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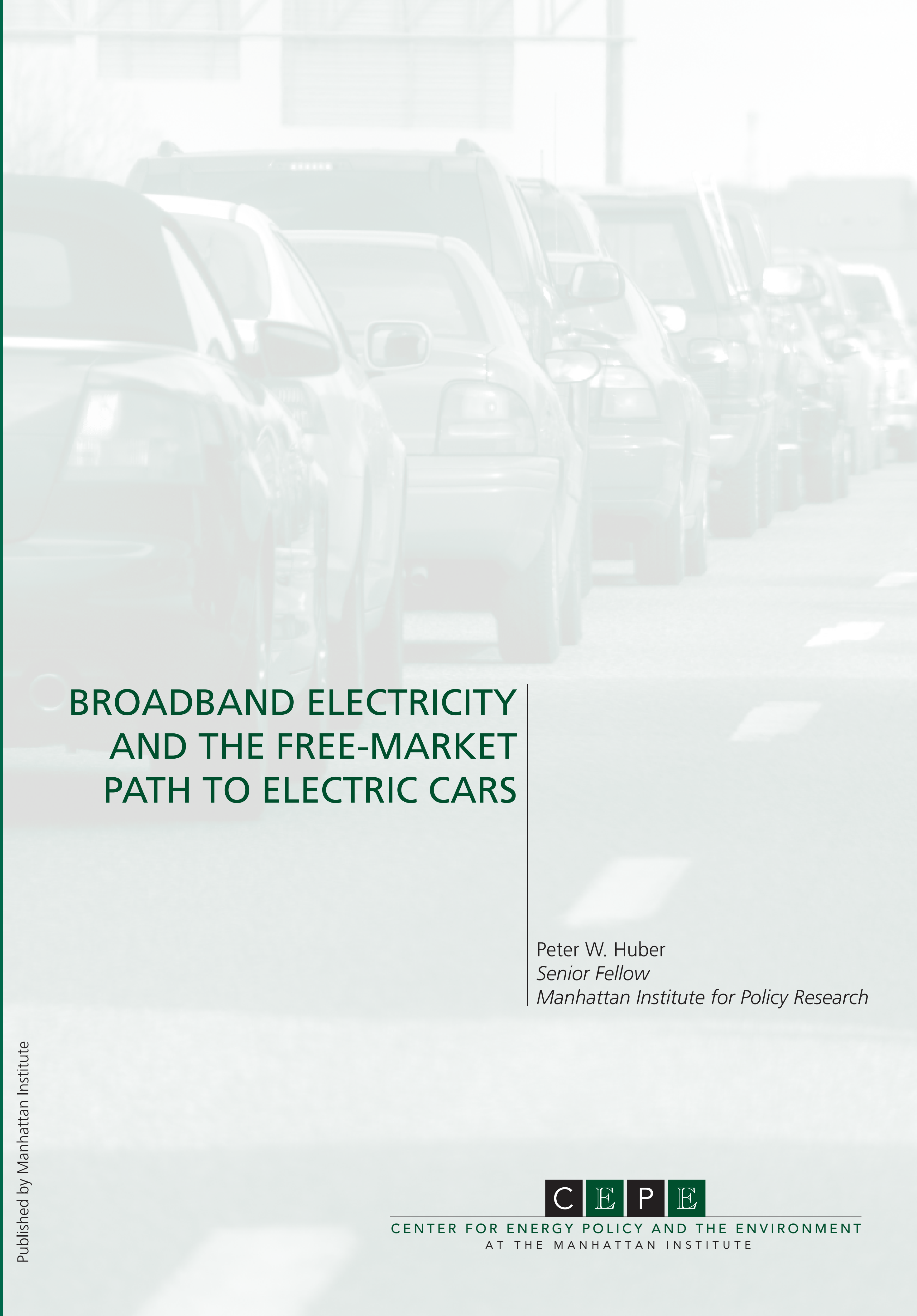

BROADBAND ELECTRICITY AND THE FREE-MARKET PATH TO ELECTRIC CARS

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Executive Summary

Batteries big enough to give an electric car significant range remain heavy and expensive. Many policymakers seem to be staking the electric car's future on the development of much cheaper batteries. The wishful battery future has also been the path of least regulatory and political resistance, particularly when it leads to tax breaks and direct subsidies, directed mainly at the development of technology that might end up in the cars or at the drivers who might buy them.

More capital investment in the relatively low-voltage lines, transformers, and terminal equipment that distribute power to city blocks, high-rises, and suburban neighborhoods is a direct substitute for much of the additional capital investment that must otherwise be funneled into the electric car. This "last mile" grid investment will likely play a much larger role in delivering electric miles cheaply, reliably, and conveniently.

Higher voltages in high-power battery-charging stations can cut recharging times from hours to minutes. Technological and economic considerations both favor more investment in the last mile of the grid and less in the car itself. Electric utilities have compelling reasons to make that investment, if regulators give them the freedom to do so in ways that allow them to earn profits commensurate with the risks.

Market forces have propelled the progressive electrification of factories, offices, and homes for over a century. Electric motors and associated systems that convey and control the electricity they need, powered by onboard diesel generators, have likewise displaced mechanical alternatives in locomotives and monster trucks. High-power semiconductors developed in the 1980s are now being deployed inside cars to electrify water and oil pumps, radiator-cooling fans, brakes, throttles, steering systems, shock absorbers, and engine valves. These trends all point toward the last great leap, the one already taken by locomotives and monster trucks: electric drivetrains will knock out the gearbox, driveshaft, differential, and related hardware. Electric drives are much cheaper to manufacture, and they convey far more power in much smaller, lighter conduits—and they convey it far more precisely and reliably than mechanical drives that rely on shafts, gears, belts, and hydraulic fluids. As drivetrains are progressively electrified, everything shrinks, everything gets lighter, and every aspect of performance improves.

In one key respect, passenger cars present an especially attractive opportunity for going electric. Internal combustion engines run at peak efficiency when they run at a fast, steady rate—as they do, for example, when a car cruises down a highway. Efficiency plummets when the engine's speed keeps changing, as it must whenever the driver brakes or accelerates. Adding storage capacity in a battery allows an onboard generator to run more steadily and therefore more efficiently. Even a very modest amount of onboard electric storage can boost efficiencies significantly. Today, for drivers who spend a lot of time in urban traffic, the "light hybrid" architecture that simply turns off the engine and relies on battery power whenever the car stops moving is cost-effective.

How much more battery in the car makes sense hinges on a complex balance of driving patterns, fuel costs, and hardware costs. But as soon as engineers start down this road, they open the door to a dramatically new opportunity. However small or large the onboard battery may be, it can be topped off with power drawn from the grid whenever the car is parked. At the curb, the energy in the electricity drawn from the grid is much cheaper and cleaner than electricity generated on board or gasoline miles provided by a conventional engine. Car batteries also offer utilities and their customers an extraordinary opportunity to boost revenues while lowering the average cost of electricity for everyone.

Most of the cost of grid electricity is tied to capital investment in the hardware that turns cheap, raw fuel at the power plant into high-grade power at the plug. The economics of electric miles is even more capital-intensive. The amortized cost of the batteries in the electric car currently dwarfs the cost of the grid power that could be used to charge them. And as soon as they arrive in any significant numbers, plug-in electric cars will also require new investment in the grid—without it, the cars will soon start blowing network fuses and blacking out homes and neighborhoods.

