NREL National Renewable Energy Laboratory
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Office of Energy Efficiency & Renewable Energy
Innovation for Our Energy Future

Fuel Cell/Battery Hybrids: An Overview of Energy Storage Hybridization in Fuel Cell Vehicles

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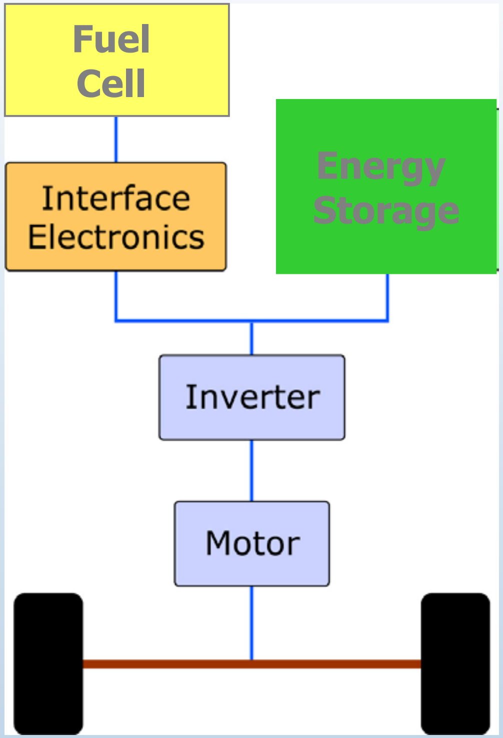
Content

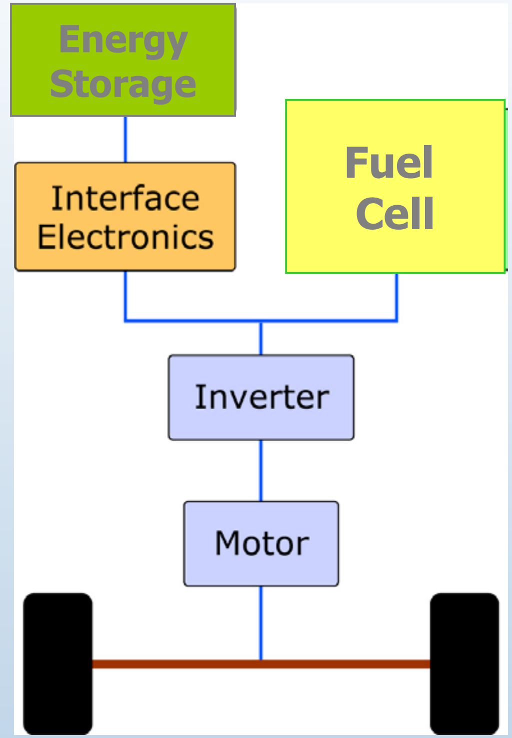
- Objectives/Background
- Motivation for using energy storage in fuel cell vehicles
- Analysis tool used – ADVISOR™
- Sample results
  - Performance
  - Fuel Economy
- Summary

Objectives

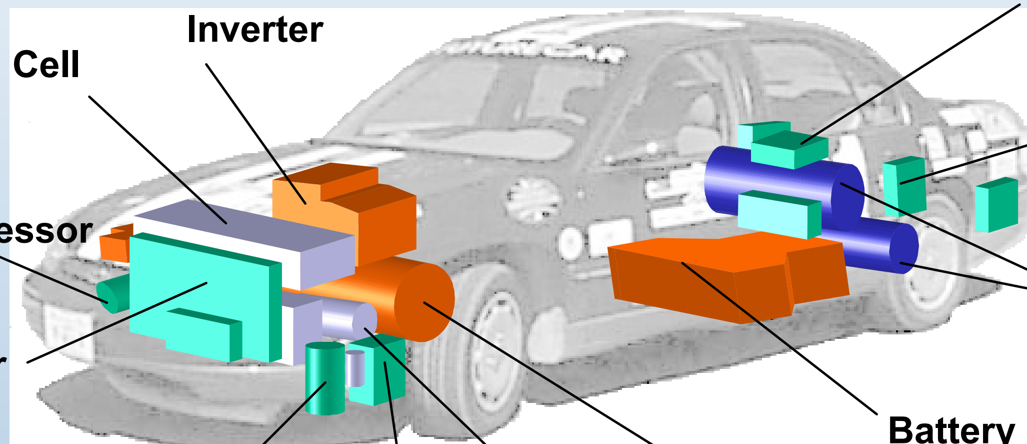
- Review previous studies on how the fuel cell and energy storage sizing and choices can affect efficiency and performance.
- Use ADVISOR^{TM} to show the fuel cell and energy storage system demands under drive cycle and performance tests.
- Support the FreedomCAR Energy Storage technical team in defining energy storage requirements for fuel cell vehicles.

