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Operational Aspects of the Electric Fuel™ Zinc-Air Battery System for EV's

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Electric Fuel™

Operational Aspects of the Electric Fuel™ Zinc-Air Battery System for EV's

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1. Introduction

The Electric Fuel (EFL) zinc-air battery system comprises three linked system elements:

1. the on-board discharge-only zinc-air battery pack, characterized by energy density of more than 200 Wh/kg and power density of 100 W/kg at 80% DOD;

2. refueling stations for fast and convenient mechanical exchange of "Electric Fuel" cassettes, to get vehicles back on the road after a stop of only a few minutes; and

3. regeneration centers for centralized recycling of the cassettes, making the most efficient and environmentally sound use of electricity to recharge the active zinc material.

Technical aspects and performance tests of the EFL zinc-air battery have been detailed in previous publications.[1] This paper analyzes several operational aspects of the system, including energy efficiency, life-cycle cost, and sustainable power.

Previous assessments of competing battery technologies for electric vehicles have focused on independent calculations of each of the key performance characteristics, such as energy densities, power densities, charging efficiency, etc., yielding comparative lists of seemingly unrelated figures.[2]

This paper explores the interrelations between battery specific energy, i.e., gravimetric energy density, and other battery assessment criteria. Specifically, the analysis will show that higher specific energy means more than just extended driving range, and will examine the following effects:

- higher system energy efficiency because less energy is wasted in transporting the weight of the battery

- lower life-cycle cost because each cycle is longer and because more payload can be transported

- more sustainable high power for highway driving and hill-climbing

2. Energy efficiency

The conventional measure of electrochemical battery efficiency has been round-trip DC-DC efficiency, i.e., the proportion of the electrical energy invested in a battery during charging that is returned by the battery upon discharge. This measure, accounts for voltaic and coulombic losses, but ignores on-stand losses and differences in charging conditions.

This measure is appropriate for comparison of batteries that are alike in nature, such as two types of lead-acid battery. However, this is inadequate for comparing dissimilar batteries such as, for example, a sodium-nickel chloride battery (electrically rechargeable, with moderate specific energy and a high thermal loss rate) and a zinc-air battery (mechanically rechargeable, with high specific energy and centralized zinc regeneration).

When comparing such dissimilar technologies, it is more appropriate to consider a measure of efficiency for the energy system as a whole, so that differences in charging conditions or other factors can be taken into account.

Ultimately, what is needed is a determination of how much of the overall electrical energy input is used to transport people and goods, and is not

- lost in the charging system,
- used to heat the battery,
- lost through self-discharge,
- used to carry excess battery weight resulting from low specific energy, or
- wasted through inefficient utilization of vehicles with limited range and/or cargo capacity.

This can be accomplished in two steps:

1) Analysis of the net system efficiencies for each battery technology, accounting for losses in the electric utility network, electrochemical losses, charging losses, and thermal and self-discharge losses on-stand. Based on operational parameters assumed (for example, time between recharges, for calculation of on-stand losses), this can be considered an absolute number, calculated independently for each battery technology.

2) Adjustment of the efficiencies calculated in the first step, according to the respective rate of energy consumption required for each unit of vehicle travel or cargo transport. This is a relative number, dependent on the relation between the respective battery specific energies of the battery technologies compared.

Table 1 shows a breakdown of an efficiency calculation for the EFL zinc-air battery and for several other batteries considered to be near- to mid-term technology solutions for electric vehicles: sodium-nickel chloride (ZEBRA), nickel-metal hydride (several developers), and advanced lead-acid (Horizon) batteries.

There is an additional column representing a hypothetical electrically rechargeable battery that meets all of the mid-term criteria established by the United States Advanced Battery Consortium (USABC).

The calculation includes all energy uses and losses incurred from the AC output of the electric power plant to the DC output of the battery, including self-discharge losses and other technology-specific on-board uses of battery energy. The last line of the table, Net Efficiency, shows that the system energy efficiency of the zinc-air battery meets the implied requirements of the USABC mid-term criteria, and surpasses that of the hot sodium-nickel chloride battery.

