LEAST-COST HYBRIDITY ANALYSIS OF INDUSTRIAL VEHICLES

Arnold R. Miller, PhD
President and Director
Fuelcell Propulsion Institute
Denver, CO
USA

Because fuelcells cost more than batteries, intuitively it would seem that the least-cost configuration of a fuelcell-battery hybrid would have the fuelcell operate continuously at the mean power of the duty cycle. This generally, however, is not correct. While batteries are less expensive on a per kW basis, an acceptable cycle life for an industrial vehicle requires a shallow depth of discharge and therefore a battery oversized by as much as a factor of 20. When fuelcell capital cost, oversized battery capital cost, and battery cycle life are simultaneously optimized, the least-cost configuration has the fuelcell operate above the mean power.

INTRODUCTION

The Fuelcell Propulsion Institute, an international technical consortium[1] founded in 1996, is developing a fuelcell-battery hybrid loader (also called "front-end loader") for mining applications. The basis of powerplant design is the duty cycle, or load profile, which we define as the power p as a function of time t as the vehicle executes its functions. An example of a duty cycle for a large mine loader is shown in the accompanying illustration. The vehicle requires a maximum of 185 kW as a narrow power spike as it drives its bucket under the load, 132 kW as it ascends a ramp hauling the load, and -100 kW as it descends the ramp with empty bucket. The negative power could be in the form of dissipated heat in the brakes or recoverable electrical energy via regenerative braking. Loader duty cycles are highly periodic. This one has a period of 23 minutes, and the vehicle may execute as many as 10,000 cycles per year. Typical of industrial vehicles, the mean power over the duty cycle, 47 kW, is 1/4 to 1/3 of the maximum.

An early design-analytic question is the following: What value of fuelcell power minimizes capital cost of the hybrid powerplant? At first thought, since fuelcells cost more per kilowatt than

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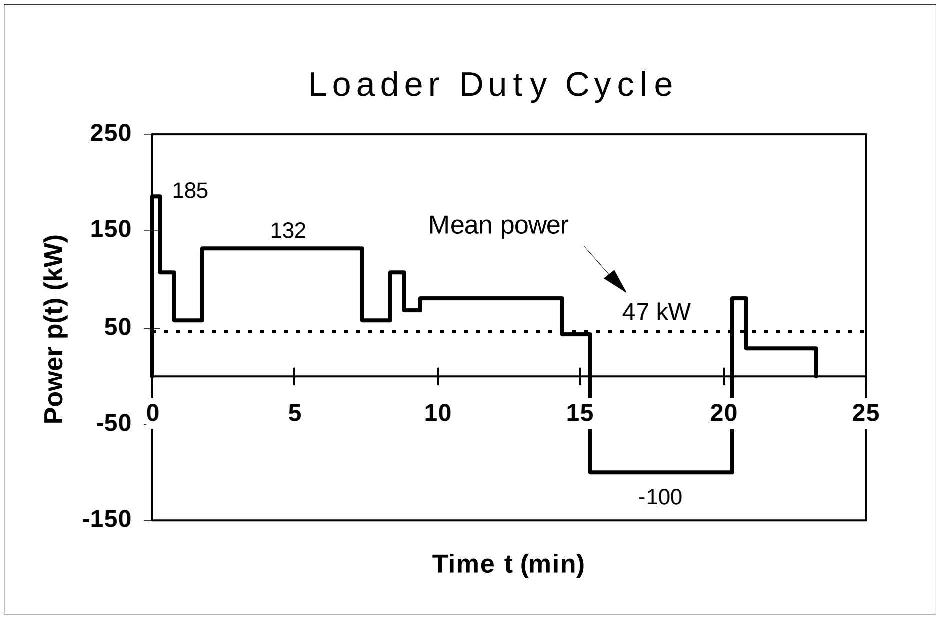
[1] Atlas Copco Wagner Inc, Barrick Gold Corporation, Bituminous Coal Operators' Association (BCOA), Canada Centre for Mineral and Energy Technology (CANMET), Cast Resource Equipment Ltd, H Power Corporation, Hydrogenics Corporation, Inco Limited, Instituto de Investigaciones Eléctricas, Joy Mining Machinery, Long-Airdox Company, McNally International Inc, Mining Technologies International Inc, National Mining Association, National Renewable Energy Laboratory, National Rural Electric Cooperative Association (NRECA), Newmont Mining Corporation (pending), Noranda Inc, Pennsylvania State University, Placer Dome Inc, RA Warren Equipment Ltd, Sandia National Laboratories/California, Sandia National Laboratories/New Mexico, Sandvik Tamrock Corporation, Société de Recherche et Développement Minier (SOREDEM), South Dakota State University, Stuart Energy Systems, Virginia Tech, Westinghouse Safety Management Solutions, Inc, Westinghouse Savannah River Company



