Assessing the Viability of Level III Electric Vehicle Rapid-Charging Stations

by

Radu Gogoana

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Submitted to the Department of Mechanical Engineering
on May 10, 2010 in partial fulfillment of the
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ABSTRACT

This is an analysis of the feasibility of electric vehicle rapid-charging stations at power levels above 300 kW. Electric vehicle rapid-charging (reaching above 80% state-of-charge in less than 15 minutes) has been demonstrated, but concerns have been raised about the high levels of electrical power required to recharge a high-capacity battery in a short period of time. This economic analysis is based on an existing project run by MIT's Electric Vehicle Team, of building a 200-mile range battery electric sedan capable of recharging in 10 minutes. The recharging process for this vehicle requires a power source capable of delivering 350 kW; while this is possible in controlled laboratory environments, this thesis explores the viability of rapid-charging stations on the grid-scale and their capability of servicing the same volume of vehicles as seen by today's gas stations. At this volume, building a rapid-charging station is not only viable, but has the potential to become a lucrative business opportunity.

Thesis Supervisor: John Kassakian

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BIOGRAPHICAL NOTE:

Radu Gogoana and five colleagues at the MIT Electric Vehicle Team began a project to build a rapid-recharge sedan capable of a 10-minute recharge and a 200-mile range; a 2010 Mercury Milan was converted over the summer of 2009 and continues as a test-platform for EV research at MIT. In the fall of 2009 he and four team members designed and demonstrated a prototype modular battery pack for an electric motorcycle, complete with a charging system, capable of recharging in less than 10 minutes. To demonstrate viability, a purpose-built automatic cell cycler tested the cell used in the battery pack (LiFePO4) to over 1,400 12-minute charge cycles (at 90% total depth of discharge), with no significant loss in capacity when the cell was maintained at a constant temperature. He continues his graduate studies in the area of electric vehicle rapid-charging at MIT in the Department of Mechanical Engineering.

ACKNOWLEDGEMENTS:

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I'd like to thank the following people for taking the time to discuss the implications of the power draw from a rapid-charging station, at the electrical utility level:

Mr. Keith Sueker – Curtiss Wright Flow Control

Mr. Watson Collins – Northeast Utilities

Mr. Corey Landy – Benshaw, Inc. (A Division of the Curtiss Wright Flow Control Company)

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1. BACKGROUND

1.1 Brief Electric Vehicle History:

Electric vehicles were around before gasoline cars. In the early 1900's the competing technologies for light-duty vehicle propulsion were steam, electric and gasoline power: steam cars were complex and dangerous for the average consumer to operate, while electrics had a limited range and took hours to recharge. Overcoming these troubles, gasoline came to dominate consumer vehicle propulsion for the next century.

That's not to say that electric vehicles went down without a fight: Thomas Edison experimented with alkaline batteries that had a flushable electrolyte – all in the name of getting around the problem of inconvenient recharge times. At the time, the power/weight ratio of electrics was comparable to the first gasoline-powered cars; the Ford Model T was barely pushing 20 horsepower. Limited range due to long recharge times sealed the fate of the electric car.

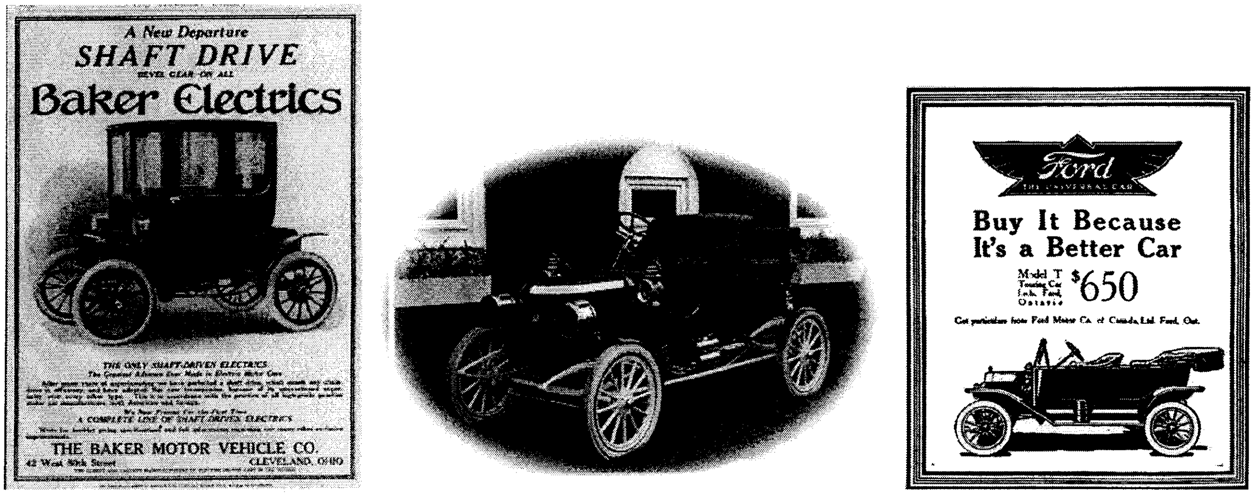

Figure 1: Electric vs. Steam vs. Gasoline (from the left: Baker Electric, Stanley Steamer, Ford Model T).
Source: Manufacturer Advertisements

Table 1: EV Charge Time, Performance and Battery Type

Year	Vehicle	Range (mi)	Battery Type	Charge Time >80% capacity (hrs)	Top Speed (mph)
1909	Baker Electric	50	PbA	4	25
1911	Detroit Electric	80	Ni-Fe	4	20
1958	Henney Kilowatt	60	PbA	4	60
1996	GM EV1	160	NiMh	3	80
1997	Honda EV Plus	110	NiMh	8	80
1997	Toyota Rav4 EV	87	NiMh	5	78
1998	Ford Ranger EV	74	NiMh	6	75
1999	Th!nk City	53	Na	6	56
2006	Mitsubishi iMiEV	100	Li-Ion	0.5	80
2008	Tesla Roadster	240	Li-Ion	3	130
2011	Nissan Leaf	100	Li-Ion	0.5	87

