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Energy Storage Fuel Cell Vehicle Analysis

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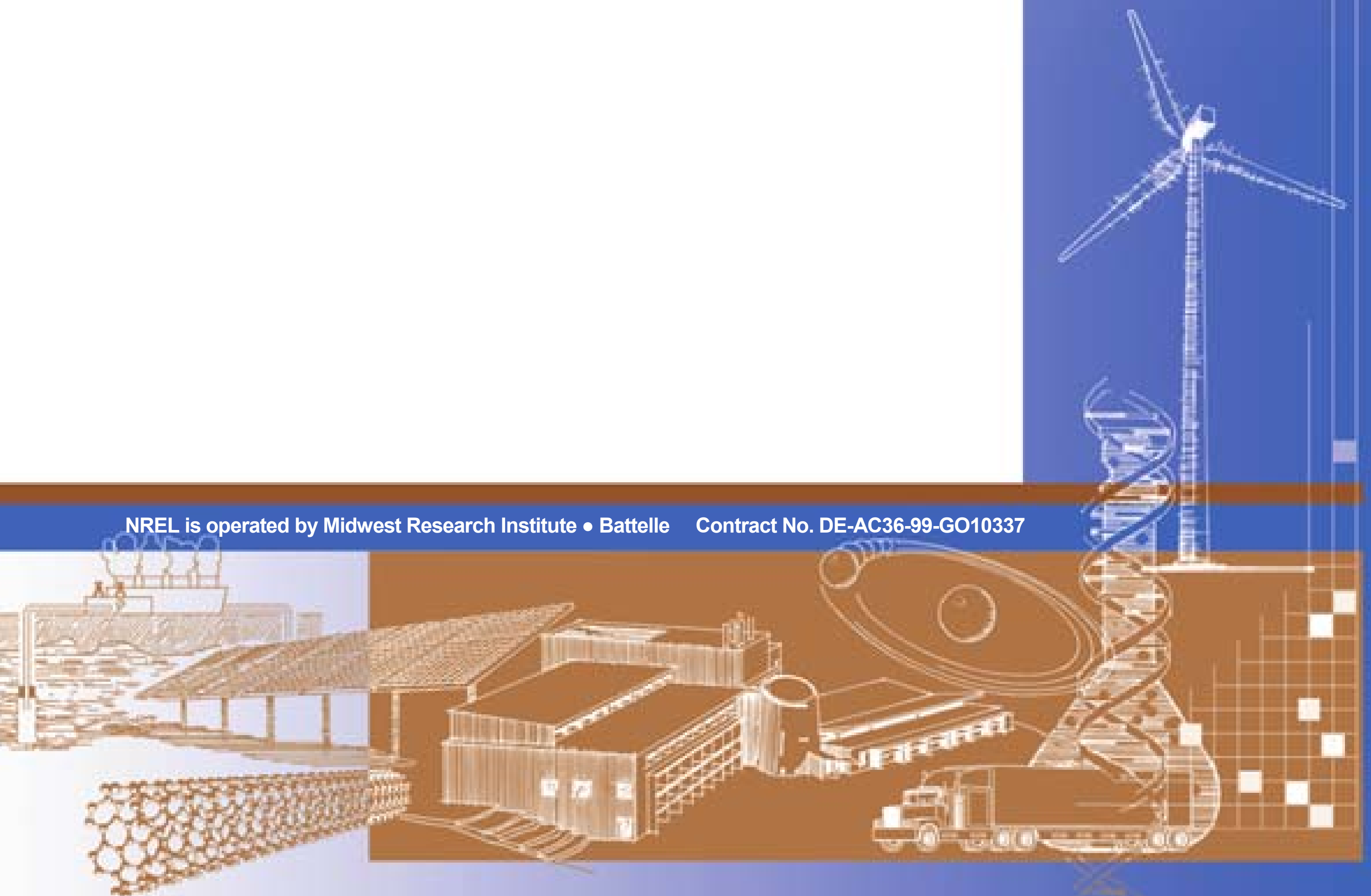

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Energy Storage Fuel Cell Vehicle Analysis

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Abstract

Hybridizing fuel cell (FC) vehicles with energy storage (ES) could result in improved performance and fuel economy, and reduced cost. We analyzed ES needs for a light mid-size car with a hydrogen FC as the main power source. We used the ADVISOR™ vehicle simulator with its ES and FC components for the analysis, and tested several different drive cycles, FC characteristics, and different ES to FC power ratios. We assumed that at idle, the fuel cell is not shut down and consumes enough hydrogen fuel to sustain itself without generating net power. Regen braking and vehicle deceleration were the major sources of charging for the ES for later use. The optimum fuel economy occurs when peak FC efficiency is around the average power demand for a particular drive cycle. There is positive benefit to downsizing the FC if the peak efficiency is shifted toward the typical power operating point. We proposed an ES system with 25 kW discharge (12 seconds), 20 kW charge (5 seconds) with available energy of 250 Wh and a 56 kW FC for the light mid-size car. The fuel consumption of this hybridized case was about 30% less than fuel cell only case.