batteries, it would seem the fuelcell should operate continuously at the mean power of the duty cycle, or 47 kW in the example. (Power below the mean, in our view, does not constitute a hybrid.) The answer to this question gives the "hybridity" — the degree to which the powerplant is hybrid — that minimizes cost. I define hybridity h as follows:

$$h = p_b/(p_b + p_f),\ p_{mean} \leq p_f \leq p_{max}$$

where h is the hybridity, p_b is rated battery power (kW), p_f is rated fuelcell power (kW), p_{mean} is the mean power of the duty cycle, and p_{max} is the maximum power. By this definition, a pure fuelcell vehicle has a hybridity of zero. With fuelcell power fixed, hybridity increases toward unity as battery power increases.

Possibly contrary to intuition, the least-cost powerplant generally has the fuelcell power above p_{mean}. As the model below shows, this occurs because an acceptable cycle life of the battery requires a shallow depth-of-discharge and hence an oversized battery. Although the battery is relatively inexpensive per kW, a large battery can exceed the cost of the fuelcell. Least-cost hybridity occurs when fuelcell cost, oversized battery cost, and battery cycle life are simultaneously optimized.

MODEL

Parameters and Assumptions. Input parameters to the model include battery capital cost ($/kWh), battery life (y), battery depth-of-discharge (%), fuelcell capital cost ($/kW), power-to-energy ratio[2] of the battery (1/h), battery efficiency (decimal fraction), and fuelcell power. We assume identical efficiencies for battery charge and discharge and that the fuelcell operates continuously at its rated power p_f, which lies between p_{mean} and p_{max}.

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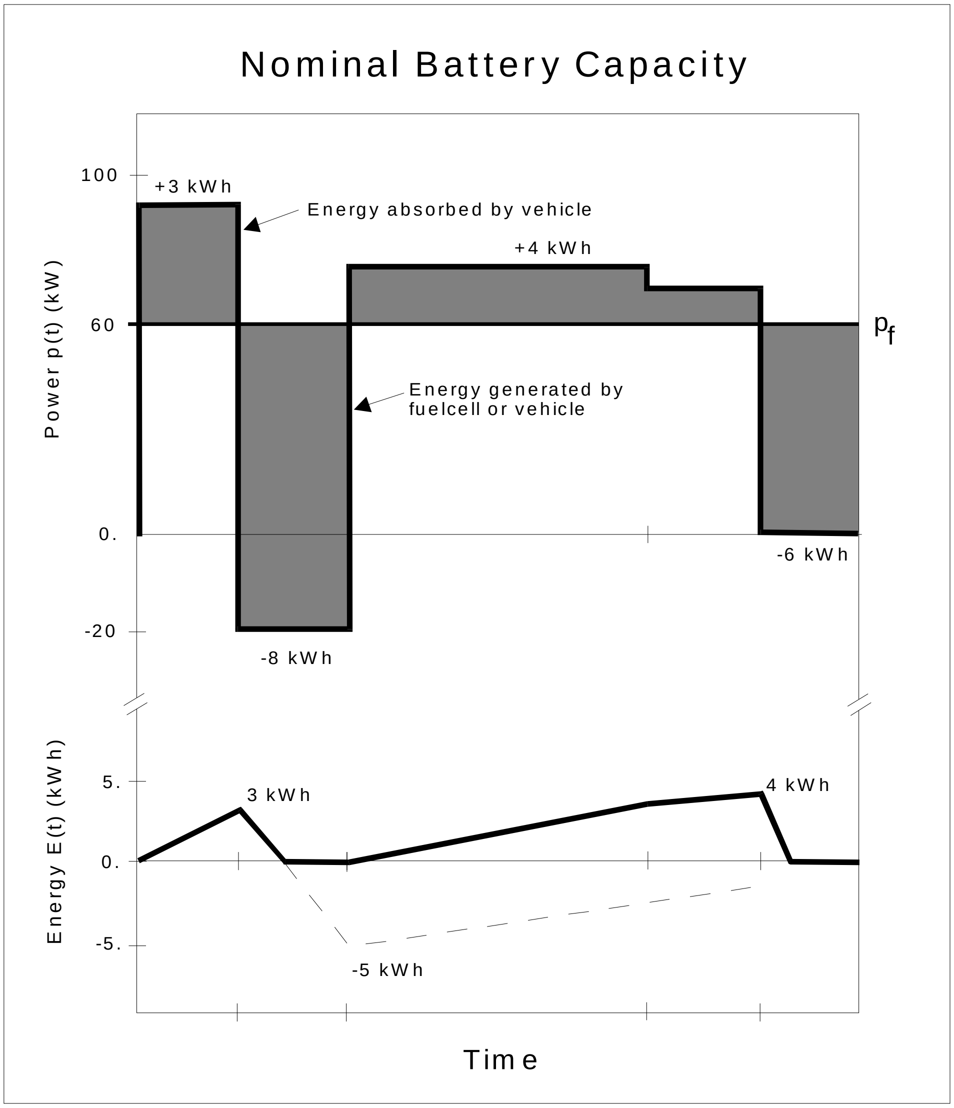
[2] Unlike fuelcells, battery power and energy capacity are not independent, and fixing one determines the other.