Source: Data from respective manufacturers

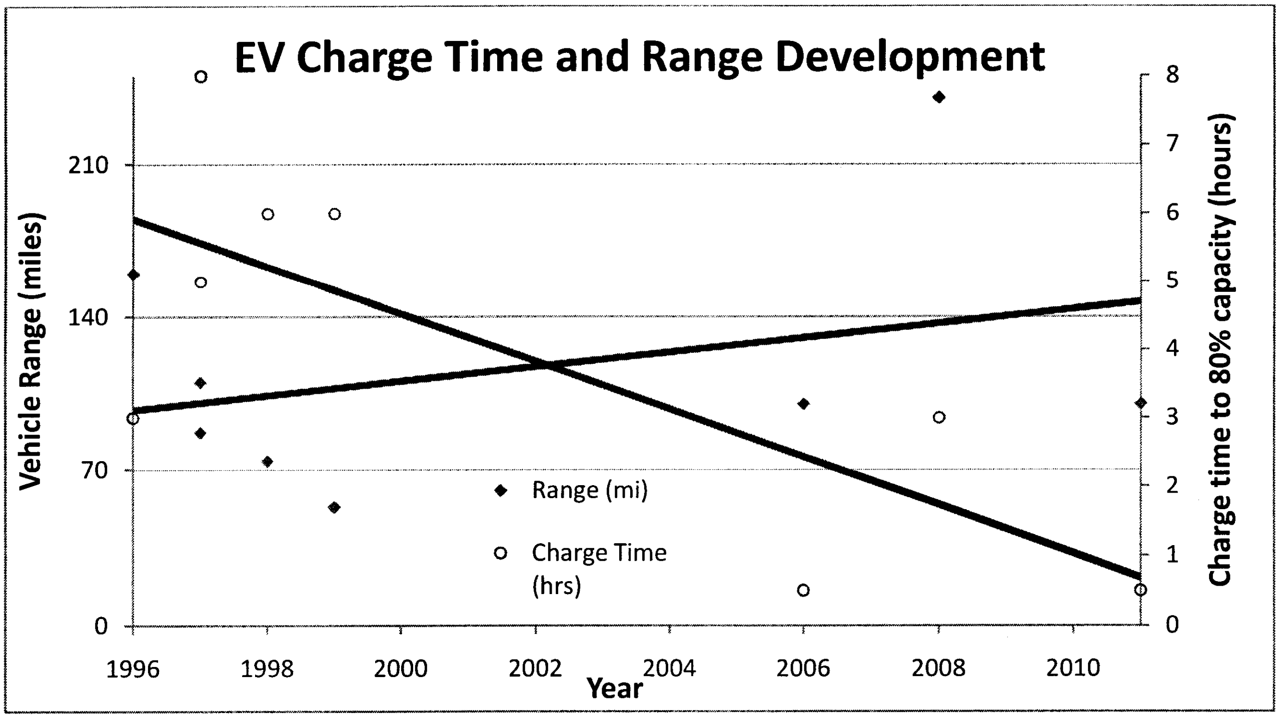

Figure 2: Graphic Representation of Table 1.

Almost a century later, battery technology has improved in both areas of energy density and recharge time. The development of lithium-based battery chemistries over the past twenty years has allowed for light, energy-dense batteries that enable electric vehicles with hundreds of miles of range on a single charge.

Nissan Leaf	Mitsubishi MiEV	Tesla Roadster
100 mi range	100 mi range	240 mi range
30 minute charge	30 minute charge	3 hour charge

Figure 3: Contemporary EV Charge Time and Range.
Source: Manufacturer Data [1] [2] [3]

Recharge time remains a question: while these cars have the range, they still take much longer to "fill-up" than a gasoline car – an inconvenience for most consumers. One answer to this problem is the Plug-In Hybrid Electric Vehicle (PHEV), which features an on-board engine/generator set to provide the electricity for longer trips once the battery has been depleted. However, until recharge-time reaches levels comparable to the time it takes to refill the tank of a gasoline car, the mass adoption of pure battery-electric vehicles will remain in question.

1.2 Current Battery Chemistry

Recent improvements in battery chemistry have reduced recharge time to as little as ten minutes. Cycle-life testing of commercially available lithium-based cells (available to consumers since 2006) has been proven to over a thousand cycles with negligible decreases in capacity. While these developments are promising for the future of electric vehicles, scaling the power requirement from recharging a single cell to a full-sized vehicle battery pack becomes problematic.

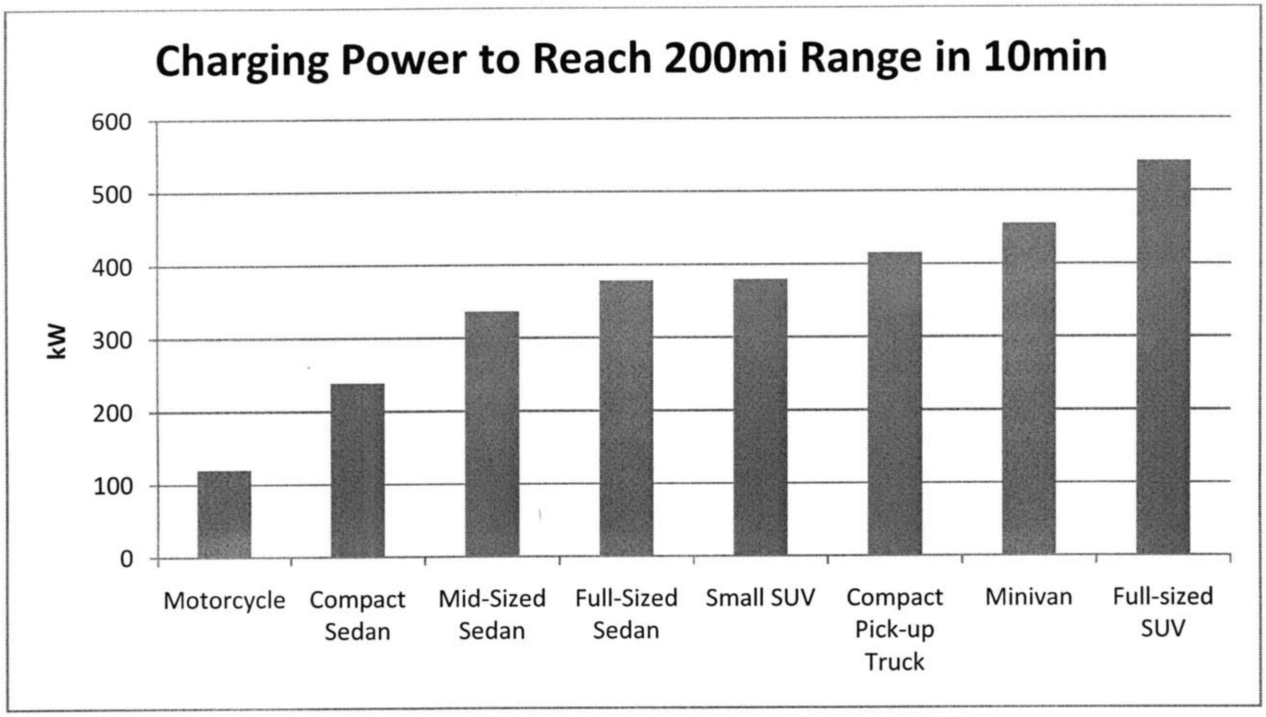

Figure 4: Charging power required, based on vehicle efficiency at 60mph constant speed. Data: Idaho National Laboratory EV testing [4], MIT Electric Vehicle Team. See Appendix A.

While rapid-charging of full-vehicle-sized battery packs has been proven at a bench-test-level, the question remains whether this is feasible on a larger scale: could rapid-charging be sustainable for a fleet of electric vehicles in the hands of consumers? What premium could be charged for this service and is it competitive with the distribution of fossil fuels? What is the impact of these high power requirements on the electrical grid?

2. TECHNICAL FEASIBILITY

Recent advancements in battery technology have allowed for rapid-charging times below 15 minutes; trials conducted by the MIT Electric Vehicle Team has demonstrated this with over 1,400 charge/discharge cycles at 12 minute charge cycles.