Keywords: energy storage, fuel cell, simulation, HEV (hybrid electric vehicle), regenerative braking

1 Introduction

In recent years, hydrogen fuel cell (FC) vehicle technology has received considerable attention as a strategy to decrease oil consumption and reduce harmful emissions. However, the cost, transient response, and cold performance of FC systems may present significant challenges to widespread adoption of the technology for transportation in the next 15 years. Several previous studies have shown that hybridization of FC vehicles with electrochemical energy storage (ES) devices provides cost, performance, and operational improvements, as well as fuel economy benefits that are attractive and should be considered [1 - 4]. Among the current pre-production hybrid FC vehicles, the Toyota FCHV [5] has a nickel-metal hydride ES system similar to that of the Toyota Prius, and the Honda FCX-V4 uses an ultracapacitor ES system that provides regenerative braking and power assist capability [5 and 6]. The requirements of the ES for power assist and 42V hybrid vehicles are defined by the United States Advanced Battery Consortium (USABC) and FreedomCAR Program and can be found at www.uscar.com/consortia&teams/consortiahomepages/con-usabc.htm.

The objectives of this effort were to perform ES modeling with FC vehicle simulations to quantify the benefits of hybridization and to identify a process for setting the requirements of ES for hydrogen-powered FC vehicles for U.S. Department of Energy's Energy Storage Program. The analysis was in support of USABC and the FreedomCAR Electrochemical Energy Storage (EES) Technical Team, which are developing requirements for ES systems for FC vehicles for the FreedomCAR Program in the United States.

It is important to note that the ES sizes recommended here strongly depended on our assumptions. Using different vehicle characteristics and requirements, fuel cell characteristics, and operating strategies would have resulted in a different set of energy storage requirements. However, the approach we used here could be applied to other scenarios.

2 Major Assumptions

For the vehicle, the EES Technical team suggested using an aerodynamic, lightweight, mid-size car. The vehicle was assumed to be similar to average mid-sized cars in the United States such as the Chevrolet Malibu or Chrysler Stratus. The weight of the glider (vehicle without powertrain) was assumed to be about 60% of today's cars to account for future reductions in weight, such as using a structural aluminum body. The drag coefficient was assumed to be around 0.25, with a frontal area of 2 m^2 and rolling resistance of 0.007. The requirements for the car to meet were: minimum range of 500 km, maximum speed of 160 km/h, 0-100 km/h acceleration of 11 seconds, and ability to sustain grade of 5.5% at 88 km/h.

For the rest of the assumptions, we used the 2010 FreedomCAR Program technical targets [7] for FC, ES, power electronics, traction motor, and hydrogen storage systems (Tables 3-7). The fuel was assumed to be hydrogen from compressed hydrogen cylinders. For the FC system, we assumed a system peak efficiency of 60% at 25% rated power and a system efficiency of 50% at full rated power (designated as FC_FC50_P25). We assumed that the FC system ramps up in power from 10% to 90% in 1 second while it takes 15 seconds to warm up the fuel cell from cold start to the rated power. The FC system's specific power was assumed to be 500 W/kg. For the ES system, we assumed average specific power of 1200 W/kg and total specific energy of 70 Wh/kg with 90% round trip efficiency. The following tables summarize the assumptions we used.

Table 1: Vehicle characteristics

Assumption Description	Units	Value
Vehicle Description	--	all wheel drive mid-size car
Base Vehicle Glider Mass	*kg*	636
Cargo Mass	*kg*	136
Aero. Drag Coef.	--	0.25
Frontal Area	*m^2*	2
Tire Size	--	P215/60R16
Rolling Resistance	--	0.007
Vehicle Range	*km*	500

Table 2: Vehicle performance requirements

Assumption Description	Units	Value
Acceleration 0-100 km/h	*s*	11
Top Cruising Speed	*km/h*	>=100
Grade @ 88km/ at Curb Mass + 408kg	%	>=5.5
Drive Cycle Tolerance	*km/h*	<=2
ESS energy to Fuel ratio	%	<=1

Table 3: 2010 fuel cell system assumptions

Assumption Description	Units	Value
Fuel Type	--	hydrogen
Fuel Cell Peak Efficiency	%	60
Fuel Cell Efficiency at 25% Power	%	60
Fuel Cell Efficiency at Rated Power	%	50
Fuel Cell System Specific Power	*W/kg*	500
Fuel Cell System Power Density	*W/L*	500
Fuel Cell System Cost	*$/kW*	105 32
Fuel Cell System 10-90% Power Transient Response Capability	*s*	1
Time from Start to Full Power Output Capability (20C)	*s*	15