Table 1. Comparison of Net Energy Efficiency (from power plant AC output to battery DC output)

EFL Zinc-Air		ZEBRA[a]	Nickel-Metal Hydride[b]	Horizon Lead-Acid[c]	USABC Mid-Term[d]
Net of losses in the electric utility grid to the regeneration[e]	94%	Net of losses in the electric utility grid to the socket [f]			
		91%	91%	91%	91%
Multi-MW power converters[g]	98%	DC power supply for recharging [h]			
Net of power consumption for regeneration operation	95%	85%	85%	85%	85%
Battery/regeneration DC-DC round-trip efficiency	57%	Battery DC-DC round-trip efficiency			
		85 (48)%[i]	80%	75%	75%
Net of self-discharge losses on-stand, on-board energy use	97%	Net of self-discharge losses on-stand, on-board energy use			
		98%[j]	80%[k]	98%	77%
Net of energy usage for Electric Fuel distribution [l]	97%	Net of gain from regenerative braking [m]			
		106%	106%	106%	106%
Net Energy Efficiency	47%	39%	52%	60%	47%

Notes to Table 1:

a. Reported in D Sahm and J L Sudworth, "Lifetime and Reliability Testing of Zebra Batteries," EVS-12 Proceedings, Vol. 1, pp. 323-339, Anaheim, California; December 1994.

b. Reported by Ovonic Battery Company in D A Corrigan, S Venkatesan, P R Gifford, M A Fetcenko, S K Dhar, and S R Ovshinsky, "Ovonic Nickel-Metal Hydride Electric Vehicle Batteries: From the First 10,000 Miles to the First 10,000 Vehicles," EVS-12 Proceedings, Vol. 2, pp. 208-217.

c. Reported by Electrosource Inc. in B E Jay, A Datta, C Matthews, and R Blanyer, "Performance of the Horizon® Advanced Lead-Acid Battery", Proceedings of the Ninth Annual Battery Conference on Applications and Advances, Long Beach, California; January 1994.

d. "USABC Advanced Battery Technology Request for Proposal Information," April 4, 1991.

e. Approximation based on provision of high-voltage line to centralized Electric Fuel regeneration plant rather than through sub-distribution network to socket for single-battery charging. Source: Israel Electric Company R&D Department calculations.

f. US Energy Information Agency, reported in "Annual Energy Outlook 1987," DOE/EIA-0383(87), US Department of Energy, Washington, DC; 1988.

g. Based on General Electric 10-MW inverter installed at Chino, California, in 1988, with measured efficiency of 97.4% at 10 MW. Source: L H Walker, "10-MW GTO Converter for Battery Peaking Service," IEEE Transactions on Industry Applications, Vol. 26, No. 1, January/February 1990.

h. Pacific Gas and Electric Company reported charger energy efficiency between 72% and 95% in C Haslund and O M Bevilacqua, "Evaluating EV Charging Infrastructure," EVS-12 Proceedings, Vol. 2, p 564. Thomson CSF reported on an on-board charger jointly developed by Thomson CSF and Siemens, with efficiency of 88% at 3 kW, in M Assouline, J Langheim, and F Leonard, "Synchronous Drive with Electric Excitation," EVS-12 Proceedings, Vol. 2, p 493.

i. Source: same as Note a. Based on a 27-kWh battery with thermal losses of 250 W on-stand. Assuming recharging twice weekly, four hours' driving and 6 hours' recharging per cycle, yielding 74 hours on-stand per charge, then (250 X 74) = 18,500 W. Assuming — best case — that all thermal management energy comes directly from the network (AC), then we add this 18,500 W to the (27,000 / 0.85 / 0.85) = 37,370 W AC needed for discharge, and then 27,000 / (37,370 + 18,500) = 0.48.

j. Source: same as Note c. Based on 140-W blower requirement and assuming four hours' driving per 27-kWh cycle, then (140 x 4) / 27,000 = 2% loss per cycle

k. Source: same as Note b. Based on 87% charge retention in 48 hours, and assuming recharging twice weekly, four hours' driving and 6 hours' recharging per cycle, yielding 74 hours on-stand per charge, then (1.00-0.87) x (74 / 48) = 20% loss per cycle.

l. Not a use of electricity, but an estimate of equivalent energy required for distribution of Electric Fuel zinc anode cassettes (discharged as well as regenerated). Source: estimation by Technical University of Munich researchers for T? V Bayern Sachsen feasibility study, August 1992

m. Source: 6% average for 92,535 km of G-van in-service testing, reported in R D Colasanti Jr., D R Landsberg, T A McHugh, F E Porretto, "G-Van Data Acquisition and Analysis," EVS-12 Proceedings, Vol. 2, p 819.

