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Our electric automotive future: CO_2 savings through a disruptive technology

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Abstract

The transition from oil to electricity for personal transportation is underway with virtually every automaker now seeking to produce an electrical automobile, of some form, under its brand. The pace of this transition, however, is dependent upon both technical and institutional changes. Electricity has the opportunity to play both a disruptive role in transportation and a transformational role in renewable energy, to the benefit of moderating climate change. In transportation, electricity can be both a cleaner and cheaper fuel than petroleum. Moreover, automobile batteries can play a pivotal role in enhancing the use of renewable energies in our daily lives. Development of the full potential of this transformation awaits the formulation of an innovative and clever business plan or value package that integrates the automobile industry with a changing electricity sector.
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1. Introduction

The future for personal vehicle transportation is transitioning from oil to electricity (AllianceBernstein, 2006; Economist, 2008, 2006; Romm & Fox-Penner, 2007; IBM, 2008; Sperling & Gordon, 2008). The major uncertainty in this is the pace of the transition. After numerous false starts, dating back over a century ago (Hoyer, 2008) to as recent as a decade ago (Paine, 2006), events and technological progress have merged sufficiently to provide assurance that a transition to electrical cars is underway. The move to full electrical vehicles may progress in stages from hybrid electric vehicles (HEVs), to plug-in hybrid electric vehicles (PHEVs), and finally to full electric vehicles (EVs), but the transition now appears inevitable. The consequences of this transition for climate change will be positive, but exactly how positive will depend not only on electrical car penetration but how vehicles are integrated with renewable energies also being developed at this time.

For the most part, society is now thinking of electricity only as a superior substitute for fuel in our existing automobiles. This linear substitution model or paradigm, however, is shortsighted. Electricity for transportation is more likely to be a *disruptive* technology, allowing for new ways of structuring transportation, land use, and domestic energy use. As a disruptive technology it is likely to overturn existing institutions and bring about new ways of providing services we have come to depend on. Thought on how this will play out over time, and in the context of the United States, is provided in subsequent sections of this article.

In short, we can expect transformative changes. The familiar automobile and energy providers are in an unprecedented period of turmoil and transition. The U.S. automobile industry is unlikely to survive in its current form due to higher oil prices, global financial meltdowns, and a surplus in vehicle production capacity. Energy companies

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will need to transition to a low-carbon future, presenting both risks and opportunities. The electric or hybrid electric automobile can be the catalyst for designing a more sustainable energy and automotive future. It will require, however, new and compelling business cases that are still in their infancy.

2. The transition

Virtually all automakers are now committed to producing vehicles that have a major electrical system as central components of these vehicles. The makeup of these vehicles and their projected role in the companies' future plans, however, vary enormously, as no fewer than 75 models have been projected to be road-ready by 2013 (Tollefson, 2008).

HEVs have been the first electric vehicles to make their presence felt. HEVs come in many forms, but at their most basic, simply mean a vehicle that uses two or more distinct power sources (usually an internal combustion engine with an electric motor) to propel the vehicle. Led by the success of the Japanese, and particularly by Toyota with its icon, Prius, American consumers now have between 20 and 25 hybrid-engine models from which to choose, and there are many more in the planning stages (HybridCarBlog.com, 2008). Toyota has announced that hybrid-engine systems will be available on all the models it produces by 2020. While other automakers have not been so explicit, a recent industry report claimed that all vehicles will run on hybrid power by 2020 (IBM, 2008). Thanks largely to the success of the Prius, sales of hybrids have been growing briskly, but as of 2007 still constituted only 1.2% of all autos sold in the United States.

The most reluctant automakers to join the HEV bandwagon have been the Europeans who have claimed that advanced diesel vehicles constitute a superior alternative to HEVs. Even these automakers, however, have belatedly joined the HEV movement. HEVs are attractive to consumers because they extend the fuel efficiency of automobiles and light-duty trucks. Using larger battery packs and taking advantage of regenerative braking, electricity assists the internal combustion engine in its basic task of propulsion. How much assistance depends on the size and scale of the electrical system. In some cases, electricity is only being asked to add one or two miles per gallon (''mild'' hybrids), and in other cases (''full'' hybrids) its impact on fuel economy will be more substantial. Obviously, the more electricity is asked to do, the more costly it is to provide the necessary electrical infrastructure. In no cases to date, however, are HEVs capable of providing more than one or two miles of propulsion on the electrical system alone. In most cases, therefore, the efficiency gains achieved through HEVs are modest and are commensurate with the kinds of fuel efficiency improvements one gets with the use of diesel-fueled vehicles, or simply through improvements in internal combustion engines (ICEs) alone.