But this also points to the opportunity for lowering costs and raising revenues. The grid is engineered to deal with the very highest loads it will face only once every few years—in mid-afternoon on the very hottest day in summer. On average, day and night over the course of an entire year, about half of the total generating capacity and an even larger fraction of the capacity in the wires are just waiting for a customer. The capital invested inside electric cars themselves will typically stand idle about 90 percent of the time, and—unlike capital invested in the grid—it can't be shared with others.

Batteries can, however, cheerfully tolerate interruptions in the flow of power to their charging systems. From the perspective of the private investors who might invest in grid infrastructure, car batteries are therefore extremely attractive customers. Batteries are the customers that are eager to buy the power that nobody else currently wants to buy. They offer the existing owners of an enormously valuable capital asset an opportunity to use it profitably when it would otherwise be standing idle.

From the outset, these facts tilt the economics of electric miles away from more battery and toward more investment in high-speed recharging stations in garages, parking lots, compact parking-meter-like units, and other shared spaces. By reducing the size of the battery required in the car, fast charging stations, widely deployed, further boost the car's efficiency and range by reducing its weight. However cheap it may be, the first thing a car's battery has to move is itself. Investing less in the car and more in the last mile of grid also leads naturally to schemes that embed more of the capital cost in pay-by-the-mile charges, which will surely suit many car buyers much better than paying thousands of dollars more up front.

New investment in an infrastructure needed to power electric cars will be especially risky. Without a significant stake in the upside, utilities have good reason to let buyers of electric cars take the lead before rolling out a new battery-charging grid infrastructure. But many potential buyers who could benefit from making the switch probably won't do so without a charging infrastructure in place. The stage is thus set for an "after you" waiting game played out between electric companies and car buyers, with oil companies likely to emerge as the winners.

The free-market path to getting grid electricity to our wheels hinges on giving every company that already owns, or cares to invest in, any part of the electron pipeline—electric utilities certainly included—the freedom and flexibility to invest new capital, set prices, recover costs, and earn profits commensurate with the risks, while working closely with car companies, car owners, municipalities, employers, mall owners, parking garages, individual homeowners, and others. The free-market policies that will mobilize private capital to deliver broadband electricity to our wheels will, by and large, resemble those that unleashed private capital to deliver broadband bits to our computers, PDAs, and wireless phones.[1]

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[1] Fuller treatments of a number of issues discussed in this paper appear in my book *The Bottomless Well* (New York: Basic Books, 2005), coauthored with Mark P. Mills; in our May 2005 article for *American Society of Engineering Magazine*, "the end of the m.e.?"; and in my two previous Manhattan Institute reports, "The Million-Volt Answer to Oil" (October 2008) and "Kill Oil with Natural Gas and Electricity: A Carbon Strategy the World can Afford" (September 2009).

About the Author

PETER W. HUBER is a senior fellow at the Manhattan Institute and the author of numerous books and articles on energy, the environment, science and technology, legal policy, scientific evidence, and telecommunications. He taught mechanical engineering at the Massachusetts Institute of Technology, and clerked for Judge Ruth Bader Ginsburg at the D.C. Circuit Court of Appeals and for Justice Sandra Day O'Connor at the U.S. Supreme Court. He has a Ph.D. from MIT and a J.D. from Harvard Law School. His most recent book, co-authored with Mark P. Mills, is *The Bottomless Well* (Basic Books, 2005).

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Broadband Electricity and the Free-Market Path to Electric Cars

Peter W. Huber

INTRODUCTION

The challenge is to do to electrons what we have spent the last several decades doing to digital bits. Cheap, reliable, electric miles require, above all else, an infrastructure that can deliver large amounts of grid electricity very quickly to hundreds of thousands of locations scattered across the country. More capital investment in the last mile of the grid is a direct substitute for much of the additional capital investment in the car. The grid-side investment will almost certainly deliver electric miles more cheaply, reliably, and conveniently. It will also lead naturally to pricing schemes that allow drivers to pay for those miles as they go, rather than up front when they buy the car.

Batteries that are big enough to give an electric car any significant range remain heavy and expensive; they currently account for about one-quarter of the cost (about $10,000) and a comparable fraction of the weight of today's all-electric cars. When plugged into a standard 110-volt outlet, they also take a long time to recharge. On an hour of charging through a standard household outlet, a battery on one of today's typical hybrid or electric cars would provide about ten electric miles, at most. A typical car could drive several thousand miles on an hour of pumping at a gas station.

Proponents of plug-in hybrids often point to aspects of our driving habits that seem to mitigate "range anxiety" concerns tied to battery capacities and charging times. Nobody drives several thousands of miles without stopping. Few drive even several hundred without pit stops. Most cars are driven well under fifty miles a day. Most trips are punctuated by breaks for work, shopping, or something else after less than ten miles of driving. Cars have plenty of time to recharge when parked, as they are most of the time. And the typical household that owns any cars owns more than one and may therefore be able to use one only for shorter-haul trips.

These arguments are all valid, so far as they go, but fail to address basic consumer psychology. We are accustomed to buying cars that can take us on long trips and that can be quickly refueled almost anywhere. Novel technology is almost always less reliable than the tried and true, and most ordinary buyers will hesitate to spend tens of thousands of dollars on a car that presents a real risk of leaving them stranded far from home. Battery costs may very well drop sharply as technology improves and the economies of mass production kick in, but this remains to be seen.

Now consider how much can be done to address these perfectly reasonable concerns on the grid side of the plug. A standard 120-volt socket can typically deliver power at a rate of about 1.5 kilowatts—slightly more than required by a microwave oven or an air conditioner. But battery packs can be designed to be recharged at much higher rates. On the grid side of the plug, higher rates require higher voltages, more robust hardware, and very careful attention to safety. Direct-current (DC) systems can recharge batteries faster than AC systems and also require less AC-to-DC conversion hardware in the car.

The voltages and currents involved are routinely used in many industrial applications and to power central air-conditioning systems in large private homes—as well as in the drivetrains of electric cars themselves. They typically deliver electrical energy at least ten times faster than a regular wall socket can, and they can be pushed far higher than that. They can thus cut recharging times from many hours to tens of minutes. And it seems likely that on longer trips, many people would readily accept somewhat more frequent but fairly short stops to buy fuel priced at the equivalent of well under a dollar a gallon.

On both the supply and the demand sides of the market, the economics of electric miles thus depends at least as much on the cost and ubiquity of stationary hardware invested in the grid as it does on hardware in the car. The common assertion that the future of the electric car hinges on the cost of onboard batteries simply ignores the capital and know-how of the very large companies that generate, transmit, and distribute electricity.

No one yet knows what the optimum mix will be here between more investment in the cars themselves and more investment in the grid—no more than anyone knew how best to provide ubiquitous broadband connectivity to computers and wireless phones in 1980. But technological and economic considerations strongly favor more investment in the last mile of the grid and less in the car itself. There are compelling reasons to believe that private investors will eagerly make that investment, if regulators give them the freedom to do so in ways that allow them to earn profits commensurate with the risks.

