Analysis of Fuel Cell Vehicle Hybridization an Implications for Energy Storage Devices

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Matthew Zolot

Tony Markel

Ahmad Pesaran

(ahmad_pesaran@nrel.gov)

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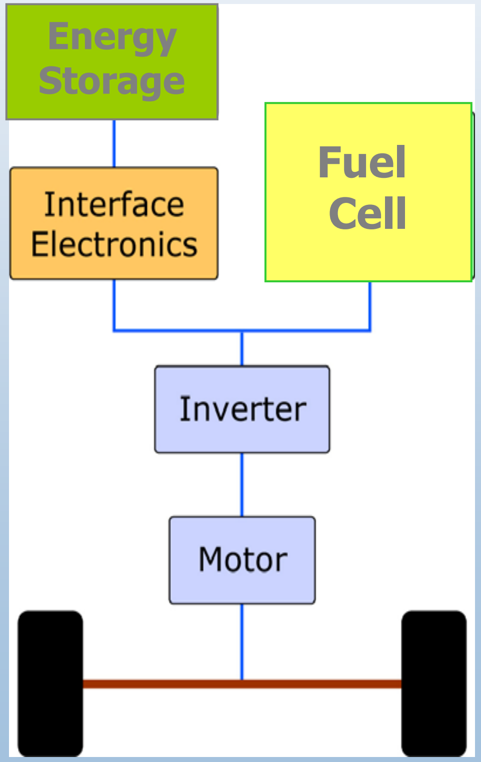
Previous Studies

- Hybridization of a fuel cell vehicle with energy storage improves fuel economy, performance and make it practical (UCD, VTech, ANL, NREL)
  - Capturing regenerative breaking
  - Improving transient response
  - Smaller fuel cell - lower cost
  - Fuel cell or reformer warm up
- Some demonstration prototype fuel cell vehicles are hybrids
  - Toyota FCHV, Ford Focus– (batteries)
  - Honda FCXV4 – (ultracapacitors)



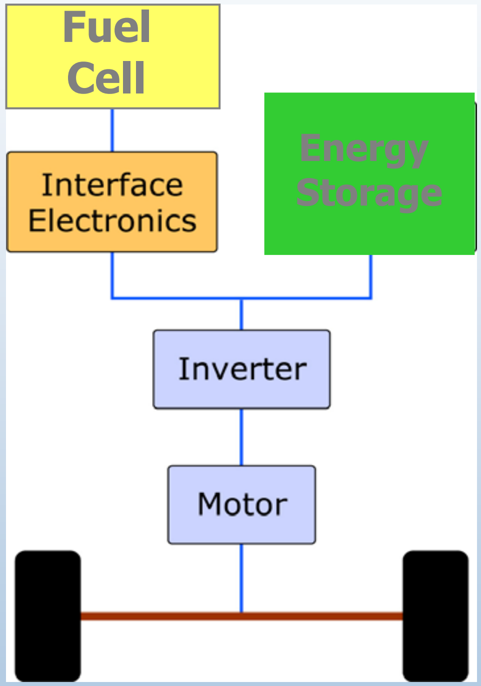
Content

- Objectives
- Motivation for using energy storage (ES) in fuel cell (FC) vehicles
- Analyses
- Summary

Objectives

- Investigate the degree of hybridization benefit from:
  (A) Fuel cell efficiency characteristics
  (B) Fuel cell downsizing
  (C) Displacing fuel cell tasks with the ES functionality
  (D) Energy recovery through regenerative braking

Motivation for this Study

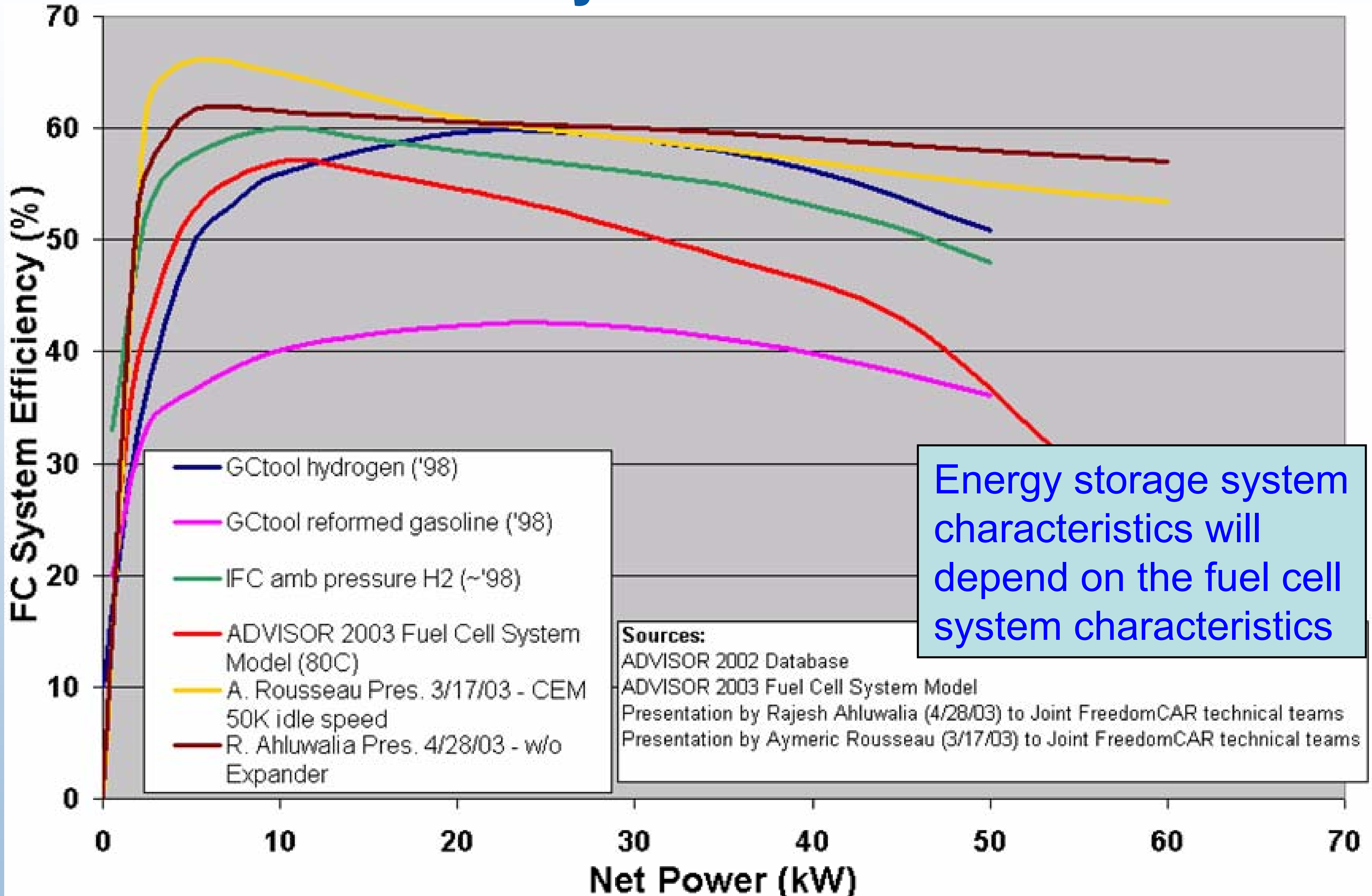


- Previous studies have not separated the degree of hybridization benefits from:

  (a) fuel cell efficiency characteristics,
  (b) fuel cell downsizing,
  (c) displacing fuel cell tasks with the ES functionality
  (d) energy recovery through regenerative braking