What is driving the further electrification of automobiles, of course, is the advancing development of batteries. While these advances have not been as dramatic and game-changing as advances in computer chips, they are bringing about the conditions necessary for a transition from oil to electricity. While improvements are still being made in lead-acid and nickel-metal-hydride batteries (the nickel-metal-hydride battery packs in most of today's HEVs have performed admirably), most observers feel that the battery of the future will be lithium-ion batteries (Santini, 2006; EPRI, 2008; Muller & Stone, 2008). These are the batteries that have made mobile phones and other small, electronic devices possible. Scaling up to automobile size batteries is not simple, and potential combustion concerns have led to a go-slow, methodical, approach to commercialization. Still, lithium, combined with various other materials, at nanometer scales, appears to be the key to producing the best battery with respect to weight, power density, energy, longevity and cost. Competition to produce the most effective batteries is fierce, with at least 50 companies vying to become major battery producers to the automotive industry (Evanoff, 2006).

Improving batteries and cost profiles will bring the next big step in the electrification of automobiles, either in the form of plug-in capabilities (PHEVs) or pure battery electric vehicles (EVs). PHEVs promise to provide batteries capable of pure electricity operation for at least 20–40 miles. This is extremely important because approximately 50% of the everyday commute in the United States extends less than 20 miles, round-trip, and 78% less than 40 miles (Bureau of Transportation Statistics, 2001). Hence, for most commuters our automobiles would be running solely on electricity, and could be recharged every night while vehicle owners sleep. If trips were more than 40 miles in length, the ICE would seamlessly kick-in allowing liquid fuel (gasoline, ethanol, or other) to be burned. PHEVs, therefore, eliminate what has been the major objection to electric vehicles, namely their limited range.

The commencement, intensity and duration of the PHEV era are open to speculation at the moment. Most publicity has focused on the Chevy Volt that General Motors has publicly announced will roll out in late 2010 (Muller & Stone, 2008). It is not an exaggeration to say that General Motors is staking its reputation, and perhaps its continued existence, to the success of the Volt. After some reluctance, Toyota has also committed to a PHEV rollout in 2010 (Toyota, 2008). The Volt and Toyota PHEVs are based on different versions of the technology, with the Volt being primarily an electric drive vehicle (a series hybrid, that General Motors calls an extended-range electric vehicle) and Toyota's still relying primarily on its internal combustion engine (a parallel hybrid). Chrysler has indicated that it will produce two PHEVs with one likely to be in production by 2010 (Bennett & Boudette, 2008), and Ford will have a road-ready PHEV by 2012 (Ford, 2008).

Other automakers have shown more reticence toward PHEVs. Honda has indicated no interest to date, but is rather focusing on an HEV competitor to the Prius and a more long-term bet on a fuel cell vehicle. Volkswagen is interested in converting some of its fleet to PHEVs, but has also made no commitment to commercialization.

Daimler and BMW appear more interested in EVs, feeling that the combination of electrical and mechanical drive systems is too cumbersome. And Nissan has been an outspoken advocate for EVs, making the commitment to sell a full-scale EV in the U.S. by 2010 (Vlasic, 2008). In addition to its PHEV interest, Ford intends to have a full electric van on the road by 2010 and a sedan by 2011 (Ford, 2008).

As can be seen, all major automakers see electricity as part of their future, but their strategies for integration within their fleets vary significantly. It is impossible to pick a winner today, and, as will be discussed later, it is likely that none of the strategies being pursued by the major automakers today will prove viable.

3. Implications for carbon emissions

Transportation accounts for roughly one-third of the CO_2 emissions generated through combustion in the United States, and about a quarter globally. Light-duty vehicles (defined as automobiles and light trucks) produce a major portion of the U.S. transportation total, approximately 62%. This constituted over 1.3 billion short tons of CO_2 emissions emitted to the atmosphere in 2005—higher than the emissions of all but four countries (Marland, Boden, & Andes, 2008). Globally, there are over 600 million light-duty vehicles in operation today, with predictions of 1 billion around 2020 and as many as 3 billion by 2050 (Economist, 2008). Even with efficiency gains, the consequences of such growth for climate change are frightening.

There have been no federal regulatory actions taken in the United States to explicitly reduce CO_2 emissions from light-duty vehicles. The primary statewide regulatory action to do so has been in California where regulators have promulgated a requirement for automakers to sell a certain number of ''zero emission vehicles'' by 2012 (CARB, 2007), established a future low-carbon fuel standard (Office of the Governor, 2007) and set forth future tailpipe CO_2 emission requirements covering all automobiles sold in the state. The refusal of the U.S. Environmental Protection Agency (EPA) under the Bush Administration to grant a federal waiver allowing these tailpipe emissions standards to go forward (despite adoption by 17 additional states) has put the plan in limbo (while the matter goes to the courts for settlement or the Obama Administration reverses the EPA decision). The EPA claims that the new fuel efficiency standards set forth in the federal Energy Independence and Security Act of 2007, mandating average fleet efficiency standards of 35 mpg by 2020, obviate the need for California's initiative. California, on the other hand, claims that fuel efficiency standards would have to be raised to 44 mpg to meet its CO_2 tailpipe target. All of this needs to be placed in the context of national fuel efficiency standards in light-duty vehicles that prior to 2007 had not been raised for over 20 years (USEPA, 2007).