Table 4: 2010 energy storage assumptions

Assumption Description	Units	Value
Capacity	*Ah*	12
Charge Mode Efficiency	*%*	95
Discharge Mode Efficiency	*%*	95
Mass per cell	*kg*	0.525
Volume per cell	*L*	0.245
Packing factor	--	0.6
Mass factor	--	0.85
Energy	*Wh*	42.7
Power	*W*	709
Specific power	*W/kg*	1200
Energy Storage Cost	*$/kW*	20

Table 5: 2010 hydrogen storage assumptions

Assumption Description	Units	Value
H2 Storage Energy Density	*kWh/L*	1.2
H2 Storage Specific Energy	*kWh/kg*	1.5
H2 Storage Cost	*$/kWh*	4

Table 6: 2010 power electronic assumptions

Assumption Description	Units	Value
Efficiency	*%*	95
Specific Cost	*$/kW*	5

Table 7: 2010 motor/controller assumptions

Assumption Description	Units	Value
Specific Power (Motor and Controller)	*kW/kg*	0.75
Specific Cost (Motor and Controller)	*$/kW*	11
Power Density (Motor and Controller)	*kW/L*	3.53

It is important to note that we assumed that the "combined" FC and ES hybridized system must meet the performance target requirements of the vehicle (Table 2), which are acceleration, top cruising speed, and grade. To avoid a large ES system, we assumed that top cruising speed or grade sustainability was met with power from only the fuel cell.

In addition, we made the following assumptions about the operation of the vehicle and FC, and the roles of ES:

- 700 W of constant accessory loads during idle or operation. But during vehicle driving, the accessory load requirement is supplied by the FC.
- FC is always "on" even at vehicle stops/idles (i.e. no start/stop operation like in internal combustion engines or hybrid electric vehicles).
- At idle (or vehicle stops) the hydrogen fuel consumption of the FC was 0.3% of rated power consumption. This means that although there is "gross" power from the FC, its auxiliary loads such as compressors and pumps consume all this "gross" power and the "net" power from the FC is zero.
- The ES is used for traction assist during acceleration.
- When the FC is downsized, the ES provides traction assist during high power transients to meet the drive cycle power requirements.
- The ES system provides traction assist during FC "warm" startup from idle.
- The ES provides power/energy to start the FC from cold starts.
- The ES was not used for sustained gradeability.
- All or a major portion of the available regenerative braking is captured by the ES for later traction use. We used two regen braking strategies.
  - ES is sized to limit regen power pulse to a "fixed" percentage (100%, 75%, or 50%) of the peak regen power observed during a drive cycle. Friction braking absorbs the remainder.
  - % of regen energy recaptured is based on a "deceleration-rate" strategy.
    - A fractional split between driveline and friction brakes defined as a function of deceleration rate is assumed.
    - We assumed that below 1g deceleration force (=9.8 m^2/s * mass), all braking is driveline (i.e., it is captured as regen braking), above 3g all braking is friction (i.e., no regen braking captured).
    - Between the 1g and 3g, the split between drivetrain and regen braking is proportioned linearly.
    - We found that, in this strategy, the driveline would recapture between 70% and 90% of the available braking energy depending on the drive cycle.

3 Approach

We used the ADVISOR vehicle simulator for the analysis. We simulated a range of FC-ES configurations (cases) as shown in Table 8. In all cases, we assumed that top cruising speed or grade sustainability was met with power only from the FC. This dictated the minimum size of the FC for the power needed for this vehicle. The minimum power for the top cruising speed was found to be 47 kW, and the minimum power needed for grade sustainability was 34 kW. Therefore, the minimum FC size was selected to be 47 kW. As mentioned before, we assumed that the combined ES discharge power and FC power must meet the acceleration and drive cycle requirements. In the case of the fuel-cell-only with no ES and no regen capture (Case 5), the vehicle needed 75 kW of power.

In Case 1, we picked the smallest FC that is sized for top speed and largest ES (discharge) that when combined with FC power can meet the required acceleration. The ES charge capability was sized for maximum regen capture. We used a DOE-target FC system that is at its maximum efficiency (60%) at 25% rated power and is 50% efficient at full rated power (FC_FC50_P25). In Case 1, we used a deceleration-based strategy discussed in the Assumptions Section. Cases 1a through 1c have similar FC and ES power ratios, but with different regen capture capability. Case 1f is the same as Case 1a, but the maximum FC efficiency at 10% rated power (FC_FC50_P10).

In Cases 2 through 4, FC size was increased incrementally while the ES was sized to satisfy acceleration constraints. Note that the total mass of the hybrid vehicle in Cases 1–3 is less than the FC only case, so the vehicle power requirement for acceleration is less than 75 kW as seen in Table 8. Case 5 is with a FC only, with maximum efficiency at 25% rated power (FC_FC50_P25). Case 5f is the same as Case 5 with a FC that is most efficient at 10% rated power (FC_FC50_P10). In Cases 5a through 5c, while the FC remains at 75 kW, ES is added to capture an increasing percentage of peak regen pulse power. Our strategy included maintaining the ES state of charge (or energy) and included regen recovery, kinetic energy accounting, and opportunity to charge and discharge the ES to make the system more efficient; i.e., ES charge/discharge was executed if it made the overall system efficiency better.