FREE-MARKET ELECTRIFICATION

There is much more electric transportation already out there than most people realize. General Electric's 6,000-horsepower, diesel-electric AC6000CW locomotive is powered by an enormous diesel-fueled engine-driven generator; everything beyond is electric. Komatsu's 960E—a monster mining truck with 300-ton capacity—is propelled by a 2-megawatt Detroit diesel-electric generator. Everything else, right down to the twelve-foot-tall wheels, is driven electrically. Submarines have been all-electric for decades, and the surface ships now on the navy's drawing boards are all-electric, too, from the propeller to the guns. In designing these platforms, engineers have concluded—all on their own, without mandates, subsidies, or other help from Washington—that the best way to move the goods is to transform the raw energy into electricity immediately, and then funnel the electricity through an all-electric drivetrain to do everything else.

Factories began making this same transition long ago. The nineteenth-century factory was powered by a single driveshaft spanning the length of the building; belts and chains delivered power to each individual work bay. That factory-long mechanical driveshaft has since given way to electric cables that power motors that, in turn, power the lathe, drill, or milling machine in each workstation. Today's industrial robots are complex configurations of electric motors; the electric power now runs right to the final threshold of where the power is needed. Packed with sensors, the robots are now precise, sensitive, and far more compact than any mechanical alternative. They are also very much more flexible—they can now be instantly reconfigured to perform new tasks through software alone, a dramatic advance over previous systems that required hours of manual rewiring.

Electrical drives are displacing mechanical ones because they are much cheaper to manufacture and maintain, and they perform much better. Compared with mechanical drives that rely on shafts, gears, belts, and hydraulic fluids, electric drives convey far more power in much smaller, lighter conduits, and they convey it far more precisely and reliably. Pneumatic and hydraulic fluids leak, turn into molasses when they get cold, and are easily contaminated. Shafts, belts, and pulleys need lubricants, get bent out of shape when they expand or contract, corrode, and need periodic maintenance. Electric wires don't.

Until quite recently, the big obstacle to electrification was that electricity is inherently difficult to control. Electric drives are fast but tend to jitter, overshoot, jerk out of control, and fall off the edge. But big motors and their electric power supplies can now be built compact and precise enough to mimic the small muscles of a hand. The key breakthrough occurred in 1982, when two engineers at RCA invented the Insulated Gate Bipolar Transistor. IGBTs are high-power semiconductor gates—they control kilowatts almost as quickly, compactly, and efficiently as logic semiconductors control the picowatts that we call bits.

Step by step, these high-power semiconductors are now being deployed inside cars to electrify the peripheral systems—water and oil pumps, radiator-cooling fans, brakes, throttles, steering systems, shock absorbers, and engine valves. As this process advances, everything shrinks, everything gets lighter, and every aspect of performance improves dramatically. To power these systems, manufacturers are installing larger alternators and starter motors under the hood.

These trends all point toward the last great leap, the one already taken in monster trucks and locomotives: high-power silicon switches and electric power will knock out the entire gearbox, driveshaft, differential, and related hardware. The engine's entire output will be converted immediately into electricity that will directly power the motors that turn the wheels. High-power semiconductors now make it possible to build high-power motors the size of a coffee can, and prices are dropping fast. Cars shed many hundreds of pounds, and every key aspect of performance improves considerably.

As diesel locomotives and monster trucks have already established, there are significant advantages in going electric even when the power is generated on board, on the fly, using a comparatively small and inefficient diesel generator. In one key respect, passenger cars present an even more attractive opportunity for going electric.

The locomotives and monster trucks have captured their respective markets by providing better, cheaper locomotion. Their superior performance is, of course, tied to the types of loads that they carry and the speeds, accelerations, and other operating conditions that their engines must address. Passenger cars operate under significantly different conditions. Street driving typically involves many more stops and starts, quick acceleration, and frequent braking. In this environment, electric drivetrains can offer even bigger gains. But those gains begin with the addition of more capacity in the battery. Internal combustion engines run at peak efficiency when they run at a fast, steady rate—as they do, for example, when a car cruises down a highway. Efficiency plummets when the engine's speed keeps changing, as it must whenever the driver brakes or accelerates. Adding storage capacity in a battery allows the generator to run more steadily and therefore more efficiently.

Even a very modest amount of onboard electric storage can boost efficiencies significantly. The lightest hybrids on the road today deal with the zero-efficiency engine, the one idling when the car isn't moving at all: they combine a better starter motor with a somewhat larger battery to turn off the engine whenever the car stops. The battery—often a cheap, conventional lead-acid battery—keeps heat, air conditioning, and other accessories running, and it restarts the engine at the first touch of the accelerator but never propels the car directly. Small generators linked to the brakes help keep the battery fully charged. In congested urban traffic, this architecture alone has a substantial impact on fuel economy. For drivers who spend a significant amount of time in this kind of traffic, the fuel savings can easily justify the cost of the additional hardware in the car.

From there on out, everything hinges on a complex balance of driving patterns, fuel costs, and hardware costs. The car's engine can be made to run even more steadily, and therefore more efficiently, by adding more battery, more regenerative braking, and electric motors to provide a boost whenever the car must accelerate or climb a hill. The progressive electrification of the drivetrain can continue until 100 percent of the power generated by the onboard engine is being converted to electricity. The electricity is used immediately to propel the car, as it is in a monster truck or locomotive, or used to recharge the battery. Much of the time, the car runs on battery power alone. Much of the enabling technology is available, familiar, and already widely used in other contexts. But again, how far it makes sense to push electrification inside the car depends on how the car is driven and on the relative cost of fuel and hardware.

As soon as engineers start down this road, they open the door to a dramatically new opportunity. However small or large the onboard battery may be, it can be topped off with power drawn from the grid whenever the car is parked. The car then ends up being propelled, part of the time, by the huge, remarkably efficient, power plant located hundreds of miles away. This is where the free-market path to electric cars is very likely to diverge from any minutely prescriptive pathway to electric miles that might be concocted in Washington.

THE EFFICIENT GRID

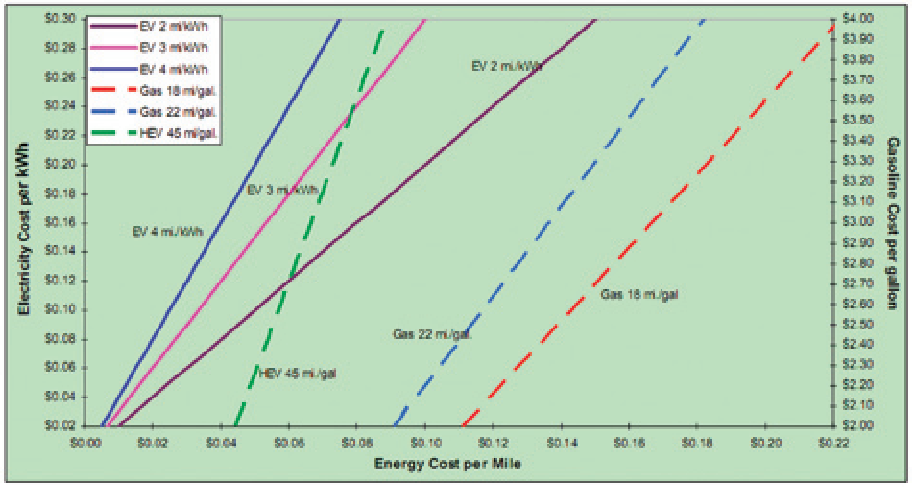
If we could plug locomotives, monster trucks, and ships directly into the electric grid, we certainly would. If we could plug in our cars (a much more likely prospect), we certainly would. If we could choose the best time and place to plug them in, idle capacity in existing plants could power almost all the miles we drive.