The Europeans have tried to address CO_2 emissions from tailpipes more explicitly. In the 1990s the European Automobile Manufacturers Association entered into a voluntary agreement with the European Commission to reduce CO_2 emissions per kilometer. The target was 140 g CO_2/kilometer by 2008, down from an average of 187 g CO_2/kilometer in 1995. By 2005, it was apparent that the target was not going to be reached (World Resources Institute, 2005). In response the European Commission has, after much push-back from European automakers, extended the time of compliance to 2012, but reduced the target to 130 g CO_2/kilometer (Chaffin, 2008). Clearly, from both the U.S. and the European experiences, we can see that the regulatory approach to reducing CO_2 in vehicles can be contentious.

If we calculate emissions on the basis of a single vehicle using gasoline, the general rule of thumb is that the average American light-duty vehicle on the road today—averaging 20 miles per gallon—emits 1 lb. of CO_2 for every mile traveled. Electric vehicles, on the other hand, are non-CO_2-emitting. This ignores, however, the CO_2 emitted in the generation of electricity that powers these vehicles. Consequently, in order to make valid comparisons, it is necessary to calculate both the kilowatt hours used in the transport of an electric vehicle and the CO_2 emissions coming from the power plant attributable to these kilowatt hours.

A median number for miles per kilowatt is 4. Hence, if we travel 100 miles, we will use 25 kW. A national average of CO_2 produced per kilowatt at the power plant is 1.36 lbs. Consequently, if we travel 100 miles in an electric car, we would produce an average of 34 lbs. of CO_2. This would be only 34% of the CO_2 produced from our average vehicle today. If we use the multiplier for a heavily coal-dependent location, such as Bismarck, North Dakota, (1.81), the 100 mile trip would produce 45 lbs. of CO_2—still clearly a winner for the electrical vehicle. If we calculate more conservatively, assuming a conventional vehicle gets not 20 but 25 miles per gallon, and the electric vehicle in a PHEV mode travels only 50% of the time on its battery, the CO_2 advantage diminishes but does not disappear. We still have CO_2 savings of roughly a third. This correlates well with a finding of 42% savings nationwide by Lilienthal and Brown (2007) of the National Renewable Energy Laboratory (NREL).

Electrification reduces emissions because electric motor drive is inherently much more efficient in powering the vehicle than is the familiar internal combustion engine. ICE engines typically convert no more than 15–30% of the primary energy (gasoline or diesel) to power the car, with the rest being dissipated through heat loss. Electric motors, on the other hand, are 90% efficient, offsetting the losses typically found at the power plant when converting primary energy to electricity.

A joint study conducted by the Electric Power Research Institute and the Natural Resources Defense Council (2007) determined that the introduction of PHEVs into the light-duty vehicle fleet mix would reduce greenhouse gas emissions in every region of the country. The extent of the reduction would vary according to the level of market penetration and the electricity sector's CO_2 intensity. With a relatively low penetration rate and high CO_2 electricity intensity, the cumulative CO_2 reduction by 2050 would be at least 3.4 billion metric tons. Assuming an aggressive penetration rate and lower CO_2 intensities, the reductions by 2050 grow to 10.3 billion metric tons. It is clear that electric utilities will have significant obligations under a future climate change regulatory regime to reduce the carbon intensity of their electricity. Significant emissions savings subsequently will depend upon the pace of PHEV or EV market penetration.

4. Consumer acceptance

Even if the evidence on carbon savings is compelling, it is undoubtedly insufficient, in itself, to bring the American public to accept vehicle electrification. There are a host of other factors, however, that will compel Americans to go electric at some time in the future. Most significant is the price of vehicle fuel. Based on oil priced on \$140 a barrel, gasoline prices shot up above \$4 per gallon during the summer of 2008, coming as an unwelcome shock to Americans (prices in Europe, of course, were considerably higher). The most immediate response was to drive less, purchase smaller vehicles, and seek out mass transit (Campoy, 2008; Welsh, 2008). A return to \$2 per gallon gasoline on a permanent basis appears highly unlikely (Kerr, 2008). Some have claimed that despite enormous reserves of petroleum, we have reached a peak in our productive capacity and that supplies will be on a downward slope from now on (Deffeyes, 2002; Simmons, 2005). Even if not true, demand in Asia and elsewhere will continue to present challenges to oil suppliers as they work in difficult and unstable parts of the globe. Historically oil prices have fluctuated considerably, and there is no reason to suppose this won't be the pattern in the future. But the chances of exceeding a purchase price of oil at \$140 a barrel are just as probable as chances for purchase prices to fall well below that mark.

