged in virtually everywhere across the electrical system at peak times may also be ‘shed’ essentially instantaneously by modern electronic means. The interplay among these options makes it possible to operate the network much closer to its maximum installed capacity.

The one major snag for application in Ontario is that so few carbon dioxide storage sites have been identified so far. There are, however, depleted natural gas reservoirs in the southwestern region of the province that might be used. The advantage of such energy complexes for meeting the energy needs of Ontario is that this class of solution can be approached incrementally applying the various technologies as they are perfected. It only requires foresight to fit them together in the best possible way.

Conclusion

This paper was prepared during a period of unprecedented activity across the full range of the field of energy technology. Advances are occurring almost daily. There can be little doubt there will be unexpected and unpredictable developments in many fields that will materially affect the future. Nevertheless, it is possible to draw conclusions that are valid in Canada now and will be for perhaps for as long as a few more decades:

- A major Plug-In Hybrid Electric Vehicle (PHEV) option (up to one million vehicles) can be supported by the existing electrical network with the need for only minor (if any) modifications in most parts of Canada;

- The near-term option depends critically for its success on the development of the lithium-ion battery system, and a better monitoring system is required to adequately follow advances in this field;

- Despite the growth in distributed generation to be expected over the next decades particularly in the home, the electrical network will remain essential not least because PHEV vehicles should preferably be re-charged at night;

- The integration of the growing large-scale centralized wind generation option will also require the balancing action of the grid;

- Two quite different coal processes will be needed in the medium term: combustion techniques to meet mid-range loads and gasification processes to produce hydrogen much of the time for other uses including the powering of fuel cell-equipped vehicles, and generate power at peak times. The importance of the latter technique is that the generation of electricity from hydrogen in gas turbines may serve to meet peak needs in place of natural gas-fired turbines with the same short characteristic dispatch times if and when the price of gas increases. Both classes of process should be equipped for carbon capture and sequestration. Both may consume oxygen derived from shared air separation facilities;

- It is difficult to imagine the continuing deployment of a major PHEV option without the continued expansion of nuclear energy in Ontario and perhaps in some other provinces, and;

-The advent of a major PHEV option, taken together with the evolution of the electrical network to support it, leads naturally step-by-step to an important hydrogen option for the future.

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