In the second step of the efficiency analysis, it is useful to see what happens to the energy released by the battery. Two separate efficiency paths are described in the following sections: one for passenger vans or empty cargo vans, and the second for loaded cargo vans.

Passenger vans or empty cargo vans

For passenger vans or empty cargo vans, the best measure of energy efficiency is energy usage per unit of distance traveled (e.g., kWh/km).

Below highway speeds, the kinetic energy of a vehicle is nearly proportional to the mass (there is some rotational energy 'lost' in the motor, and at highway speeds air resistance becomes significant), and therefore we see that much of the energy of heavier batteries is being used to move the extra weight of the battery itself.

In Table 2, we assume a 1,300 kg vehicle (weight without battery) with energy consumption of 120 Wh per ton-km; we further assume a driving range appropriate to the respective specific energy of each battery, and thereby arrive at a practical vehicle/battery design for each technology. Note that the driving range is not directly proportional to the battery energy, as energy consumption (kWh/km) rises with battery weight.

In the last line of the table, the Net Energy Efficiency figure is multiplied by the relative energy consumption (per kilometer) for each battery compared with zinc-air, yielding an Adjusted Energy Efficiency figure that better reflects the real use of energy for transportation of people.

Note that the driving range shown is based on factoring in the effect of the on-board losses (self-discharge and other on-board energy uses), but since the on-board losses were already accounted for in Table 1, this effect is *not* used in the other calculations in Table 2, to avoid double-counting of losses.

Table 2. Net energy efficiency, adjusted for required energy inputs per kilometer relative to zinc-air, for full-sized passenger vehicle

EFL Zinc-Air		ZEBRA[a]	Nickel-Metal Hydride[b]	Horizon Lead-Acid[c]	USABC Mid-Term[d]
Energy density (Wh/kg)	200	82	71	45	80
for range of... 300 km		150 km	125 km	100 km	125 km
Battery Energy (kWh)	59.2	30.8	33.1	21.9	33.5
Battery Weight (kg)	296	375	467	486	419
Energy consumption (Wh/km)	192	201	212	214	206
Additional energy consumed per km (vs. zinc-air)	-	5%	11%	12%	8%
Adjusted Energy Efficiency	47%	37%	47%	54%	44%

Notes to Table 2:

a.-d. See Table 1 Notes for previous source references

It should be noted that a number of important efficiency impacts are not considered here because of the difficulty of applying them in a general analysis. These include:

- the impact of extra driving to and from the charging station on the efficiency of the electrically charged vehicles (their range is half that of the zinc-air or less)
- the lower efficiency of charging at ‘quick-charging’ stations
- for the energy lost through ‘conditioning cycles’ and the like

The table clearly demonstrates the impact of high specific energy on energy efficiency, and shows that among this group of battery technologies only the lead-acid battery is more efficient than the EFL zinc-air battery for transporting people. However, we did not assume any energy penalty for heating the lead-acid battery in cold weather or for its performance degradation, and consideration of this would likely show that the lead-acid battery is *less* energy-efficient than the EFL zinc-air battery in cold weather. The EFL zinc-air battery suffers no capacity loss in cold weather and only a brief performance impact.[3]

Loaded Cargo Vans

For cargo vans, the best measure of energy efficiency is energy usage per weight of payload, per distance transported (e.g., kWh/ton-km).

When we look at the payload capacity of a van as a function of battery technology, we again see that much of the energy of heavier batteries is being used to move the extra weight of the battery itself at the expense of cargo capacity. Using our Mercedes Benz 180E van as an example, we assume an empty vehicle weight of 1,700 kg (without battery), gross vehicle weight of 3,500 kg (with battery and payload) and energy consumption of 400 Wh/km. Again we assume a driving range appropriate to the respective specific energy of each battery, and thereby arrive at a practical vehicle/battery design for each technology.