In contrast, electricity prices are likely to be both considerably lower and more stable. Average electricity prices today produce the equivalent of 75 cent per gallon gasoline. Even if electricity prices go up considerably, as should be expected in the movement to carbon-free sources, the equivalent cost to gasoline should remain decidedly lower.

Convenience is an additional incentive to cost. Much of the infrastructure for electric vehicles is already in place. This is in contrast to other alternatives to petroleum, such as ethanol/biodiesel, natural gas, and hydrogen. Home occupants can recharge vehicle batteries overnight with nothing more than an extension cord. Moreover, electric utilities have considerable capacity to supply electric vehicles with the power they need. A Pacific Northwest National Laboratory (PNNL) study (2007) determined that because the U.S. electric power infrastructure is under utilized most of the time (non-peak hours), *existing* capacity infrastructure could recharge up to 73% of the light-duty vehicle fleet, were it converted to electricity. This assumes, of course, that the recharging would take place overnight while home occupants sleep.

Not all infrastructure issues have been worked out yet. Obviously, a more robust recharging system must be put in place, covering the non-home owning population, workplace and urban locations, and a long-distance system. Utilities will want to create a system that at least discourages, and perhaps prevents, citizens from recharging their vehicles during peak load operations. Nevertheless, the absence of these features should not inhibit moving forward with the initial stages to transportation electrification.

At the current time, the major disincentive to electrification beyond HEVs appears to be the anticipated purchase price of the vehicles themselves. Automakers claim there will be considerable expense associated with the new, more powerful, batteries, and the shift to electric drive. Those Prius owners seeking to have their HEV converted to a PHEV have typically had to pay firms at least $10,000 for the conversion (a practice Toyota seeks to discourage by invalidating the car's warranty). General Motors has yet to set a purchase price for its Volt. Speculation has suggested that it could range anywhere from $30,000 to $50,000. If it is at the higher end, there may be relatively few takers for it. On the other hand, one has to question whether GM is in sufficient financial health to subsidize the purchase by offering a price toward the lower end (a loss-leader strategy). To be sure, there will always be buyers for high-end, high-performance luxury electrical vehicles, such as the Tesla Roadster, (costing approximately $100,000) (Tesla Motors, 2008). But a fundamental transformation of our vehicle fleet will not take place at these price levels.

The purchase price problem can, to some extent, be offset by government tax credits. Federal tax credits, ranging in value from hundreds of dollars to a few thousand, have been used to partially offset the price premiums associated with the purchase of HEVs. Moreover, as many as 37 states currently provide some form of incentive toward the purchase of HEVs (Hybrid Owners of America, 2008).

We can expect the incentives associated with PHEVs and EVs to be at least as generous as those associated with HEVs. New federal legislation has established a tax credit of up to $7500 for qualified PHEVs beginning in 2009. Barack Obama pledged a similar credit during his presidential campaign. As electrical vehicles become more mainstream we would expect incentives to diminish. But we would also expect mass production to lower the premium associated with production of electrical motor systems in vehicles.

There are other cost offsetting factors associated with EVs. For one, they are likely to save consumers money in maintenance costs, since EVs obviate the need for such things as engine oil, spark plugs, valves, fuel pumps and other equipment associated with ICEs. One EV advocate put the savings at roughly $1500 per year (Balkman, 2008). Moreover, as will be discussed in a subsequent section, PHEV and EV owners may be able to receive compensation from electric utilities for services rendered to the electric grid.

The basic reason for the U.S. government's willingness to assist in the transformation to electrification stems primarily from its national security concerns. U.S. dependence on foreign oil is already significant, constituting 60% of the oil used or 12.5 million barrels per day. This is up from a dependence of just 3 million barrels per day 25 years ago. Domestic supply of oil peaked in 1972 and has decreased to its lowest levels today. Greater offshore development and drilling off of Alaska can perhaps reduce the decline in domestic production, but it cannot offset projected dependence levels associated with increasing demand for transportation fuels in the future. This dependence on foreign oil, with its $600–$700 million per day price tag and its association with unstable political regimes abroad, led President George Bush, in his State of the Union Address (2006), to propose a technological undertaking that would end ''our addiction to oil.''

By moving away from oil to electricity we would be transitioning from a foreign-based source (oil) to a domestic-based resource (electricity). Oil makes up only 2% of our sources of electricity nationally, and all the other sources of electricity, save for a small amount of natural gas and electricity from Canada, are based on domestic resources. One study (Pratt et al., 2007) has shown that an aggressive deployment of electric vehicles could displace approximately 6.7 million barrels of oil per day. The implications of a reduction in oil imports of this magnitude could have a profound impact on the conduct of foreign policy as well as simply impacting our transportation system.

5. Unconventional wisdom

As was detailed previously, virtually all the major automakers have some entry into the electric vehicle sweepstakes, though the configurations vary considerably. Conventional wisdom has it that the sweepstakes are still some time in the future. A recent report from MIT states the case (Bandivadekar et al., 2008).

