Energy Storage System Requirements for Hybrid Fuel Cell Vehicles

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Abstract
This paper summarizes a methodology for determining desirable characteristics and requirements of the energy storage system for fuel cell hybrid vehicles. The purpose of this work was to provide supporting analysis for the FreedomCAR Technical Teams in defining energy storage requirements for fuel cell vehicles. The power and energy requirements related to specific roles of the energy storage system have been determined for two vehicle class scenarios, a mid-size car and a mid-size SUV. The specific roles of the energy storage system considered included driveline traction power during fuel cell start-up, power-assist capability during the drive cycle, regenerative braking energy recapture capability, gradeability and acceleration performance improvement, electrical accessory loads, and fuel cell startup and shutdown loads. Considering the requirements for each role individually provides the ability to mix and match the characteristics desired based on the specific design scenario. In the short term, specific cost and specific volume of fuel cell systems will likely lead to hybridized fuel cell vehicles to satisfy cost and volume constraints. The process was applied to define the energy storage system characteristics for several scenarios. Through hybridization, it has been demonstrated that the powertrain system cost and volume can be reduced in the near-term scenario over the fuel cell only vehicle scenario.

Introduction
Hydrogen powered fuel cell vehicle technology has received considerable attention lately as a means to address the environmental and oil dependency issues in the United States. Given the current state of fuel cell technology and future predictions, the cost, mass, and volume of the fuel cell systems are likely to present significant challenges to early introduction in the transportation industry. Therefore, initial fuel cell powered vehicle introductions are likely to be hybrid electric vehicles. Vehicle hybridization with electrochemical energy storage technologies including lead-acid, nickel-metal hydride, lithium-ion, and ultra-capacitors could provide an alternative path to breaking current barriers to fuel cell application.

The only limited pre-production fuel cell vehicles available today are the Toyota FCHV and the Honda FCX. It has been reported that the Toyota FCHV has a nickel-metal hydride energy storage system similar to that of the Toyota Prius [1]. Likewise, the Honda FCX uses an ultra-capacitor energy storage system to provide regenerative braking and power assist capability [1]. Hybridizing fuel cell vehicles with electrical energy storage (batteries and/or ultra-capacitors) can have several benefits, including capturing regenerative braking energy, enhancing fuel economy, providing a more flexible operating strategy, overcoming fuel cell cold-start and transient shortfalls, and lowering the cost per unit power.

Recent studies by Wipke et al. [2] and Markel et al. [3, 4] have reviewed the application of optimization tools to the component sizing and energy management strategy of a fuel cell hybrid sport utility vehicle (SUV). The ADVISOR™ vehicle simulator [5] was used to predict the variation in fuel economy over a variety of drive cycles while the optimization tools were used to select design variable settings to maximize fuel economy while providing performance comparable to the baseline conventional vehicle. In Markel et al. [4] it was demonstrated that the hybridization of the fuel cell vehicle could compensate for the limited transient response capability of the fuel cell system and provide 50% fuel economy improvement over the fuel cell vehicle without an energy storage system. The fuel economy impact of fuel cell 'cold-starts' on a hybrid reformed gasoline fuel cell vehicle for a range of reformer system warm-up durations and warm-up fueling rates was also recently studied [6]. Hybridization was shown to provide one alternative to overcoming this technical limitation of gasoline reformed fuel cell systems by providing traction power and energy for the first portion of the drive cycle.

Previous studies, which focused on maximizing fuel economy, have indicated that a large energy storage system with a small fuel cell system operating in primarily thermostatic mode with some power-following provides the best design for maximum fuel economy. For those studies it was assumed that the fuel cell would be able to shut down and start up on an as needed basis; however, the energy penalty to do so was not included. Likewise, cost and packaging constraints were also not considered. Since the cost per unit power of energy storage technology is currently assumed to be less than that of fuel cells, and is expected to continue to be less in the next several years, it is anticipated that adding an energy storage system will lower the cost of the fuel cell vehicle. This may potentially aid the transition of fuel cell vehicles from short-term limited-use to long-term widespread commercial success.

This paper extends the previous studies to determine, from a requirements standpoint, how the fuel cell and battery sizing choices can impact not only efficiency but also cost, mass, and volume constraints. The fuel cell and energy storage system demands under drive cycle and performance tests will be analyzed for two vehicle platforms using ADVISOR™. Several sizing scenarios and energy storage technologies will be considered in detail. The purpose of this study is to support the FreedomCAR technical teams in defining energy storage requirements for fuel cell vehicles.

Modeling Assumptions

Based on the recommendations of a joint task force from FreedomCAR energy storage, fuel cell and vehicle system engineering and analysis technical teams, a mid-size SUV and mid-size car were considered for this study. The characteristics in Table 1 represent those of a typical conventional vehicle in each of these vehicle classes. These characteristics will be applied to the fuel cell hybrid vehicle scenarios.

Table 1: Vehicle Assumptions

Assumption Description	Units	mid-size SUV	mid-size Car
Vehicle Description	--	Rear wheel drive mid-size SUV	Front wheel drive mid-size car
Base Conventional Vehicle Mass	*kg*	1865	1480
Base Vehicle Glider Mass	*kg*	1276	1074
Cargo Mass	*kg*	136	136
Fuel Cell Vehicle Mass	*kg*	1923	1553
Aero. Drag Coef.	--	0.41	0.33
Frontal Area	*m^2*	2.6	2
Rolling Resistance Coef.	--	0.012	0.009
Wheel Radius (effective)	*m*	0.343	0.314
Vehicle Range	*mi (km)*	300 (483)	300 (483)

The vehicle performance constraints listed in Table 2 will be enforced to provide performance parity with the conventional vehicle. Note that of the three acceleration performance constraints, typically only one will be active at any time while the vehicle performance will be better for the other two.