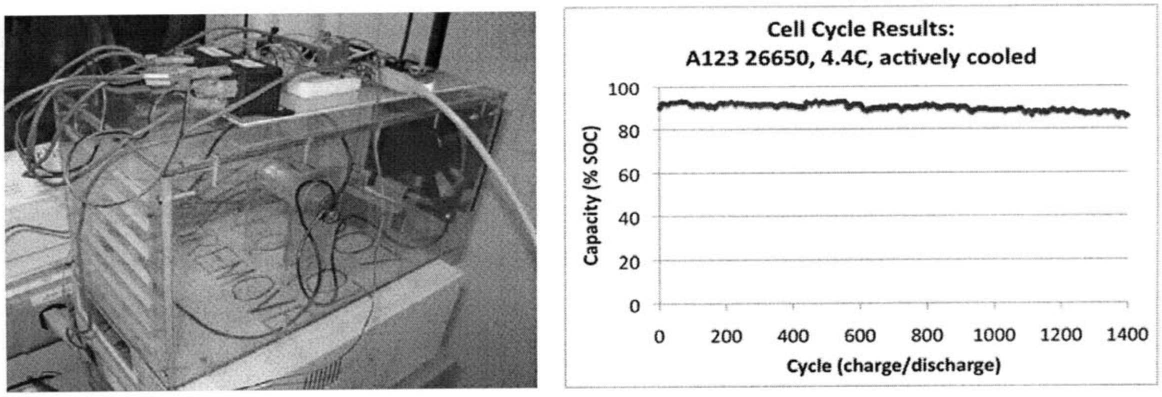

Figure 5: Rapid-cycle life testing of A123 26650 cell.

Source: MIT Electric Vehicle Team

The automated cell cycler in Figure 5 features convective forced-air cooling across the bare body of the test cell; a temperature probe recorded the maximum temperature of the cell body during testing and it consistently stayed below 25C (room temperature). During charging, one A123 26650 cell dissipates approximately 1W in heat when charged at a 5C rate.

The standard expected lifespan for a consumer vehicle is 150,000 miles; when considering 1,400 cycles for an electric vehicle with a 200-mile range, this equates to 280,000 vehicle miles. With this particular cell, the battery pack will outlast the expected life of the vehicle, by almost a factor of two, even if every single charge cycle is conducted rapidly. While this testing does not take into account the other effects that may cause battery degradation in vehicular applications (cold-weather operation, vibration, etc…), it proves that batteries exist that can support rapid-charging to enough cycles to enable vehicular use, if properly cooled.

2.1 Rapid-Charge Battery Pack Design

Using the same cells, we have further developed battery modules for a motorcycle featuring forced-air cooling across the cell body to validate rapid-charging on a pack-level.

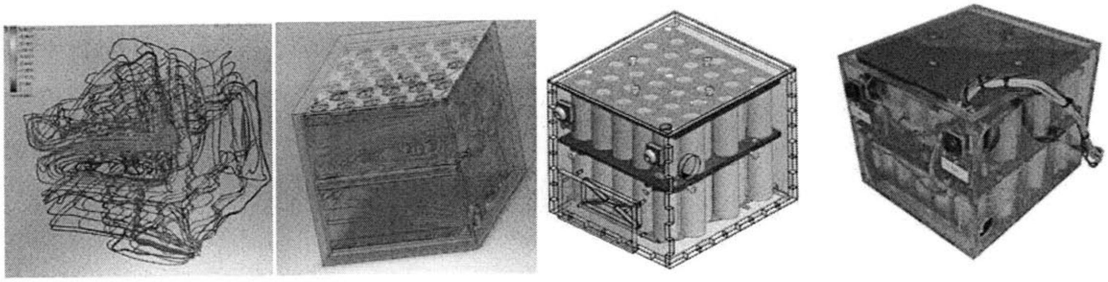

Figure 6: Rapid charge battery module design.

Source: MIT Electric Vehicle Team

The A123 26650 cells used in this testing and development have been used in power-tool applications since 2006. Other manufacturers are also entering the field of rapid-charging, with EnerDel and AltairNano both claiming rapid-charge capabilities.

2.2 Prior Art:

Other demonstration projects that have been done in the area of rapid-recharge at levels above 100 kW include:

Table 2: Prior Rapid Charge Projects

Group	SatCon	Altairnano/Aerovironment	Altairnano/Aerovironment
Time	1994	2007	2008
Battery Type	PbA	Li-MnO2	Li-MnO2
Charge Power	150 kW	210 kW	125 kW
Vehicle	Blue Bird Bus	Phoenix Sport Utility Truck	Fiat Doblo Delivery Van

Source: Manufacturer Data

Figure 6: Prior rapid-charge EV projects. From the left: Satcon, Phoenix/Altairnano, Altairnano/Aerovironment.
Source: Respective Manufacturers

The ability to rapidly recharge a vehicle has been proven independently; there bare now commercially available DC power supplies sold as chargers for this purpose. While ensuring the appropriate electrical service for a demonstration project using a single vehicle is typically not an issue, problems are expected to arise when such charging stations are expanded to recharge multiple cars at once, continuously, creating heavy point loads on the electrical grid. Assuming that the technical side from the charger to the vehicle is handled, is it feasible to create rapid-charging stations for public use? Technically, it can be done – but can it be done in a self-sustaining, economically feasible way?

3. IMPACT ON INFRASTRUCTURE

There are a few variables to consider when sizing components for a rapid-charge station, as each will have an impact on the total electrical power required at that point.

- Number of charge ports
- Maximum power capacity of each charge port
- Duty cycle throughout the day

Although rapid-charge stations will initially share space with petrol stations and the business model is similar, the duty cycle for a rapid-charge station will be fundamentally different. For internal-combustion vehicles, the only source of energy is a petrol station, so these stations experience peak demands during rush-hour traffic. Electric vehicle owners have Level II charging stations installed in their own homes and will leave home with a fully-charged battery pack, so common commuting traffic does not need to charge at public stations.

In order to arrive at cost figures for building such a station, assumptions must be made for each of these numbers. Given that there currently are no commercially available vehicles capable of taking a 350 kW charge, a few assumptions must be made about what a charging station will look like in the future.

Rapid-charge stations will be initially most useful at highway rest-stops to enable long-distance trips between cities. As a feasibility study, we will be analyzing the potential for building a rapid-charging station halfway between New York City and Boston. The trip is 240 miles long when traveling on I-95; vehicles with a 200-mile range capability will be able to traverse this distance if provided with a quick-charging stop. Granted, the traffic flow per charge station will be much higher than it is currently for gas stations that are spread out at every exit, but the economies of scale for a higher volume service area work out favorably in reducing the continuous/peak loading ratio on utilities and providing cheaper service per kWh (this is discussed further in section 4.5).

A feasible location for a pilot rapid-charge station is a public full-service rest area; accessible from both sides of the highway, featuring both a petrol service station and fast-service restaurants. This case study will focus on the practicality of building a rapid-charge station at the Exit 74 rest stop on I-95 in Connecticut; it features all of these amenities and is 112 miles away from Boston, 120 miles from New York City.