> *It will take longer (~20 years) for more complex or advanced technologies, such as hybrids, to result in significant overall reductions in fuel consumption and GHG emissions, due to their higher cost and slower*

development. Radically different technologies—such as plug-in hybrids and hydrogen and fuel cells—could take more than 30 years to be developed to the point where they are market feasible and deployed in substantial numbers.

While commercial development of hydrogen and fuel cells still appears well into the future, the linking of plug-in hybrids to this same timeframe is probably unjustified. One can envision plausible near-term rollouts of not only PHEVs, but also EVs. This could result from a technical change (i.e., extraordinary improvements in battery performance) and/or from social/institutional changes (re-envisioning the nature of personal vehicle requirements and system components). At the current time, the major automakers are only envisioning the former, but, in fact, chances may be greater that the latter will be equally, if not more important, to the transition to electric vehicles.

Aside from the PHEVs and EVs mentioned previously, there are other EVs expected to be produced in the near term (0–5 years) that will enter the electrical car sweepstakes. Frequently mentioned are Mitsubishi's iMiEV, an electrical Mini-Cooper from BMW, a Miles Electric (China) vehicle called XS500, a Subaru R1e/G4e, a Norwegian THINK vehicle, and a Phoenix SUT made in Korea. These EVs are small, to be sure, but they are touted as being capable of fulfilling all the current American consumer road requirements for small cars. As such, it is anticipated that they will cost anywhere between $30k and $50k. At this price, automakers have good reason to be concerned as to whether this new generation of automobile batteries will be ready for ''prime time.'' Within the technical community there is still considerable doubt as the whether the new batteries will match performance expectations over the entire life of the vehicle (Wald, 2006; Anderson, 2007; Darlin & Feder, 2006; Cain, 2008; Axsen, Burke & Kurani, 2008).

It is possible that EVs will become ubiquitous even while not fully satisfying current consumer requirements. We have EVs today that are termed Neighborhood Electrical Vehicles (NEVs), and more derogatively called ''converted golf carts.'' These vehicles have traditionally had little electrical range and have been shunted to selected locations (e.g. neighborhood associations and college campuses). Chrysler has produced and sold over 40,000 NEVs under the Global Electric Motors (GEMs) brand over the past 10 years (Chrysler, 2008). A new generation of NEVs, with enhanced batteries, is in the pipeline, however, that offer more promise. These include the three-wheeler from ZAP called Xebra, the Canadian two-seaters Zenn and Nemo, and the Miler-Electric from Miles Electric. This new generation of NEVs is expected to hit the market at a price range of between $10 and $20k.

6. A disruptive technology

Automobile electrification demonstrates many of the classical characteristics of disruptive technologies (Bower & Christensen, 1995). In fact, Christensen (1997) devoted a chapter in the book, *The Innovator's Dilemma*, over a decade ago, to explaining why he feels the electric automobile has significant potential to be a disruptive technology. His thesis was that electric automobiles failed to garner mainstream automaker enthusiasm because: (1) they failed to meet the performance needs or desires of the mainstream public; (2) the costs appeared excessive (particularly if additive to existing ICE technologies); and (3) the vehicles were small in comparison to existing vehicles. The relative neglect of this product, therefore, presented an opportunity for new firms who weren't put off by the vehicle's limitations to get a foot in the door. With this opening, these new firms could either engineer improvements in the vehicle over time, or package the vehicle in a way that presented a new and attractive value set (low cost, convenience, and simplicity, for example) to the consumer.

As noted, existing firms resist developing disruptive technologies precisely because of their initial shortcomings. They are unable to envision how new and incipient technologies can gain mainstream acceptance while being sold at existing market prices. The General Motors experience with its electric vehicle in the 1990s (the EV-1) illustrates the misgivings existing firms have with developing disruptive technologies. Despite the fiercely loyal support of a dedicated minority of EV-1 drivers, General Motors discontinued the model because it could not envision how the vehicle could meet the more mainstream performance requirements of the general public and because producing ''more of the same'' was vastly more profitable at the time.

Even with the aforementioned hybrid and electric vehicles promised by major automobile producers, one senses that the field is still ripe for new automotive entrants. This is so because existing automakers first seek to build vehicles meeting or exceeding mainstream expectations and then add on the costs of electrification. Consumer acceptance, therefore, is contingent upon consumer willingness to pay a premium for ''greenness'' or having the government offset the extra costs through tax write-offs. Such a strategy can be charitably characterized as wishful thinking.

The alternative approach, likely to be adopted by new entrants, is to build inexpensive electric vehicles that do not currently meet mainstream expectations but have the ability to alter consumer preferences. An example of this strategy historically might be the introduction of the Volkswagon ‘‘beetle’’ into American society in the 1960s. When first introduced, the vehicle was disparaged as too small and too slow for the American public. Nonetheless, the combination of low cost and offbeat styling appealed to a significant demographic segment of the American public and ushered in an era of more stylish and small Japanese vehicles.