Table 2: Vehicle Performance Constraints

Assumption Description	Units	mid-size SUV	mid-size Car
0-60 mph (0-97 kph)	*s*	<=11.2	<=12
40-60 mph (64-97 kph)	*s*	<=4.4	<=5.3
0-85 mph (0-137 kph)	*s*	<=20.0	<=23.4
Grade @ 65mph (105kph) for 20min. @ Curb Mass + 408kg	*%*	>=6.5	>=6.5
Drive Cycle Tolerance	*mph (kph)*	<=2 (3.2)	<=2 (3.2)
SOC Balancing	*%*	<=0.5%	<=0.5%

The assumptions for the fuel cell system, the hydrogen storage system, and the energy storage system are provided in Tables 3, 4, 5, and 6, respectively. The fuel cell data and model used in this analysis represent a pressurized hydrogen fuel cell system. The energy storage estimates in Table 5 are our best estimates of currently available technology. The targeted cost numbers in Table 6 are from the power assist column of the Office of Transportation Technologies' 2001 Vehicle High-Power Energy Storage Program report [7].

Table 3: Fuel Cell System Assumptions

Assumption Description	Units	2005	2010
Fuel Type	--	hydrogen	hydrogen
Fuel Cell Peak Efficiency	%	62.9	62.9
Fuel Cell Efficiency at 25% Power	%	60	60
Fuel Cell Efficiency at Rated Power	%	53.6	53.6
Fuel Cell System Specific Power	W/kg	500	650
Fuel Cell System Power Density	W/L	500	650
Fuel Cell System Cost	$/kW	96	27
Fuel Cell System 10-90% Power Transient Response Capability	s	2	1

Table 4: Hydrogen Storage System Assumptions

Assumption Description	Units	2005	2010
H2 Storage Energy Density	kWh/L	1.2	1.5
H2 Storage Specific Energy	kWh/kg	1.5	2
H2 Storage Cost	$/kWh	6	4

Table 5: Energy Storage System Assumptions

Assumption Description	Units	PbA	NiMH	Li-Ion	Ultra-capacitor
Energy Storage Energy Density	Wh/L	75	100	190	5
Energy Storage Specific Energy	Wh/kg	35	55	100	4
Energy Storage Power Density	W/L	1600	2000	2800	4500
Energy Storage Specific Power	W/kg	550	1000	1300	3500
Energy Storage Cost (power)	$/kW	$10.00	$40.00	$60.00	$15.00

Table 6: Office of Transportation Technologies Energy Storage Power Assist Cost Targets

DOE-OTT High-Power Vehicle Energy Storage Target	Units	
Energy Storage Cost (energy)	$/kWh	$1,666.67
Energy Storage Cost (power)	$/kW	$20.00

For each vehicle platform and timeframe (2005 and 2010) a fuel cell vehicle (without an energy storage system for traction) was created in ADVISOR™ that satisfies the applicable performance constraints. These vehicles were simulated over the Urban Dynamometer Drive Schedule (UDDS), Highway (HWFET), and US06 drive cycles. Likewise, the performance demands on the maximum acceleration test and a gradeability test were predicted. These simulation results provide boundary conditions on the performance requirements. Reductions in the fuel cell rated power lead to power and energy requirements for the energy storage system. However, compensating for the downsized fuel cell is only one of the many roles that the energy storage system may provide.

Energy Storage Roles in Fuel Cell Vehicle Hybridization

In order to size a vehicle's primary and secondary power sources, in this case the fuel cell power plant and electrochemical energy storage unit, the roles of secondary power system should first be established. The following roles have been considered for the electrochemical energy storage system, and will be discussed in more detail in subsequent sections:

- Traction power during fuel cell start-up
- Power-assist during drive cycles
- Regenerative braking energy recapture
- Gradeability performance
- Acceleration performance
- Electrical accessory loads
- Fuel cell startup and shutdown

Traction Power During Fuel Cell Startup

Under ambient and cold-start conditions it is likely that the fuel cell system power output will be significantly less than its rated power. Haraldsson and Wipke [8] indicate that the reduction in power output capability from rated power at 80C could be as large as 50% when the system has been soaked at 20°C (referred to as an "ambient start") based on model predictions. In some configurations, the energy storage system will be expected to compensate for the limited fuel cell system performance. As a result, the energy storage requirements could be substantial under normal consumer driving. The following series of figures quantifies the vehicle traction power and energy demands over typical drive cycles. For simplicity and clarity the results do not include vehicle electrical accessory loads or power for starting the actual fuel cell system.

Figure 1 summarizes the peak traction power encountered as a function of drive cycle time for the SUV (left) and car (right). Connecting the peak power points as they are encountered during the drive cycle creates the power profiles provided in . This forms an envelope defining how quickly the system must be able ramp-up its power output capability. The peak power trace ends when the peak power point of the cycle is encountered. After that point, all other power requirements are less than the drive cycle peak.

To illustrate this role of the energy storage system, we will show a simple example of the startup possibilities, and then explore it in more detail graphically. If it is assumed that the fuel cell is sized at a rated power of 100 kW for the SUV, and it is only able to provide a peak of 50 kW (50% of rated power) for the first 120 s of the US06 drive cycle, then from, the battery will be relied upon to provide peak power of up to 50 kW. In this scenario, the battery would not need to contribute on the UDDS or Highway cycles since the peak power in the first 120 s is less than 50 kW. The fuel cell system worst-case start-up time and peak power capability under ambient and cold start conditions will contribute to determining minimum energy storage unit power requirements to meet drive cycle traction loads.

