The 21st Worldwide Battery, Hybrid and Fuel Cell Electric Vehicle Symposium & Exhibition

EVS 21 MONACO

2 - 5 April 2005

Energy Storage Fuel Cell Vehicle Analysis

Ahmad Pesaran
National Renewable Energy Laboratory
Golden, Colorado, USA

NREL/PR-540-38143
August 2005

Acknowledgments

Co-Authors

Tony Markel (NREL)
Matthew Zolot (NREL)
Sam Sprik (NREL)
Harshad Tataria (GM/USABC)
Tien Duong (DOE)

Support and Guidance

FreedomCAR Energy Storage Technical Team
USABC Technical Advisory Committee
Ted Miller (Ford)
Cyrus Ashtiani (DaimlerChrysler)
Dave Howell (DOE)

Outline

- Study Objectives
- Assumptions & Requirements
- Analysis Approach
- Results
- Conclusions

Objective

Determine ESS Requirements for Fuel Cell Hybrid Vehicles for FreedomCAR Tech Teams

FreedomCAR Goals		Fuel Cell Hybrid Battery
Characteristics	Units	
Pulse Discharge Power (x s)	kW	TBD
Max Regen Pulse (y s)	kW	TBD
Total Available Energy	kWh	TBD
Round Trip Efficiency	%	>90
Cycle Life	Cyc.	TBD
Cold-start at -30°C (TBD kW for TBD min.)	kW	TBD
Calendar Life	Yrs	TBD
Max Weight	kg	TBD
Max Volume	liters	TBD
Production Price @ 100k units/yr	$	TBD
Maximum Operating Voltage	Vdc	TBD
Minimum Operating Voltage	Vdc	TBD
Maximum Self Discharge	Wh/d	50
Operating Temperature	°C	-30 to +52
Survival Temperature	°C	-46 to +66

Will these requirements will be different than ones for ICE-HEVs?

Vehicle Attributes for Analysis

Forward-looking

(What would be the vehicle characteristics when the fuel cell technology is ready and affordable?)

- Midsize
  - Initial focus (popular)
  - Needs smaller fuel cell, thus lower cost
- Extremely Lightweight
  - For the same increase in fuel economy, it is more cost effective to take weight out of the vehicle rather than using a larger fuel cell
    - Light weighting \$/kg >> Larger fuel cell \$/kW
- Aerodynamic (relatively low drag coefficient)

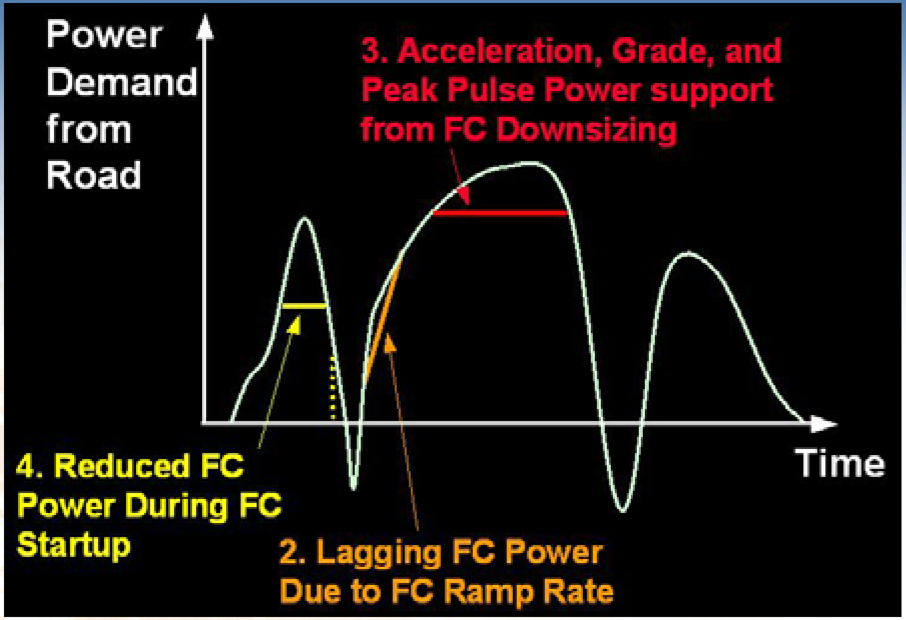
Vehicle Assumptions
Characteristics and Requirements

Characteristic	Chevrolet Malibu Model Year 2004 Mid-size car	Final NREL Assumptions for Mid-Size Car (similar to Basic Malibu Sedan)
Dimensions [mm] (L x H x L-wheelbase)	4,783 x 1,460 x 2,700	4,749 x 1,416 x 2,656
Curb Weight [kg] (calculated)	1437 kg	**TBD** kg = 1060*0.6 + PT Mass
Glider Mass [kg]	1030 (w/ driveline)	**636** =1060*0.6
Weight Fraction (Front:Rear) [%]	63:37	**50:50**
Center-of-Gravity Height [m]	0.5 – estimated	**0.45**
Coefficient of drag	0.30	**0.25**
Frontal Area [m^2]	2.0 (calculated)	**2.0**
Rolling Resistance Coefficient	0.008 – 0.009	**0.0070**
Range (composite City/highway)	756 km	(320 miles) 500 km **(minimum)**
Maximum Speed (FC only)	Better than 160 km/hr	(100 mph) 160 km/h
(0-60 mph) 0-100 km/h Acceleration	11.0 seconds (estimate)	**11** seconds
Gradeability (FC only)	Better than 6.5% Grade @ 65 mph	**5.5% Grade @ 55 mph (88 km/h)**

Roles of Energy Storage System (ESS)

- Mostly likely
  - ✓ 1. Regenerative braking capture
  - ✓ 2. Traction assist during acceleration (FC slow ramp rate)
  - ✓ 3. Traction assist during high power transients (down sizing FC)
- Probably
  - ✓ 4. Traction assist during fuel cell "warm" startup from idle
    - ➢ Traction assist and power for ancillaries during fuel cell system "cold" startup & shutdown
- Probably not
  - – Sustained gradeability
  - – Electrical accessory loads (in steady state)

✓: assumed in this study



The combined FC and ESS hybridized system must meet performance target requirements of the vehicle

- Acceleration
- Top speed
- Grade sustainability

Other Assumptions
2010 FreedomCAR/DOE Targets

Fuel Cell

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	32
Fuel Cell System 10-90% Power Transient Response Capability	s	1
Time from Start to Full Power Output Capability (20C)	s	15

Motor/Controller

Assumption Description	Units	Value
Specific Power (Motor and Controller)	kW/kg	0.75
Specific Cost (Motor and Controller)	$/kW	12
Power Density (Motor and Controller)	kW/L	3.53