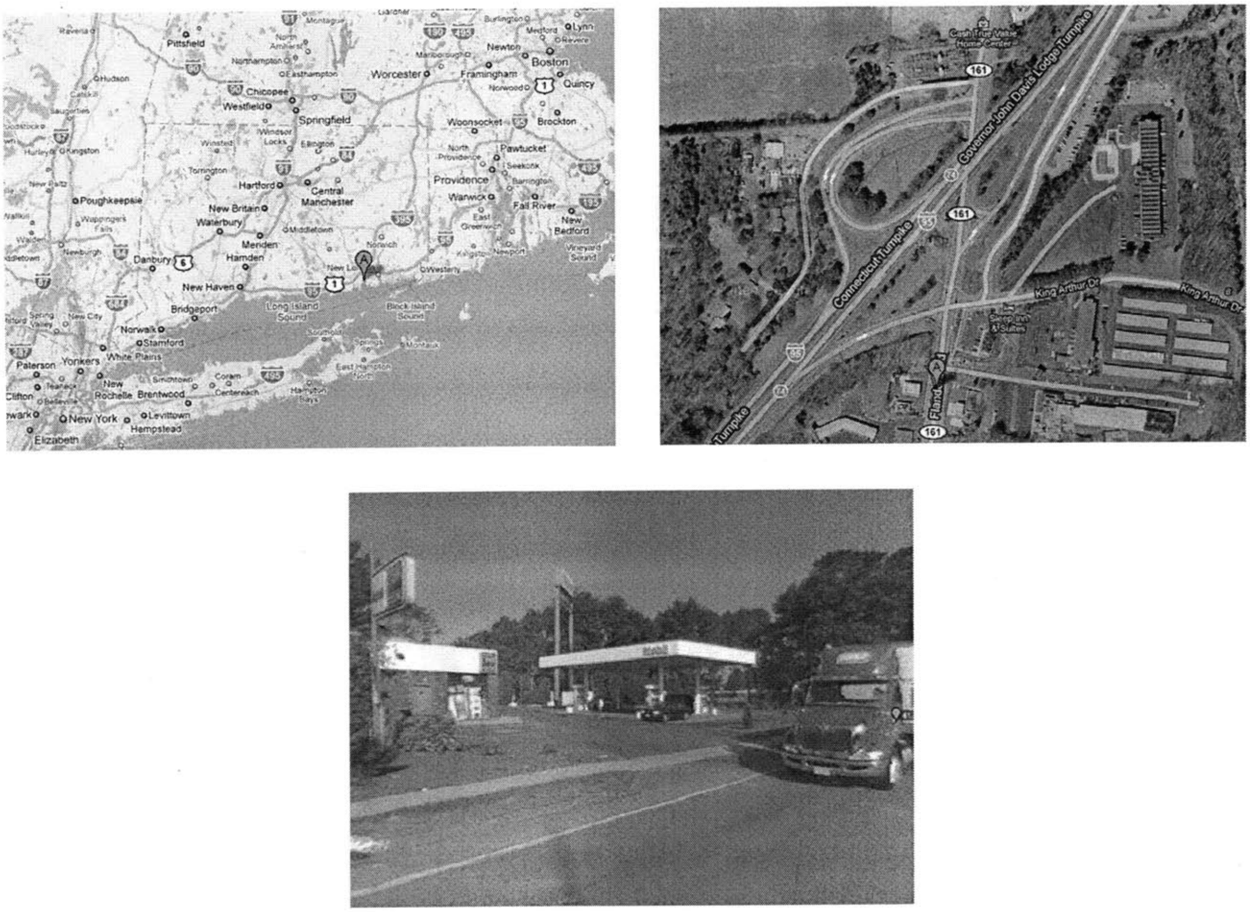

Figure 7: Location of Exit 74 "midway-point" rest stop: East Lyme, CT.
Image Sources: Google Maps.

3.1 Assumption of Station Load and Vehicle Traffic:

This report will analyze the "dream big" scenario where there are enough electric vehicles on the road to assure the same traffic flow that is seen at current rest-stop gasoline stations along I-95. In this futuristic setting, each car also has the capability of recharging at 350 kW (this is enough power to give a mid-sized sedan a 200 mile range in a 10 minute charge time), to get an idea of whether rapid-charging stations at this power level will ever be economically feasible.

For example, the Mobil gas station at Exit 74 in Connecticut is accessible from both north and south sides of the highway and sees between 300 and 400 cars on a weekday, between 400 and 500 cars on a weekend[1].

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[1] From a private conversation with the manager of Niantic Mobil, 262 Flanders Rd, 06357

Assuming a flow of 400 cars per day and a 12-minute cycle time for each vehicle (10 minute charge, along with the time it takes to disconnect and have the next car pull into the station), six charging connections are needed to allow for a station duty cycle of 55% averaged over the entire day.

With these numbers, the station will experience a peak power consumption of 2.3 MW and an energy usage of 26 MWh per day. The next question is – what is the cost of delivering electric service at this power level?

3.2 Electrical infrastructure of East Lyme, CT:

The power to East Lyme, CT is supplied by Connecticut Light and Power (CL&P). Their rates and tariffs for service above 1 MW are available on their website and drawing in a 2 MW service line is a documented process.

There are two scenarios to enable this:

1. CL&P installs a high-voltage electrical circuit near the service point and owns the transformer and related equipment (converting 13 kV to 480 V) on-site. This equipment is then rented to the user at a flat fee per month, along with the bill per kWh used.
2. The user installs the step-down transformer and all related power conversion equipment from 13kV down to 480V. CL&P only bills the electricity.

The advantage to the first approach is that the up-front capital investment is lower for the user, but there are other fees and installation costs to account for in the overall costs of building a rapid charging station that can service an equivalent number of cars as a highway-side gas station.

Power service lines above 1 MW are nothing new for industrial applications; utilities have been capable of handling the addition of high-power-draw manufacturing buildings for years. The grid-level infrastructure problems arise when hundreds of charging stations spring up on the grid; however, this phenomenon is unlikely to happen overnight. The ramp-up of rapid charging stations can only occur hand-in-hand with the mass-adoption of similarly capable electric vehicles, a process that will take years.

4. ECONOMIC SUSTAINABILITY

4.1 Cost of Electricity:

The cost per kWh of electricity for an industrial application is based the prices listed below:

Table 3: Conneticut Light and Power Company Large Time-Of-Day Electric Service Rates for Non-Manufacturers [5]

	Flat Fee / mo	Per kVA	Per kWh
Customer Service Charge	2,125.00		
Distribution Demand Charge		5.36	
Production / Trans. Demand Charge		4.82	
Systems Benefit Charge			0.00135
Conservation Charge			0.00300
Generation Charge (on peak)			0.09433
Renewable Energy Charge			0.00100
FMCC Delivery Charge			0.00602
FMCC Generation Charge			0.00300

Explanation of Costs:

Customer Service Charge: a flat monthly fee, for the lease of an on-site step-down transformer to provide this power level to the rapid charging station. If this piece of equipment were to be purchased by the charging station, this monthly charge would disappear. This is a bracketed fee: for a 2-5 MW transformer the fee is $2,125; for a .25-1 MW transformer the cost is $1,025/mo and a 5 MW+ transformer is $4,200/mo.