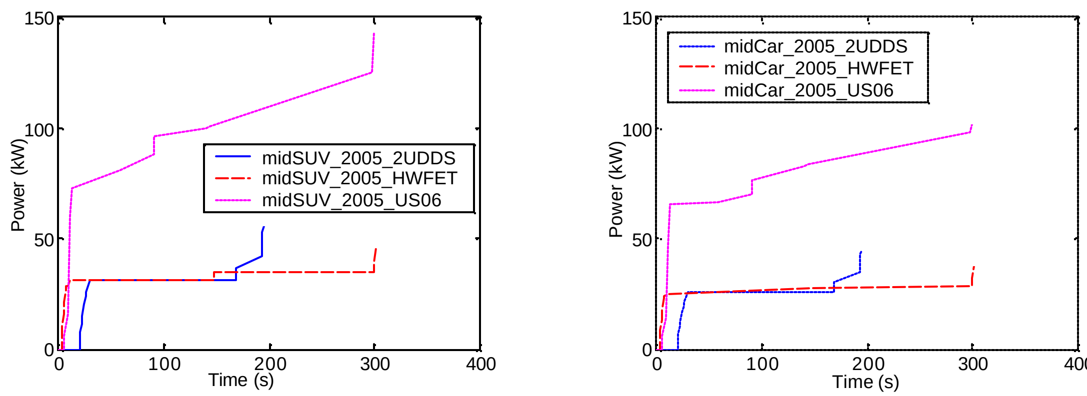

Figure 1: Vehicle Peak Traction Power Envelope Over Three Typical Drive Cycles

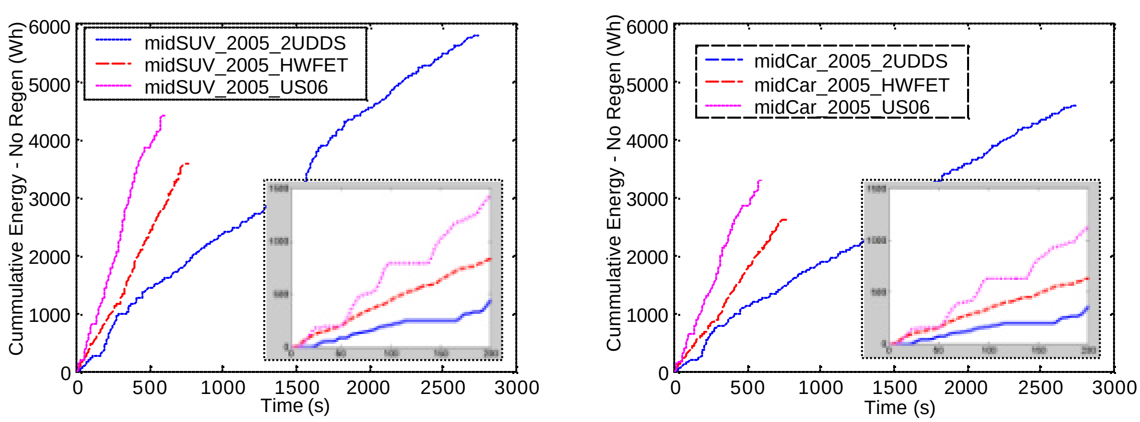

Figure 2: Cumulative Traction Energy (no regenerative braking) Required for Typical Drive Cycles

Likewise, the energy storage system will also need to be sized to adequately provide the traction energy requirements during fuel cell system start-up. Figure 2 shows the total cumulative traction energy used in three drive cycles for both the SUV (left) and car (right). The insets of the figure provide a close-up view of the energy demands in the first 200 s of the drive cycles. The figure provides only positive traction energy. Negative traction energy (i.e. regenerative braking) will be considered separately.

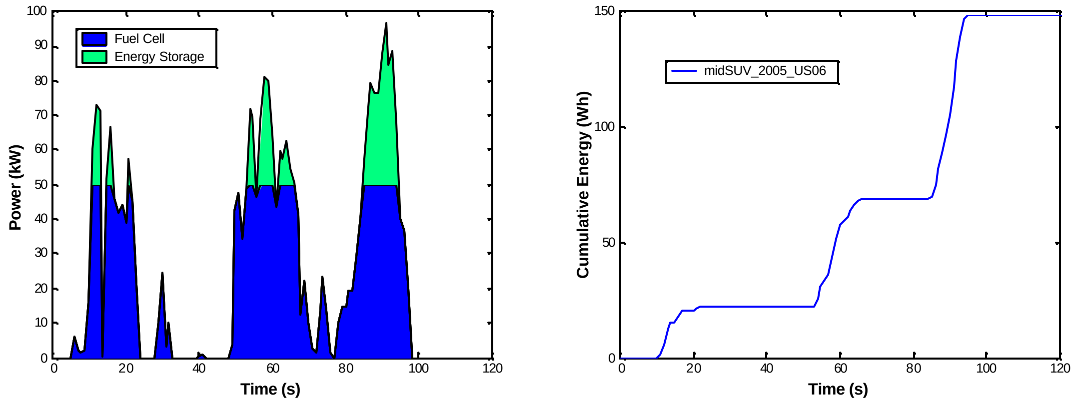

Figure 3: Fuel Cell and Energy Storage Power (left) and Cumulative Traction Energy (right) Required from Energy Storage System During Ambient Start for 2005 SUV

In the previous example, we determined the energy storage power requirements when the fuel cell could only provide 50 kW of power under an ambient start. Using the data in Figure 2 and removing the contribution of the fuel cell, we obtain the battery power and energy requirements illustrated in Figure 3. In this case, the energy storage system would need to provide a peak of 45 kW and 150 Wh during the first 120 s of the US06 cycle, in addition to the fuel cell power, to satisfy the traction loads of the drive cycle.

Power Assist During Drive Cycles

The energy storage system can provide power-assist capability during the drive cycle in multiple ways. First, the energy storage system can perform peak shaving. In this case, the fuel cell system rated power has been reduced such that the drive cycle loads are greater than its capability and the energy storage system provides power during these transient peak power events. Secondly, the energy storage can be used to improve the transient response of the traction system in a system in which the fuel cell may not be capable of responding quickly enough to an increase in power.

Figure 4 provides the power and energy requirements of the energy storage system in the case of peak shaving for a range of fuel cell sizes. As the fuel cell rated power is decreased, the energy storage energy requirements increase exponentially (right graph). The power shown on the left represents the difference between the peak power of the fuel cell and the peak power required during the drive cycle.