Power Electronics

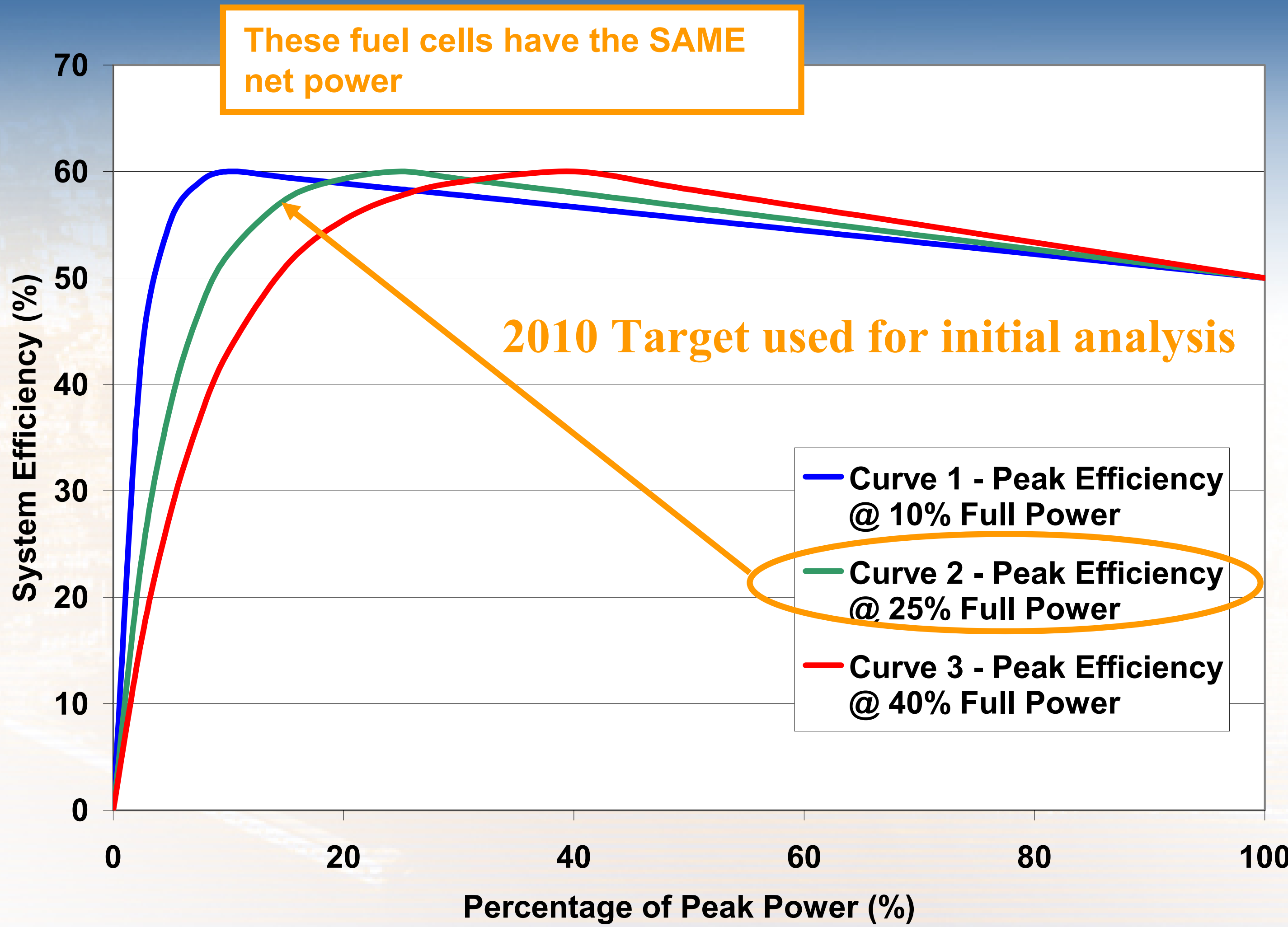
Assumption Description	Units	Value
Efficiency	%	95
Specific Cost	$/kW	5

Hydrogen Storage

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

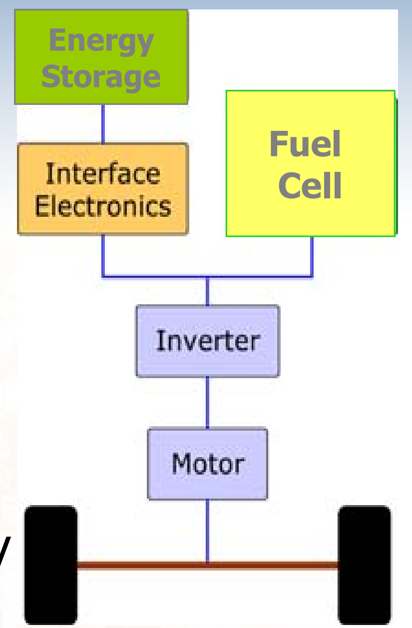
- Assumed 700 W constant accessory loads
- Fuel cell is always on (i.e. no start/stop operation)
- Fuel cell net power is zero at vehicle stop/idle (gross power >0)
- At idle, hydrogen fuel consumption 0.3% of rated power consumption

Fuel Cell Efficiency Characteristics



Analysis Approach using ADVISOR™

- Implemented an ESS control strategy (energy management) and regen capture strategy
- Simulated a range of FC/ESS configurations (Cases)
  - Smallest fuel cell (Case1: sized for top speed)
    - Cases 2-4 : incrementally increased fuel cell size; ESS sized to satisfy acceleration constraints
  - Fuel cell only case (Case 5)
    - Cases 5a-5c: ESS size increased to capture % of peak regen pulse power
  - Fuel cell plus ESS sized for max regen capture (Case 5a)
- Analyzed ESS power (kW) profile and Energy (Wh) history over several profiles
  - Urban, Highway, US06 cycles, and European cycles
  - Acceleration and gradeability tests