- Supporting FreedomCAR in identifying requirements of energy storage for hybrid fuel cell vehicles

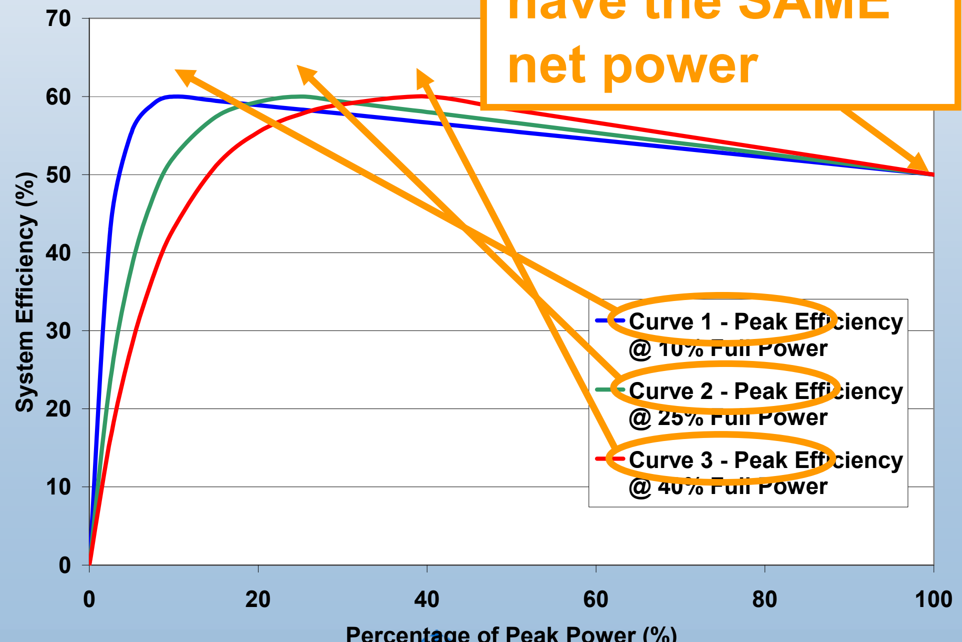
Fuel Cell System Efficiency Variability Could Affect FC-ES Hybridization Outcome



Fuel Cell and Hydrogen Storage System Assumptions

- Fuel Cell
  - Sized to provide at least grade performance.
  - 1 s or 3 s transient response time (10% to 90% power).
  - Reaches maximum rated power in 0 s (ideal case), 15 s (2010 target), or 60 s (today's) for cold start from 20°C.
  - System efficiency of 60% at maximum & 50% at rated peak power (DOE Technical Targets) .
- Hydrogen Storage
  - Pure compressed hydrogen.

These fuel cells have the SAME net power



Proposed theoretical FC efficiency curves are based on DOE Targets

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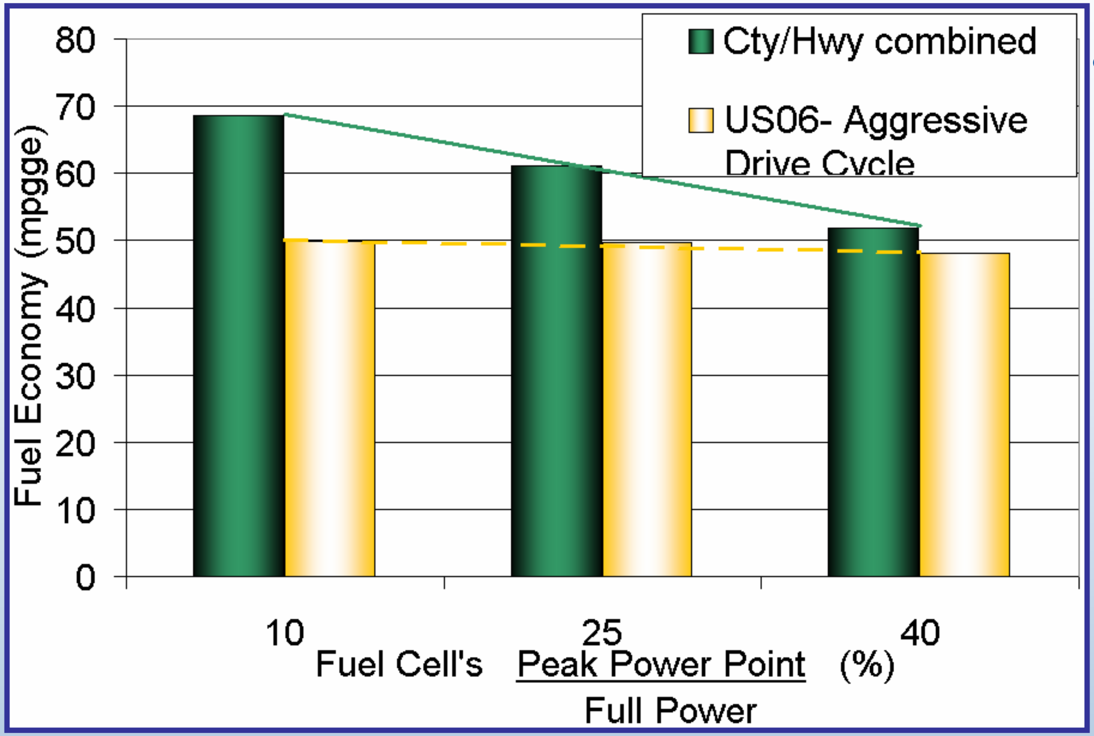
Fuel Economy is Affected by the Position of FC Peak Efficiency

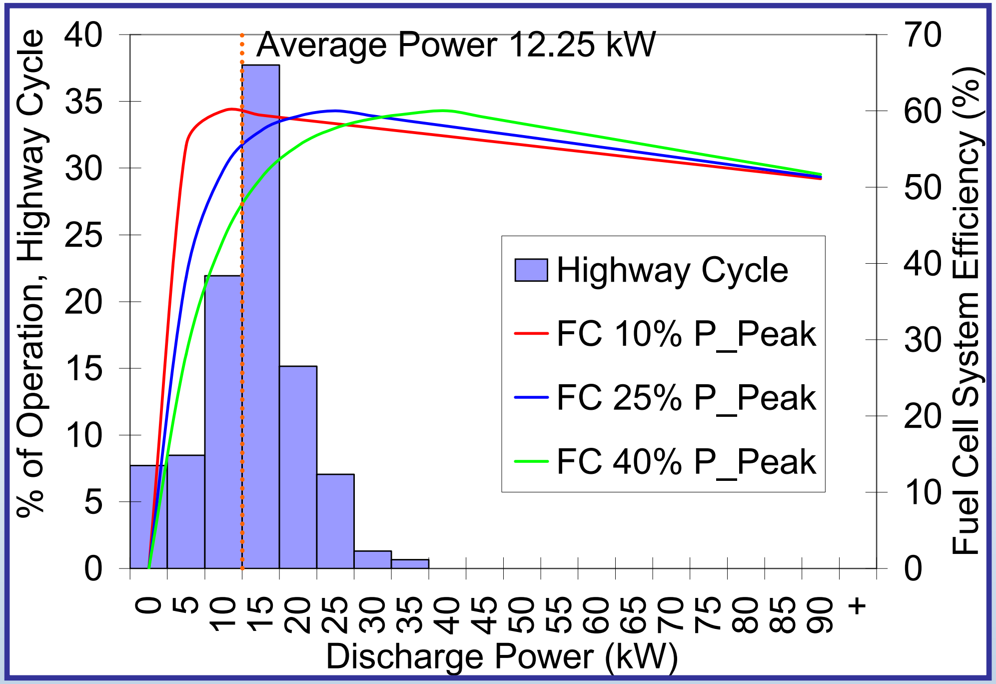


- 10% peak efficiency FC achieved the best city/highway fuel economy

  +12% improvement over the 25% peak efficiency configuration

  +32% improvement over the 40% peak efficiency configuration

When Peak Efficiency ≅ Typical Power Point, Results in the Best Fuel Economy



- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.