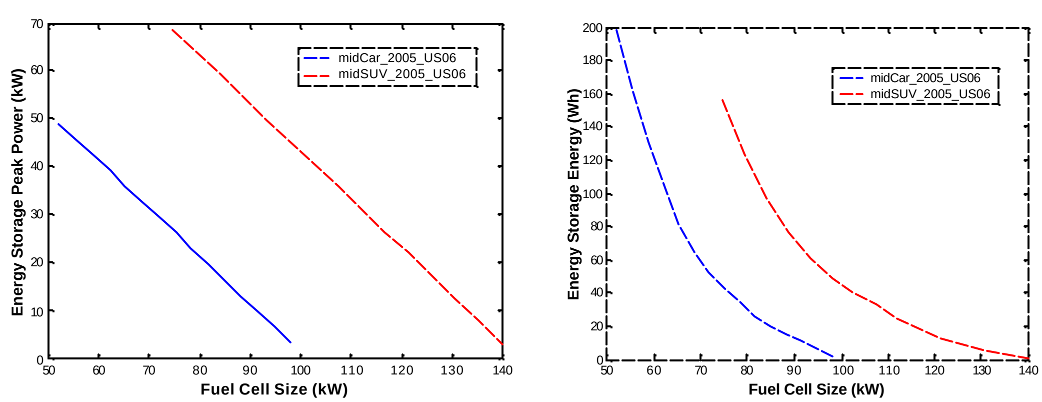

Figure 4: Energy Storage System Power (left) and Energy Requirements (right) During Peak Shaving on the US06 Drive Cycle

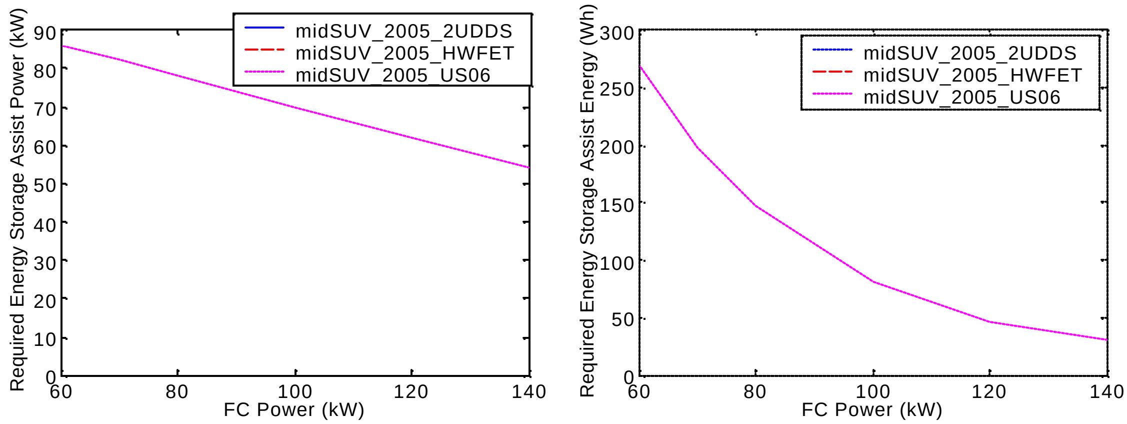

Figure 5: Power and Energy Requirements Due to Fuel Cell Power Response Capability of 2s

The transient response capability of the fuel cell system has been characterized by the time it requires to increase its power output from 10% of rated power to 90% of rated power. For a direct hydrogen system this could be in the range of 0-5s. In Figure 5, the energy storage system's power and energy requirements associated with a transient response capability of 2 s are provided for fuel cell sizes ranging from 140 kW to 60 kW. At a response rate of 2 s, neither the UDDS nor the HWFET needed assistance from the energy storage system. For the 100 kW fuel cell example, the transient power required from the energy storage system is 70 kW, and the cumulative energy requested from the energy storage over the US06 cycle was about 80 Wh.

Regenerative Braking Analysis

Figure 6 illustrates the total available regenerative energy that is dissipated at the friction brakes in the two fuel cell vehicles studied without any regeneration capability. The results can be used to determine the minimal battery pack size that would be able to collect all of the available regenerative braking energy. Regenerative braking occurs in discrete events each with a unique duration and power profile. Figure 7 quantifies the power, duration, and energy characteristics of each braking event in the individual drive cycles for both vehicles. The US06 cycle has some significantly large regenerative braking events that have a peak power of over 50 kW and durations of up to 30 s for the SUV case. However, the majority of braking events for the UDDS and Highway cycles are less than 15 s and less than 35 kW for the SUV. There is a significant cluster of points during the UDDS cycle that have an energy content of between 25 and 75 Wh and durations on the order of 10 s.

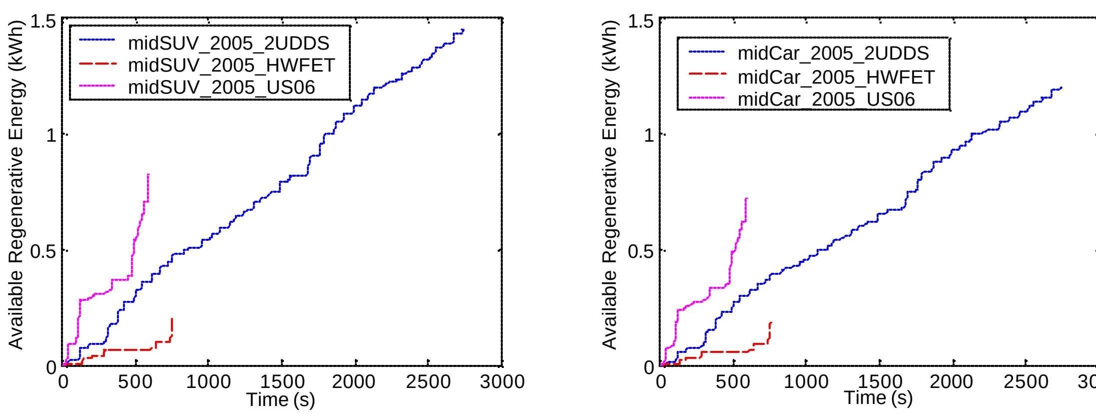

Figure 6: Available Energy Dissipated in Friction Brakes For Three Drive Cycles

The requirements displayed graphically in Figure 7 can help to determine the required battery pack size for optimal regenerative braking energy capture. However, these requirements do not necessarily lead us to the correct balance between fuel cell power capability and battery pack power capability. To investigate the correct balance between a fuel cell size and battery pack size, it is useful to consider the peak power and energy requirements encountered on the acceleration and grade performance tests, explored in the next section.