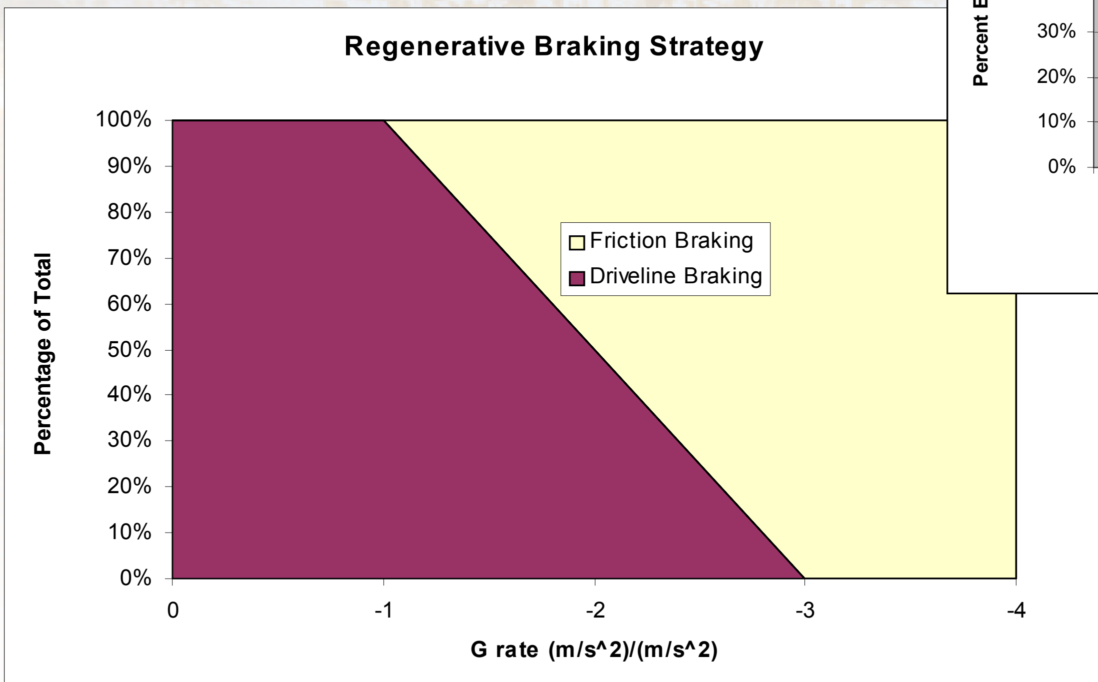


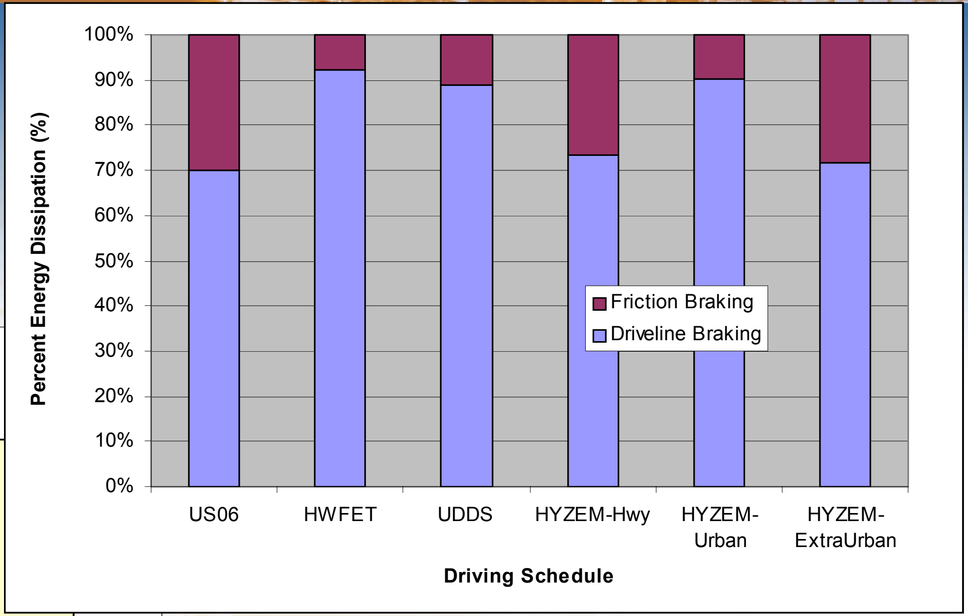
Energy Management Strategy/Assumption Used

- Monitored changes in ESS and modified the fuel cell command to maintain ESS energy level
- Included
  - Accounting of kinetic energy
  - Opportunity charge and discharge functionality (only take action if it makes the overall system efficiency better)
  - Monitored delta ESS energy to fuel-use ratio for correcting fuel economy
- Used multiple parameters to manage the strength of various elements of control
- A Design of Experiments was performed on each case to determine the best parameter settings
- Two Regenerative Braking Energy Capture
  - A fraction of total possible
  - Deceleration rate-based

Deceleration Rate-Based Regenerative Braking Strategy

- Fractional split between driveline and friction brakes defined as a function of deceleration rate





Given the current input assumptions (below 1g all driveline braking, above 3g all friction braking) the driveline would try to recapture between 70-90% of the available braking energy depending on the drive cycle.

Matrix of Vehicle Configurations Evaluated

- Case 1-4 varies fuel cell size with "deceleration-based regen strategy"
  - ESS sized to satisfy acceleration performance constraints
- Case Xa-c with increasing regen power limits
- Case Xf differs from Xa by the fuel cell characteristics
  - Xa peak eff at 25% power (DOE goal)
  - Xf peak eff at 10% power

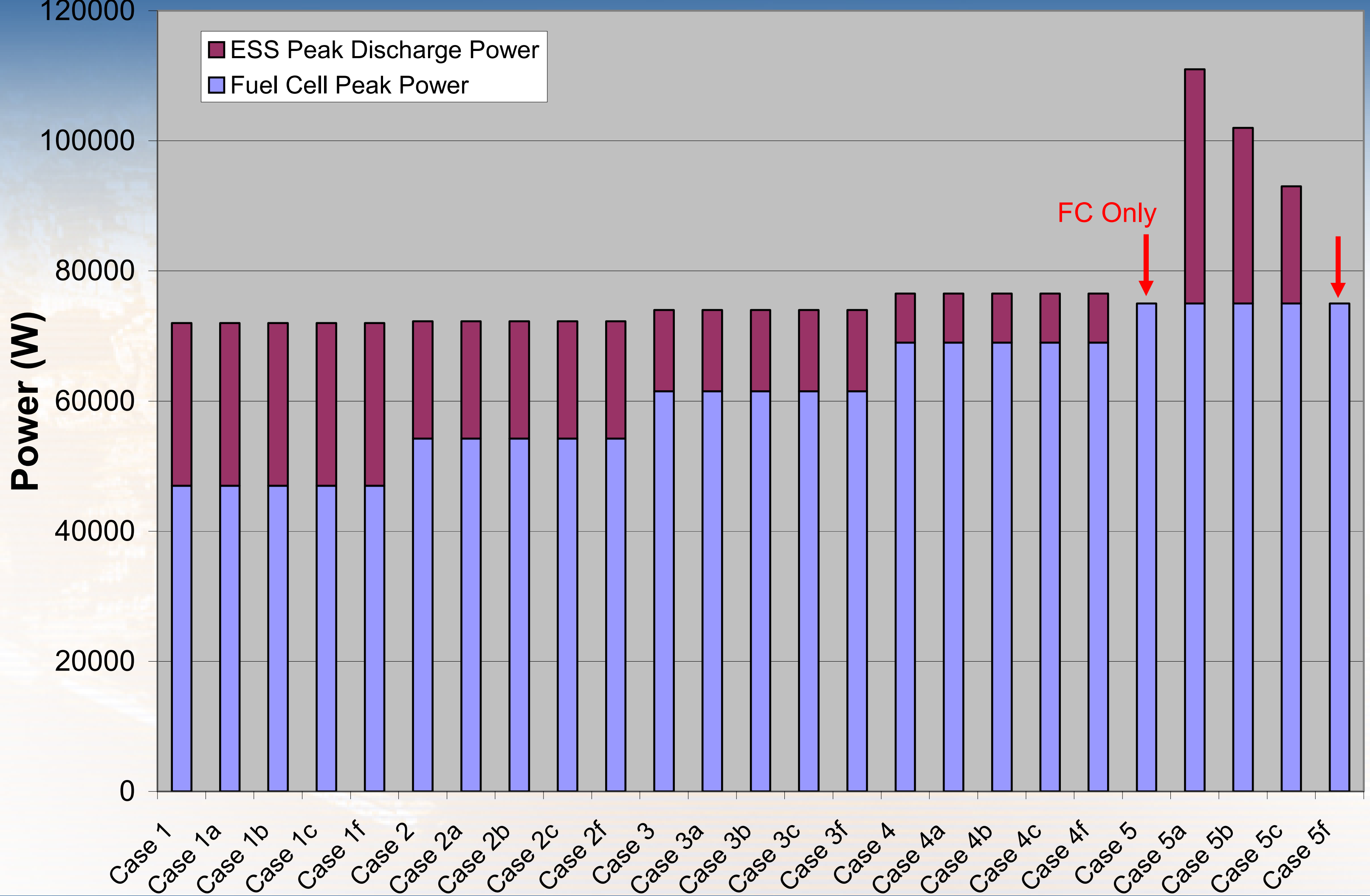
Power Requirements (FC-Only):

- **Accel 0-60 mph:** 75 kW
- **Top speed 100 mph:** 47 kW
- **Gradeability (55 mph @ 5.5%):** 34 kW