In the last line of the table, the Net Energy Efficiency figure is multiplied by the relative energy consumption (per ton-kilometer of payload) for each battery compared with zinc-air, yielding an Adjusted Energy Efficiency figure that better reflects the real use of energy for transportation of goods.

As in the previous table, the driving range shown is based on factoring in the effect of the on-board losses (self-discharge and other on-board energy uses), but since the on-board losses were already accounted for in Table 1, this effect is *not* used in the other calculations in Table 3, to avoid double-counting of losses.

Table 3. Net energy efficiency, adjusted for required energy inputs per ton-kilometer of payload transport, relative to EFL zinc-air, for 4-ton GWV loaded cargo van

	EFL Zinc-Air	ZEBRA[a]	Nickel-Metal Hydride[b]	Horizon Lead-Acid[c]	USABC Mid-Term[d]
Energy density (Wh/kg)	200	82	71	45	80
for battery of ...	124 kWh	61 kWh	63 kWh	41 kWh	65 kWh
with range of ...	300 km	150 km	125 km	100 km	125 km
Battery weight (kg)	619	747	881	907	812
Payload capacity (kg)	1,181	1,053	919	893	988
Energy consumed per ton-km of payload transport (Wh)	339	380	435	448	405
Additional energy consumed (vs. zinc-air)	-	12%	28%	32%	20%
Adjusted Energy Efficiency	47%	35%	41%	45%	39%

Notes to Table 3:

a.-d. See Table 1 Notes for previous source references

The results show that the zinc-air battery, even when configured for more than twice the driving range, requires less energy to transport cargo, per unit of cargo weight, than other batteries.

The extended range of the Electric Fuel zinc-air battery also gives fleet operators the same degree of freedom and management flexibility that exists with today's fleets, whereby any vehicle can perform any duty cycle. At the same time, deployment of limited-range, electrically recharged vehicles will almost guarantee a less efficient utilization of resources and a less flexible and responsive vehicle fleet.

What is perhaps most important, zinc-air vehicles with significantly longer range and greater payload capacity will mean smaller fleets, which translates directly to reduced costs and less primary energy usage.

3. Life-cycle Cost

An examination of life-cycle cost should be broad enough to allow comparison between dissimilar battery technologies with different charging schemes and cycle lives.

We derive here a projected running cost to the vehicle owner over the life of the vehicle/battery, expressed in terms of cost per kilometer (or per ton-kilometer for cargo vehicles) for the battery ownership component and for the refueling/recharging component. An underlying assumption is that other operating costs (e.g., maintenance, insurance, etc.) will be the same for all battery-powered vehicles and can therefore be ignored. This may not be a valid assumption, as the bulk of the other operating costs could be related to the cost of the battery, which is lowest for the EFL zinc-air battery among the technologies compared.

Table 4 continues the comparative analysis of the EFL zinc-air system with that of other battery technologies, and specifically summarizes a cost analysis based on the vehicle and battery scenarios developed in Table 2 for full-sized passenger vehicles. The result of the analysis is a comparison of running cost per kilometer.

The table is based on the first 120,000 km of the vehicle's life, which means that during this time all batteries have to be replaced, except for the zinc-air. Only the pro-rated portion of the replacement batteries was considered. No attempt was made to 'levelize' costs by using a discount rate for cost of capital.

For example, the 59.2 kWh zinc-air battery with a driving range of 300 km costs 9.1 cents/km for battery ownership and refueling costs (including investment recovery and operating costs of the refueling and regeneration facilities) over the first 120,000 km, while the 33.5-kWh hypothetical "USABC mid-term" battery with a driving range of 125 km costs 9.2 cents/km for battery ownership and recharging.

The recharging infrastructure cost shown for the electrically rechargeable batteries includes only the minimal costs involved in rewiring a home garage for EV recharging. The significant costs of opportunity-charging points and quick-charging points, as well as for utility investment ranging from local transformer upgrading to transmission network improvements and peak capacity generation builds, are not included here because of the difficulty of determining them reliably.