Nominal Battery Capacity. Nominal battery capacity c_b is the capacity of the battery, assuming 100% depth of discharge, required to carry the vehicle through the power peaks that exceed the constant fuelcell power p_f. With the duty cycle fixed, as p_f is raised or lowered, c_b varies because the peak areas above the horizontal line p_f vary.

Illustration of how c_b is computed is shown in the accompanying diagram based on a hypothetical duty cycle. The energy to carry the vehicle through peaks above the fuelcell continuous power p_f of 60 kW is provided by the battery; the energy represented by troughs below p_f is potentially recharging energy for the battery. The area under a peak or above a trough, i.e., above or below p_f, is the theoretical energy, assuming 100% efficiency, required from or provided to the battery. For example, the first peak requires 3 kWh from the battery; the second, a trough, can provide 8 kWh to the battery either from the fuelcell or from the vehicle via regeneration.


Nominal Battery Capacity

Function E, shown below the duty cycle in the diagram, is the cumulative energy that the battery must provide. It is the integral, truncated at zero, of function p - p_f. E is truncated at zero because we seek to minimize battery size — the battery will be sized to absorb no more energy than necessary to provide the energy for peaks *above* p_f.

If the efficiency of the battery were 100%, the nominal battery capacity c_b would be given by the maximum of function E, namely, c_b = 4 kWh in the example. Although function p has been presented as a step function, it may more generally be smooth. The general definition of nominal battery capacity c_b is the following:

$$c_b = \max_t \{\max[\int_0^t (p(t) - p_f)dt, 0]\}$$

$$= \max_t \{\max[\int_0^t p(t)dt - p_f, 0]\}$$

However, the areas under the peaks and over the troughs, and hence the values E(t), must be corrected for an actual efficiency less than 100%; I denote the corrected function E_{eff}. The areas above p_f must be made larger and the troughs below made smaller through, respectively, dividing or multiplying by the efficiency. For example, if the battery efficiency were 0.75, the energy stored in the battery to provide the 3 kWh required for the first peak must be 4 kWh. Likewise, only 6 kWh of the 8 kWh theoretically provided by the first trough will be absorbed by the battery.

After correcting for battery efficiency, the maximum of function E_{eff} gives the corrected nominal battery capacity c_{eff}, which besides establishing nominal energy capacity, determines[2] battery power p_b.

Least-Cost Model. With nominal battery capacity c_{eff} computed for each value of independent variable p_f via a separate program, the least-cost model of hybridity is a straightforward spreadsheet model. An example based on the mine loader duty cycle is given as Table 1. Model input parameters are displayed on the six lines under the title. The first column lists independent variable p_f, and the third column gives c_{eff} corresponding to each value of p_f. For example, for the loader duty cycle, if p_f = 120 kW, the corresponding nominal battery capacity is 1.60 kWh — i.e., given a battery efficiency of 0.70, a nominal battery capacity of only 1.60 kWh is sufficient to handle any power peak encountered by the vehicle.