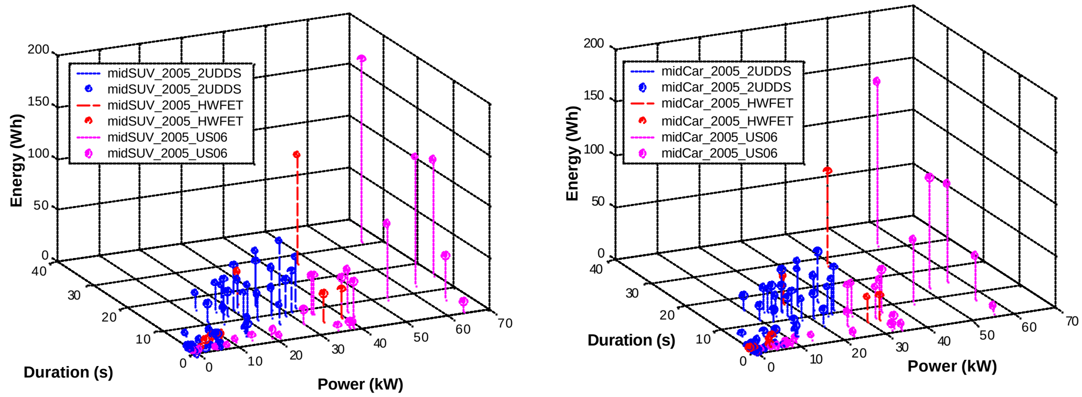

Figure 7: Regenerative Braking Event Analysis for SUV (left) and Car (right)

Acceleration and Grade Performance Requirements

The maximum *power* demands from a vehicle are typically encountered during maximum effort acceleration tests, while the highest *energy* demands are encountered during a long-term gradeability test. Figure 8 illustrates the average energy storage system power and energy required to maintain maximum acceleration performance (0-60 mph acceleration) with respect to the rated power of the fuel cell system. The plots were generated by sweeping the vehicle's fuel cell size from 100% to 50% of the rated power capability. Once again, these results are for the traction power and energy only and do not include accessory loads or fuel cell startup and shutdown energy requirements. The usable energy storage capacity required to sustain the maximum acceleration is shown on the right side of Figure 8.

If we again assume that the fuel cell can only provide 50% of its rated power under ambient start conditions, then even for a full size fuel cell rated at 140 kW for the SUV, the system would need to include an energy storage system that can provide an average power of 45 kW and 35 Wh to maintain performance over a range of ambient temperatures. These calculations assume a single acceleration event, and it is common to size the energy storage system capacity for multiple repeat acceleration tests. It is also assumed that we must maintain performance parity with the conventional vehicle regardless of operating conditions.

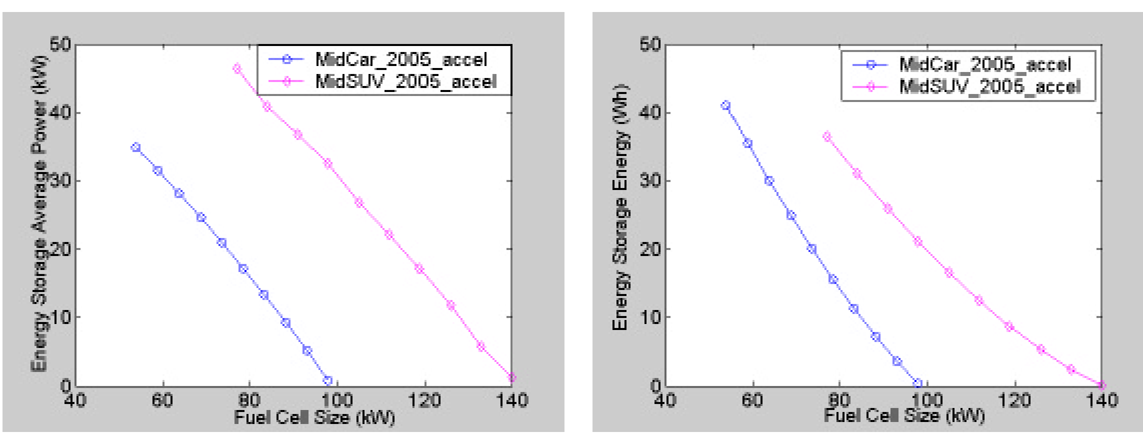

Figure 8: Energy Storage System Average Power (left) and Energy (right) Required to Maintain Acceleration Performance as Fuel Cell is Downsized

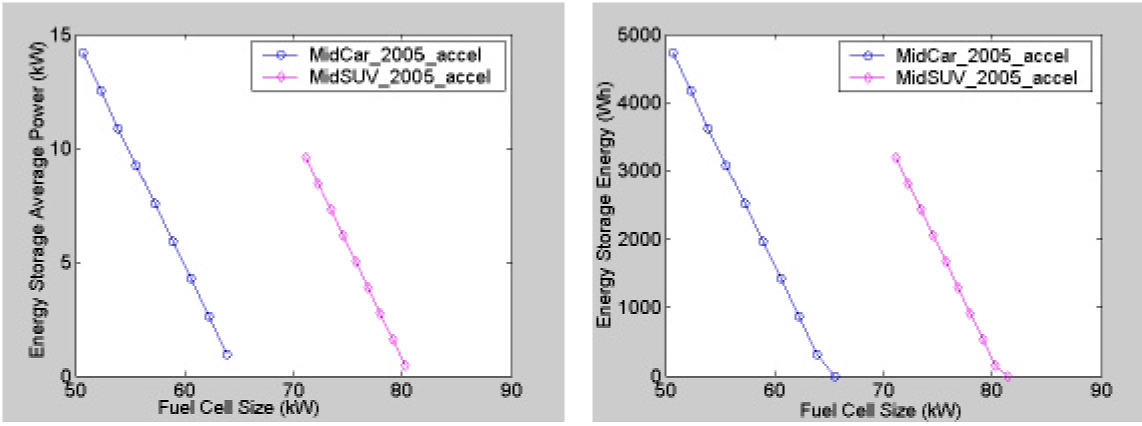

Figure 9: Energy Storage System Average Power (left) and Energy (right) Required to Maintain Gradeability Performance as the Fuel Cell is Downsized