NREL National Renewable Energy Laboratory

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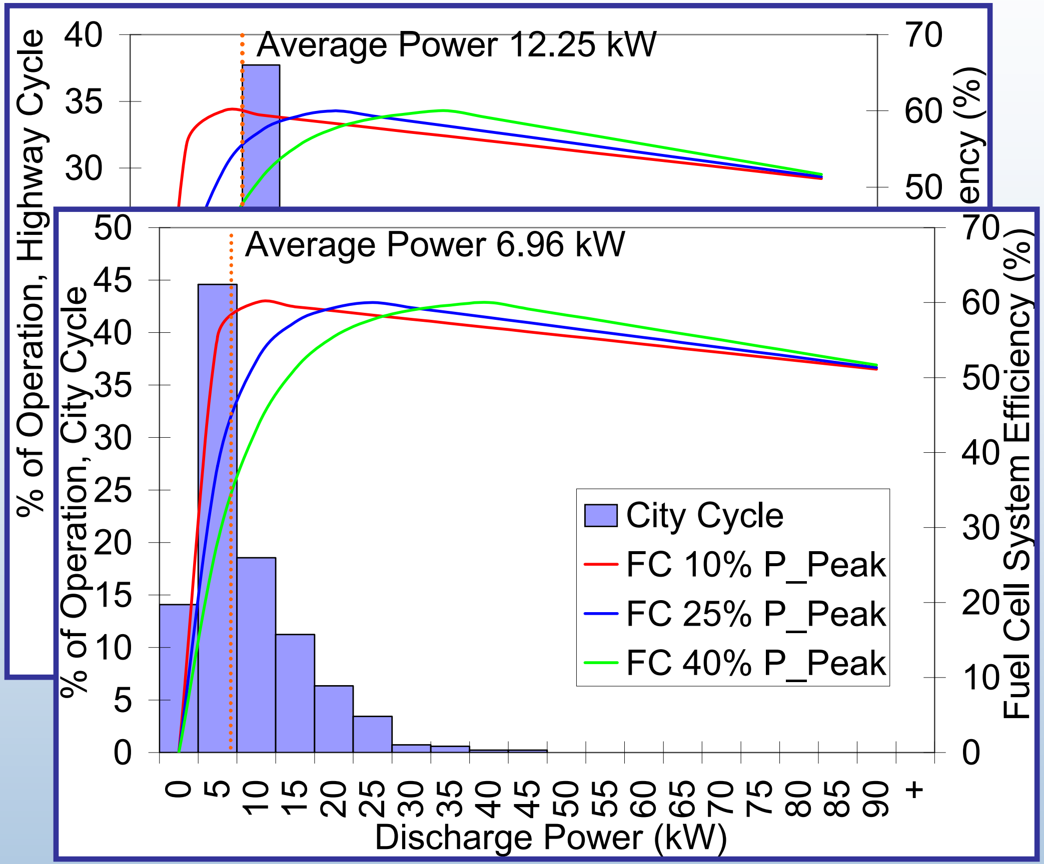

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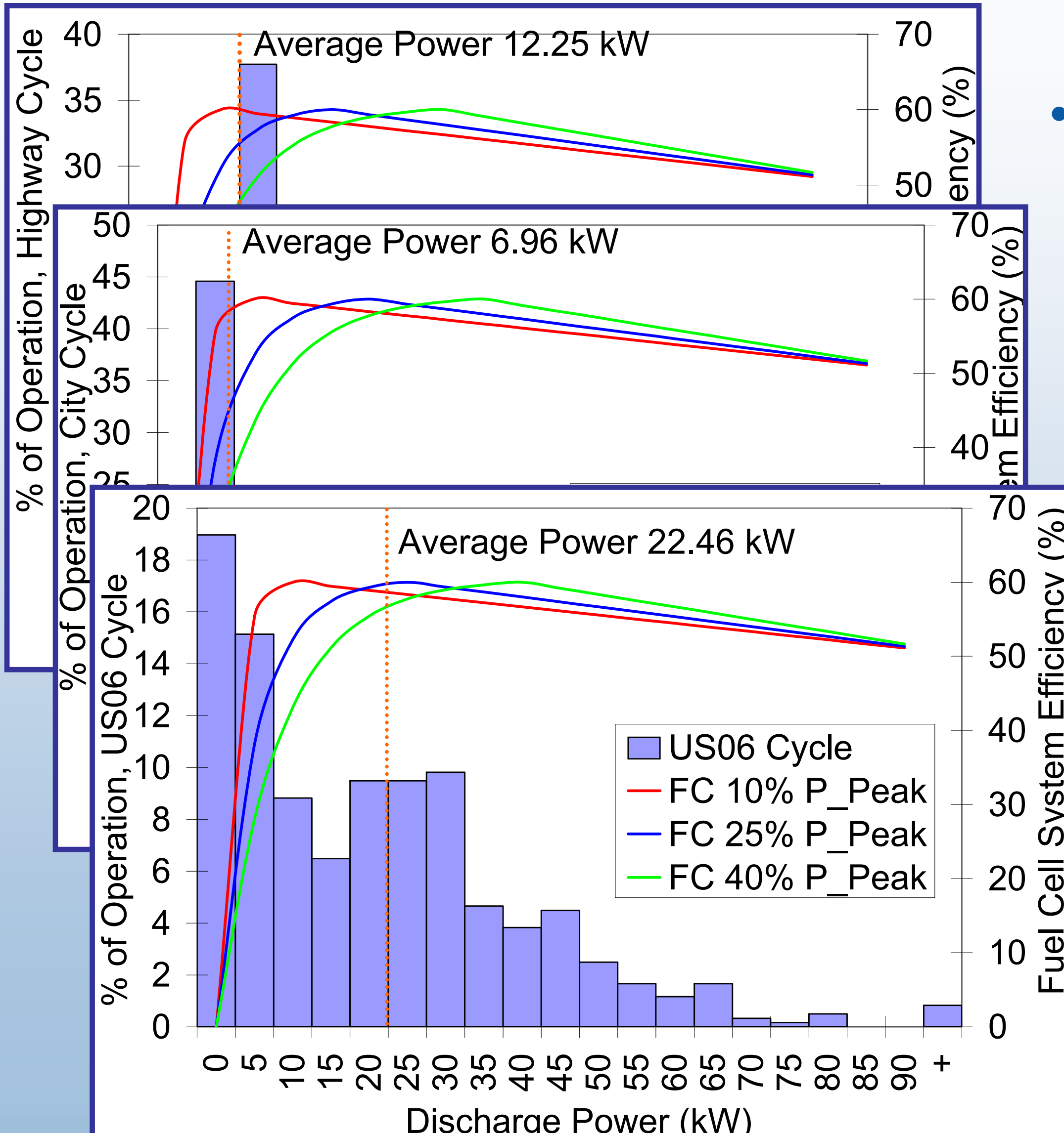

- 10% peak efficiency FC has the highest fuel economy because its peak efficiency is better aligned with the power requirements.
- Little fuel economy difference over US06 cycle.
  - wider power distribution
  - similar efficiency at P_{avg}