Fuel Cell/Energy Storage Hybridization





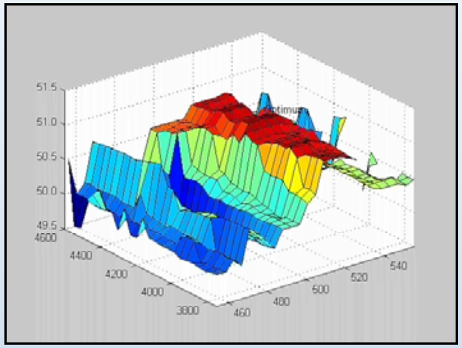
Fuel Cell HEV –
Fitting the System in the Car



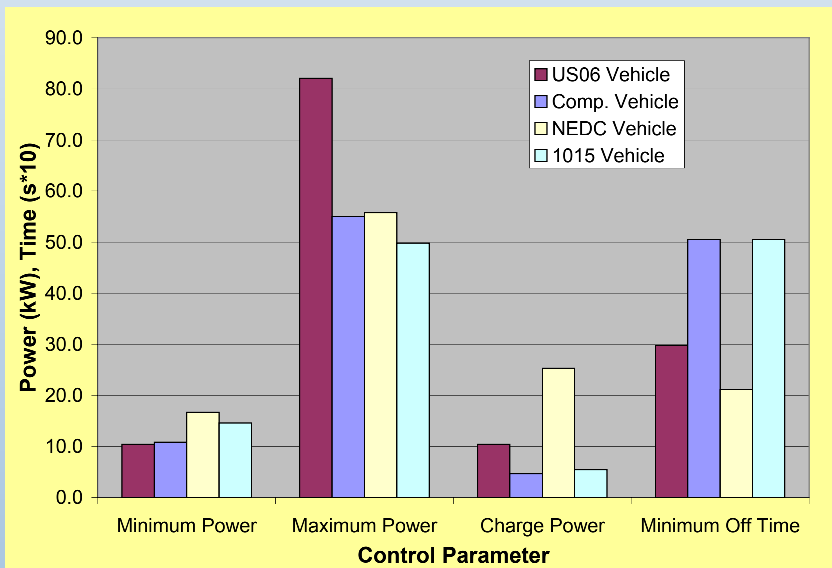
Previous Studies

- **Hybridization of a fuel cell vehicle with energy storage improves fuel economy and performance, and makes it practical (UCD, VTech, ANL, NREL). Hybridization:**
  - Captures regenerative breaking.
  - Improves transient response.
  - Uses a smaller, lower cost fuel cell.
  - Warms up the fuel cell or reformer.
- **Some demonstration prototype fuel cell vehicles are hybrids:**
  - Toyota FCHV – (NiMH batteries)
  - Honda FCXV4 – (ultracapacitors)