Certainly the price now proposed for NEVs could be attractive to the mainstream American public. But existing NEVs are likely to be overmatched by vehicles produced by entrepreneurial Indian and Chinese automakers. While most of their attention is being devoted to feeding the vast, untapped markets in developing countries for personal transport vehicles, some are now planning on exporting electric vehicles to the United States and Europe. India’s Tata Motors has expressed an interest in selling electric vehicles in Europe (Financial Times, 2008). The Chinese battery and automotive enterprise, BYD, has set its sights on selling EVs or PHEVs to the United States (Schwartz, 2008). Each has the potential to be a disruptive firm at the expense of the existing automotive enterprise.

Tata Motors and BYD Automotive can benefit from being unencumbered with characteristics of existing firms, namely: (1) having a number of existing or competing products in the market, some of which might be more profit-generating than their electric models; (2) the establishment of high cost structures associated with labor and supply chain arrangements. As such, they can compete at the low end of the market where low costs are important, and where some of the full performance attributes of current vehicles may be unnecessary. Structural conditions are such that many vehicles are used for short-range commutes, and, in many developed societies, possession of at least two vehicles is the norm rather than the exception. This allows for the favorable adoption of one low-cost, low-performing vehicle (the commute vehicle), while maintaining a more costly household vehicle for more extended, high-speed, trips and purposes. By entering the market at the low end and gradually building vehicle capabilities over time (associated with improving battery performance), Indian and Chinese automakers could gain a foothold in the market and enhance their brand loyalty.

Tata Motors has aspirations to market its automobiles at the low end not only in developed societies but also within India. It is developing the so-called ‘‘Nano’’ brand, designed to sell for as little as $2500 (Economist, 2008). An electric vehicle Tata Motors has designed for export (called the Indica EV) will undoubtedly cost more than the Nano, but there is plenty of pricing room still available while remaining at the lower end.

While Tata Motors is a major automotive firm already, BYD Automotive is still in the process of transitioning from an established battery maker (it is the world’s second largest battery producer) to a successful automaker. Nonetheless, with its acknowledged expertise in batteries, it is well-positioned to be a major player in the global low end electric vehicle market. Moreover, it may be the first automaker to offer a commercial PHEV, as it has announced it will begin sales in 14 Chinese cities in December of 2008 (ChinaStakes.com, 2008). It has plans to export PHEVs and EVs to both the U.S. and Europe in the next couple of years; and it is seeking to open a manufacturing plant in the United States.

7. A different automotive future

While the low cost of electric vehicles may be a necessary component of a disruptive strategy, it is by no means sufficient. As studies have shown (Turrentine & Kurani, 2007; Heffner, Turrentine, & Kurani, 2006; Kurani, Turrentine, & Heffner, 2007) consumers rarely make automobile purchases on the basis of careful economic calculations. Other factors, such as control over refueling, or identity affirmation, may be at least as important as initial costs and payback periods. In essence, automakers will have to provide a more compelling value package to offset initial technological limitations.

The most audacious transformational change is being put forth by Shai Agassi, former head of product development at the software giant SAP and now President and CEO of the organization he founded called A Better Place (2008). Agassi presents a new business model in which ownership of automobile batteries is divorced from automakers, and individuals pay for transportation through a contract based on miles driven. The business model is one common to the mobile phone industry and could have application to transportation.

At the heart of this arrangement would be a for-profit Electric Recharge Grid Operator (ERGO) which owns the batteries, writes contracts with consumers, and installs the necessary infrastructure—including recharging stations within the city and automated battery swapping locations for long-distance travel. Consumers would have the choice of signing contracts for unlimited miles, a maximum of miles per month limit, or a pay-as-you-go system. Agassi (2008) claims that due to the cost savings associated with moving to electricity from petroleum-based fuels, the vehicles themselves could be offered for ‘‘free or nearly free.’’

The concept has gone well beyond the ‘‘blue sky’’ phase. Backed by $200 million in venture capital, Agassi has begun to put together the pieces that would make this vision a reality. Renault has committed to producing EVs for initial pilot projects and has committed to mass production of electric vehicles by 2011. The vehicle would be based on Renault's popular Megane model, and would be much more than a transformed golf cart. It is proposed to have a range of 120 miles per charge and the ability to travel 0.60 miles in 7.5 s. Agassi has commitments from the governments of Israel, and Denmark to move forward, and has initial agreements with Australia and Portugal to test the *Better Place* model when the vehicles become available. The *Better Place* model may or may not become reality but it is illustrative of new transportation alternatives that could accompany electrification. Agassi's vision is consistent with the projections of Urry (2004, 2008) who claims that the era of steel-bodied cars and petroleum engines is coming to an end. He envisions drivers accessing, but not necessarily owning, small, light ‘‘mobile pods’’ for their personal transportation needs. According to Urry, this change will not be brought about by mainstream automakers, but by firms currently at the periphery of the automotive industry.