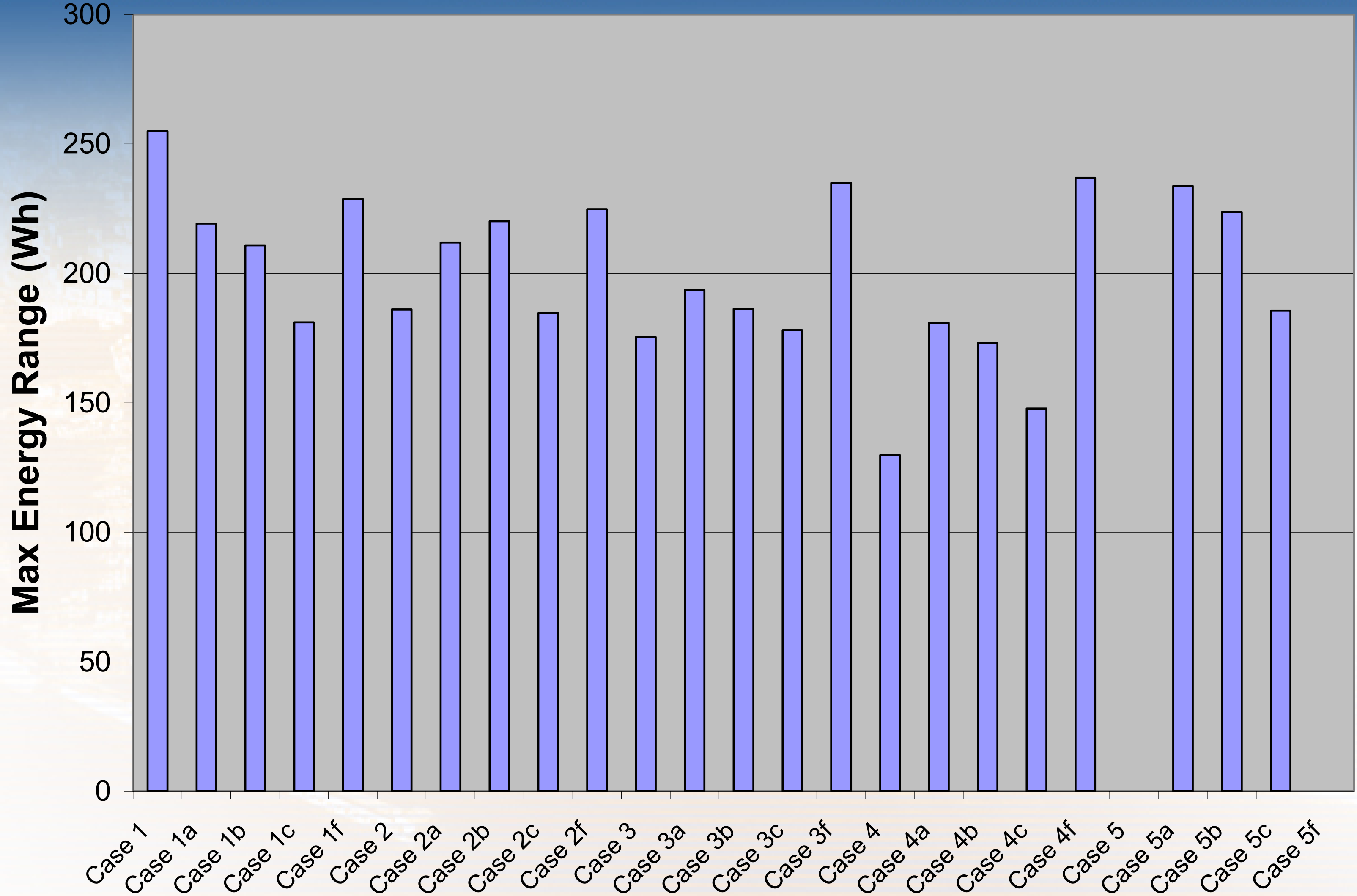
Name	Description	Fuel Cell (kW)	ESS Regen (kW)	ESS Discharge(KW)
Case 1	FC sized for grade/top speed; decel regen strategy; FC_FC50_P25	47000	34000	25000
Case 1a	Case 1 + 100% regen	47000	34000	25000
Case 1b	Case 1 + 75% regen	47000	25500	25000
Case 1c	Case 1 + 50% regen	47000	17000	25000
Case 1f	Case 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

EVS 21 MONACO
2 - 5 April 2005

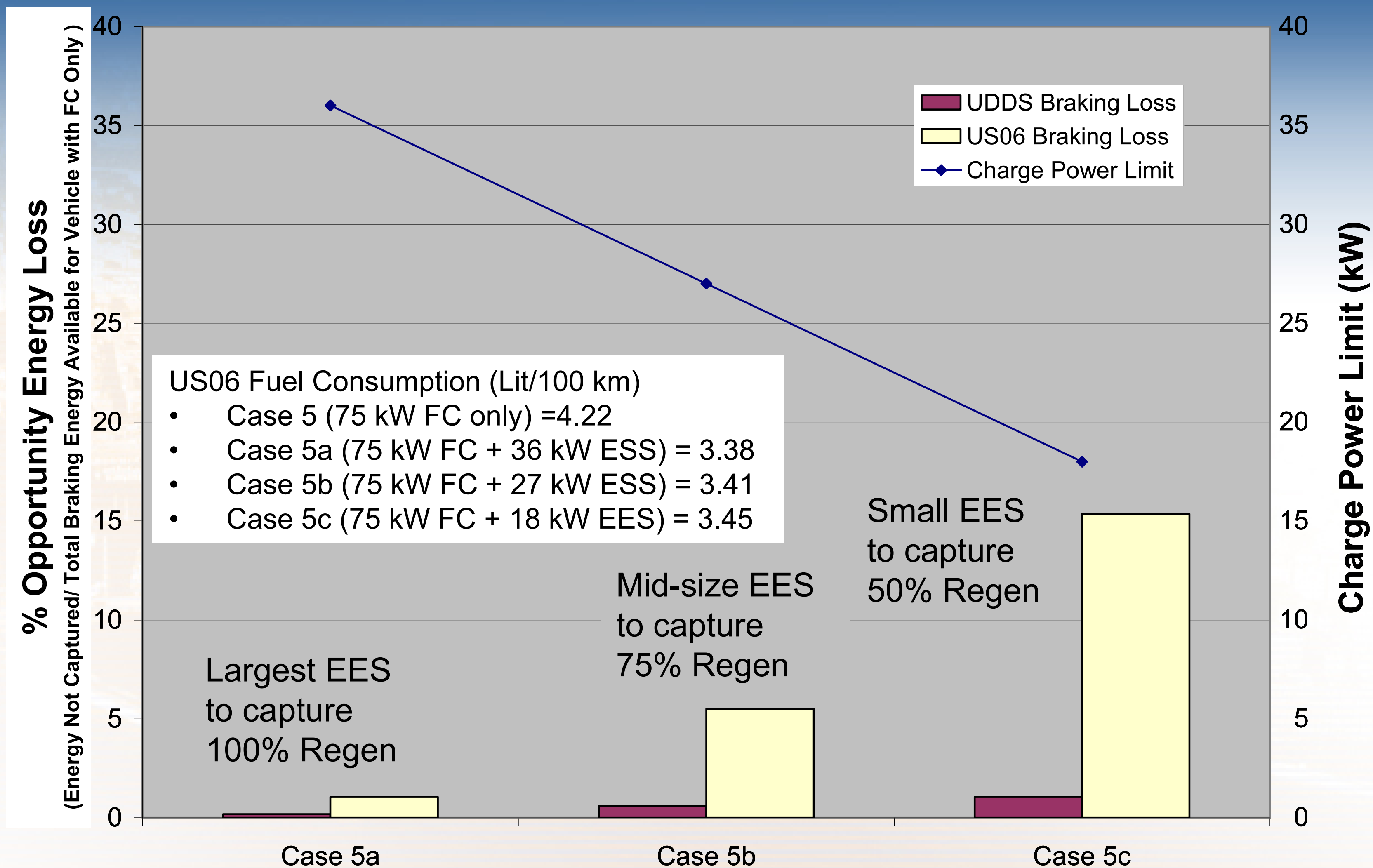
Fuel Cell and Energy Storage System Discharge Ratings