Table 8: Matrix of vehicle configurations evaluated

		Fuel Cell	**ESS**	
Name	**Description**	**(kW)**	**Regen (kW)**	**Discharge(KW)**
Case 1	FC sized for grade/top speed; decel regen strategy; FC_FC50_P25	47000	34000	25000
Case 1a	Case 1 + 100% regen	47000	34000	25000
Case 1b	Case 1 + 75% regen	47000	25500	25000
Case 1c	Case 1 + 50% regen	47000	17000	25000
Case 1f	Case 1a + FC_FC50_P10	47000	34000	25000
Case 2	Fuel cell - sized to 25% point; decel regen strategy; FC_FC50_P25	54250	34000	18000
Case 2a	Case 2 + 100% regen	54250	34000	18000
Case 2b	Case 2 + 75% regen	54250	25500	18000
Case 2c	Case 2 + 50% regen	54250	17000	18000
Case 2f	Case 2a + FC_FC50_P10	54250	34000	18000
Case 3	Fuel cell - sized to 50% point; decel regen strategy; FC_FC50_P25	61500	34000	12500
Case 3a	Case 3 + 100% regen	61500	34000	12500
Case 3b	Case 3 + 75% regen	61500	25500	12500
Case 3c	Case 3 + 50% regen	61500	17000	12500
Case 3f	Case 3a + FC_FC50_P10	61500	34000	12500
Case 4	Fuel cell - sized to 75% point; decel regen strategy; FC_FC50_P25	69000	34000	7500
Case 4a	Case 4 + 100% regen	69000	34000	7500
Case 4b	Case 4 + 75% regen	69000	25500	7500
Case 4c	Case 4 + 50% regen	69000	17000	7500
Case 4f	Case 4a + FC_FC50_P10	69000	34000	7500
Case 5	Fuel cell only - no ess; FC_FC50_P25	75000	0	0
Case 5a	Fuel cell only plus 100% ess	75000	36000	36000
Case 5b	Fuel cell only plus 75% ess	75000	27000	27000
Case 5c	Fuel cell only plus 50% ess	75000	18000	18000
Case 5f	Case 5 + FC_FC50_P10	75000	0	0

4 Results

4.1 Energy Analysis

As mentioned, the analysis showed that the power needed for sustained gradeability of 5.5% at 100 km/hr was 34 kW, and for a top speed of 160 km/h was 47 kW, which dictated the minimum size of the fuel cell. The power needed for acceleration of 0-100 km/h for the FC-only case was 76 kW. We used the ADVISOR™ simulator to analyze the cases in Table 8 for U.S. City (UDDS), U.S. Highway, US06, and HYZEM drive cycles. The Delta ESS energy to fuel-use ratio was monitored for correcting fuel economy. We used multiple parameters to manage the strength of various elements of control. We performed Design of Experiments on each case to determine the best parameter settings.

Figure 1 shows the results of the adjusted combined city and highway fuel consumption for each of the 25 cases in Table 8. Here are the observations from Figure 1.

- Comparing Case 5 and 5f (FC only cases) with other cases, indicates that fuel consumption decreases as the vehicle is hybridized with ES. This is due to capturing and using regen energy for traction to support the drive cycle.
- Most of the time downsizing the FC creates a positive fuel consumption benefit.

- Comparing FC only (Case 5) to the best case of the hybridized vehicle (Case 1b), the fuel consumption is reduced from 4.25 Lit/100 km to about 3 Lit/100 km or a roughly 30% reduction in fuel consumption. This is due to both downsizing and capturing and using regen.
- The lower fuel consumption (higher fuel economy) case occurs when the peak FC efficiency occurs at 10% rated power (comparing cases 5 with 5f, 1a with 1f, 2a with 2f, 3a with 3f, and 4a with 4f). This is due to the fact that the average power demand for both city and highway drive cycles is 10%-15% of the rated power from the FC and thus the FC is more efficient at 10% rated power than 25% rated power [2].
- The smaller FC and largest ES gives the lowest fuel consumption (Case 1).
- Adding ES, even to a full size FC (Cases 1a-1c), improves the fuel economy since the regen energy is captured and used later.