America's big, centralized power plants currently consume about as much raw energy as oil delivers to all our cars, trucks, planes, homes, factories, offices, and chemical plants. They also operate much more efficiently than the much smaller, dispersed engines that run on oil. Several thousand electric power plants in the United States burn 30 percent more fuel than 200 million car and truck engines and run about three times as efficiently, producing almost four times as much useful power.

The engineering facts are beyond serious dispute—it is far more efficient to burn fuel in the giant, meticulously maintained, and tightly regulated external combustion engine of a central power plant and transmit electricity than to burn the same fuel in a far smaller internal combustion engine of almost any kind. This is true whatever the fuel being burned may be. The bigger the power plant, the hotter it can operate, and hotter operation boosts thermodynamic efficiency. There is, of course, much more than that to the engineering of efficient power plants. But first and foremost, the rule is simple: bigger plants can run hotter, and hotter is more efficient. Bigger plants require more grid to move their power to end users, but power losses in the wires are quite small. High-voltage electricity is such a dense, pure form of power that it can be dispatched over enormous distances with relatively modest losses, much as a beam of laser light can circle the globe through a sufficiently pure strand of glass.

Electricity is comparatively cheap, too, partly because the gigantic furnaces and boilers that spin million-horsepower turbines and generators are so much more efficient and partly because they run mainly on fuels that cost much less than oil. With current technology, and at current retail prices for grid electricity and

Figure I. Comparing Energy Costs per Mile for Electric and Gasoline-Fueled Vehicles



HEV stands for Hybrid Electric Vehicle
EV stands for Electric Vehicle

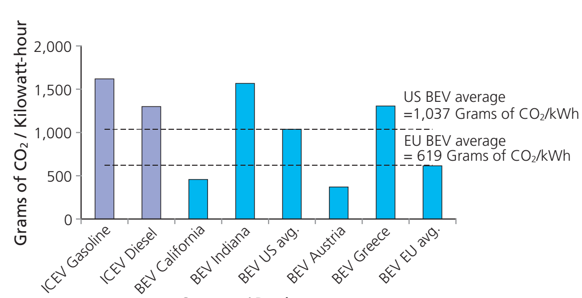
Source: Idaho National __ Lab inel // U.S. Department of Energy
http://www1.eere.energy.gov/vehiclesandfuels/avta/light_duty/fsev/fsev_gas_elec2.html

gasoline, kilowatt-hours delivered to the curb could—if conveyed to the wheels at no additional cost—provide electric miles at roughly one-quarter the price of gallons of gasoline at the pump. The gap widens to about one-eighth if grid electricity is priced efficiently—at marginal rather than average cost—and if batteries are recharged only opportunistically, using otherwise idle capacity in the power plants and wires.

The electric grid's capital-intensive, technology-rich infrastructure also keeps getting smarter and more efficient. As a result, even as fuel prices have fluctuated and fuel mixes have changed, the average retail price of the kilowatt-hour at the plug has fallen almost without interruption since the dawn of the electrical age. Where electricity rates have risen sharply, as they have in some states in recent years, the principal causes have been domestic regulatory choices and policies—some economic, some environmental.

Because they are so much more efficient, so carefully maintained and tuned, and so closely scrutinized and regulated, big centralized power plants also operate far more cleanly than small dispersed ones. Contrary to all small-is-beautiful intuition, it is better for the environment to burn fuel in the external combustion engine of an electric power plant than to burn it in the internal combustion engine of a typical car. In growing numbers, leaders of the environmental community are not only accepting but embracing these facts. As the indubitably green World Wildlife Fund recently concluded, powering cars with electricity rather than gasoline would lower carbon emissions even in Indiana, which generates most of its electricity with coal, because higher power-plant efficiency more than offsets the dirtier fuel. "Despite … the fact that electric powertrain technology is relatively immature, the battery electric vehicle can be over 60 percent more

Figure 2. CO_2 Intensity of Motive Energy



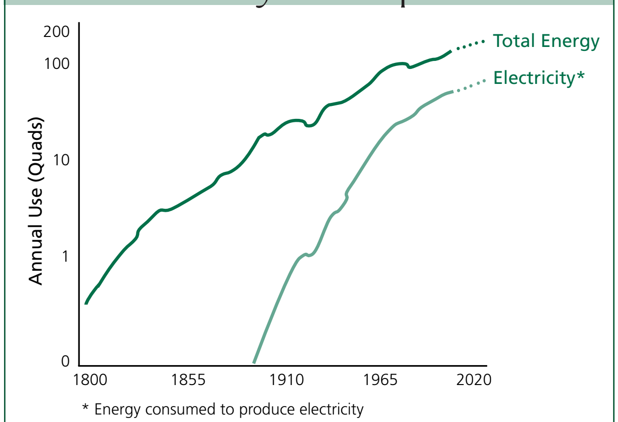
ICEV stands for Internal Combustion Engine Vehicle
BEV stands for Battery Electric Vehicle

Source: Gary Kendall, *Plugged In: The End of the Oil Age*, World Wildlife Fund, p. 89,
http://assets.panda.org/downloads/plugged_in_full_report___final.pdf

energy-efficient than today's conventional [internal combustion engine vehicle], across the entire plant-to-wheels life cycle."

Happily for the environment, the economic advantages of electrification were recognized long before environmental concerns came to the fore, and electricity has been progressively displacing other forms of energy in factories, offices, and homes since Thomas Edison fired up his Pearl Street generators in New York in 1882. The electrification of these sectors was propelled by normal market forces and rapid innovation in technologies that turn electricity into heat and motion. Most recently, electricity has emerged as the only form of energy that can power the information technologies responsible for our burgeoning postindustrial wealth. Over 60 percent of our GDP now comes from industries and services that run on electricity; in 1950, the figure was only 20 percent. More than 85 percent of the growth in U.S. energy demand since 1980 has been met with electricity.

Figure 3. U.S. Energy and Electricity Consumption



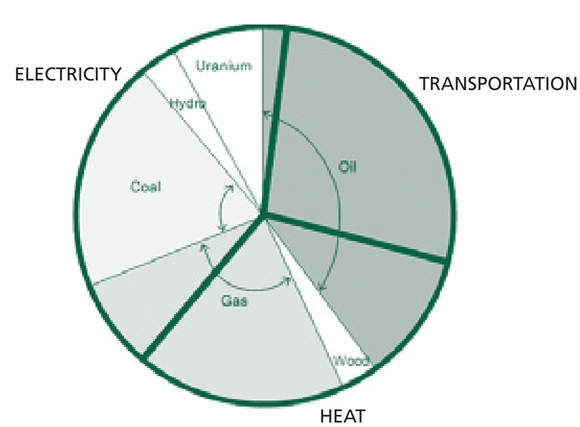
* Energy consumed to produce electricity

Source: Energy Information Administration and U.S. Census Bureau

Finally, with electricity, America controls its own destiny. We currently consume about 7 billion barrels of oil a year and get the energy equivalent of about 11 billion barrels of oil from coal, gas, uranium, and hydroelectric dams.

We generate almost all our electricity with fuels from the not-oil side of the ledger, and electric power plants consume over half of the not-oil fuel. Oil's share of the global and the U.S. energy economies has fallen more than ten points since the Arab oil embargo of 1973. Gas (a growing fraction of it used to generate electricity) and coal (almost all of it used for electricity) grabbed half of what oil lost, and uranium took the rest. Taking into account the electricity generated with those three fuels, coal, gas, and uranium have crushed oil in markets that account for over 70 percent of total U.S. energy consumption.