Facilitating this vision could be the segregation of vehicle transportation systems based on the weight and speed of vehicles. In other words we could begin to see dual-transportation networks offering a set of roadways for light-weight NEVs and other slow transportation alternatives (e.g. bicycles and motor scooters) and another set for the automobiles we have today. Delucchi, Kurani, Nesbitt, and Turrentine (2002) set forth in some detail how a new city being established could be designed to satisfy the separate needs of both high-speed and low-speed vehicle owners. Most cities today could alter existing roadways for this purpose, although complete segregation of the two networks would not be possible. An attractive NEV costing $10k or less, and designed for the work-to-home commute, could be the impetus for putting such plans in motion. In short, better automotive batteries are likely to spark new thinking on how to structure personal transportation, leading to a series of disruptive changes difficult to predict at this time.

8. The electric utility perspective

Up to this stage, we have viewed the transition from oil to electricity within a transportation context. It is equally important and noteworthy to take a step back and think about what such a transition means for the supplier of this electricity: primarily, the centralized, electric utility. In doing so, we see that the utility is faced with challenges, opportunities, and ultimately, a number of large risks. The utility industry as a whole is only now beginning to think and plan for this new world which could radically alter its landscape.

The first-order effect, of course, will be the impact of automobiles drawing down electricity from the grid. The amount of electricity required for a single recharge is not large, drawing from 1.4 to 2 kW of power, equivalent to what a dishwasher uses (EPRI, 2008); but when aggregated nationwide will have an impact that is significant. Initially, there appears to be a fortuitous match between consumer and supplier. Consumers can easily recharge their automobiles when the vehicles are safely ensconced in garages at night. This is precisely the time when electricity suppliers have surplus electricity to sell due to the requirement for continual baseload power operations. From the utility perspective, therefore, this appears to be a new revenue stream unencumbered with the need to build new generation capacity.

The issue is not cut-and-dried, however. Only 50% of the American public has access to garages with electricity, and there will undoubtedly be a desire as well to recharge vehicles at different times of the day. Should vehicle owners want to recharge their vehicles during daytime hours while at work or on travel, this could correspond to peak operating periods, thereby exacerbating the well-known peaking problem of electric utilities (Hadley & Tsvetkova, 2008). In order to prevent or discourage this practice, utilities are researching the possibility of installing software in vehicles that would prevent recharging at peak periods, say, from 2:00 to 6:00 p.m., or at least raise the costs of electricity purchased during the period to such levels that vehicle owners have a strong disincentive to recharge. Considerable attention to this issue will be necessary to match consumer and producer interests.

9. Vehicle-to-grid (V2G)

Perhaps the most exciting opportunity for both the transportation and electricity industries is what is termed vehicle-to-grid operations or V2G, for short. Up to this time we have been dealing with the one-way grid-to-vehicle dimension exclusively. It can work the other way, however. To the electricity industry, electric vehicle batteries offer a huge and unprecedented storage network; one that can be called upon for power at designated times of the day. This is a resource that the electricity industry has never had, as its product, for the most part, has had to be consumed as it is dispatched. There are a number of storage options being evaluated at this time, but the emergence of automobile batteries is surely the most promising and revolutionary. It has been estimated that if the entire light-duty fleet were converted to electricity, the fleet would possess 24 times the power capacity of the entire electricity generation system (Kempton & Tonic, 2005).

The opportunity arises from the fact that the automobile sits idle 90–95% of the day, being driven, on average, only 1 h each day. When these automobiles are off-line, so to speak, they can, with the addition of a bi-directional charger, feed electricity to the grid. Clearly, some degree of coordination will be required between the utility and the vehicle owner because the owner will not wish to find his/her batteries depleted just when driving becomes imperative. On-board controls can be installed that would prevent full-discharge without driver consent.

Vehicle batteries are ill-suited to provide economic baseload or peakload power to electric utilities at the current time, though they are well-suited to provide emergency services stemming from isolated power outages. A more likely near-term service would be to meet the utility's continuing need for grid or power management services (Letendre & Kempton, 2002; Lund & Kempton, 2008). These so-called ancillary services are essential activities that are little known to the public, but which are critical for the successful dispatch of electricity.

The ancillary services of interest are frequency regulation and spinning reserves. Electricity suppliers need bursts of power to balance the dispatch of generation with changing levels of consumption. Under contract, automobile owners could allow their batteries to be used for frequency response. The batteries need to be available on an on-line basis, but all that is needed are tiny bursts of power for balancing. The battery is discharged when the electricity supplier calls for more power, and charged when there is a surplus of power being dispatched. Hence the battery is never far from equilibrium. Spinning reserves are required less frequently, and only when a generator goes off-line unexpectedly or transmission/distribution lines fail. More power is needed for this function, but it is normally called upon for very few hours each year.