Distribution Demand Charge and Production/Transmission Demand Charge: the cost of "reserving capacity" from the utility. The cost per kVA is based on the customer's highest average 30-minute demand in the current month and the preceding 11 months. One thing to note is that the cost per kWh of electricity will be very high if a customer draws a very peaky load (e.g. having one 30-minute period of high demand per month, and the rest of the time only drawing a fraction of this peak demand), as distribution and transmission demand charges will be very high.

Generation Charge: Cost of producing the electricity. On-peak times are between 12pm and 8pm; all modeling in this thesis is done using peak electrical prices.

To determine the price of electricity at these rates, assumptions must be made about the traffic flow through the charging station. By assuming the same traffic flow as the current Exit 74 Mobil station, the following data is entered into the CL&P pricing model.

Demand Assumptions

Vehicle Flow	400	cars/day
Total Equipment Power Factor	> 0.9	PF
Energy per Charge	60	kWh
Max Station Power	2,333	kW
Total Station Energy	720,000	kWh / mo

Figure 8: Assumptions of Station Load.

The total monthly cost comes to $110,664 ($0.1537per kWh), with 25,878 of that being fixed based on power level demanded and 84,786 of that varying based on the amount of energy used.

4.2 Cost of Electrical Installation:

Although the step-down transformer can be leased from the utility company, all installation costs must be paid for by the industrial customer. This includes drawing a cable to the nearest distribution line (13-26kV) from the charging station, burying the cable (having the high-voltage setup above ground requires security fencing, is unsightly and is generally not used outside of industrial areas), and installing the panel for a 480VAC connection. This cost is in the tens of thousands of dollars[2], depending on the proximity of the station to a distribution line and geographical conditions. For this study, we will assume that the electrical installation costs (all equipment from the distribution line to the 480VAC connection panel) total to $50,000.

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[2] From a telephone conversation with Mr. Watson Collins, Manager of Business Development at Northeast Utilities

4.3 Cost of 400 kW DC Power Conversion

There are very few manufacturers of power supplies at this power level. As a made-to-order product, Magna-Power International sells a 400 kW system for $167,000 [6]. These costs can only go down with mass manufacturing, but we will use the available numbers for this study. Six of these power supplies will be needed.

In speaking with Mr. Keith Sueker, consultant at Curtiss-Wright Flow Control systems, the basic electrical schematic for a power converter from 480 V to 400 V looks like:

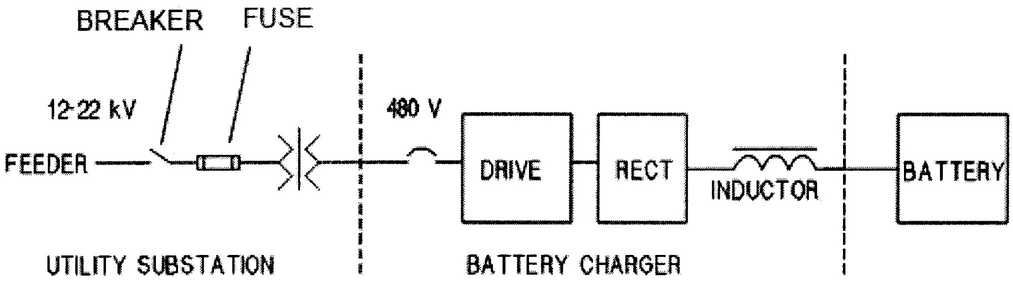

Figure 9: Basic Schematic Diagram of a Battery Charger.
Source: Mr. Keith Sueker

For an order-of-magnitude cost estimate, a power converter rated for 400 kW load, 480 V input, 400 V output, 1000 A output, as a complete stand-alone unit, with power converter mounted inside an industry standard metal enclosure, with integral input circuit breaker disconnect, associated wiring, controls, and UL listed is in the range of $75,000 with no input harmonic filtering and no output filter, and $105,000 when filtered at both ends.[3]

This is for a single unit, and contrasts with the price quote of Magna-Power's laboratory grade power supply above at $167,000 [6]. However, both of these quotes are at single-piece volumes; these numbers can only be expected to decrease to the price of the components and raw materials as production volume ramps up for commercial use of rapid-charging stations.

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[3] Email conversation with Mr. Corey Landy of Curtiss-Wright Flow Control Systems

4.4 Sale of Electricity:

The ability to rapidly charge is a convenience service; the price per kWh will be more at a rapid-charge station than at home on a Level II charger, as the customer pays for the convenience of having such a high-power electrical connection. To find this price, a rough calculation to gauge the customer's willingness-to-pay for the energy to go the same distance, in the same car, if it were to run on gasoline is below; Figure 11 shows that the resulting electricity cost is comparable.

2010 Mercury Milan Hybrid

Highway Gas Mileage	36	mpg
Cost of Gasoline	3	$/gal
Cost per Mile	0.0833	$/mi

2010 Mercury Milan Electric Conversion

Vehicle Efficiency	300	Wh/mi
Cost of Electricity	0.2778	$/kWh
Cost per Mile	0.0833	$/mi

Figure 10: Gasoline vs. Electric Cost of Energy per Mile (at 60mph).

The electric vehicle efficiency numbers are based on modeling by the MIT Electric Vehicle Team for the efficiency of their electric conversion of a 2010 Mercury Milan; the highway fuel efficiency numbers for the same vehicle are from the vehicle's EPA Rating.

With gasoline prices at $3.00/gallon, a customer is willing to pay up to $0.278 per kWh to drive the same distance. This modeling assumes that gasoline prices are at their current level and there will be a slight incentive to attract customers to buy electrical energy instead, at $0.25/kWh. This number will only increase as gasoline prices increase, sweetening the business plan for building a rapid-charge station 20 years down the line.

With a monthly energy usage of 720,000 kWh/month (Figure 9), the gross monthly revenues of such a charging station come to $195,000, with gross profit at $84,240.

4.4 Economics of a Comparable Gasoline Station:

From searching listings of gas stations of comparable size in nearby Connecticut, the market value of the Exit 74 Mobil station in Niantic, CT is between $900,000 and $1,200,000 [7]. However, this includes the cost of the in-ground tanks, convenience store and auto-service shop.

The profit margin on gasoline is extremely slim (retailers make 5-6% on fuel sales) and often rely on the convenience stores and car-washes associated with the location to supplement their business [8].

4.5 Financial Projections of a Comparable Rapid-Charge Station:

As a very basic, high-level feasibility study, the inputs into the financial projection are:

INPUTS:		
Customer Flow	400	cars/day
Energy sale per vehicle	60	kWh
Cost of electricity	0.14	$/kWh
Sale of electricity	0.25	$/kWh
Labor Costs (cashier)	35,000	$/yr
Taxes (State + Federal)	20	%
PP&E Investment	2,000,000	$
Depreciation Rate (linear)	20	yrs
YIELDS:		
Revenue Per Year	2,190,000	
Total Cost of Revenues	1,361,400	
EBIT	828,600	
Net Earnings	662,880	

Figure 11: Financial projections of a high-volume, energy buffer-less rapid charge station.

At this rate, the break-even point for a rapid charge station is less than four years, after which it will net over $600,000 from energy sales alone. The gross profit margin on electricity (at $0.15/kWh cost and $0.25/kWh sale) is 44%, compared to the 6% of petrol stations.