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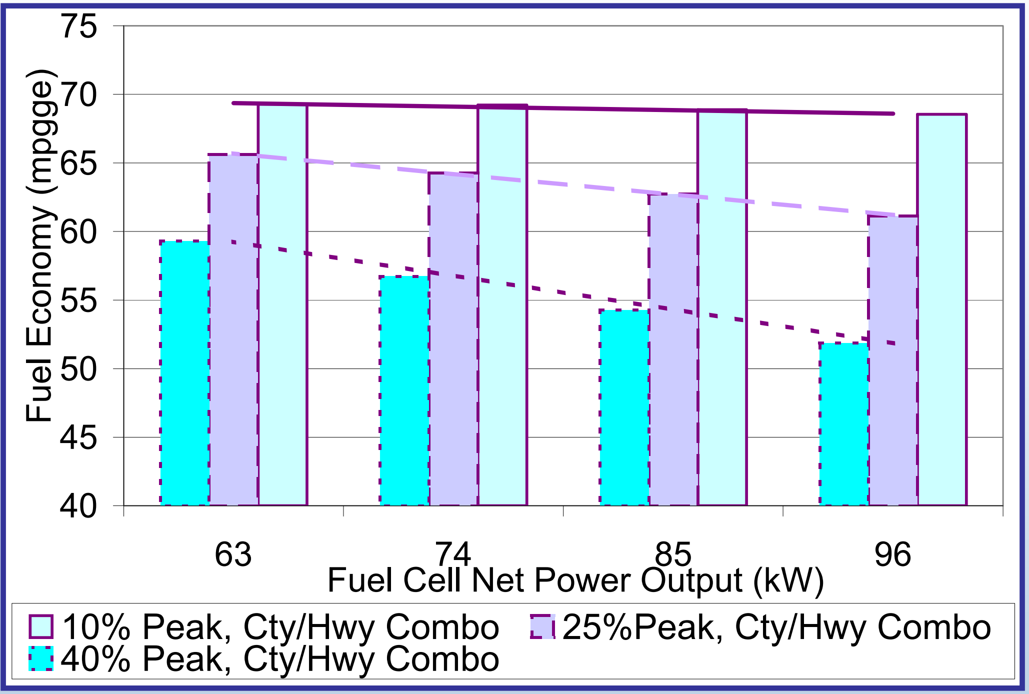
The Benefit of Downsizing the Fuel Cell varies as a function of Peak Efficiency Position



- Downsizing the 10% peak efficiency FC results in the least potential fuel economy improvement
  - **≤ 1.0% (combined city/highway) improvement**
- Downsizing the 40% peak efficiency FC results in a moderate to significant potential fuel economy improvement
  - **≤ 15.0% (combined city/highway) improvement**

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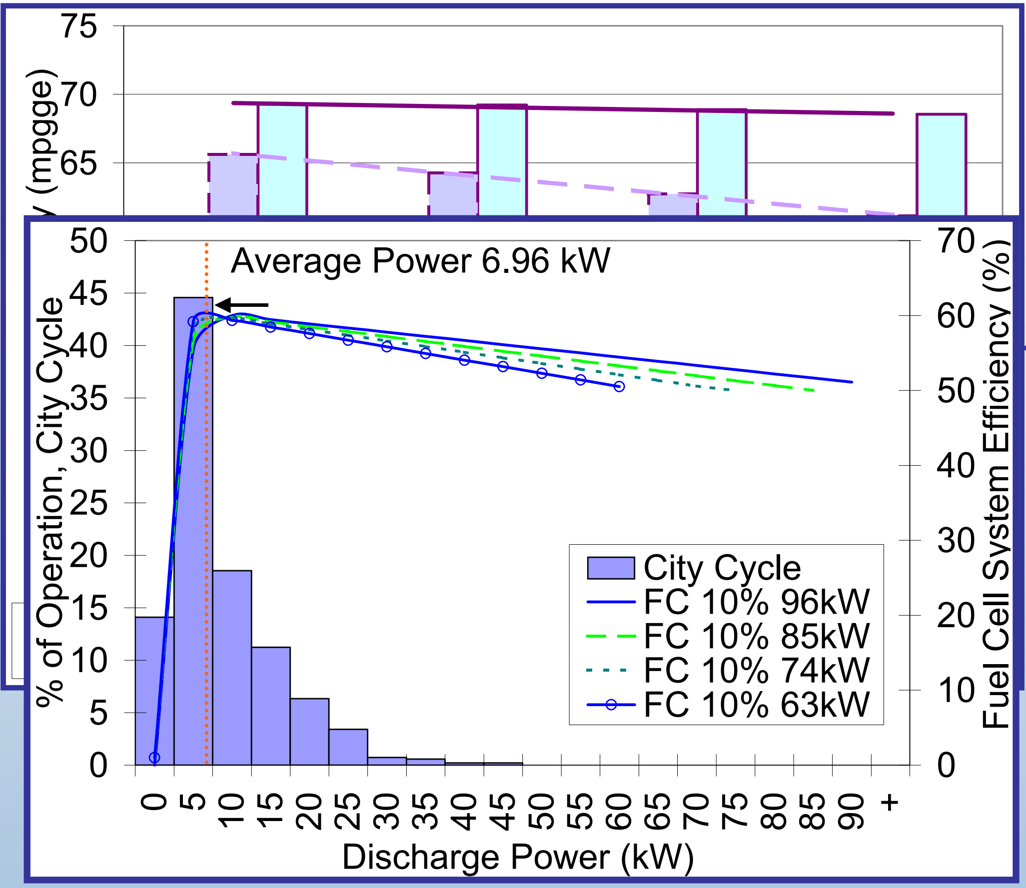

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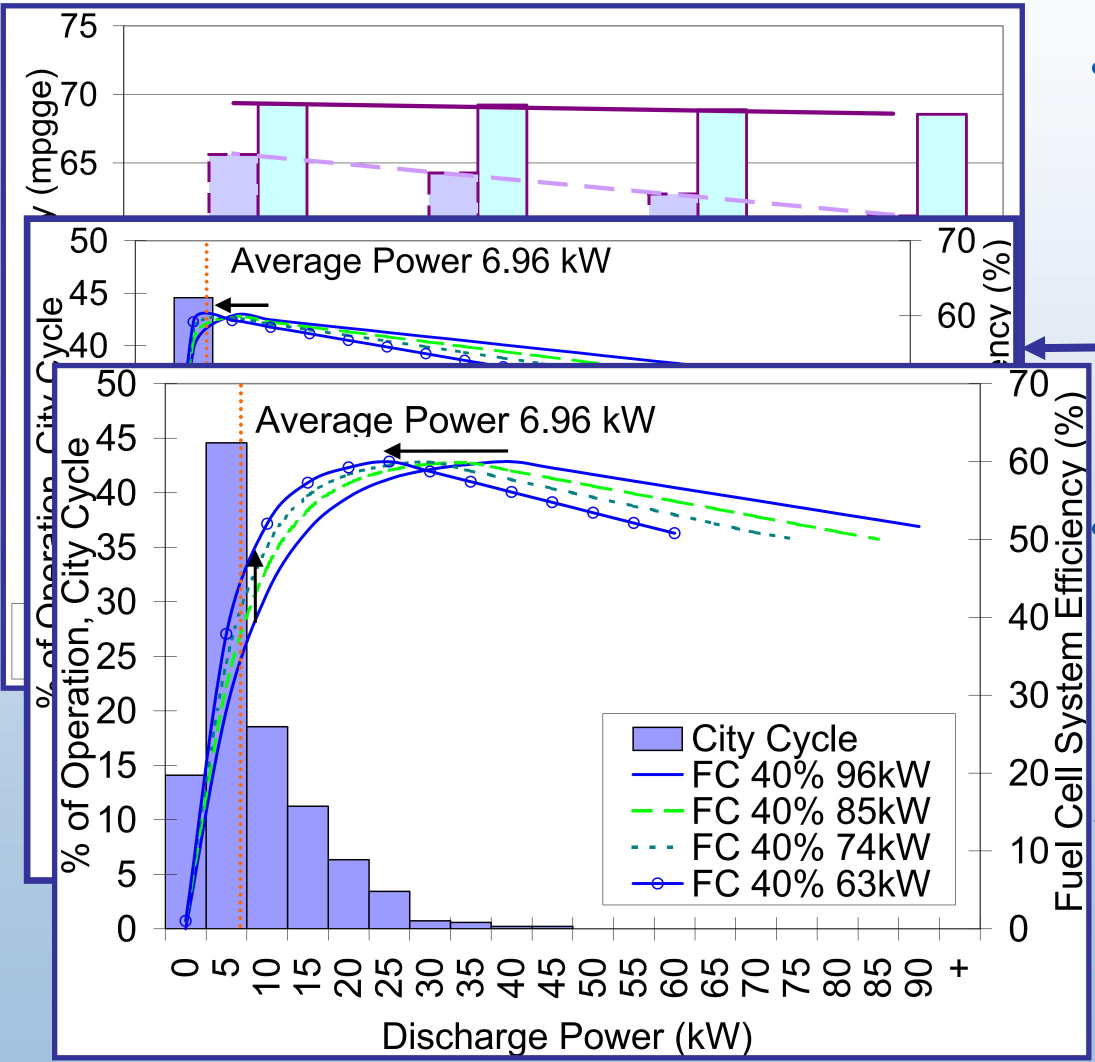