Figure 4. Primary Fuels and Uses

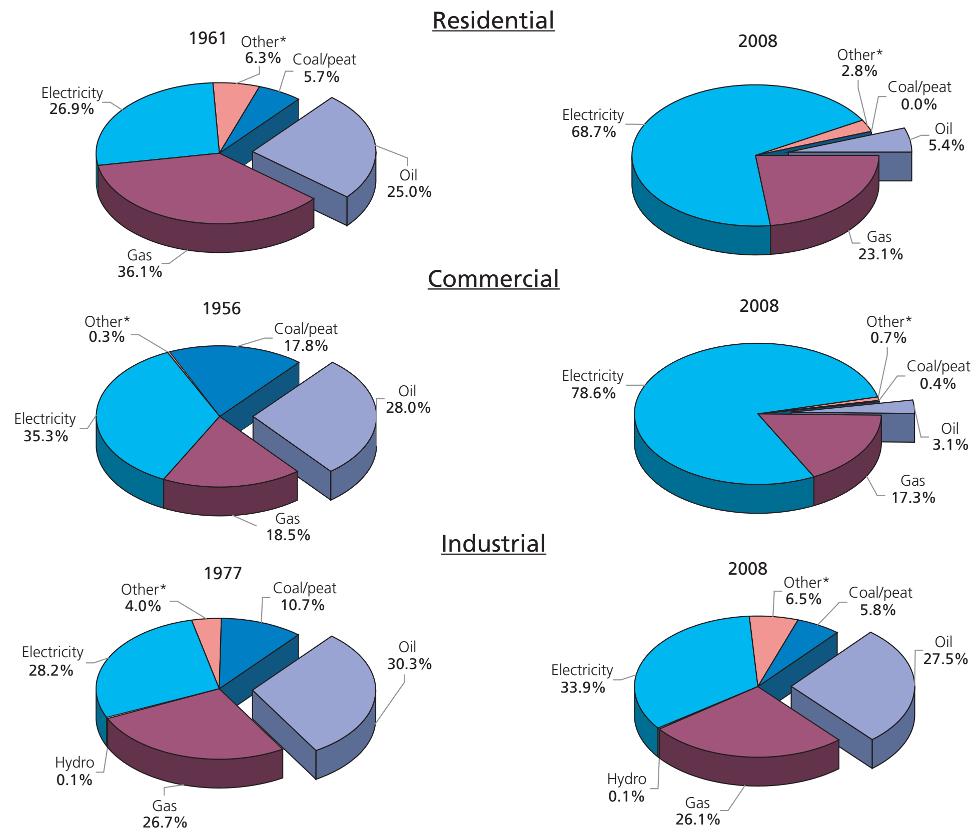


Source: P. W. Huber & Mark P. Mills, *The Bottomless Well* (Basic Books, 2005)

Looking to the future, power plants can run on almost anything. They can spin their turbine generators with steam—which they can produce by burning coal, gas, oil, wood, trash, or other combustibles—or they can replace the furnace with a uranium reactor, or they can replace the steam with water in a hydroelectric plant or wind turning a windmill. Solar cells skip the spinning stage, transforming sun directly into electricity.

However the electricity is generated, it will be generated almost entirely with domestic, not-oil fuels. We have abundant supplies and reliable access to all fuels that we currently use to generate electricity, and the development of wind, solar, and other renewables will only expand our homegrown options. Moreover, and in any event, the cost of our electricity depends mainly on the cost of capital, labor, and know-how, the most inexhaustible and renewable resources on our planet.

Figure 5. Squeezing Oil Out of Three U.S. Sectors — Peak and 2008



*"Other" includes geothermal, solar, and biomass

Source: Energy Information Administration, http://www.eia.doe.gov/emeu/aer/txt/ptb0201b.html; http://www.eia.doe.gov/emeu/aer/txt/ptb0201c.html; http://www.eia.doe.gov/emeu/aer/txt/ptb0201d.html

PUTTING IDLE CAPITAL TO PROFITABLE USE

One way or another, the companies that own and manage the last mile of electric grid will have to play a large role in any scheme to deliver grid power to our wheels. It may well have to be a considerably larger role than many policymakers currently assume. Without aggressive, risky, forward-looking capital investment by the old-guard electric companies whose capital and know-how keep the grid lit today, electric miles may end up too expensive and inconvenient for all but a very small minority of drivers.

The most important economic fact about electricity is that most of its cost is tied to capital investment in the hardware that turns cheap, raw fuel at the power plant into high-grade power at the plug. We generate about 80 percent of our electricity in plants that run on coal, uranium, or water behind a dam, and in all these plants, the amortized cost of the hardware dwarfs the cost of the fuel. Roughly half of the hardware is in the plant itself, the other half in the vast network of wires that moves the power from the plant to millions of dispersed users. The wires alone cost more than the fuel. Most of the additional cost of getting the electricity to the wheels also lies in the cost of the hardware, not the additional energy required to get it there.

The economics of electric miles is even more capital-intensive. That kilowatt-hours are four to eight times cheaper than gasoline at the curb is, at present, almost irrelevant; for now, the amortized cost of the batteries in the electric car dwarfs the cost of the grid power that could be used to charge them. For most drivers today, these cars would not make economic sense even if grid electricity were free.

Moreover, as soon as they arrive in any significant numbers, plug-in electric cars will also require new investment in the grid—without it, the cars will soon start blowing network fuses and blacking out homes and neighborhoods. The issue isn't whether distant power plants can generate enough electric power—they can—but whether the grid's last-mile wires and transformers can deliver it. In most areas, they cannot. The kinds of buyers who are likely to buy the first generation of plug-in hybrids are very likely to want the high-speed, higher-voltage chargers. Those chargers draw up to 7 kilowatts—about as much as three typical homes need when all their air conditioners, major appliances, and lights are running. Utilities in California, Texas, North Carolina, and other areas are already hard at work upgrading transformers and other equipment in neighborhoods that are most likely to buy these cars.

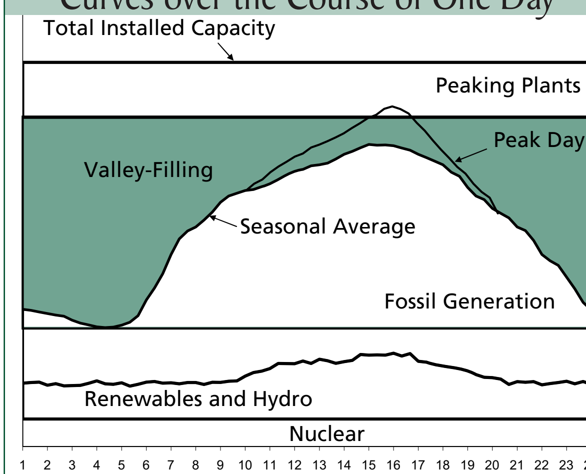
But even something as seemingly simple as upgrading pole-mounted transformers points to the far larger opportunity that electric cars present. The grid is currently engineered to guarantee "always on" service. It has to be because so much of our daily life and economic productivity shuts down when the power fails. A complete loss of power blacks out telephone switches, wireless cell towers, bank computers, E911 operator centers, police communications networks, hospital emergency rooms, air-traffic control, streetlights, and the electrically actuated valves and pumps that move water, oil, and gas, along with the dedicated, highly specialized communications networks that control those physical networks.