Preferred Usable Energy Window for EES



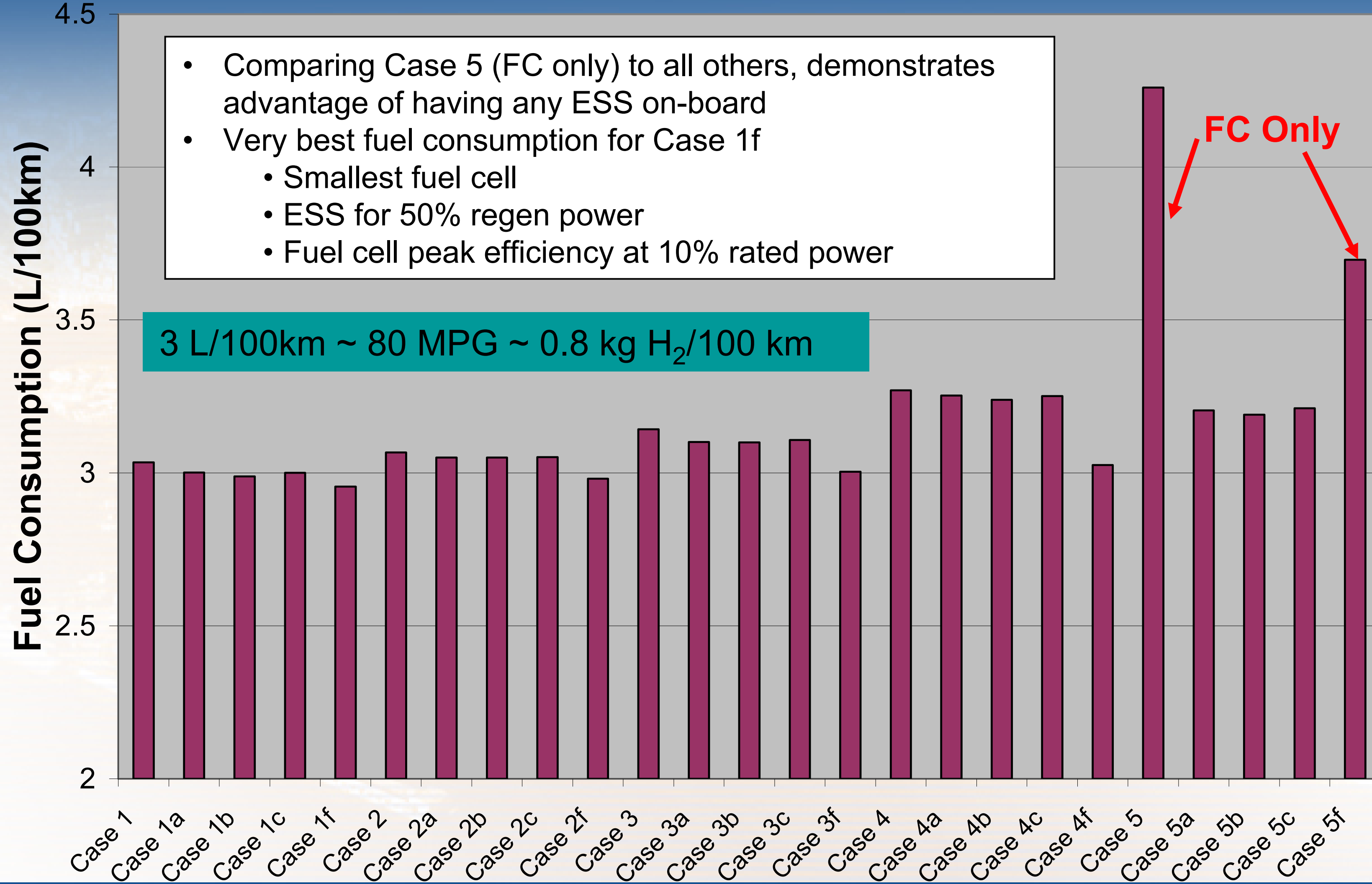
Braking Energy Losses Due to Charge Power Limits



Fuel Consumption Results
Adjusted City/HWY Composite

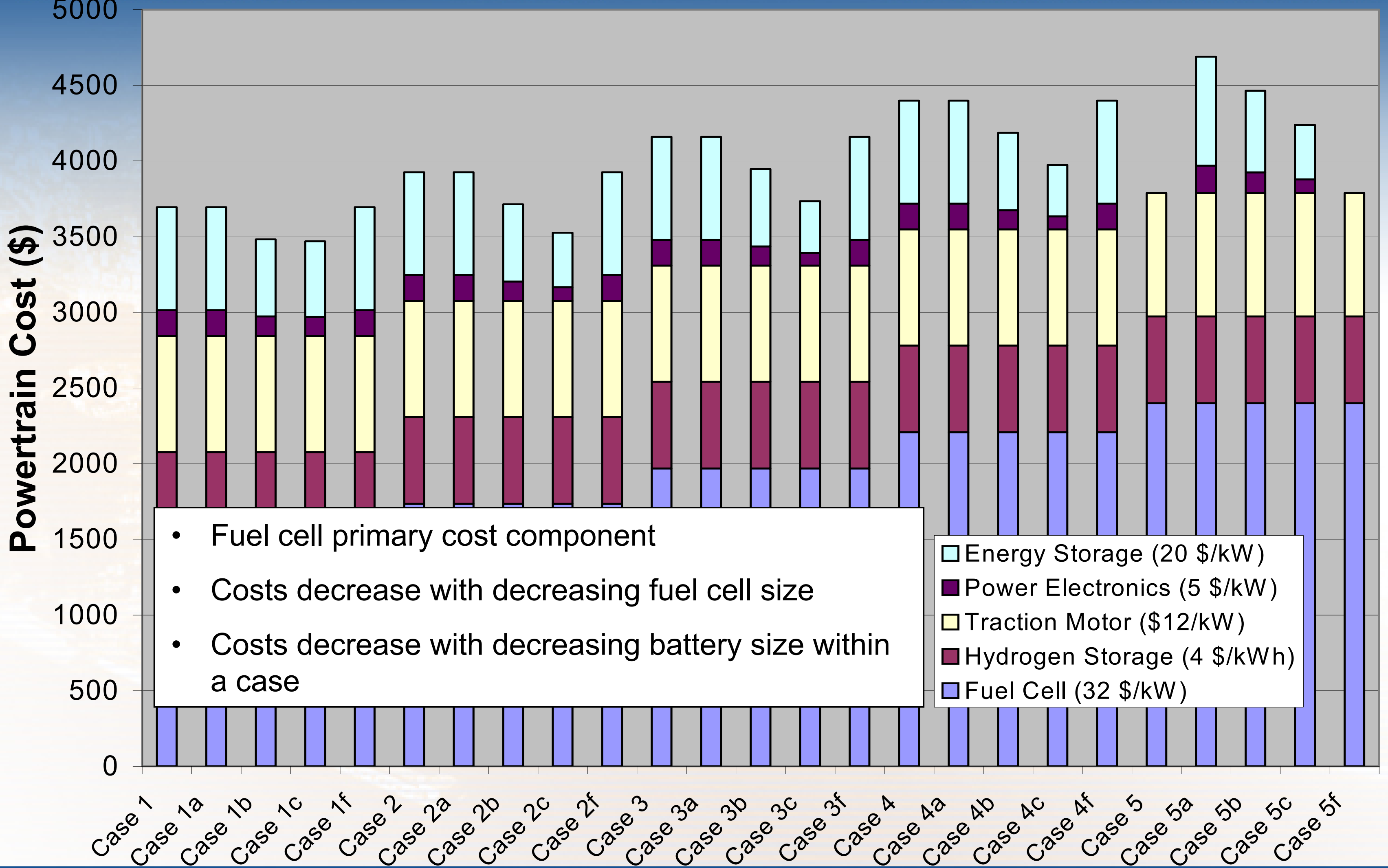
- Comparing Case 5 (FC only) to all others, demonstrates advantage of having any ESS on-board
- Very best fuel consumption for Case 1f
    - Smallest fuel cell
    - ESS for 50% regen power
    - Fuel cell peak efficiency at 10% rated power