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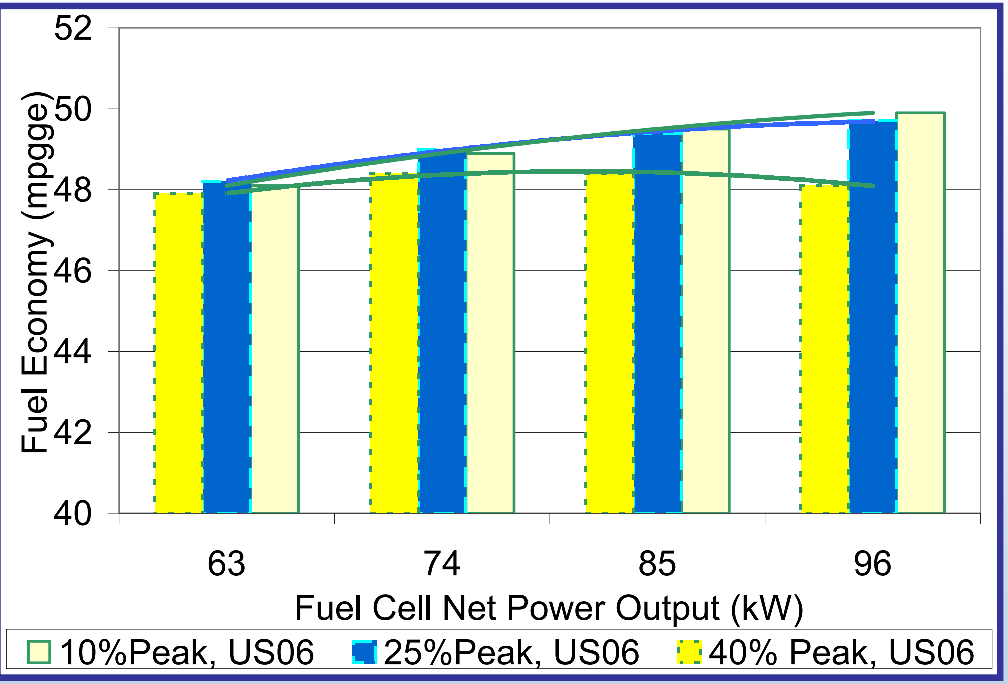
Downsizing the Fuel Cell Can Have a Negative Affect on the US06 Cycle Fuel Economy



- Downsizing the 10% & 25% peak efficiency FCs results in up to…

  2 mpg less fuel economy

- Downsizing the 40% peak efficiency FC results in…

  fairly even fuel economy

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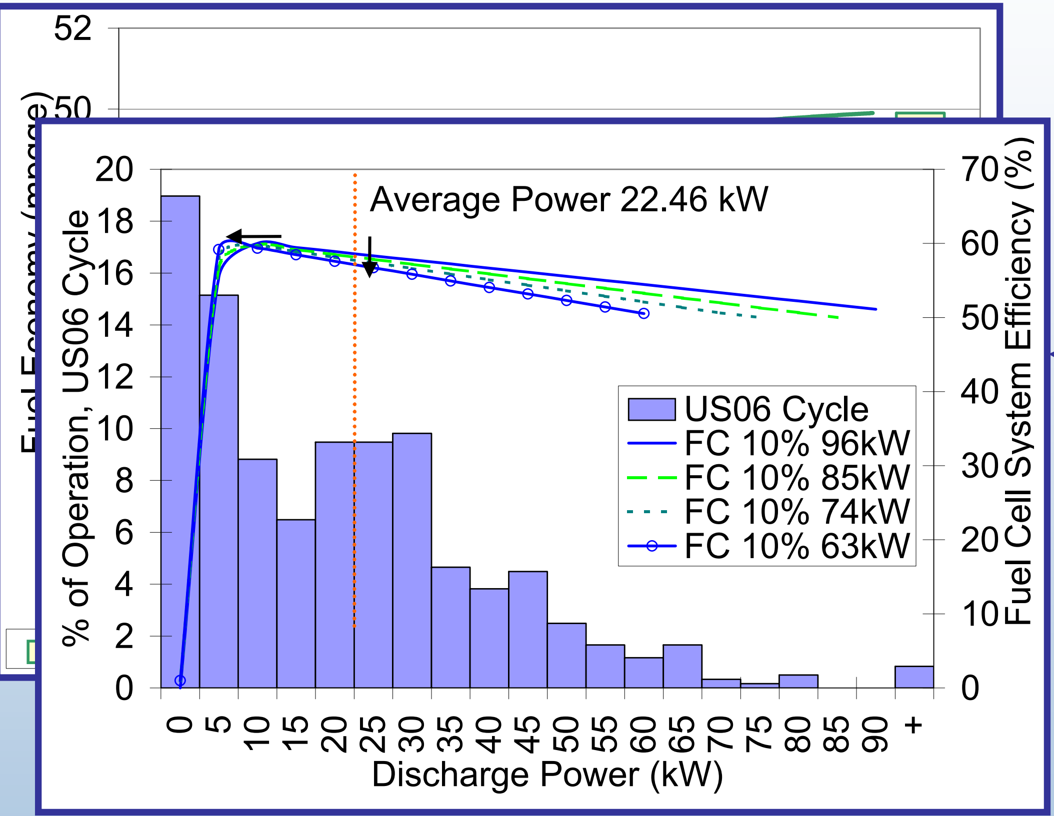