Table 4. Life-cycle cost comparison: projected battery plus refueling/recharging costs over first 120,000 km, for full-sized passenger car and battery of Table 2

EFL Zinc-Air		ZEBRA(a)	Nickel-Metal Hydride(b)	Horizon Lead-Acid(c)	USABC Mid-Term(d)
	cents per km	cents per km	cents per km	cents per km	cents per km
Cost of battery with range of ...	300 km	150 km	125 km	100 km	125 km
Battery energy (kWh)	59.2	30.8	33.1	21.9	33.5
Cycles in first 120,000 km	400	800	960	1,200	960
Cycle life per battery	400	600	600	900	600
Battery cost ($/kWh)	75	250	250	200	150
Total pro-rated battery cost	4,440	10,266	13,240	5,840	8,040
Battery cost per km	3.7	8.5	11.0	4.9	6.7
Cost of Refueling/Recharging:					
Electricity(n)	1.4	2.6	2.0	1.8	2.2
Infrastructure(o,p)	4.0	0.3	0.3	0.3	0.3
Recharging cost per km	5.4	2.9	2.3	2.1	2.5
Total cost per kilometer	9.1	11.4	13.3	7.0	9.2

Notes to Table 4:

a.-d. (See Table 1 Notes for previous source references)

n. Electricity price assumed to be 3.5 cents/kWh for centralized recharging or regeneration, and 5 cents/kWh for home recharging. Cost per kilometer derived from this per-kWh price, Energy consumption (Wh/km) from Table 2, and Net Energy Consumption from Table 1.

o. Infrastructure cost for EFL zinc-air derived from EFL economics model based on year 2005 regeneration center (and refueling locations) to serve 2.1 million kWh (battery output) capacity weekly; total power required approximately 30 MW, total zinc capacity: 116,000 tons/year, equivalent to 30,000 vehicles x 70 kWh x 1 refueling per week. Total investment cost approximately $60 million.

p. Infrastructure cost for electrically recharged batteries includes only $400 for home rewiring (Source: M. DeLuchi, Q. Wang, and D. Sperling, "Electric Vehicles: Performance, Life-Cycle Costs, Emissions, and Recharging Requirements", *Transportation Research*, Vol 23A, No. 3 (1989) 255-278.

Table 5, with methodology similar to that of Table 4, summarizes a cost analysis based on the vehicle and battery scenarios previously developed in Table 3 for a loaded cargo van. The result of the analysis is a comparison of running cost per ton-kilometer of payload transported.

For example, the 124-kWh zinc-air battery with driving range of 300 km and payload capacity of 1,181 kg costs 18.2 cents for every ton-kilometer of payload transported, for battery ownership and refueling costs (again including investment recovery and operating costs of the refueling and regeneration facilities) over the first 120,000 km, while the 65-kWh hypothetical "USABC mid-term" battery with a driving range of 125 km and payload capacity of 988 kg costs 19.8 cents per ton-km for battery ownership and recharging.

Table 5. Life-cycle cost comparison: projected battery plus refueling/recharging costs over first 120,000 km, for loaded cargo van and battery of Table 3 (See Table 1 Notes for previous source references)

EFL Zinc-Air		ZEBRA[a]	Nickel-Metal Hydride[b]	Horizon Lead-Acid[c]	USABC Mid-Term[d]
	cents/ ton-km	cents/ ton-km	cents/ ton-km	cents/ ton-km	cents/ ton-km
Cost of battery with range of ...	300 km	150 km	125 km	100 km	125 km
and payload capacity of	1,181 kg	1,053 kg	919 kg	893 kg	988 kg
Battery energy (kWh)	124	61	63	41	65
Cycles in first 120,000 km	400	800	960	1,200	960
Battery cost ($/kWh)	75	250	250	200	150
Total cost for batteries ($)	9,300	20,333	25,200	10,933	15,600
Battery cost per ton-km of cargo transported	6.6	16.1	22.9	10.2	13.2
Cost of Refueling/Recharging:					
Electricity[q]	3.0	3.6	2.7	2.3	3.0
Infrastructure[r,s]	8.6	3.6	3.6	3.6	3.6
Recharging cost per km	11.6	7.2	6.3	5.9	6.6
Total cost per ton-kilometer	18.2	23.3	29.2	16.1	19.8

Notes to Table 5:

a.-d. See Table 1 Notes for previous source references

q. Electricity price assumed to be 3.5 cents/kWh for centralized recharging or regeneration.