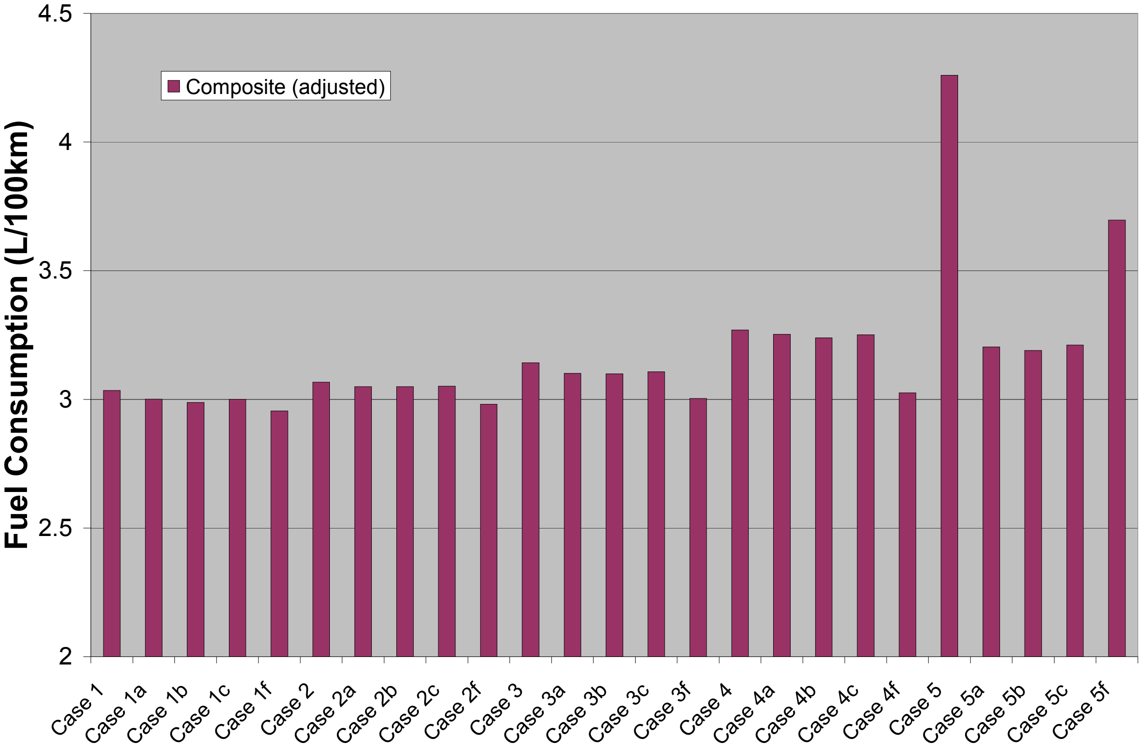
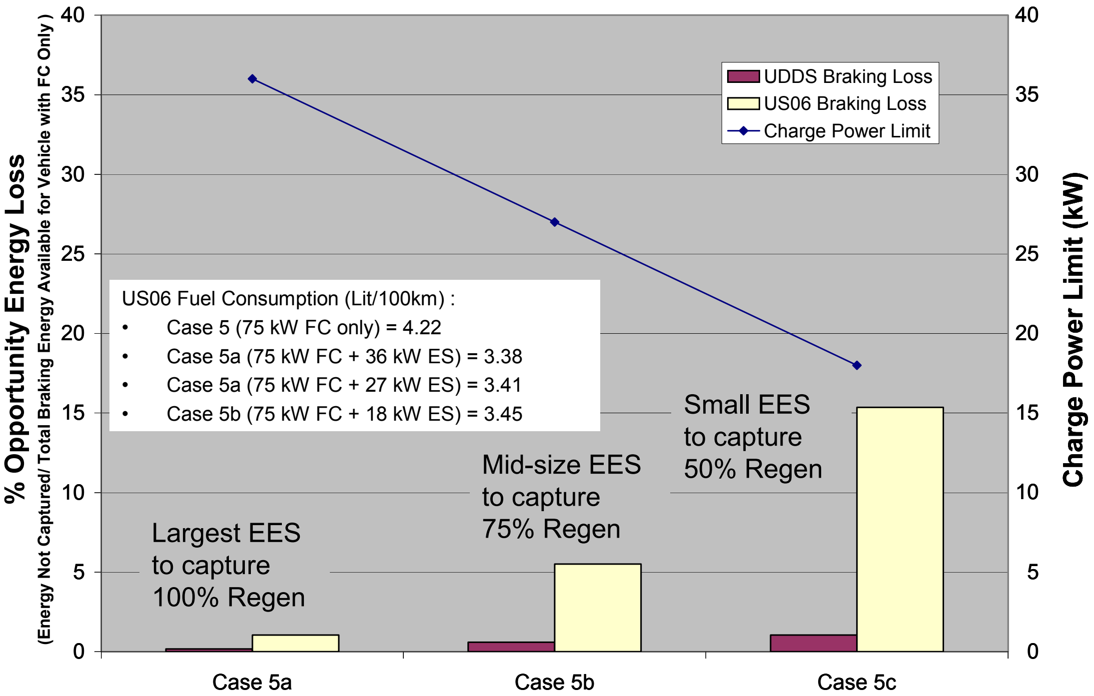