To provide something close to always-on service, electric utilities must grossly overengineer their networks. They have to deploy enough capacity in both power plants and wires to accommodate the very highest loads that the grid will face only once every few years, in mid-afternoon on the very hottest day in summer. All the rest of the time, much of that capacity stands idle. On average, day and night over the course of an entire year, about half of the total generating capacity and an even larger fraction of the capacity in the wires are just waiting for a customer.

Even so, the grid sometimes fails. This is why backup generators, uninterruptible power supplies (UPSs), and standby batteries are already so widely deployed. Roughly 3 to 5 percent of the public grid's capacity is currently complemented and conditioned by UPSs—about 25 gigawatts of large UPS capacity in businesses and government buildings and another 10 to 15 gigawatts of capacity in smaller desktop-size units located in both businesses and residences. Batteries don't need always-on grid power. Quite the contrary: they are widely deployed to address the inescapable fact that the grid power is not always on. Batteries cheerfully tolerate interruptions in the flow of power to their charging systems. Many utilities already offer cheap power under "interruptible" tariffs to customers that can tolerate a short-term loss of power during certain defined periods of the day; batteries are uniquely able to tolerate "highly interruptible power" that cedes even more on-and-off control to the grid.

From the perspective of private investors who might invest in grid infrastructure, car batteries are therefore extremely attractive customers. Batteries are the customers that are eager to buy the readily available power that no one else wants. They offer the existing owners of an enormously valuable capital asset

Figure 6. Stylized Demand and Supply Curves over the Course of One Day

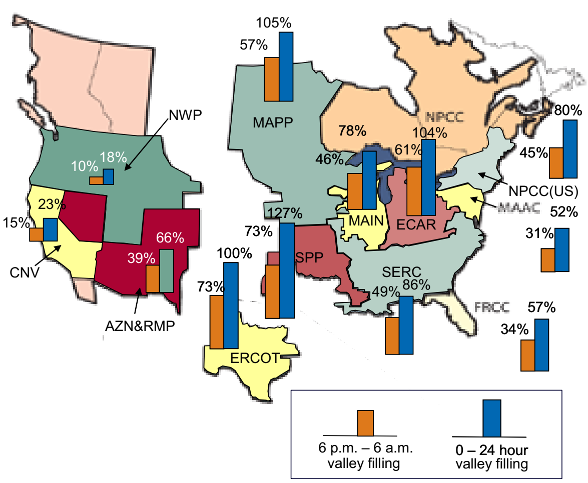


Source: Michael J. Scott, Michael Kintner-Meyer, Douglas B. Elliott, and William M. Warwick, "Impacts Assessment of Plug-In Hybrid Vehicles on Electric Utilities and Regional U.S. Power Grids," Pacific Northwest National Laboratory (November 2007).

an opportunity to use it profitably when it would otherwise be standing idle—"valley filling," in the accompanying figure.

Based on an analysis of 2002 data, for example, the Pacific Northwest National Laboratory (PNNL) concludes that using idle nighttime capacity in existing power plants and wires to recharge plug-in hybrid cars would lower the average cost of electricity in a fairly typical urban market (Cincinnati's) by about 8 percent. Anything that can lower costs by this much could alternatively boost profits by some comparable amount. The PNNL analysis also concludes that idle capacity and today's grid could power about 85 percent of all the miles driven by passenger cars, pickups, and SUVs. That would displace about one-third of current total U.S. oil consumption.

Figure 7. Percentage of Light-Duty Vehicle Miles That Existing Plants and Wires Could Power (2002)



Source: Pacific Northwest National Laboratory

Significant savings—or profits—can be captured by making better use of existing capacity in the wires alone. The wires account for roughly 30 percent of the average residential retail price of electricity, with roughly two-thirds of that cost attributable to short-haul, local distribution networks. San Diego Gas and Electric owns one nuclear power plant and buys the rest of its power (almost two-thirds of it) from others. The PNNL analysis concludes that using idle capacity in the wires to recharge plug-in hybrid cars during off-peak hours would reduce their average cost by almost 60 percent. Cincinnati Gas and Electric, which generates most of its own power near its customers, would realize a 6 percent reduction in average wire costs.

Now consider the far worse problem of idle capital inside electric cars themselves. A car is typically driven only a few hours a day, at most. Every extra dollar invested in moving electricity from the curb to the wheels will therefore sit idle about 90 percent of the time. When built in to the car, these assets cannot be shared with others. When built in to the grid instead, they can be shared. From the outset, this tilts the economics of electric miles away from batteries and toward more investment in high-speed recharging stations in garages, parking lots, compact parking-meter-like units, and other shared spaces. A single charging station in any such location can be used by many cars and by still more when it recharges them faster. By reducing recharging times and thus reducing the size of the battery required to allow convenient use of the car, fast charging stations, widely deployed, further boost the car's efficiency and range by reducing its weight. However cheap it may be, the first thing a car's battery has to move is itself.

Investing less in the car and more in the last mile of grid also leads naturally to schemes that embed more of the capital cost in pay-by-the-mile charges, which will surely suit many car buyers better than paying several thousand dollars more up front when buying the car. Employers, shopping malls, and parking garages, among many others, might well conclude that it makes business sense to give away electric miles as fringe benefits or loss leaders. Given flexibility on the prices charged for the electricity itself, utilities could certainly develop a wide variety of pricing schemes that cover all capital and associated maintenance costs from the distant power plant to the high-power link that connects with the car. That is how they have been paying for the capital investment in electrical infrastructure all along.

UTILITIES AND INFRASTRUCTURE

It is easy to suppose that existing electric utilities need not be much involved in any of this. Utilities can just file new tariffs to provide high-voltage, highly interruptible power to all comers. Regulators will review and approve these tariffs in the usual way, ensuring that they are high enough to cover costs and generate a "reasonable" profit for the electric company, but no more.

But this view of things ignores the political realities of utility regulation. At the end of the day, public utility commissions are political institutions with a strong inclination to keep tariffed prices low. When regulated utilities make new investments that boost efficiency and lower costs, the commissions are usually quick to pass the savings through to end users. When new investments don't work out well, there is often strong political pressure to force the utility and its shareholders to shoulder much of the loss. In this regulatory environment, prudent utilities have strong incentives to proceed cautiously with new investments. Getting well out ahead of demand is economically perilous.

New investment in infrastructure intended to serve electric cars will be especially risky. How soon the cars will arrive in sufficient numbers to become profitable customers, if ever, depends on car companies, drivers, oil markets, environmental politics, and countless other factors. Even if a national, high-speed charging infrastructure could be wished into existence overnight, retiring enough gasoline cars to make this new infrastructure profitable would still take many years. Without a significant stake in the upside, utilities have good reason to let buyers of electric cars take the lead before deploying new battery-charging infrastructure. But many potential buyers of the cars who would use it probably won't buy without infrastructure in place.

The stage is thus set for an "after you" waiting game played out between electric companies and car buyers, with oil companies most likely to emerge as the winners. This may explain why many car manufacturers and policymakers seem to be staking so much on the development of much cheaper batteries. If they can wish a very rosy battery future into existence, the proponents of electric cars need not wish for anything else. The wishful battery future is also the path of least regulatory and political resistance, particularly when it leads only to government tax breaks and subsidies.