While the convenience stores of gas stations this size have revenues between $30,000 and $80,000 per month, a similar model could be applied to a rapid-charging station – but the longer wait times of a rapid charge station (10 minutes vs. 4-5 minutes for a gasoline fill-up) also allows for the service business to be supplemented with fast-food restaurants for the customer to grab a bite to eat while they wait, further expanding the possibilities of this business model.

Scalability:

Everything looks great with a high sales volume, but the same can be said of many underperforming businesses. Until electric vehicles with rapid-charging capability reach mass adoption to assure the sales volumes in the model above, they need to be supported by an infrastructure at a smaller scale. A natural location for rapid-charging stations is as a supplement to existing gas stations; however, the pricing model looks different with a much lower vehicle throughput.

Demand Assumptions

Vehicle Flow	20	cars/day
Equipment Power Factor	0.9	PF
Energy per Car	60	kWh
Max Power	400	kW
Total Energy	39,000	kWh / mo

Figure 12: Demand assumptions of a small-scale rapid charge station.

The same billing structure applies as in Figure 8, other than the flat fee per month for renting a transformer, which is now lowered to $1,025/mo. Although the customer service charge is less than half of that of a 2-5 MW transformer, the on-peak generation charge jumps to $0.134 per kWh (42% higher). This is for a transformer that can handle up to 1 MW – allowing the gas station to easily add another DC converter for a second charging port once the demand reaches levels where a second port makes fiscal sense.

However, running these costs through the standard CL&P billing profile yields a surprise; with this load profile the cost of electricity per month comes to a staggering $0.23/kWh! This is because of the peaky nature of the load demanded. The difference between the load profile of the

6-station, 400 vehicle-per-day scenario and the 1-station, 20-vehicle-per-day scenario is that the total amount of energy transferred is reduced by a factor of 20, but the peak power requirement is only reduced by a factor of 6. To put it another way,

Continuous/Peak (20 cars/day) = 52.4 kW/400 kW = .131

Continuous/Peak (400 cars/day) = 1,048 kW/2,300 kW = .456

In this case, for smaller rapid-charging stations (and until stations can guarantee this kind of vehicle volume), an energy buffer on-site will make sense.

Figure 13: Aerial view of the vehicle line at the high-volume gasoline station at the Vince Lombardi Service Area along I-95 in NJ.
Image Source: Google Maps

4.6 On-Site Energy Buffer Systems:

An on-site energy buffer system makes sense for smaller charging stations, as it allows for:

A) A much higher continuous-to-peak power ratio, lowering costs of electricity.

B) Lower cost power-electronics

Using the same station demand modeling as in Figure 13, of twenty vehicles per day (20 cars arriving over a 12-hour period), the average power consumption over that 12 hour period is only 100 kW. The peak load has been cut by a factor of 4, leading to a much lower electrical bill, as shown in Fig. 15:

Table 4: CL&P small general electric service rates.

	Flat Fees / mo	Per kVA	Per kWh
Customer Service Charge	572.50		
Distribution Demand Charge		4.42	
Production / Trans. Demand Charge		0.00	
Systems Benefit Charge			0.00144
Conservation Charge			0.00300
Generation Charge (3rd party-only option)			0.11423
Distribution Service Rate			0.01780
Renewable Energy Charge			0.00100
FMCC Delivery Charge			0.00313
FMCC Generation Charge			0.00300

With the low-volume vehicle flow, the cost per kWh is $0.1712. This approach also allows for lower-cost power electronics:

DC Power Supply:

The most expensive component of the energy buffer-less rapid charge is the 400 kW DC power supply. With a DC energy storage system, that component will only have to be rated for 100 kW. (For reference, Magna-Power's quote for a 400 kW DC power supply was $167,000; for a 100 kW power supply that plunged to $36,500).

Energy Buffer:

4.6.1 Lead-Acid:

One of the lowest-cost-per-kWh energy storage methods is by using lead-acid batteries. They're often used for grid-level energy storage, have been around for over a century and are a very mature technology. Their price per kWh of deep-cycle, maintenance-free Lead-Acid Batteries currently hovers around $150/kWh[4]. Lead-Acid batteries typically don't do well with high discharge rates or high depths-of-discharge. Their capacity is rated at a C/20 rate (the battery being discharged at a low enough current to deplete it over 20 hours); discharging at a higher C rate will significantly lower the capacity that can be drawn from the battery.

When originally sizing a lead-acid battery bank for DC-DC charging use with the MIT Electric Vehicle Team's elEVen project, to pull 60 kWh from a lead-acid battery pack in 10 minutes required a lead-acid battery bank of at least 150 kWh.

Discharging at this rate yields a near depletion of the lead-acid battery bank: to withstand cyclical use in a commercial application, it must be significantly oversized to avoid discharging to 100% depth-of-discharge.

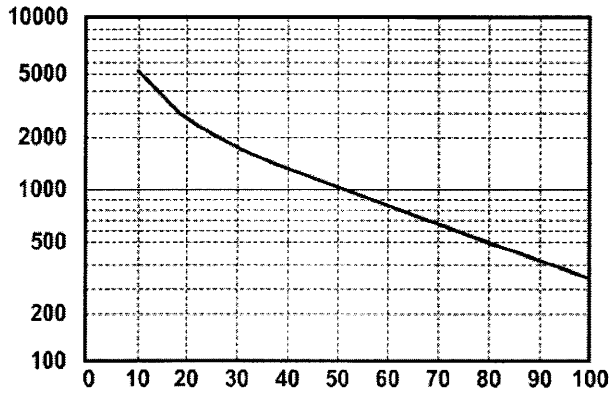

Figure 14: Lead-Acid Battery Cycle Life [9].

However, in our application, the battery bank simply acts as a buffer, and will be supplemented by a 100 kW DC power source simultaneously. Thus, only (100 kW/360 kW)*60 kWh = 43 kWh will be depleted from the lead-acid battery bank.

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[4] Commercially available quotes from http://www.alibaba.com

Using the same 2.5:1 over-sizing ratio as recommended by Trojan Battery Company[5], a 108 kWh battery bank will be needed to reach a 100% depth-of-discharge ratio for a single charge. However, this yields a best-case scenario of only 250 cycles for the life of the battery bank. Keeping in mind that with a business model of 20 vehicles per day, there will be 7,200 cycles on this stationary battery bank per year, the battery pack will need to be oversized by more than a factor of 10 – and at that point it will barely last one year. Suddenly the very attractive price of $150/kWh jumps to $1,500/kWh and it's still not good enough. Lead-Acid batteries are not an appropriate storage method for long-term operation of a rapid-charging station.

4.6.2 Lithium-Ion:

Most lithium-ion batteries have better cycle life than lead-acid cells (some Li-Ion cycle lives are in the thousands), but the cost of the stationary battery pack must still be depreciated.