Figure 1: Fuel consumption of various hybridized FC cases shown in Table 8

Figure 2 shows the impact of energy storage charge acceptance capability on the amount of energy that could be recaptured from regen braking. From this and other results, not shown due to limited space, we can observe the following:

- The reduction of fuel consumption from Case 5 to the cases with added energy storage (5a, 5b, and 5c) to capture regen is roughly 20% for US06 cycle.
- When limiting energy storage charge acceptance to 18 kW, 15% of regen braking could not be captured during the US06 cycles since some of the peak power pulses are more than 18 kW. For the city cycle this is only about 6% opportunity loss.
- Increasing the ES charge acceptance to 36 kW to capture almost 98% of available regen has only a small impact on reducing fuel consumption (2% for US06 and even lower for City and Highway cycles).



US06 Fuel Consumption (Lit/100km) :

- Case 5 (75 kW FC only) = 4.22
- Case 5a (75 kW FC + 36 kW ES) = 3.38
- Case 5a (75 kW FC + 27 kW ES) = 3.41
- Case 5b (75 kW FC + 18 kW ES) = 3.45

Figure 2: Breaking energy not captured because of ES charge acceptance limitations

Since the projected cost of energy storage per unit power is lower than the projected cost of fuel cell per unit power, it would also make economical sense to replace some of the fuel cell functions with energy storage. We estimated the cost of the powertrain containing the fuel cell system, energy storage system, power electronics, motor and controller, and the hydrogen storage system. The size and cost of the hydrogen system was selected so that each vehicle case has a range of 500 km. Figure 3 shows the powertrain cost and a figure of merit (fuel economy divided by total powertrain cost) for each of the cases. Total cost decreased with decreasing FC size increase and decreasing ES size. Figure 3 indicates that Cases 1b or 1c are the best cases to consider since they have the highest fuel economy to powertrain cost.

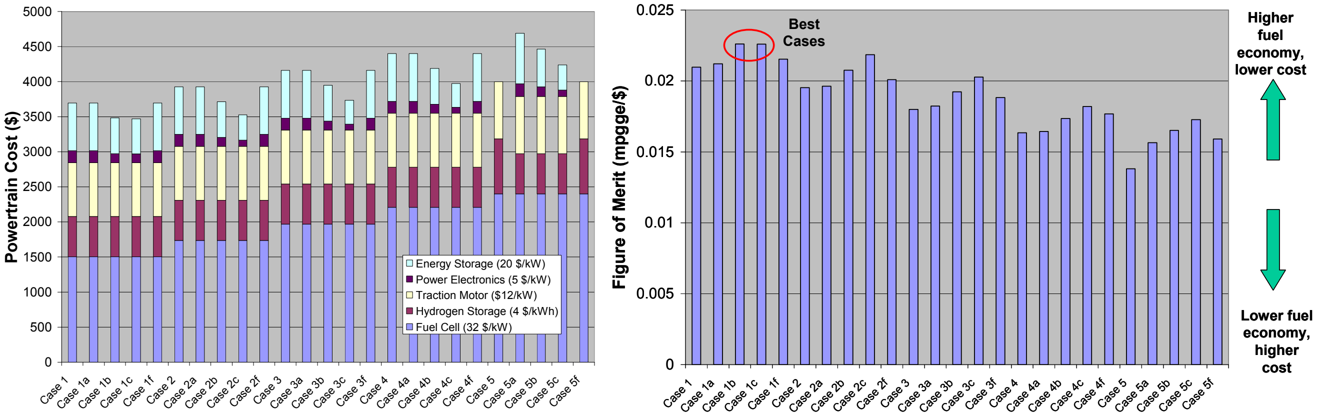


Figure 3: Total hybrid powertrain cost (left) and fuel economy normalized by powertrain cost

Now that the best case was identified, we needed to determine the energy and power requirements of the energy storage system based on the drive cycles.

4.2 Power Profile Analysis

The major question is: "How can we determine ESS requirements for meeting instantaneous power demands for a particular cycle?" From the analysis, one must come up with the required discharge power for a specified duration, required charge power for a specified duration, and amount of available energy needed to support the power profile from a drive cycle. We analyzed all the drive cycles previously indicated and separated the power demands of the FC and the ES. For the ES power profile, we overlaid all pulse power events of a driving profile on the same figure with start times set to zero. The ranges of the profile shapes were varied, some with sharp tall peaks and some broad with multiple small peaks in the middle. To simplify the analysis to be able to extract information, we assigned the duration of the events for the broad peaks and an associated average pulse power for that peak. For the sharp peak portion of each segment, we assigned a short duration for the pulse peak power and magnitude of the pulse peak power. Figure 4 depicts this representation.