In practice, however, the battery must be larger than c_{eff} because its cycle life depends strongly on the depth of discharge. The exponential-like dependency for a nickel-cadmium battery manufactured for hybrid vehicles is shown in the accompanying graph. Nickel-cadmium batteries are among the best in cycle life, and lead-acid batteries, the type currently dominant in industrial applications, are shorter lived. Because loaders are inherently periodic in operation, the number of charge-discharge cycles of the battery can be as high as 10,000 cycles per year. Consequently, an acceptable battery cycle life requires a shallow depth-of-discharge. The manufacturer recommends 5%, the value used in the example of Table 1, which makes the actual battery capacity, shown as column four, 20 times larger than nominal battery capacity c_{eff}.

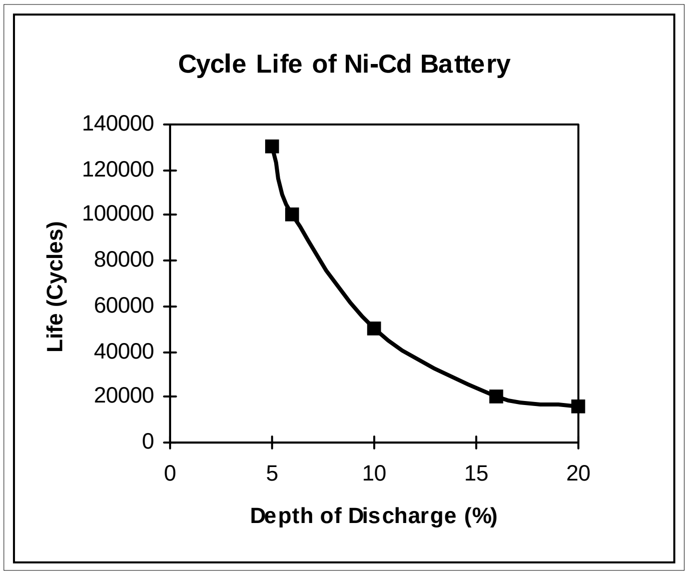
The requirement of excess battery to allow satisfactory depth-of-discharge causes the battery capital cost, column six, to exceed the capital cost of the fuelcell, column two, when fuelcell power is below approximately 60 kW.

Table 1: Least-Cost Hybridity Analysis

Bat_cost	500	Battery capital cost ($/kWh)
Bat_life	13	Battery life (years)
DOD	5	Depth-of-discharge of battery (%)
FC_cost	2000	Fuelcell capital cost ($/kW)
PE_ratio	10	Power-to-energy ratio of battery (kW/kWh = 1/h)
Bat_effic	70	Battery efficiency for both charge and discharge

Fuelcell Power (kW)	Fuelcell Capital Cost ($)	Nom Bat Capacity (kWh)	Battery Capacity (kWh)	Battery Power (kW)	Battery Capital Cost ($)	Total Capital Cost ($)	Total Power (kW)	Hybridity
50	100000	17.2	345	3450	172000	272000	3500	0.99
60	120000	13.9	278	2780	139000	259000	2840	0.98
70	140000	10.7	215	2150	107000	247000	2220	0.97
80	160000	7.69	154	1540	76900	237000	1620	0.95
90	180000	5.99	120	1200	59900	240000	1290	0.93
100	200000	4.37	87.4	874	43700	244000	974	0.90
110	220000	2.93	58.6	586	29300	249000	696	0.84
120	240000	1.60	32.0	320	16000	256000	440	0.73
130	260000	0.33	6.6	66	3300	263000	196	0.34
140	280000	0.27	5.4	54	2700	283000	194	0.28
150	300000	0.21	4.2	42	2100	302000	192	0.22

Total capital cost, the sum of fuelcell and battery costs, is computed as column seven. A cost minimum occurs at a fuelcell power of 80 kW. The accompanying chart shows a family of curves, each of which is the graph of column seven when the fuelcell capital cost, an input parameter, is varied. Cost for each case is labeled to the right of the curve. The middle curve of the family, with a minimum around 80 kW, corresponds to the data in Table 1. The curves are weakly dependent on battery efficiency, especially at small values of h.



When fuelcell capital cost is high, as in the top curve, least-cost hybridity approaches unity, which implies a large battery and small fuelcell. However, as fuelcell cost falls, least-cost hybridity approaches zero. In the future, when fuelcell capital cost is even lower than assumed for the bottom curve, hybrid vehicles will not be competitive on a cost basis with pure fuelcell vehicles.

CONCLUSION

The model analyzes capital cost of a fuelcell-battery hybrid powerplant as a function of hybridity. It demonstrates that least-cost hybridity will generally occur when the fuelcell power exceeds the mean power of the duty cycle of an industrial vehicle. Although fuelcell power at the mean, the minimum possible for a hybrid vehicle, will minimize fuelcell cost, it does not minimize total powerplant cost.