Vehicle owners would be compensated for these valuable services, which are currently supplied by traditional sources, usually at high cost. Frequency regulation is particularly valuable and according to one study (Letendre, Denholm, & Lilienthal, 2006) could bring vehicle owners as much as $3285 per year. Aligning the incentives of all parties to make such a future possible will not be an overnight undertaking. Nonetheless, the potential for automobiles to play a significant role in the delivery of electricity is considerable as we become more comfortable with our electric transportation future. Clearly, none of this can take place without significant upgrading of the electricity transmission and distribution grid, including bi-directional flow capabilities. Fortunately, the electricity industry recognizes the need for such a smart grid and is beginning the long and costly process of putting it in place (NETL, 2007).

10. Electric vehicles in a renewable energy future

Up to this stage we have placed electric vehicles in either a transportation or utility-serving context. But it is also essential to note that electric vehicles may play a key role in hastening the advent of a renewable, low-carbon, energy system, with or without the utilities. We know that renewable energy in general is critical to addressing the climate change challenge, and that renewable energy can be deployed either centrally or in a distributed fashion. Automobiles are a quintessential distributed resource and it is intriguing to imagine how this resource can contribute to, and be integrated within, a distributed renewable energy future.

We still are very much in the envisioning stage of what a renewable energy community, based largely on distributed energy resources, might look like (Carlisle, Elling, & Penney, 2008; Rocky Mountain Institute, 2008; Penny & Elling, 2005). Components include the renewable resources themselves, zero or near-zero consuming energy buildings based on high-tech energy smart systems, smart growth transportation networks, smart electric grids and bi-directional electric vehicles that can serve both transportation and energy services. The challenge is to engage developers, builders, automakers, land-use planners, financiers, and others in integrating these components that makes sense from a personal and societal perspective. The primary benefits of electric vehicles in this mix would be to compensate for the intermittency problem associated with renewable energies. As is well known, renewables offer vast amounts of energy, but not on a predictable or consistent basis. Electric vehicle batteries can assist in moderating the ramping up and ramping down process, as well as in storing energy until it is needed. The electric vehicle can refuel for transportation when renewable energy is in excess, and supply the home with energy from its storage device (battery or fuel cell) when excess energy demand is present. As such, the bi-directional electric vehicle can play a key role in matching energy needs and requirements. Toyota (2005) has provided a vision of its ''dream house'' in which houses are designed to be plug-in ready. Others (Hybrid Living, 2008) are envisioning the sale of homes that come complete with NEVs that can serve as home energy components as well as transportation vehicles. Another possibility consists of aggregating ''used'' vehicle batteries to be deployed as stationary storage devices (Rocky Mountain Institute, 2008).

It will probably take an ambitious and clever entrepreneur, the equivalent of Shai Agassi, for example, to bring all the pieces together into a compelling business case. And difficult and time-consuming integrating standards will have to be worked out as well. Nevertheless, as vehicle development proceeds concurrently with the development of renewable resources and the modernization of the electric grid, the integration of these will become more appealing and obvious.

11. Conclusion

The transportation sector is in a transition period, though the final destination is uncertain at this stage. This article has focused on personal vehicle transportation transitioning to electricity. It may be that the future is also one of multi-fuels (e.g. natural gas, synthetic liquid fuels) and more mass transit. A transition to electricity, however, provides the best opportunity for transformative and disruptive change—something that is vitally needed to address the dangers of climate change. The collective fleet of personal vehicles in the world is huge and cannot be transformed quickly. But there are no fundamental barriers preventing electrification of the vehicle fleet from beginning slowly and gathering momentum over time.

The winners will be those who can make a compelling business or value case for the integration of the automobile and electricity industries. Though they have initial plans for the electrification of at least a portion of their products, the companies currently dominating the automobile industry will not necessarily prevail. Their experience is offset by the obligations and mind-set they have inherited from the previous century. New automakers, in combination with strong battery makers, are unencumbered with such baggage and may be able to develop an appealing new vision for personal transportation.

The electricity industry is a more regulated enterprise, and the pace of change will probably be determined more by legislation and regulation than by individual power generators. We know that in response to climate change concerns, electrical grids will become less carbon-intensive. And, the movement to large-scale implementation of ''smart grids'' is already underway. Both of these developments are critical for the ultimate success of electricity as a desirable transportation fuel, and perhaps even more important, for the integration of renewable energies in our daily lives. Large-scale storage is something that has eluded the electricity industry thus far, and the distribution of millions of storage devices across the country in the form of automobile batteries, holds the promise of exciting transformative change in the future. Climate change is providing the impetus for this development, and climate change mitigation efforts will certainly be the beneficiary as well.

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