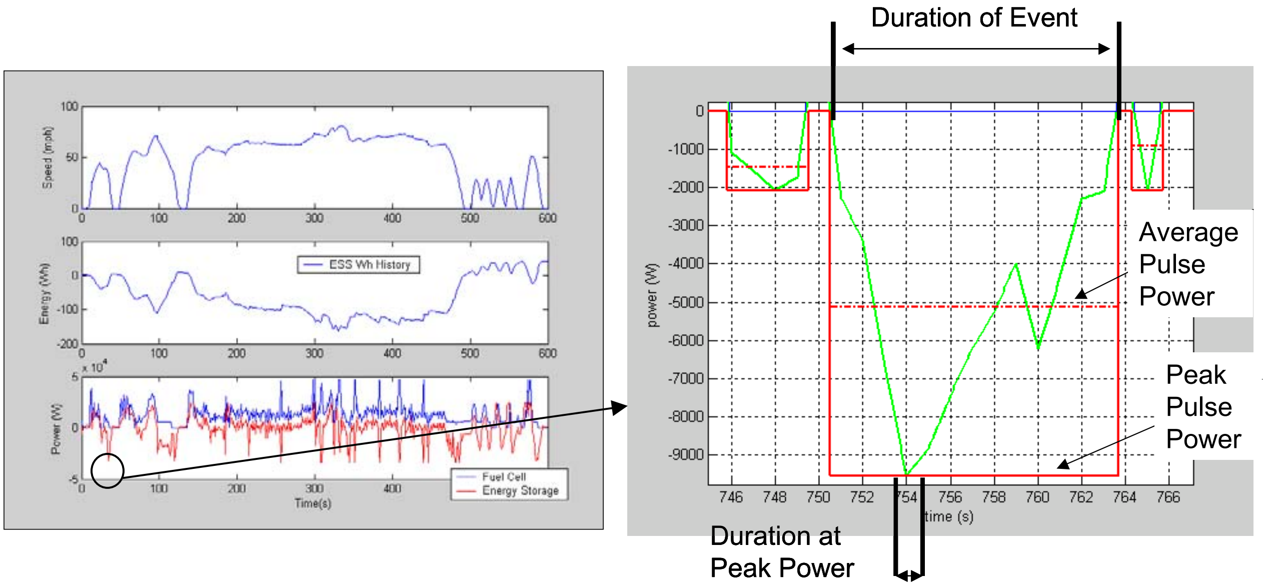


Figure 4: Analysis of energy storage power profile (example is for Case 1 with US06)

The energy captured or needed in each peak was calculated based on the average pulse power times during the duration of the event and is called usable or available energy. We then plotted the average pulse power versus the available energy for various cases. Figure 5 shows such a plot for various cases.

We also looked at the distribution of the energy storage system operating points for all the cycles to estimate mean, median, and standard deviation for the peak pulse power. Peak pulse power and average pulse power were plotted versus the duration of associated event. We included the required power for acceleration. Figure 6 shows peak pulse and average pulse power as a function of duration for various drive cycles and acceleration. It can be seen that peak power events typically only last for short durations of less than 1 second. From Figures 5 and 6, we believe that we need an ES system with 25 kW discharge capability for 12 seconds and charge capability of 20 kW for 5 seconds for all the categories in Case 1. Either NiMH or Li-ion batteries could deliver such power and energy capabilities. Of course other requirements such as cost, cycle life, calendar life, operating temperature range, and self-discharge rate will dictate the final selection. Acceleration performance sets discharge requirements and the US06 cycle sets charge requirements.

We should note that for FC startups (not traction), some FC systems may need up to 10 kW of power for 15 seconds. The energy requirements would be 42 Wh. So the energy and power requirements for cold startup will be within the capability of the recommended energy storage. The startup of the FC vehicles from very cold temperatures (below -10°C) with batteries may be challenging since the batteries have limited performance capabilities at low temperatures. Ultracapacitors have better performance capabilities than batteries at cold temperatures, so it is possible that we may select ultracapacitors over batteries for this reason, even though it may not be the most desirable approach.