As was mentioned earlier, long-term gradeability requirement can lead to a significantly large energy storage system if the fuel cell system is downsized below the continuous power requirement of the grade test. In Figure 9, the energy storage power and energy requirements are provided as a function of the fuel cell rated power. If the fuel cell rated power is above 80 kW for the SUV or 65 kW for the car, then no power or energy is needed from the energy storage system, since the fuel cell system already satisfies the continuous load. As the fuel cell size decreases below these levels, the required energy storage system capacity increases dramatically to maintain the vehicle’s performance. A 75 kW fuel cell in the SUV would require a battery with at least 2 kWh of usable capacity. If a usable range of 40% state of charge (SOC) is assumed, this leads to a 5 kWh energy storage system, which may have significant packaging and mass implications. For example, with Table 5 NiMH battery characteristics, 91 kg and 50 liters of batteries are necessary to meet the energy requirement, while only 6 kg and 3 liters are necessary for the power requirement. As a result, it should be generally concluded that the energy storage system will provide minimal contribution to the grade performance and that the minimum fuel cell system size should correlate to the power required to provide continuous grade performance capability.

Electrical Accessory Loads

In the assessment thus far, electrical accessory loads have been purposely excluded from the analysis. The electrical accessory loads in a fuel cell hybrid vehicle may include radiator fans, electric power steering, electric brakes, air conditioning systems, etc. In general, these loads will vary throughout the drive cycle, but the net effect can typically be accounted for by applying a constant average electrical accessory load over the duration of the drive cycle. In a fuel cell hybrid vehicle the battery could potentially be expected to maintain the electrical accessory loads for periods during the cycle. For example, the energy storage system must have the power and energy capacity to support these loads when the fuel cell is shut down if start/stop hybrid operation is allowed. However, over the long run, the fuel cell would need to provide the bulk energy to support the accessory loads. For these analyses, we will assume a constant electrical accessory load of 750 W for the UDDS and Highway cycles and a 1500 W load for the US06 cycle. As shown in Figure 10, integrating these values over the duration of the drive cycle provides a total energy requirement associated with electrical accessory loads.

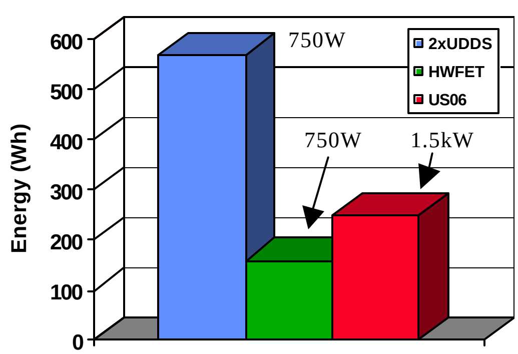

Figure 10: Electrical Accessory Load Power and Energy Requirements

Fuel Cell System Start-up and Shut-down

In a hybrid fuel cell vehicle, as has currently been demonstrated in internal combustion engine (ICE) hybrid vehicles, it would be desirable to be able to have start/stop capability. This means that while the vehicle is operating, the primary power plant (i.e. fuel cell or ICE) can be shut down and restarted on an as-needed basis. Shutting down the system under low power demand scenarios can save a significant amount of fuel. Very little information is available at this time on the process or the electrical loads for starting up or shutting down an automotive fuel cell system. These energy storage requirements will need to be included in future assessments as the technology requirements become clearer.

Cost and Packaging Considerations

The analysis thus far has focused on the power and energy requirements of the energy storage system. However, total system cost and packaging constraints can drive the final system design requirements for production vehicles. The cost per kW of the fuel cell system today is extremely high but is expected to drop dramatically in the long-term. Most energy storage technologies are less expensive than the fuel cell systems on a per kW basis today, but expected future reductions in cost are less dramatic than for fuel cell systems. Therefore, from a cost perspective, it would reasonably be expected that a system with a large battery and small fuel cell today would be logical, while in the future a system with a smaller battery and larger fuel cell will become more cost competitive. A similar scenario can be expected in terms of system volume and packaging.