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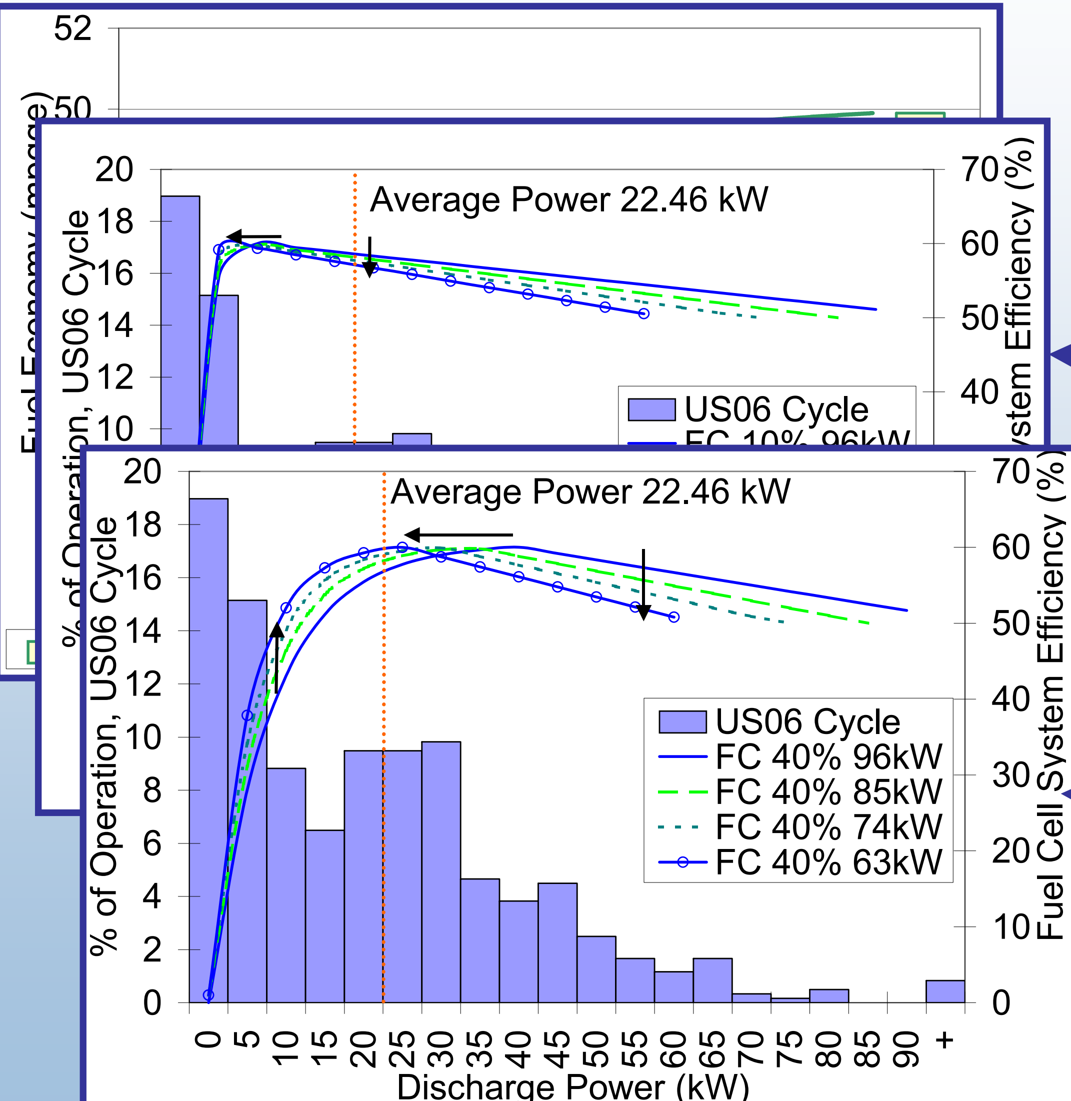

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Energy Storage Requirements for Supplementing a Full-Size FC's Limitations

96 kW Fuel Cell	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)	P_{regen} (kW)	E_{regen} (kWh)
Today's Perfomance	60	3	61.80	0.2206	-46.49	-0.7332
	60	1	61.80	0.2206	-48.05	-0.7332
	15	3	55.90	0.0580	-46.49	-0.8237
2010 Target	15	1	55.90	0.0580	-48.05	-0.8237
	0	3	48.86	0.0067	-46.49	-0.8265
"Ideal" 96 kW Case	0	1	0.00	0.0000	-48.05	-0.8265

- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.

- 2010 Target performance needs fairly similar power, but much less assist energy.

Energy Storage Requirements for Supplementing a Full-Size FC's Limitations

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Today's Perfomance	**60**	**3**	61.80	0.2206	-46.49	-0.7332
	60	**1**	61.80	0.2206	-48.05	-0.7332
	15	**3**	55.90	0.0580	-46.49	-0.8237
2010 Target	**15**	**1**	55.90	0.0580	-48.05	-0.8237
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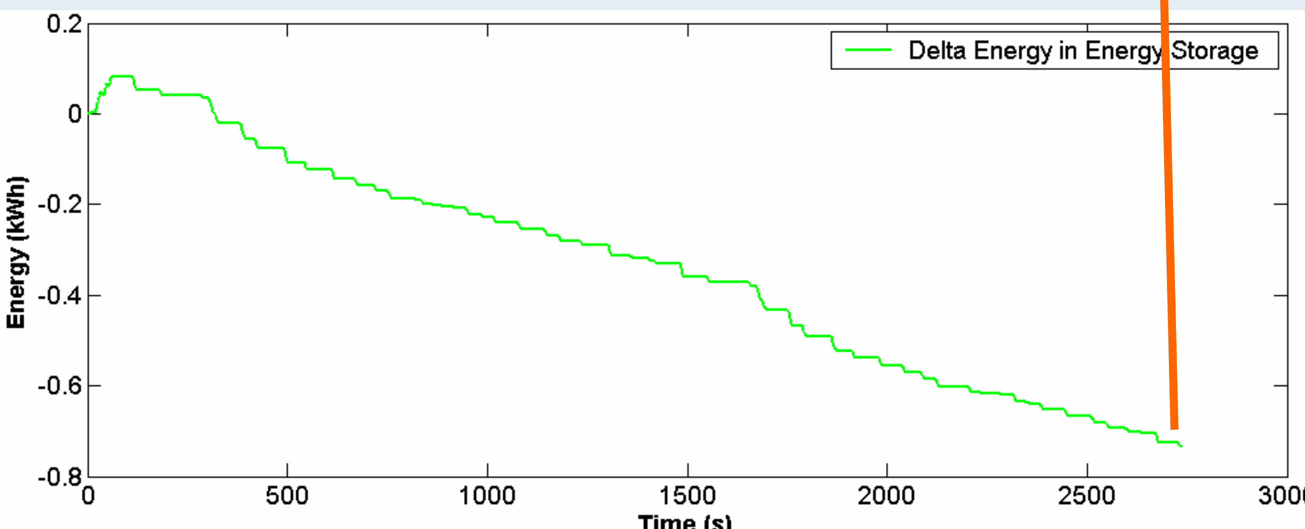

- Similar to stated Honda FCX4 ESS roles.
- Warm-up and ramp rate ESS roles require relatively little energy.
- Big Potential for more active ESS contributions.