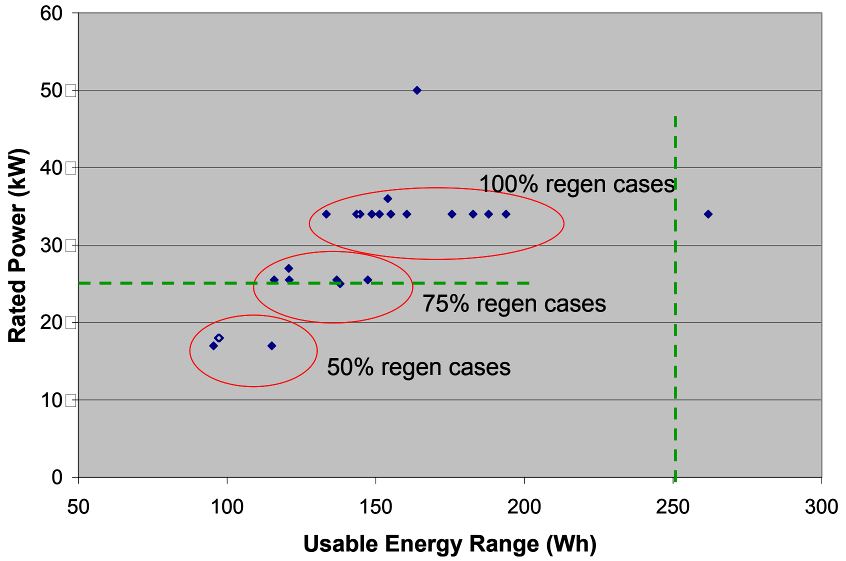


Figure 5: Power and associated energy needs for various cases studied.

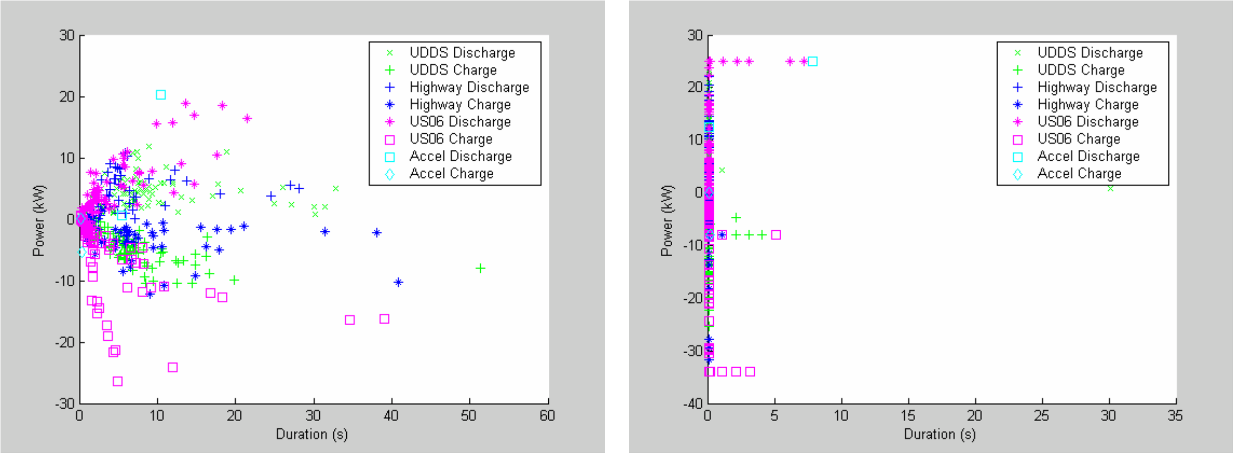


Figure 6. Peak pulse power (left) and average pulse power (right) versus duration for multiple cycles

5 Concluding Remarks

We analyzed ES roles in a FC vehicle. Hybridizing a FC vehicle with an ES system improves the fuel economy and reduces cost based on the 2010 DOE/FreedomCAR targets for components of a hybrid FC vehicle. The ES will also improve vehicle response by supplementing the FC's limited transient response. We described a process for determining ES requirements. We found that the peak power events for most drive cycles are very brief and less than 1 second. In general, 25%-30% improvement in fuel consumption can be achieved with hybridization. As long as the majority of regen is captured, regen strategy is not critical. The most fuel-efficient scenario was also the least expensive scenario (smallest fuel cell with moderate ESS). Intelligent energy management strategies to utilize captured regen energy in FC hybrid vehicles are critical. Fuel consumption is lower with a FC with peak efficiency of around 10% rated power. For the lightweight, aerodynamic, midsize car, we proposed an energy storage system with 25 kW discharge (12 seconds), 20 kW charge (5 seconds), and available energy of 250 Wh and a 56 kW FC.

We will continue working with the FreedomCAR Technical Teams to further refine the assumptions and the analysis to recommend final requirements for ES for FC hybrids. Of interest is the quantification of the energy and power available from a fuel cell system to charge the energy storage during long idles or ramping down of the fuel cell from high to lower power.

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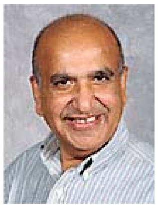

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In recent years, hydrogen fuel cell (FC) vehicle technology has received considerable attention as a strategy to decrease oil consumption and reduce harmful emissions. However, the cost, transient response, and cold performance of FC systems may present significant challenges to widespread adoption of the technology for transportation in the next 15 years. The objectives of this effort were to perform energy storage modeling with fuel cell vehicle simulations to quantify the benefits of hybridization and to identify a process for setting the requirements of ES for hydrogen-powered FC vehicles for U.S. Department of Energy's Energy Storage Program.

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