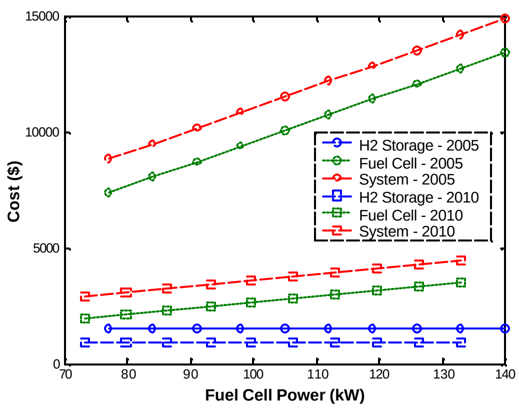

Figure 11: Fuel Cell System Cost Assumptions for SUV

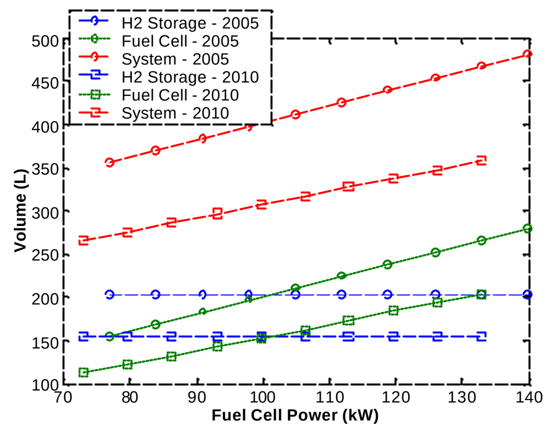

Figure 12: Fuel Cell System Volume Assumptions for SUV

Figure 11 and Figure 12 present the cost and volume assumptions for the fuel cell system of this study graphically. The hydrogen storage system and the fuel cell stack are presented individually along with the complete system results. These results do not include the electric traction system, nor do they include the energy storage system. For reference purposes, a typical mid-size SUV will have ~750 L of packaging volume for the entire powertrain. In 2005, the fuel cell stack cost dominates the system cost while in 2010 the stack and hydrogen storage costs are nearly equivalent for fuel cell systems less than about 90 kW. In terms of volume, the fuel cell and storage are quite similar in both 2005 and 2010 across the fuel cell power spectrum. The cost and volume of the other system components, specifically the energy storage system will be dependent on both the fuel cell system sizing and the roles that the energy storage will be expected to satisfy. The cost and volume attributes of the energy storage system will be directly related to the required power to energy ratio characteristics.

Level of Hybridization Selection

The basic roles that the energy storage system could potentially satisfy in a fuel cell hybrid vehicle were established in the previous section. Some of the roles were short-term, during which the fuel cell would prepare to take over the load, while others are more long-term. Secondary energy storage can also be used to satisfy peak transient demands, which allows fuel cell downsizing. Based on the analysis results it seems inappropriate for secondary energy storage to take over various continuous loads that need to be sustained, such as maintaining speed on a grade, as previously discussed.

For an internal combustion engine hybrid it is common to downsize the engine to improve the engine operating efficiency since the peak efficiency typically occurs under high load conditions. In contrast, the peak efficiency of a fuel cell system will typically occur near 25% of rated power. Therefore, fuel cell system downsizing in a fuel cell hybrid does not necessarily lead to improved system efficiency. However, other factors including cost and packaging constraints may be more influential than efficiency in determining the optimal combination of fuel cell and energy storage system.

The focus of the remainder of the paper will be on applying and combining the individual results of the requirements analysis from the previous sections to derive estimates for the preferred energy storage system characteristics for the mid-size SUV only. A similar process could be applied to derive similar trend lines for the mid-size car scenario.

Continuing the assumption of a fuel cell system that has been downsized from 140kW to 100kW in the SUV scenario, Table 7 can be compiled based on the results of the individual roles analysis. Assumptions necessary to come to these conclusions have been included in the comments column of Table 7. During tests A, B, and C the limiting case for power and energy requirements was always during the US06. To determine the energy storage system power requirements we take the peak requirement from rows A, B, C, D, and E and add an accessory load if appropriate. In the 100 kW fuel cell case, we get a 71.5 kW peak power requirement: 70 kW are required to fill in for the 2 s power response capability of the fuel cell system, which takes place during the US06, and then a 1.5 kW US06 accessory load is added. In order to size the total energy storage system to meet the energy requirements, the greatest of four cases must be determined: (1) If any energy storage power is required to sustain the grade test at the specified fuel cell size, the energy required to sustain this power plus a 750W accessory power for 20 minutes; (2) The energy required to sustain the energy storage power requirement over six consecutive acceleration tests; (3) The energy required to sustain the Highway or FTP accessory load for eight minutes, or the US06 accessory load for 4 minutes; or (4) The summation of the energies in A, B, and C. Cases A and B are additive (neglecting slight overlap), but the overlap in cases A and C is subtracted during case (4). The resulting energy requirement for the 100 kW fuel cell scenario is a 1.33 kWh storage system, and is driven by case (2). Similar analysis can be performed for the range of fuel cell system rated power to produce a range of energy storage systems characteristics that would be appropriate for fuel cell hybrid vehicles.

Table 7: Summary of Energy Storage Requirements for SUV With a 100 kW Fuel Cell System

	Event Description	Peak Power (kW)	Duration (s)	Cumulative Energy (kWh)	Comments
A	Startup Traction Loads	46.4	<11	0.15	50% rated power,120s warm-up over 2UDDS, HWFET, & US06
B	Power-assist (response)	70.0	<3	0.08	2 second 10%-90% FC response (ramp) rate (during 2UDDS, HWFET, & US06)
C	Power-assist (downsize)	43.3	<3	0.05	During 2UDDS, HWFET, & US06. US06 is limiting case
D	Gradeability (see Table 2)	0.0	1200	0.00	81.4 kW sustained load for 1200s
E	Acceleration	40.0	20	0.22	140 kW sustained load for 20s
F	Accessory Loads	1.5	600-2800	0.10	US06 peak power, energy is for US06 4 min, or FTP 8 min
G	Fuel Cell Shutdown	N/A	N/A	N/A	-
H	Regenerative Braking	70.0	<30	1.50	Pmax is during US06, energy is FTP cycle max

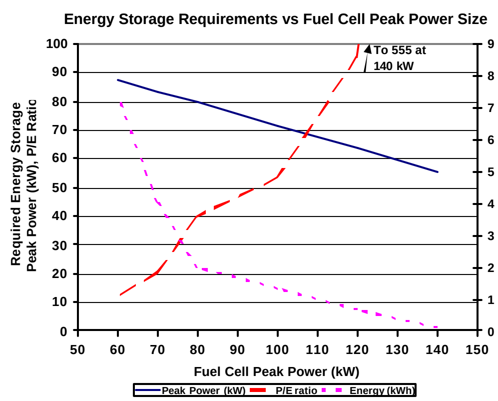

Figure 13: Energy Storage System Characteristics for SUV Scenario

The requirements for the energy storage system were tabulated as in Table 7 for the full range of fuel cell rated powers and the results are presented in Figure 13 in terms of power, energy and power-to-energy ratio. At the fuel cell rated power of 140 kW the battery requirements are quite minimal, except for a 54 kW power requirement due to the 2 s fuel cell response time. That power requirement drops dramatically with a 1 s response time. The new power requirement would be halved to 27 kW, due to startup traction assist requirements. With current technology at 2 s fuel cell response times, the power requirements grow linearly as the fuel cell power is decreased. The energy requirements increase dramatically once the fuel cell size drops below 80 kW. Below 80 kW the gradeability performance requirements dominate the energy storage system characteristics. The energy requirements from 80 kW up to 120 kW are constrained by the six 0-60 mph accelerations requirement. At 140 kW, the energy storage size is constrained by accessory load support.