Industrial vehicles such as loaders and lift trucks have highly periodic duty cycles, and fuelcell-battery hybrids require a battery with high cycle life. Satisfactory cycle life necessitates a shallow depth of discharge, perhaps on the order of 5%. Accordingly, the capital cost of the 20-fold oversized battery can exceed the cost of the fuelcell.

When fuelcell capital cost, battery capital cost, and battery cycle life are simultaneously optimized, the conclusion above will generally obtain: The least-cost hybridity occurs when the fuelcell power exceeds the mean power of the duty cycle.

ACKNOWLEDGEMENTS

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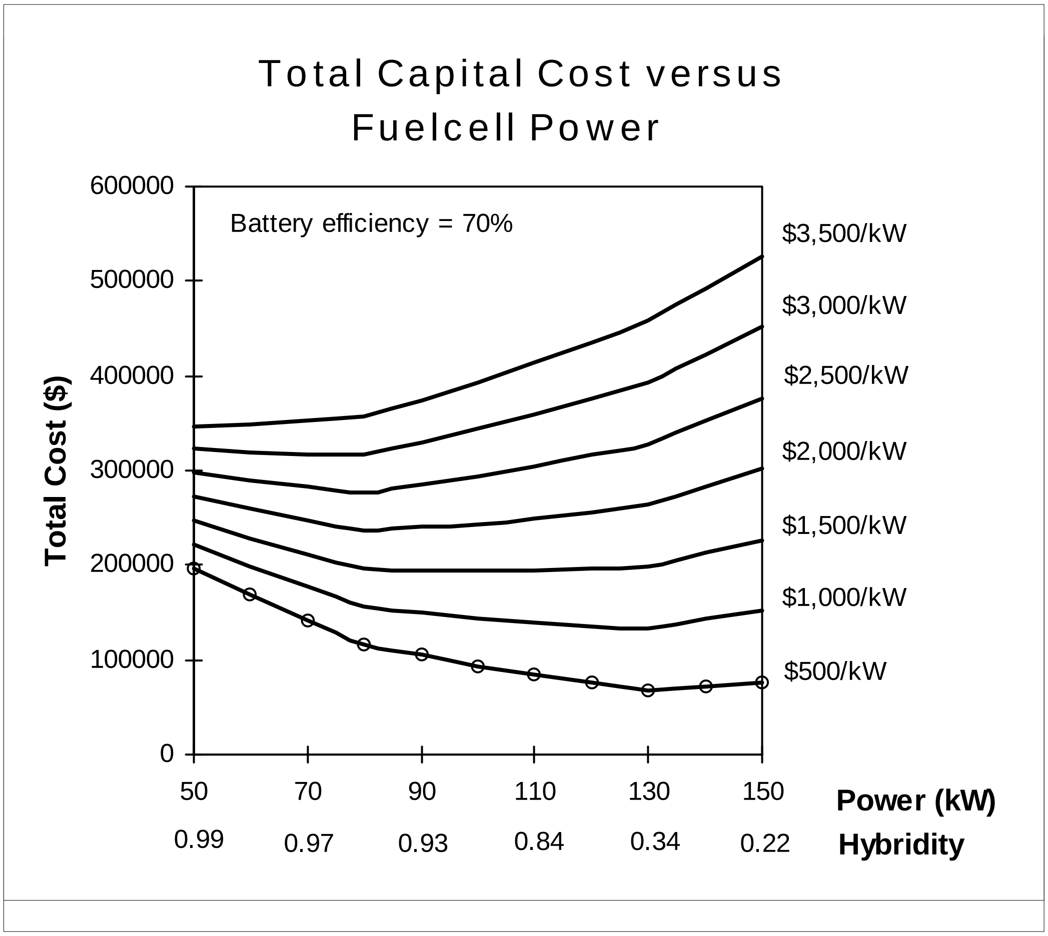
Total Capital Cost versus Fuelcell Power
Battery efficiency = 70%
Total Cost ($)
600000
500000
400000
300000
200000
100000
0
$3,500/kW
$3,000/kW
$2,500/kW
$2,000/kW
$1,500/kW
$1,000/kW
$500/kW
50
70
90
110
130
150
Power (kW)
0.99
0.97
0.93
0.84
0.34
0.22
Hybridity