r. Infrastructure cost for EFL zinc-air derived from EFL economics model based on year 2005 regeneration center (and refueling locations) to serve 2.1 million kWh (battery output) capacity weekly; total power required approximately 30 MW, total zinc capacity: 116,000 tons/year, equivalent to 30,000 vehicles x 70 kWh x 1 refueling per week. Total investment cost approximately $60 million.

s. Infrastructure cost for electrically recharged batteries includes $4,366 per vehicle for 7.4-kVA charging point (not including charging and control equipment), based on total cost of $131,000 for 30-point charging 'station', as reported in D Owen, J Simpson, and J McGuire, "UK Electric Vehicle Charging Infrastructure Case Study," EVS-12 Proceedings, Vol. 2, pp 136-144.

Additional Cost Considerations

Following are additional cost benefits that accrue to the fleet owner/operator from extended driving range due to higher specific energy. These benefits are typically difficult to quantify, but can be meaningful to the fleet operator.

- Fewer wasted trips to the recharging depot: Utilization of assets is improved when electric vehicles can stop less frequently to recharge or refuel, and special trips to the recharging depot are eliminated.
- More flexibility in fleet management: When electric vehicles are no more limited in range or payload capacity than conventionally fueled vehicles, then fleet managers retain more flexibility in vehicle deployment and route assignment.
- Less vehicle down-time: Electrical recharging means that assets are tied-up as much as one-third of the time for lengthy recharging. This is particularly problematic when fleet vehicles work more than one shift.
- A less expensive way to “battery-swap”: Fleet managers may increase utilization of electrically rechargeable battery-powered vehicles by swapping out the batteries after each discharge. Refueling the zinc-air battery can be accomplished as quickly, without the investment in additional batteries.

4. Sustainable Power

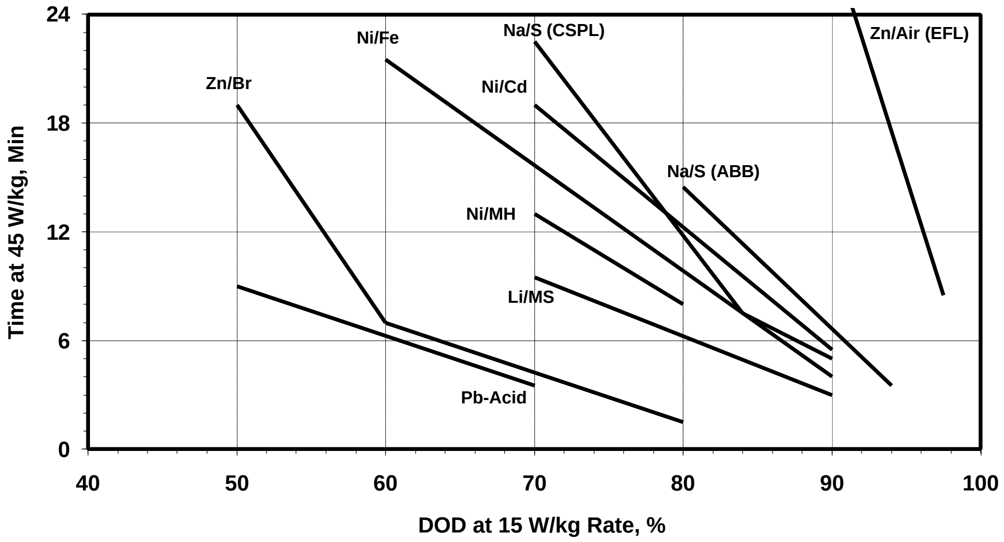
Sustainable power is a measure of the ability of a vehicle to climb hills or to maintain highway cruising speeds for extended periods of time. This attribute was calculated by the Argonne National Laboratory (ANL) using the test methodology of the USABC.

The ANL analysis calculated how long a battery could sustain a continuous discharge at 45 W/kg, as a function of DOD, where the discharge up to that DOD was at 15 W/kg. In other words, at various points during the battery discharge, how much sustainable power was left.

Although sustainable power would seem to be an attribute related to specific power, closer examination shows that the most important determinant is specific energy. This is shown in Figure 1, which is a reconstruction of a graph produced from a report on the ANL evaluations, with EFL zinc-air data from company tests added.