3 L/100km ~ 80 MPG ~ 0.8 kg H_2/100 km



EVS 21 MONACO
2 - 5 April 2005

First Cost Summary using 2010 Targets

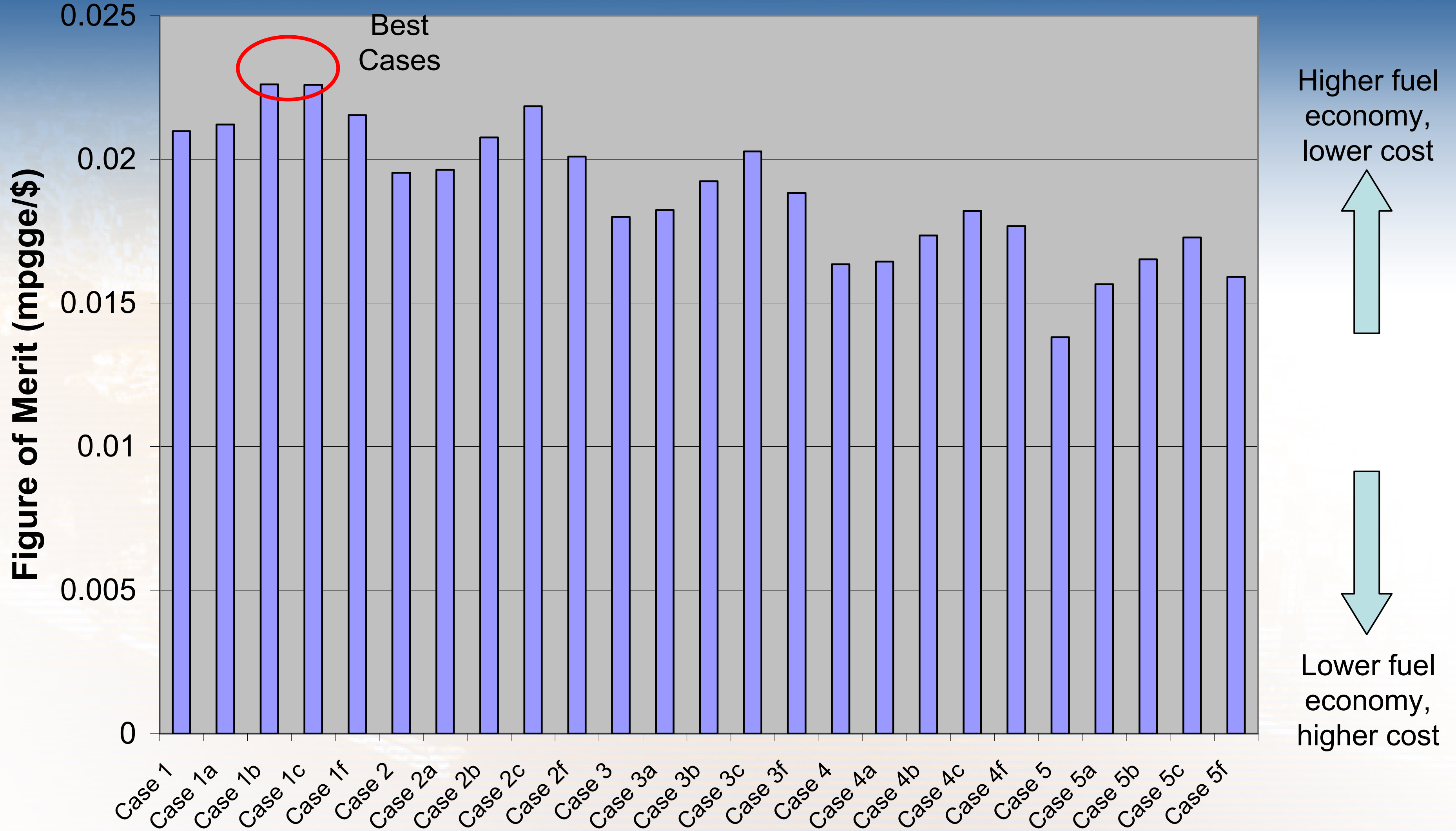


- Fuel cell primary cost component
- Costs decrease with decreasing fuel cell size
- Costs decrease with decreasing battery size within a case

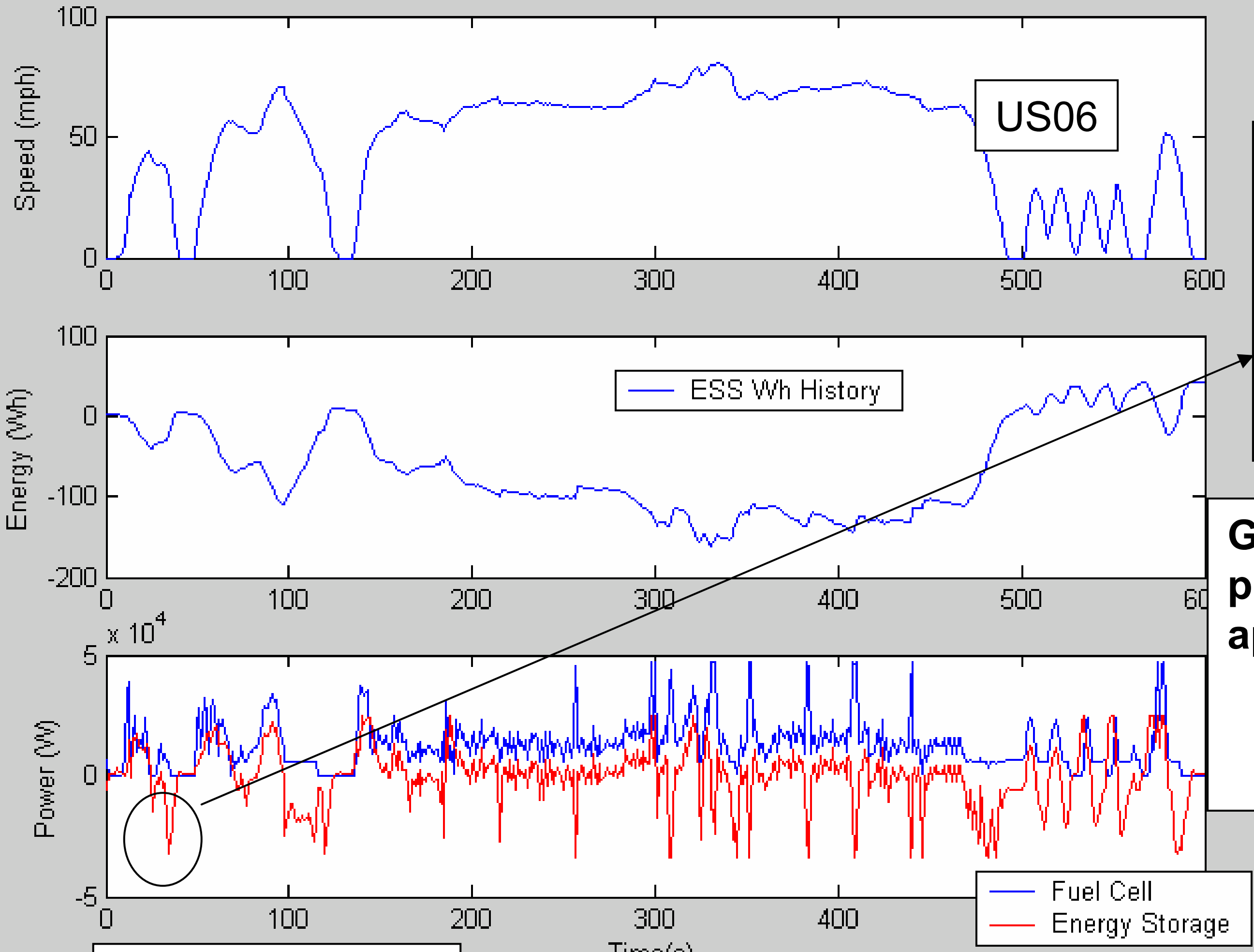
Born to be clean

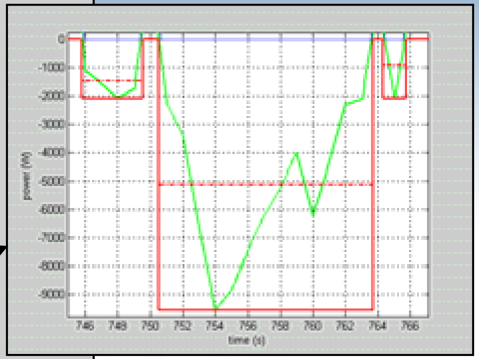
Choosing a Scenario

Figure of Merit (Fuel Economy/Cost)



How to determine ESS requirements from instantaneous power demands from cycles?