At this point, however, less wishful but more practical engineers know only that getting electricity to the wheels in the most economically efficient way will require tight coordination of capital investment from end to end. The free-market path to getting there hinges on giving every company that already owns, or cares to invest in, any part of the electron pipeline—electric utilities certainly included—the freedom and flexibility to invest new capital, set prices, recover costs, and earn profits commensurate with the risks, while working closely with car companies at one end and car owners at the other.

Policymakers who trust market forces more than their own ability to foretell the details of the technological future will focus on unleashing the capital and know-how of electric utilities because they have a great deal to unleash and will play an essential role, in any event. And this happens to be an area where new private investment, risky though it will be, holds out the promise of potentially enormous gains.

Building out an infrastructure that can pump cheap electricity quickly into batteries dispersed across cities and along highways nationwide will certainly require substantial new investment. But the sums involved are, nevertheless, very modest compared with the potential profits to be captured by turning to productive use the vast amounts of the often-idle capital already invested in electric power plants and the grid. And beyond those profits lies the possibility that these comparatively tiny—albeit risky—investments in last-mile grid infrastructure will allow a vast amount of existing but often idle capital investment to compete head-to-head against oil companies, in the (roughly) $300 billion market for powering our cars. To put that number into perspective, the entire retail U.S. electric market currently generates about $350 billion a year.

Pragmatic engineers and economists will also keep a firm grip on practical reality here. There are indeed ways to sell electric miles without involving electric utilities in the provision of anything much more than power sold at standard, tariffed prices. Off-peak power can be delivered quickly to batteries, even during peak hours, by recharging stationary batteries the night before and then using those batteries to recharge cars some hours later. Cars can be designed with battery packs that can easily be switched in about a minute, using a simple lift and trolley, with all the recharging done outside the car. Several electric-vehicle manufacturers are working on designs that will facilitate battery switching, and a number of switch-and-recharge companies have been formed to serve the market.

But almost all the extant discussion of these alternatives downplays or ignores the overarching economic facts. The most economically efficient scheme here will be the one that makes the most efficient use of capital investment in electric infrastructure from the power plant to the wheels. The old-guard companies that generate and transport electricity own and will continue to own most of that infrastructure. Investments in assets that can be shared by many users will usually be cheaper than the alternative because the grid and the cars both stand idle so much of the time. While the amount of new investment required is modest compared with what is already out there, the cost of building out a national broadband electric grid will cost a lot and require a great deal of sophisticated coordination. The big electric utilities have the resources and the patience to invest for the long term that very few other companies can match.

Because they already have so much invested in assets that are so often idle, and because batteries offer a perfect demand-size fit to that supply-side opportunity, these companies also have a much bigger incentive than anyone else, car companies included, to get electric miles rolling. They alone are in a position to earn potentially enormous profits by making productive use of otherwise idle assets already paid for in full by others who need always-on power. They also have a strong incentive to deliver this kind of power as fast as they can, whenever it's available, because idle capacity in the grid, like an empty seat on a jumbo jet, is a perishable good—use it or lose it.

A MODEST PROPOSAL

A regulatory regime crafted to engage the private capital and know-how of electric utilities in delivering electric miles might look something like this. The utility is free to sell high-voltage, highly interruptible power at any price that it cares to set. It is free to buy, own, deploy, lease, or sell wires, batteries, and all other ancillary capital assets used in delivering electric power to mobile platforms, including hardware embedded in the platforms themselves. It may sign customized contracts and service agreements with municipalities, employers, mall owners, parking garages, individual homeowners, and most anyone else. These contracts may, among other options, involve take-or-pay pricing structures that combine the cost of providing power with the deployment of new facilities required to deliver it, much as wireless carriers embed much of the cost of cell phones in monthly service costs. In providing these services, utilities are free to buy power from other companies at market prices and free to make productive use of idle capacity in facilities that they already own or may subsequently deploy. They are equally free to collaborate with manufacturers of cars and ancillary equipment however they see fit.

At the technical level, an important role for federal regulators will be to facilitate the development of nationally uniform, plug-and-roll standards for linking cars and other mobile platforms to the grid. Beyond that, both state and federal utility regulators will require no more than proper accounting to ensure that the provision of new, interruptible, high-voltage services is not cross-subsidized by higher prices charged to customers who don't use them. The federal and state agencies that regulate the prices charged for the use of existing wires and (some) power plants will allow those facilities to be used at marginal—not average—cost (including a normal rate of return) insofar as they are used to provide high-voltage, highly interruptible power to the curb. This is the economically efficient price point; in any event, and by enabling the build-out of new infrastructure that will lead to more efficient use of wires in the long run, it will lower average costs for all.

This modest proposal will sound wildly deregulatory only to those who have forgotten how the grid that carries bits rather than power made the transition from narrowband to broadband. The free-market policies that will mobilize private capital to deliver broadband electricity to our wheels will, by and large, resemble policies that unleashed private capital to deliver broadband bits to our computers, PDAs, and wireless phones.

From the 1950s, when IBM began shipping the first large digital mainframe computers to commercial customers, until well into the 1980s, most digital traffic was simply funneled through local lines and long-distance trunks that had already been deployed to carry voice traffic. End users bought and installed almost all the new hardware that allowed their data to piggyback onto the existing voice infrastructure. Many of us can still remember mounting a painfully slow analog modem inside our first, digital computer, and painstakingly configuring the modem to mimic the process of dialing up a number on a regular voice telephone line to establish a connection with a single distant server that was standing by to answer the computer's call.

As regulators saw it at the time, the phone company's role was to continue doing what it had been doing for the last half-century: maintaining a network of dumb wires and switches. The advent of digital technology hadn't changed its mission at all. The company would continue to provide "common carriage"—ubiquitous, one-size, slow connections to almost every American household, at a uniform, low price. To promote that end, federal and state regulators had, for decades, jacked up the prices for long-distance calls and all business services, subsidized rural services at the expense of urban, and put into place a snarl of other surcharges and subsidies. Cable companies, broadcasters, and other operators or wireless telecom services were hemmed in by similar, rigid regulatory visions of how these companies would advance the narrow, officially defined "public interest," what technologies should be used to provide the officially approved services, and how the services should be priced and paid for.

When computers surfaced in the 1950s, Washington's principal concern was that the old-guard regulated monopolies—the hugely wealthy and technologically brilliant Bell System, in particular—would stifle the evolution of competition in the new digital world. The Federal Communication Commission (FCC), followed by antitrust regulators, therefore imposed a policy of "maximum separation" between pure-transport "common carriage" provided by phone companies and any "enhanced" services that involved storing, retrieving, or changing the content that moved through the wires.

On the far side of this fence, the providers of computers themselves, all other forms of "customer premises equipment," and all enhanced services, whatever they might turn out to be, would be left completely unregulated. They would pay no franchise fees, file no tariffs, and be subject to no significant regulation of any other kind. To ensure that state regulators did not interfere with demands of their own, the FCC placed these products and services exclusively under federal jurisdiction, even as it declared that it would "forbear" from regulating them at all.

The new services were thus lifted out of the ambit of old, one-size-fits-all utility regulation. They were cut loose from the legacy cocoon of mandates, subsidies, technical prescriptions, and regulated tariffs that surrounded basic local phone, cable, and broadcast services, and consigned to a free market's regime of flexible, private contracts. The regulation that remained focused mainly on proper accounting to ensure that the costs of providing the new services were kept separate from the costs of providing the old.