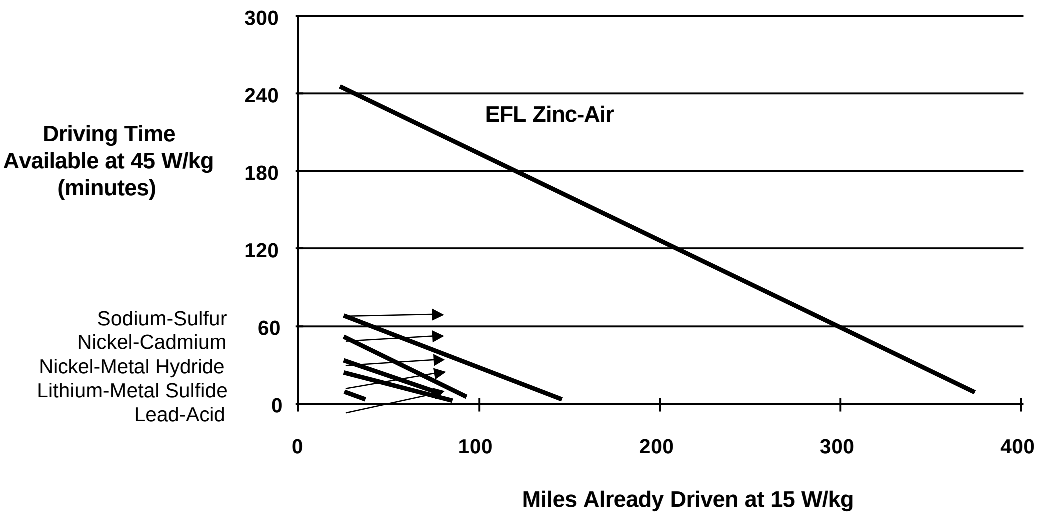
In order to get a clearer picture of the effect of specific energy on sustainable power, we normalized the DOD to miles driven, based on the range projected by ANL for each battery type, and this is shown in Figure 2.

Figure 1. Time (at 45 W/kg) that electric car (IETV-1) could sustain hill climb (7% grade) at 30 mph as a function of DOD (at 15 W/kg rate) for each advanced battery technology evaluated.



Source: W H DeLuca, K R Gillie, J E Kulaga, J A Smaga, A F Tummillo, and C E Webster, "Results of Advanced Battery Technology Evaluations for Electric Vehicle Applications", SAE Technical Paper Series No. 921572, 1992.

Figure 2. Driving time available at 45 W/kg, as a function of miles previously driven at 15 W/kg. (DOD of Figure 1 was normalized to miles driven based on the range projected by Argonne National Lab for each battery type.)



5. Conclusions

In this paper we have shown the interrelationship between several of the key battery attributes generally measured and reported, and have examined the effect of high specific energy on key attributes such as energy efficiency, life-cycle cost and sustainable power.

There are other battery attributes that are positively affected by high specific energy, such as the degree to which the use of cold-weather accessories or air conditioning reduce the range of an electric vehicle, and these may be examined in a later paper.

6. References

1. B Koretz, J R Goldstein, Y Harats, M Y Korall, "A High-Power, Mechanically Rechargeable Zinc-Air Battery System for Electric Vehicles," Proceedings of the 25th International Symposium on Automotive Technology and Automation, Florence, Italy; June, 1992.

   J R Goldstein and B Koretz, "Tests of a Full-Sized Mechanically Rechargeable Zinc-Air Battery in an Electric Vehicle," *IEEE Aerospace and Electronic Systems Magazine,* Vol 8, No. 11, Nov. 1993; pp 34-38.

   J R Goldstein and B Koretz, "Ongoing In-Vehicle Testing of the Electric Fuel Zinc-Air Battery System," Proceedings of the 11th Seminar on Primary and Secondary Battery Technology and Application, Deerfield Beach, Florida; January 1994.

2. W H DeLuca, K R Gillie, J E Kulaga, J A Smaga, A F Tummillo, and C E Webster, "Results of Advanced Battery Technology Evaluations for Electric Vehicle Applications", SAE Technical Paper Series No. 921572, 1992.

3. Goldstein and Koretz (1994)