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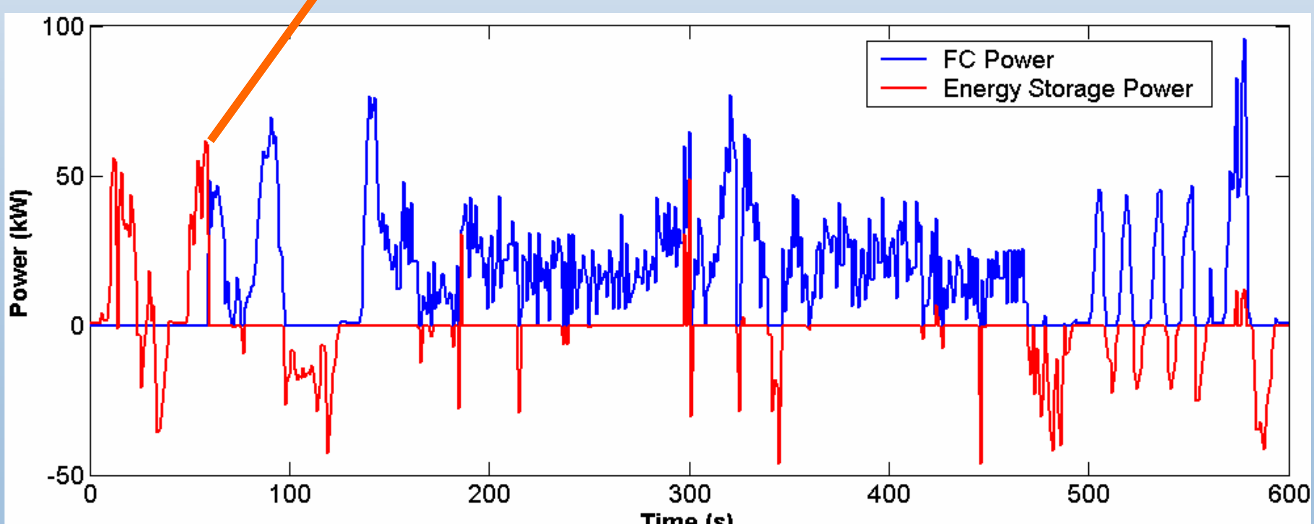

Energy Storage Requirements for Supplementing a Downsized FC's Limitations

85 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)
Today's Perfomance	85	60	3	61.80	0.2206
	85	60	1	61.80	0.2206
	85	15	3	55.90	0.0580
2010 Target	85	15	1	55.90	0.0580
	85	0	3	52.53	0.0333
"Ideal" 85 kW Case	85	0	1	28.67	0.0243

74 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)
Today's Perfomance	74	60	3	61.80	0.2206
	74	60	1	61.80	0.2206
	74	15	3	56.20	0.0611
2010 Target	74	15	1	55.90	0.0580
	74	0	3	56.20	0.0611
"Ideal" 74 kW Case	74	0	1	39.67	0.0499

63 kW Fuel Cell	Peak Shaving FC Power (kW)	Warm-Up Time (s)	Ramp Rate 10-90% (s)	$P_{req'd}$ (kW)	$E_{req'd}$ (kWh)
Today's Perfomance	63	60	3	61.80	0.2206
	63	60	1	61.80	0.2206
	63	15	3	59.90	0.0889
2010 Target	63	15	1	55.90	0.0766
	63	0	3	59.90	0.0889
"Ideal" 63 kW Case	63	0	1	50.70	0.0766

- With FC downsized, ESS must also assist during max acceleration event.
- ESS is the same as a full-sized FC requires for "Today's" fuel cell performance.

Energy Storage Requirements for Supplementing a Downsized FC's Limitations

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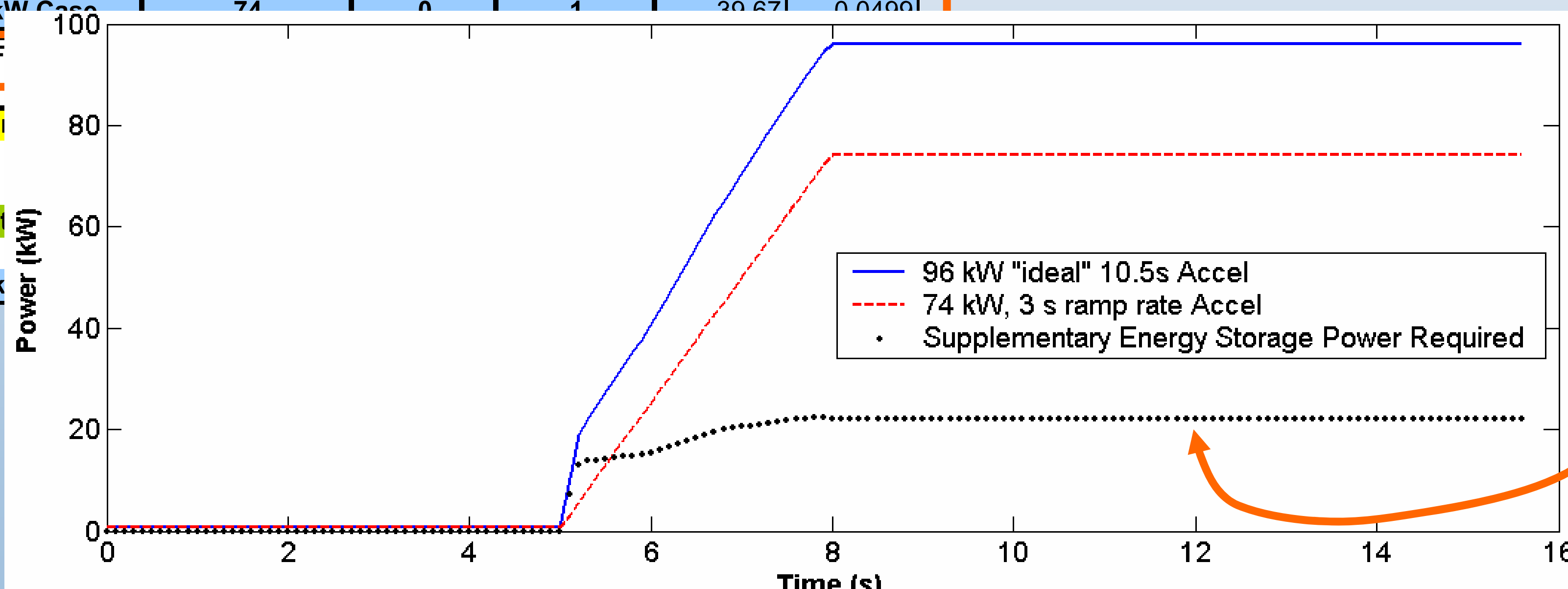