Now that the power and energy requirements for various fuel cell hybrid SUV configurations have been established, the cost and volume of the various energy storage technologies can be evaluated. Table 5 is used to determine the costs and volumes for each energy storage solution considered. The cost values in Figure 14 are determined by calculating the required weight of the pack per the specific power multiplied by the power requirement and the specific energy multiplied by the energy requirement. The constraining weight determines the pack weight, which is converted to pack power and then to cost, via the specific power and $/kW values. Similarly, the pack volume in Figure 15 is determined by the constraining power density or energy density value. Clearly, the ultracapacitor is only cost and volume competitive when the P/E ratio is very high, due to its low energy density. With the various requirements considered, the ultracapacitor only makes sense when downsizing is minimal, resulting in small energy storage energy requirement. Otherwise, the lead-acid battery is the lowest cost solution for meeting power and energy demands, irrespective of life cycle costs. The lithium battery technologies are the lowest volume solutions. Future studies will investigate the possibility of satisfying the energy storage requirements with a combination of batteries/ultra-capacitors. A lead-acid, ultracapacitor combination looks like a promising mix from the cost perspective.

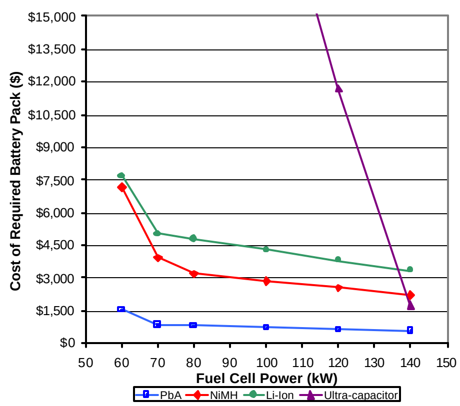

Figure 14: Energy Storage System Cost

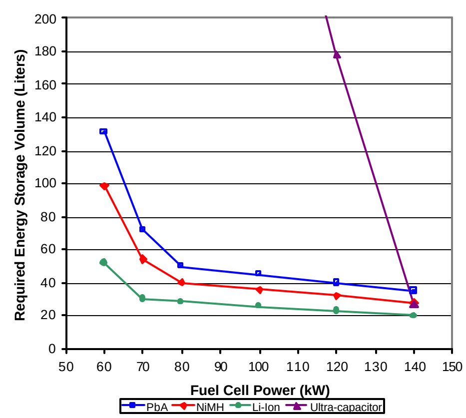

Figure 15: Energy Storage System Volume

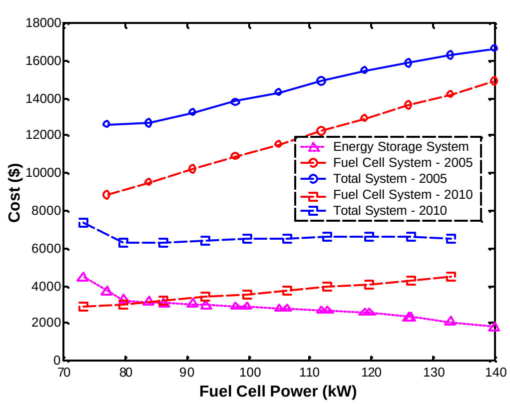

Figure 16: Powertrain System Costs for SUV

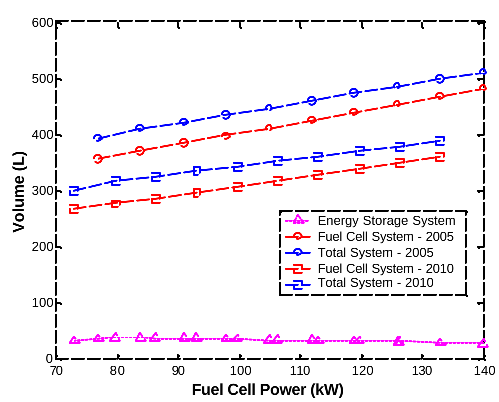

Figure 17: Powertrain System Volume for SUV

After choosing the best energy storage system cost and volume scenarios for each fuel cell size and combining that information with the fuel cell system cost and volume results presented previously, we derive the powertrain system cost and volume characteristics shown in Figures 16 and 17. In the near-term scenario, reducing the fuel cell size as much as possible seems to provide the greatest cost and volume reduction relative to the fuel cell-only case. However, in the long-term scenario the reduction in fuel cell system cost is balanced with the increase in energy storage system cost.

Conclusions

A methodology has been presented for determining the requirements of an energy storage system to be included in a fuel cell hybrid vehicle. The methodology was applied to mid-size car and mid-size SUV vehicle scenarios in the timeframes of 2005 and 2010. The power and energy requirements of the energy storage system were derived based on the specific roles that it would be expected to fill. The energy storage system requirements in this study ranged from 55-85 kW and 0-7 kWh depending on the fuel cell system size and the intended roles the energy storage system. In general, it can be concluded that significant fuel cell downsizing leads to substantial energy storage system requirements. It was found that downsizing beyond the power level required for continuous gradeability should be avoided since it led to dramatically increased energy requirements for the energy storage system. The current study did not consider the fuel economy or efficiency impacts of energy storage in a fuel cell hybrid vehicle. The study does however define the bounds for future optimization problems in which cost, volume, and mass constraints can all be evaluated simultaneously while maximizing fuel economy.

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