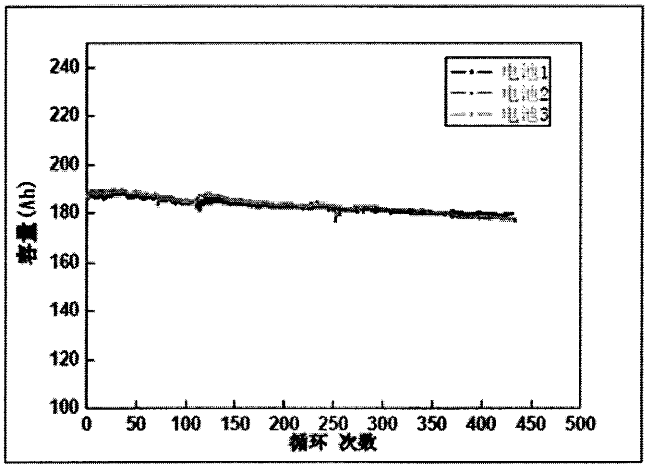

Figure 15: LiFePO4 Battery Cycle Life Data for testing a 180Ah large-format prismatic cell. (Y-axis: capacity in Ah, X-axis: cycle count).

Source: Sky Energy Corp.

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[5] Phone conversation with Mr. Ronald Paredes, Technical Product Manager at Trojan Battery Company

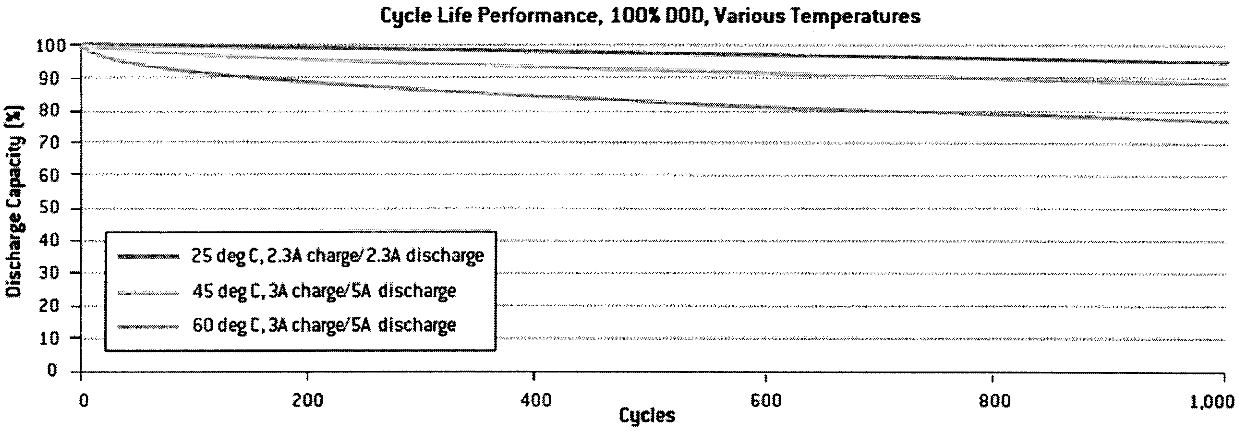

Figure 16: LiFePO4 NanoPhosphate Battery Cycle Life Data.

Source: A123Systems

Although there is little data available on the cycle life of lithium-ion cells at low depths-of-discharge to tens of thousands of cycles, their performance at 100% DOD appears promising. For pricing on these batteries, the first battery (Sky Energy) is currently available at $300/kWh and the second graph (A123 Systems) pricing has been announced by Jason Forcier, a vice president at A123 Systems:

> "Battery pack costs should fall from $750 per kilowatt hour today to under $500 by 2013 and by 2016 around $350. Half of the cost reductions will come from big volume increases and half through innovations."

Assuming a battery pack pricing of $300/kWh (both from Chinese battery manufacturers today and the pricing projections of American manufacturers) and an over-sizing of the battery pack by a factor of 3 to enable a 30% depth-of-discharge per rapid cycle, the effective price comes out to $900/kWh for this application. Thus, the stationary battery bank needs to be at 3*43 kWh = 129 kWh, costing $38,700.

Another advantage to a battery bank system is that the high power electronics to regulate DC power from the battery bank to the vehicular battery pack are cheaper in comparison to an AC to DC power supply. A 400-volt, 1,000A (continuous) capable DC motor controller is available for $5,075. Connected to an inductor to smooth out the current ripple for charging the battery pack, and the whole package can be built for under $7,000. This doesn't include the control systems or enclosure, but this large contrast gives hope that there is flexibility in the cost of the AC conversion system.

Figure 17: Café Electric DC Motor Controller: 400V, 2,000A Peak, 1,000A Continuous.

Assuming a 15,000 cycle life at 30% depth-of-discharge for the lithium-based battery pack (depreciating the battery bank linearly over two years), the financial model is as following:

INPUTS:		
Customer Flow	20	cars/day
Energy sale per vehicle	60	kWh
Cost of electricity	0.172	$/kWh
Sale of electricity	0.25	$/kWh
Labor Costs (using current gas station cashier)	0	$/yr
Taxes (State + Federal)	0	%
PP&E: (AC to DC, DC to DC, substation install)	53,500	$
Depreciation Rate on PPE	20	yrs
Consumable Equipment (Battery Bank)	38,700	$
Depreciation Rate on Consumables	2	yrs
YIELDS:		
Revenue Per Year	109,500	$
Total Cost of Revenues	97,261	$
EBIT	12,239	$
Net Earnings	12,239	$

Figure 18: Financial model for a low-volume, LiFePO4 battery energy-buffered rapid charge station.

Note that there is no labor cost (when placed at a gas station, there is already an attendant at hand), and the tax rate for electricity sold is zero (counting on incentives to speed the adoption of these units at a small scale).

With a $92,000 investment in a battery bank buffer system, 100 kW AC to DC power supply and 400 kW DC to DC converter for charging the vehicular battery from the battery bank and a $10,000 installation cost for the substation to supply 480VAC, the gross profit margin is 11.2%. The payback period for this investment is longer than a decade, primarily due to the very short depreciation period of the battery pack and the assumption of a 15,000 cycle life at 30% depth-of-discharge.

4.6.3 Flywheel Energy Storage:

Energy storage in kinetic form (massive flywheels spinning in vacuum-enclosed housings, riding on magnetic or air bearings) has been around for years. These systems are currently in use for grid-level frequency regulation and energy storage; ActivePower and Beacon Power are two large, publicly-traded firms that deal in this space.

The current energy storage cost for steel flywheels is about $3,121.2/kWh [10]. They "charge and discharge" by spinning the flywheel between two preset RPM limits and have the potential for essentially infinite cycle life, as these units have no friction/wear points with magnetic or air bearings. Their massive, under-stressed components and very low energy storage per pound ratio makes them ideal for stationary energy storage.