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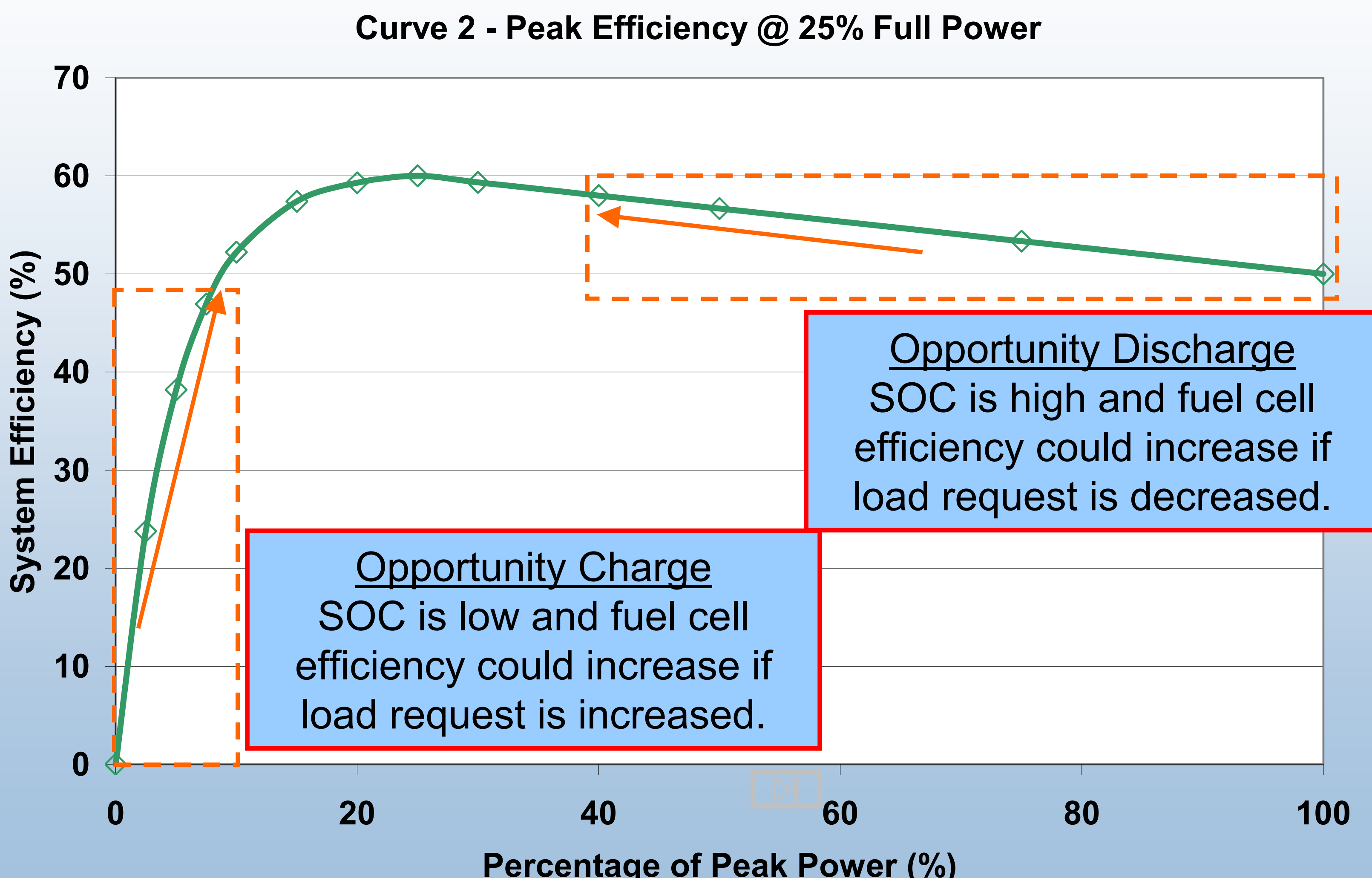
"Ideal" 63 kW Case	63	0	1	50.70	0.0766

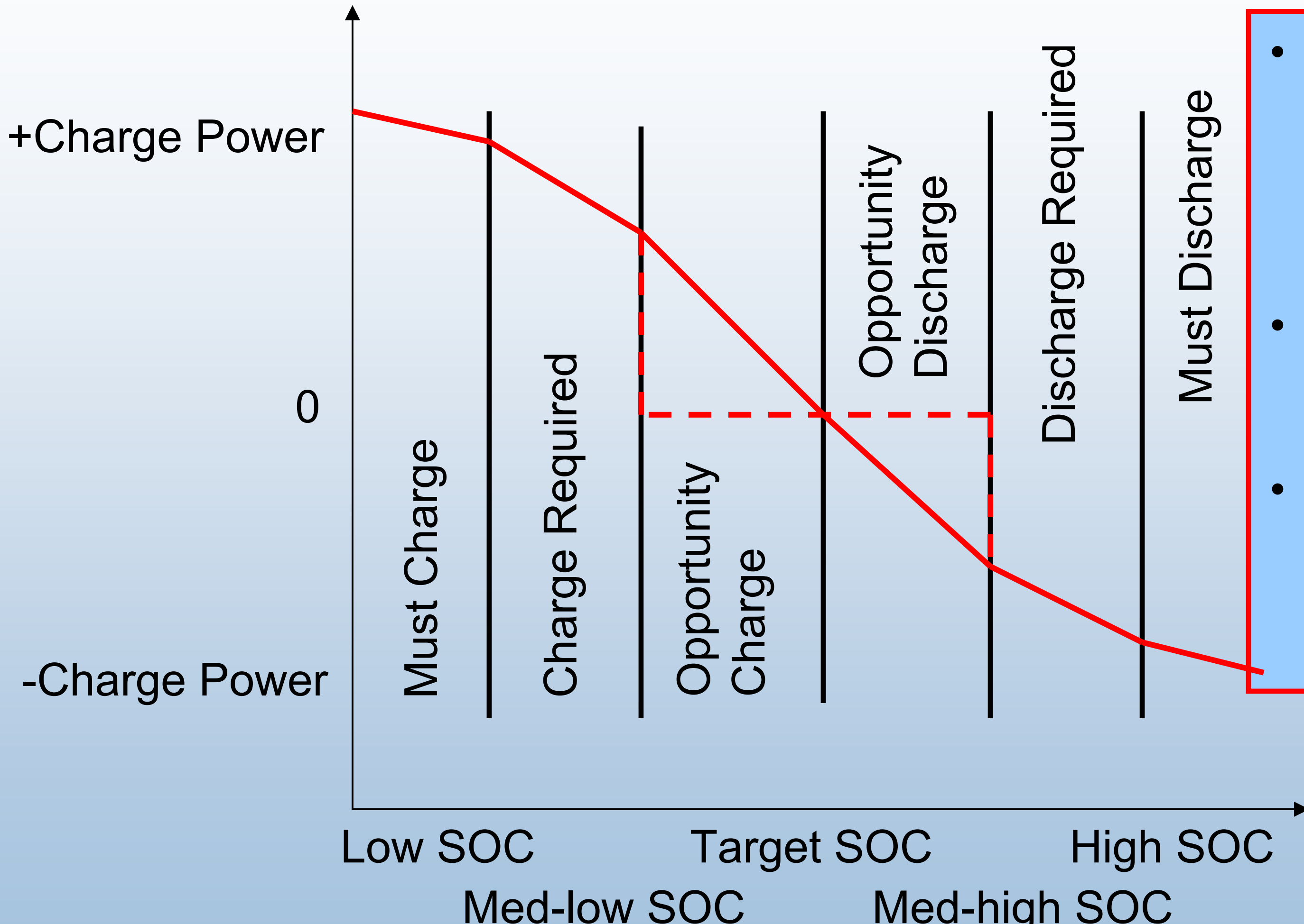
- With FC downsized, ESS must also assist during max acceleration event.
- ESS is the same as a full-sized FC requires for "Today's" fuel cell performance.
- ESS is nearly the same as a full-sized FC requires for "2010 Target" fuel cell performance.

- Therefore, downsizing provides improvement in fuel economy, fuel cell costs, and [in minimal control case] has little to no affect on ESS sizing.

Current Work - Potential Active Roles for Supplementing Fuel Cell Operation



Current Work - Multi-region "Spring" SOC Maintenance Algorithm



- Opportunity region
  - only take action if it makes the prime power plant more efficient
- Could assume different charging rates in each region
- Number of parameters makes it harder to optimize and understand impacts

Fc_pwr_r = dl_pwr_r + charge_pwr

Summary

- The best fuel economy occurs when peak FC efficiency ≅ typical power operating point (cycle dependant).
- There is positive benefit of downsizing the FC if the peak efficiency is shifted toward the typical power operating point (cycle dependant).
- ES requirements for supplementing FC limitations are suitable for Ultracapacitors or High Power Batteries.
- Downsizing a FC (toward the gradeability limit) with today's or 2010 projected characteristics, Does NOT significantly affect ES requirements (with minimal ES control case).
- There is significant potential for more actively using the ES to manage the FC operation points because of un-used regenerative energy capture.

Acknowledgements

- ADVISOR™ is used to simulate the fuel cell and energy storage system demands under drive cycle and performance tests.
- This work supports the FreedomCAR Energy Storage technical team in defining energy storage requirements for fuel cell vehicles.