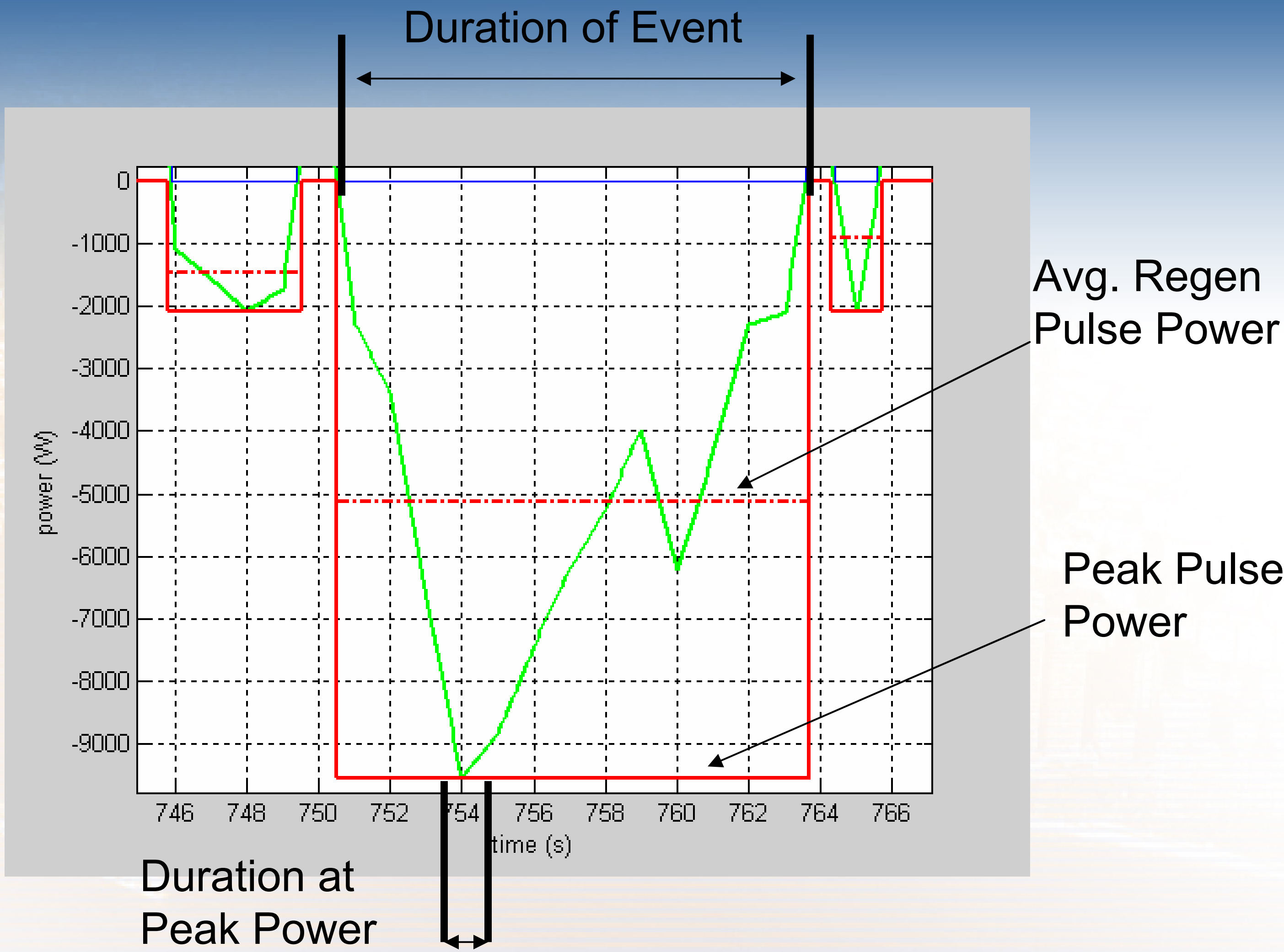


Example: Case 1

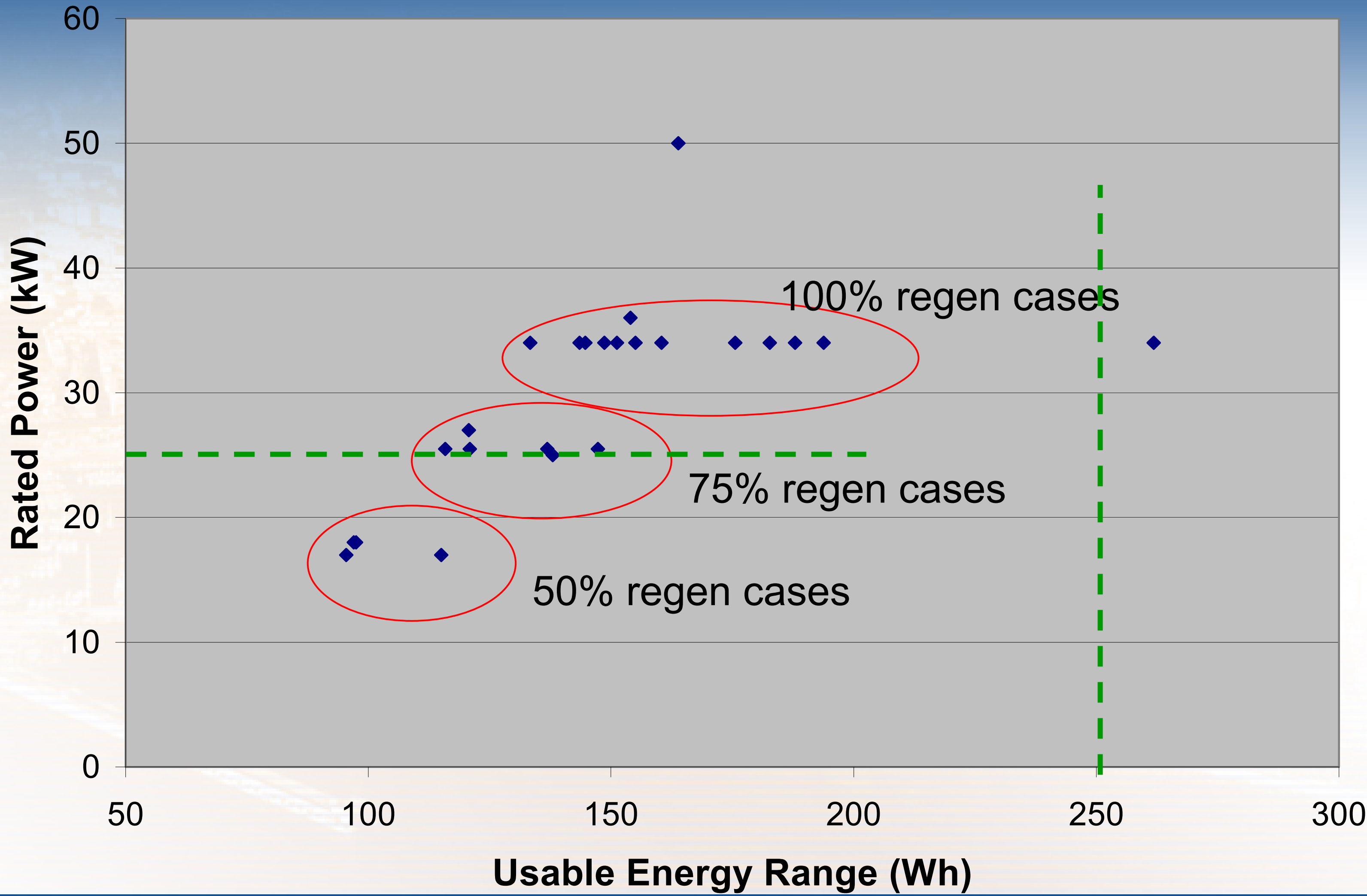
Given typical ESS power profile, what would be the appropriate:

- **Discharge power (x s)**
- **Regen power (y s)**
- **Energy range (Wh)?**

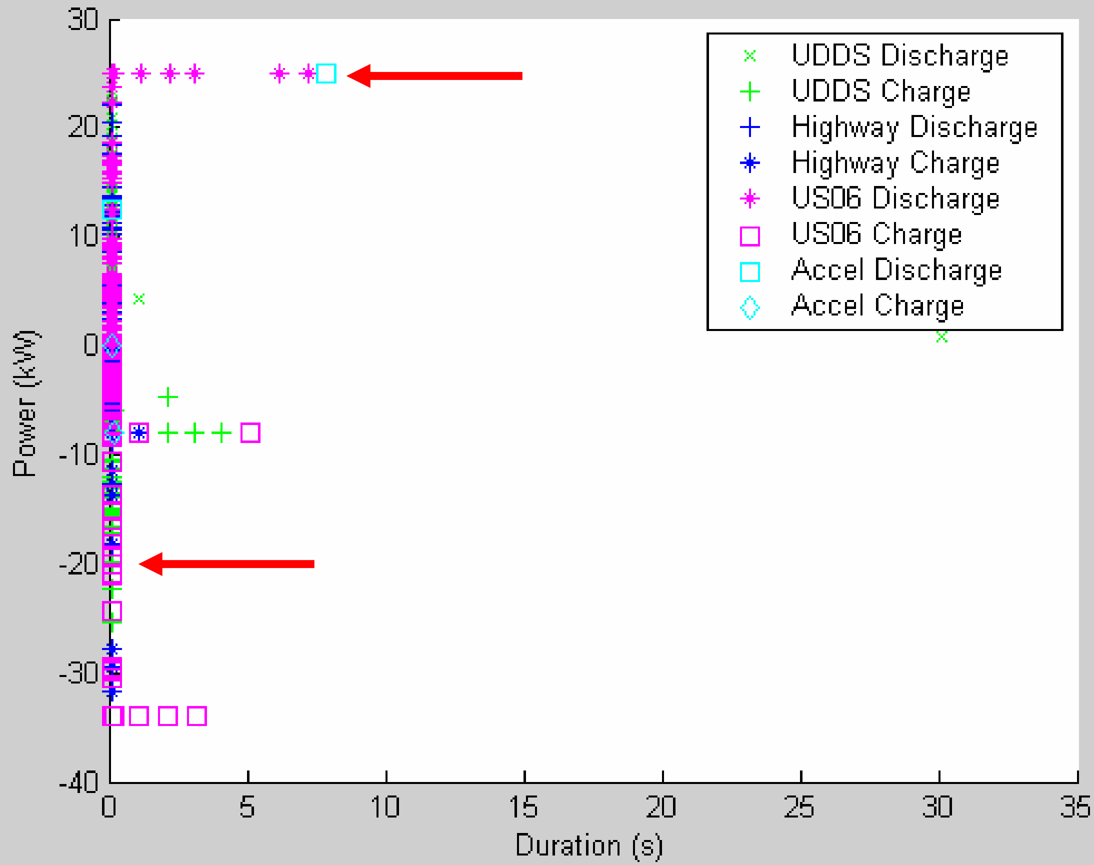
Analysis of ESS Power Profile



Power and Energy Categories

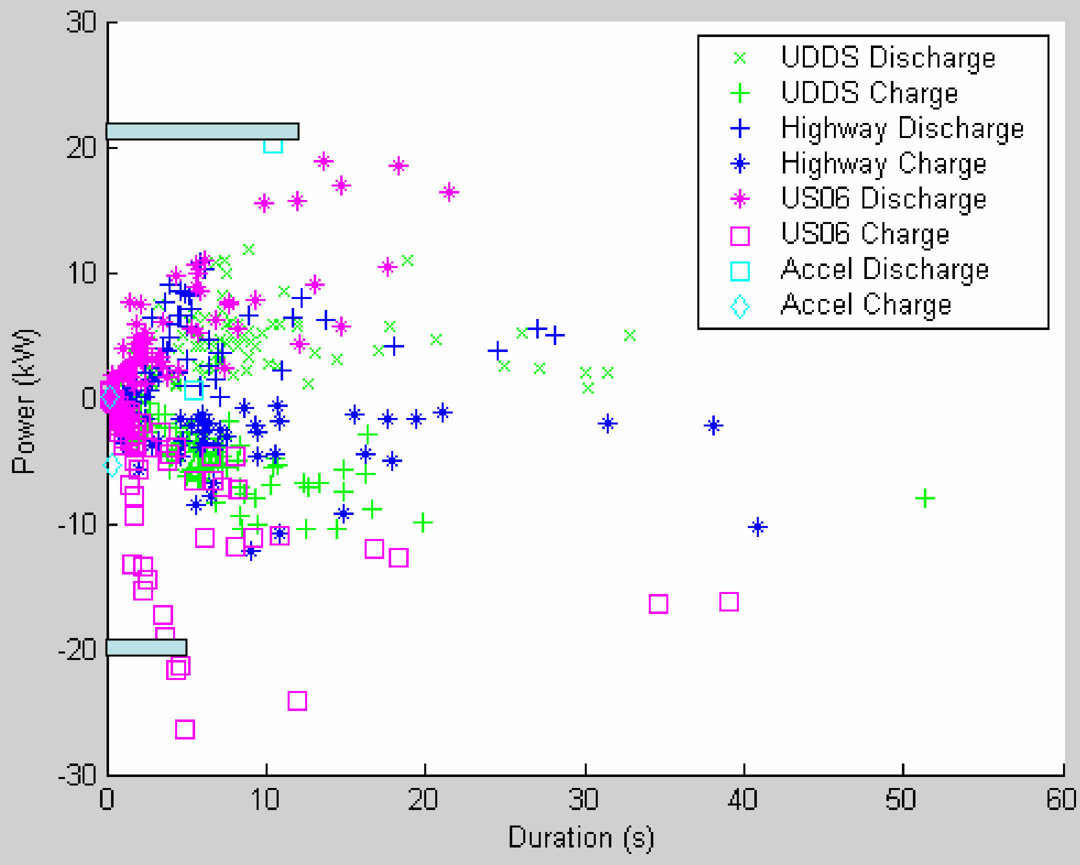


Peak Power vs. Duration Data for Multiple Cycles



- Peak power events typically only last for short duration (artifact of study approach)
- Discharge sized for acceleration
- Charge sized for US06

Avg. Power Need vs. Duration Data for Multiple Cycles



- Power is average power of an event (energy/duration)
- Duration is the time from 0 to 0 power
- Acceleration performance sets discharge requirements
- US06 cycle sets charge requirements

Proposed Recommendations for ESS for mid-size FCVs

(Smallest fuel cell with moderate ESS)
(For a light-weight, aerodynamic, mid-size car)

Goal (Specifications)	**(units)**	**ESS for FCV**
Pulse Discharge Power (12 s)	kW	25
Max Regen Pulse (5 s)	kW	20
Available Energy	Wh	250

Conclusions

- Intelligent energy management strategy to capture and utilize regen energy in fuel cell hybrid vehicle is critical
- In general, 25-30% improvement in fuel consumption from hybridization
  - As long as regen capture is maximized – regen strategy not critical
  - smallest fuel cell with moderate ESS was the most fuel efficient, but also the least expensive scenario
- ESS with 200-250 Wh of usable range seems sufficient for assumed lightweight midsize fuel cell car
- ESS with regen power of around 20 kW for 5s and discharge power of 25 kW for 10-15s appears to be sufficient for lightweight midsize fuel cell car
- Planning to perform sensitivity analysis and investigate other opportunities provided by fuel cell operating strategies