With the benefit of hindsight, we now know how much of this policy was exactly right and how much of it was dead wrong. Deregulating the new digital technology, along with prices charged and profits earned by those who deployed it, was essential. In the end, private capital poured in to transform the narrowband voice network into a broadband digital network. But it poured in a good bit later than it should have. The assumption that the capital and coordination would be provided by everyone except the old, tightly regulated phone, cable, and wireless companies proved to be diametrically at odds with engineering and economic reality.

While Bell Labs had invented the transistor, the old-guard communications companies didn't invent or manufacture fiber-optic glass, packet switches, web servers, or broadband digital radios—still less the web browsers, search engines, or social-networking services. But ultimately, the old guard did play the central role in providing the capital and overseeing the deployment of broadband technology in the network itself, right down to the digital modems and other network interfaces on customer premises. As regulators gradually relaxed the "maximum separation" policies, old-guard companies were the ones that mobilized the resources to build the digital wire-line and wireless networks that now knit together all the rest.

Phone, cable, and wireless companies quickly grasped that in a deregulated environment, digital devices and services presented major new opportunities for profitable investment. These companies also knew that they had the capital, patience, and know-how to take on the vast challenge of broadbanding America—and they had good reason to doubt that newcomers could beat them at their own game. So they invested, and have continued to invest, enormous amounts of private capital in the development of a broad, technologically varied mix of fiber-optic glass, coaxial cable, traditional but juiced-up copper telephone wires, and high-speed wireless data networks that operate on multiple different standards. They extended service first to early-adopter neighborhoods and built out from there.

Crafting the right incentives to promote a comparable build-out of a high-voltage electric network presents two additional, fundamental challenges. The build-out may well have to lead rather than follow. Standalone desktop computers were useful and affordable from the get-go; the high-speed data networks were built out later to address already established demand. It is far less clear, however, that electric cars will multiply without a high-speed charging infrastructure quite widely deployed across—at the very least—large segments of cities and their suburbs. The closest telecom analogy here is the cell phone. The wireless network has to come first, accounts for most of the cost of using a cell phone, and provides not only a connection but also much of the higher-level functionality and services.

Electric grids also require much tighter coordination than is required to direct the flow of digital traffic through data networks. A key technical breakthrough in the coordination of digital networks was the rise of the packet switch. It largely obviated the need for real-time, end-to-end, call-by-call control systems that the Bell System had used to control its "circuit-switched" network. The electric grid, by contrast, moves gargantuan amounts of raw energy, not lightweight digital bits, through a network that is inherently and inescapably hierarchical. The gigawatt grid, unlike the digital, will continue to require a very high level of integration and real-time, end-to-end oversight and control.

When networks that coordinate the flow of grid power fail, or just fail to do their job quickly enough, surges of power generated by spikes in either supply or demand slosh up and down through the wires like waves in a bathtub. At their worst, they trigger events like the blackout that struck the Northeast on August 14, 2003. The northeastern grid wasn't even particularly stressed that day. There was no great heat wave on the East Coast, the major transmission lines were not running at full load, and there was generating capacity to spare. The nominal first cause of the blackout was a single tree interfering with a major power line.

The tree had triggered an hourlong series of line failures and plant shutdowns in northern Ohio, near Cleveland—and the implications had simply gone unnoticed and unattended because a computer had been switched off and a technician was out to lunch. Neighboring utilities spotted the problem quickly and started phoning others further afield to warn them of the impending disaster, but they couldn't move the information fast enough to stay ahead of the power. As the follow-up investigation concluded, the computer tools used to diagnose the state of the grid supervised by the Midwest Independent Transmission System Operator were "under development and not fully mature" when the fateful tree fell in Ohio. The Operator itself, along with its computer systems, had been set up in late 2001, under the supervision of federal regulators, to facilitate the transition to competitive power markets across fifteen states from Texas to Ohio, and up into Manitoba, Canada. On August 14, a grid moving gigawatts of power collapsed because it failed to move a couple of screens' worth of data and execute a few hundred bits' worth of digital logic.

When things are working right, the grid's supervisory control and data acquisition (SCADA) networks move the bits that control the power. Sensors and dedicated communications links feed information about the state of the grid to regional transmission authorities and utility control centers, and the latter control the switches. With advanced control software, interconnected data networks, and high-speed, high-power switches at key locations, the grid could readily be made as smart as it is powerful. Power suppliers know where to put the software and the switches. But in the years leading up to the 2003 blackout, regulators had entirely failed to give grid operators the economic incentives to upgrade these control networks. However unwittingly, regulators had contrived to channel investment capital away from the wires that needed it most. With real-time access to SCADA networks in Ohio, utilities across the Northeast would have seen the August 14 problem coming many minutes, if not hours, before it hit, and could have activated protective switches before the giant wave swept east to overpower them.

To get broadband electricity to our wheels, the companies that own the wires will have to upgrade these control networks and extend their reach all the way to drivers and their cars. Supplying cheap electricity quickly to batteries hinges on exploiting idle capacity; the corollary is that the flow of power to charging stations must be highly interruptible. Demand for battery-charging power, as well as the availability of spare capacity in wires and power plants to supply it, changes constantly. Rapid communication with batteries—the ones driving down the road as much as those that are standing still—is therefore essential. If the car is smart enough and knows where it next plans to stop, and for how long, it can also start relying more heavily on its onboard battery to take full advantage of cheap grid electricity and recharging capabilities available just a few miles down the road. GPS navigation systems and wireless communications networks can readily be used to optimize this process. The right communications networks can simultaneously do much to dispel the driver's range anxiety.

There are no significant technical obstacles to adding this level of tight integration between the power grid and wireless networks that carry bits. But the rise of the very large fluctuations in loads that electric cars can cause as they abruptly plug into or unplug from the grid will make fast, ultrareliable electric control networks more essential than ever before. If these data networks fail, they may well trigger blackouts that extend far beyond the recharging stations. The companies that own the wires and are ultimately responsible for keeping the grid lit must be intimately involved in ensuring the robust integrity of these data networks from end to end. If regulatory and economic obstacles stand in the way, these companies will have strong incentives and good reason to proceed very cautiously with the build-out of new infrastructure that could so easily end up destabilizing large swaths of the grid. With the right incentives in place, these companies will see electric cars as their most profitable customers, and will treat them accordingly. Familiar technologies and the equally familiar economic fundamentals of large capital investments thus delineate the broad contours of how we might get fast, cheap, inherently efficient—and therefore, inherently clean—grid power to our wheels. Beyond that, it's impossible to predict the details of how the fast-evolving technologies involved might now coalesce to transform the way we power our cars and other mobile platforms.

The best public policy, in these circumstances, will be one that unleashes market forces and private capital—including, most especially, the enormous resources and technical know-how of the companies that operate and power the existing grid—to explore many different options and find their own way to the ones that make economic sense. The worst policy will be one that suppresses that process with mandates, subsidies, tariffs, and prescriptions. However well-intentioned, any such policy will inevitably tilt technology choices in this fast-evolving sphere in one direction rather than in others, and thus disrupt the market's search for economically optimal solutions.

Policymakers concerned with the transportation sector and its voracious appetite for oil should have the wisdom and courage to cut loose the private capital needed to deliver large amounts of electric power quickly and cheaply to our wheels—and let market forces take care of the rest.

The Center for Energy Policy and the Environment advances ideas about the practical application of free-market economic principles to address today's energy issues. It challenges conventional wisdom about energy supplies, production, and consumption, and examines the intersection of energy, the environment, and economic and national security.

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