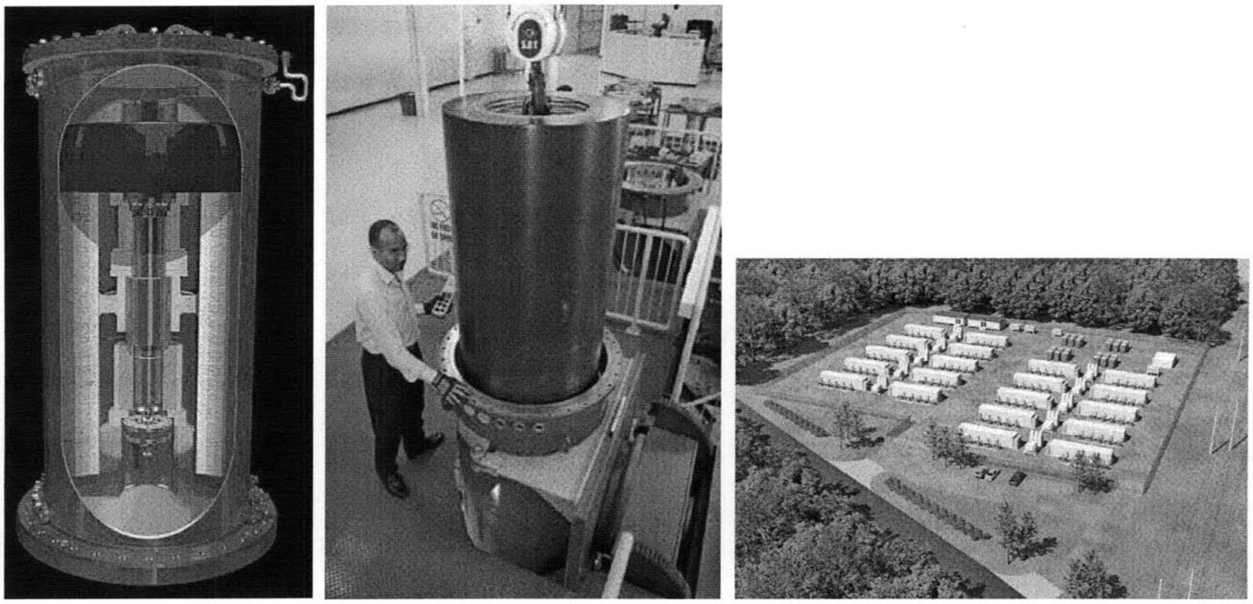

Figure 19: Flywheel energy storage systems.
Source: Beacon Power

An advantage of these systems in rapid-charging applications is that they can be used for their full rated cycle capacity. In this case, a system storing 43 kWh would cost $134,212 with "infinite" expected life. As per a report from the Investire-Network issued in 2003,

> "The high cycling capability of flywheels is one of their key features, and is not dependent on the charge or discharge rate. Full-cycle lifetimes quoted for flywheels range from in excess of 10^5, up to 10^7. The highest cycling lifetimes would only be exceeded after 20 years with continuous cycling at the rate of one full charge-discharge cycle every 100 minutes. The limiting factor is most applications is more likely to be the standby lifetime, which is quoted as typically 20 years." [11]

In addition, as these systems are designed for grid-level power leveling, they are designed to connect to AC power directly. The motors inside of the flywheels are very similar to those found in electric vehicles; their control electronics can be modified to output DC current in the same manner that vehicular motor controllers can recharge batteries in regenerative braking mode.

Summary:

Of all three on-site energy storage systems, the most attractive option appears to be a mechanical flywheel-based system. Lead-Acid batteries are out of the question and until Lithium-Ion based systems are proven to the appropriate cycle life (over 7,000 cycles per year), flywheel systems are the most sensible choice for a sustainable business model. Along with providing energy storage, they take out two of the other most costly components of the energy storage system: the AC to DC power supply and the DC-DC converter to charge the vehicular batteries from the battery bank.

Assuming the same vehicular traffic flow as in Figure 13 along with a $135,000 installation cost of the flywheel system and a $10,000 installation cost for the CL&P owned substation to supply 480VAC, the financial model is as follows:

INPUTS:		
Customer Flow	20	cars/day
Energy sale per vehicle	60	kWh
Cost of electricity	0.172	$/kWh
Sale of electricity	0.25	$/kWh
Labor Costs (using current gas station cashier)	0	$/yr
Taxes (State + Federal)	0	%
PP&E: (flywheel system + substation cost)	145,000	$
Depreciation Rate on PPE	20	yrs
YIELDS:		
Revenue Per Year	109,500	$
Total Cost of Revenues	82,586	$
EBIT	26,914	$
Net Earnings	26,914	$

Figure 20: Financial model for a low-volume, flywheel energy-buffered rapid charge station.

Due to a much lower depreciation cost than the battery-bank model, the gross profit ratio comes out to 24.6%, allowing for a payback period of 6 years when assuming a 5% discount rate. However, this is a zero-maintenance system; once installed, it should be a stand-alone generator of revenue.

5. FUTURE

There are a few fundamental differences between the business model of a current gas station and that of a future rapid-charging station.

The foremost difference is the geographic density of rapid charging stations. Because owners of electric vehicles will have a Level II (3-8 hour) slow-charging station at home, they do not need to visit a rapid-charging station other than for long trips (either locally or out of town). There are four different gasoline stations at exit 74, and there is an average of 1.5 gas stations at every exit of I-95 in Connecticut. On average, there is an exit every 3 miles. Over a 50-mile stretch of highway, drivers have the choice of visiting over 25 different gas stations, each of which get an average of over 200 vehicles per day. If there were to be a rapid-charging station every 50 miles, the flow from those 25 gas stations would be concentrated to one point – allowing for a buffer-less, high-volume charging station as described in the first scenario.

Secondly, these calculations were done using the current price of gasoline and of electricity, in Connecticut. Connecticut has one of the highest prices of electricity to commercial customers in the United States, averaging $0.1744/kWh in 2009 when compared to the nationwide average of $10.03. To be fair, the Northeastern states are likely to be early adopters of electric vehicles (the Nissan Leaf and GM Volt will be debuting there before the Midwest), so the disadvantages may balance.

However, in the projected 20 years or so when electric vehicles will be rapid-charge capable, gasoline is very unlikely to remain at $3.00/gallon. The assumed business model for a rapid-charging station involves selling electricity at just below the equivalent cost of gasoline; this will allow utilities to raise the price per kWh at a charging station far above the assumed $0.25/kWh in this report, making the business case for opening a rapid-charge station even more lucrative.

In all, the only way for a clean-energy initiative to be self-sustaining is without a perpetual government funding need. For this, it needs to be viable from a business perspective; someone needs to be incentivized to build a rapid-charging station. If the business case is lucrative enough, rapid-charging stations will spread quickly on their own, attracting private investors and ownership without a constant need for government involvement. Aside from a few tax breaks to help spur the early penetration of a rapid-charging network, the outlook is promising: building a rapid-charging station is not only viable, but has the potential to be a very lucrative business opportunity. Call it greedy, but I call it absolutely necessary for the sustainable expansion of an oil-less energy infrastructure for transportation.

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7. APPENDIX

A: Idaho National Laboratory Testing: AVTA of Full-Sized Electric Vehicles

EV Efficiencies, at Constant 60mph

Year	Vehicle	Wh/Mi	Source
1994	Solectria Force	199	INL
1999	GM EV1	168	INL
1994	BAT International (Geo Metro)	180	INL
1994	Solectria E-10 (Chevy S-10)	359	INL
1994	US Electricar Pickup (Chevy S-10)	404	INL
1997	Chevy S-10 E	307	INL
1999	Ford Ranger EV	362	INL
1994	Unique Mobility (Ford Ranger)	299	INL
1999	Toyota Rav4 EV (NiMH)	316	INL
1996	Toyota Rav4 EV (PbA)	289	INL
1994	Dodge Caravan	417	INL
1999	Chrysler EPIC	340	INL