Optimization of Fuel Cell Vehicle Design Provides Insight into System Trade-Offs



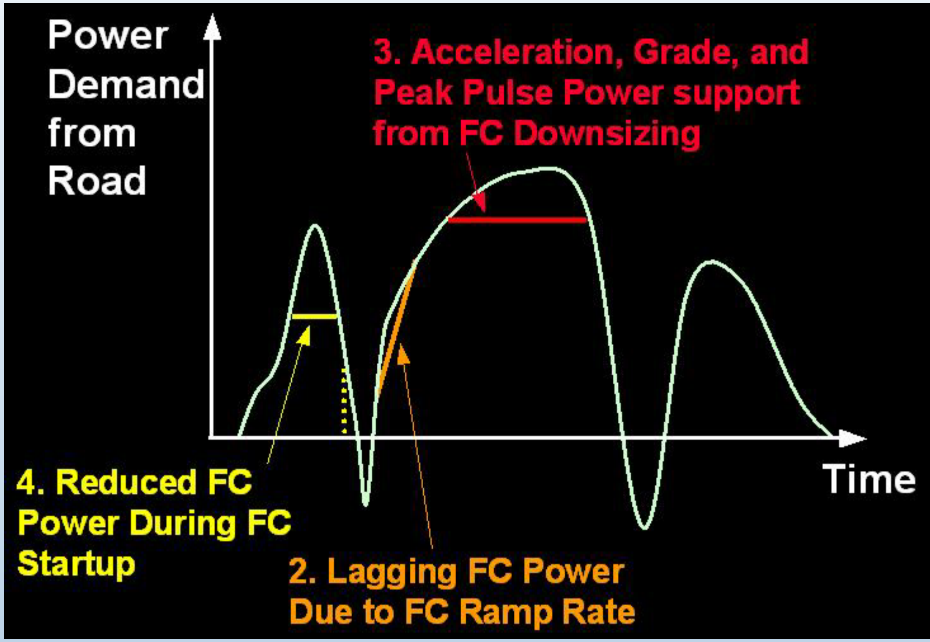
ADVISOR 2002
Advanced Vehicle Simulator



- Derivative-free optimization algorithms are necessary for the complex design space of HEVs.
- The drive cycle influences the optimal degree of hybridization and control parameters.
- Fuel cell transient response capability is critical for a “pure” fuel cell vehicle.
- An optimized hybrid design can nullify the effects of fuel cell transient response.
- The fuel economy impact of gasoline reformer warmup may be substantial.
- The relatively small energy storage system can overcome the warmup limitations of the reformer.

Roles of Energy Storage System (ESS)

- Mostly likely
  - Regenerative braking capture
  - Traction assist during acceleration (FC slow ramp rate)
  - Traction assist during high power transients (downsizing FC)
- Probably
  - Traction power during fuel cell startup
  - Fuel cell system startup and shutdown
- Not desirable
  - Sustained gradeability
  - Electrical accessory loads (in steady state)

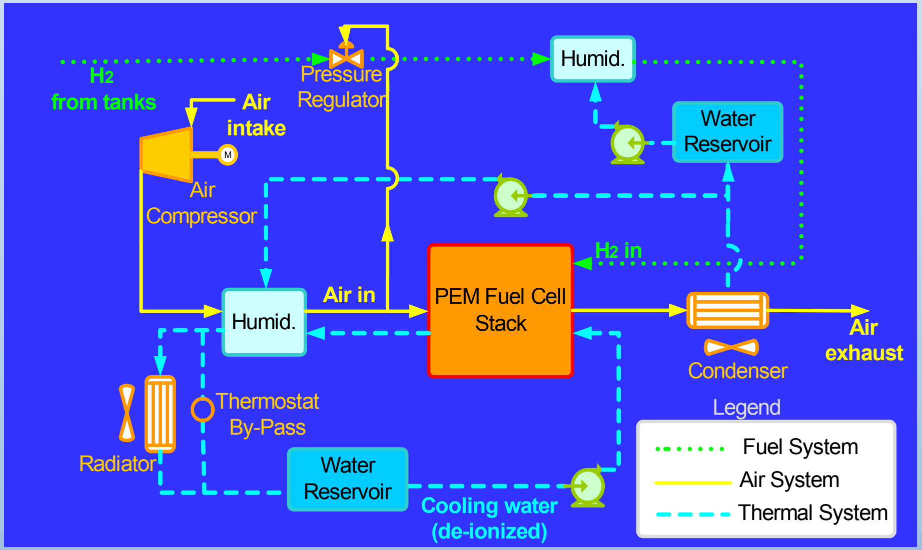


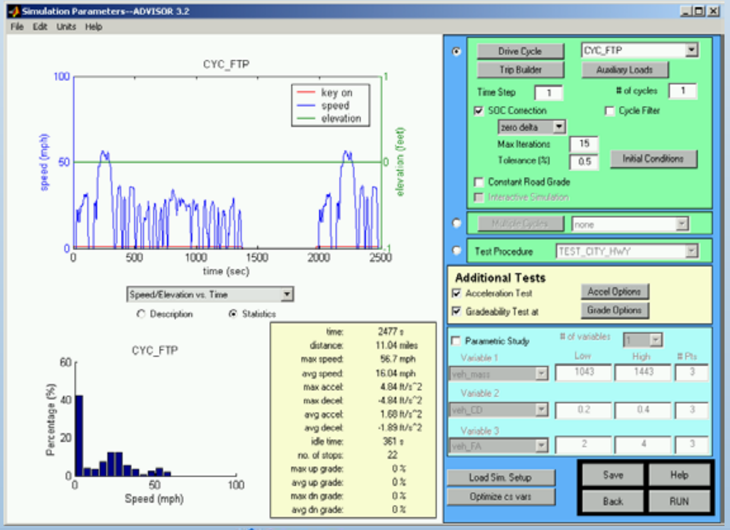
The combined FC and ESS hybridized system must meet performance target requirements of the vehicle:

- **Acceleration**
- **Top speed**
- **Grade sustainability**

ADVISOR™ Tool Is Used for HFCV Simulations

- ADVISOR™ = ADvanced VehIcle SimulatOR
  - Simulates conventional, electric, or hybrid vehicles (series, parallel, or fuel cell).
  - Simulates various components (ES, FC) and drive cycles.
- ADVISOR™ was created in 1994 to support DOE Hybrid Program research decisions.
- Available from www.nrel.gov/transportation/analysis.
- Downloaded by more than 8000 people around the world.





Typical Vehicle Specifications and Performance Assumptions

Vehicle Characteristics

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)

Performance

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%

Typical Fuel Cell and Hydrogen Storage Systems Assumptions

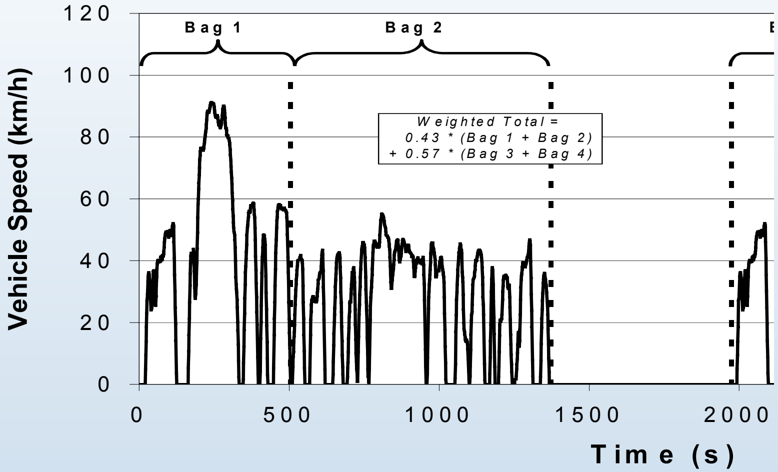
- Fuel Cell
  - Should be sized to provide at least top speed and grade performance.
  - Must have 1- or 3-s transient response time for 10% to 90% power.
  - Should reach maximum rated power in 15 s for cold start from 20°C and 30 s for cold start from –20°C ambient temperatures.
  - System efficiency of 60% at maximum and 50% at rated peak power (DOE Technical Targets) .
  - Specific energy of 400-600 W/kg.
- Hydrogen Storage
  - Pure compressed hydrogen.

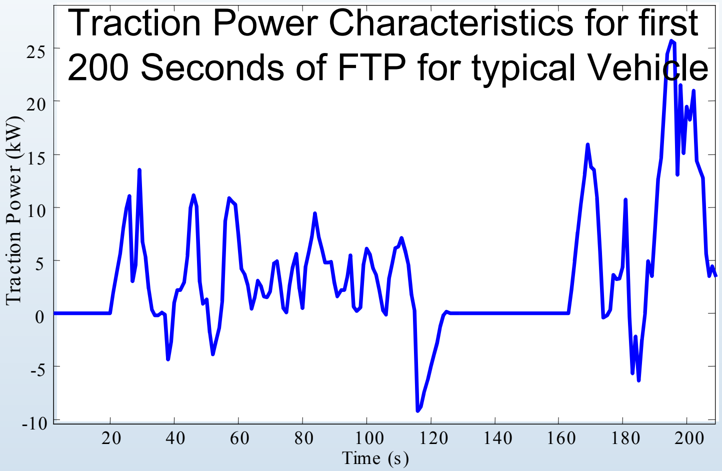
Assumption Description	Units	2005	2010
H2 Storage Energy Density	*kWh/L*	1.2	1.5
H2 Storage Specific Energy	*kWh/kg*	1.5	2

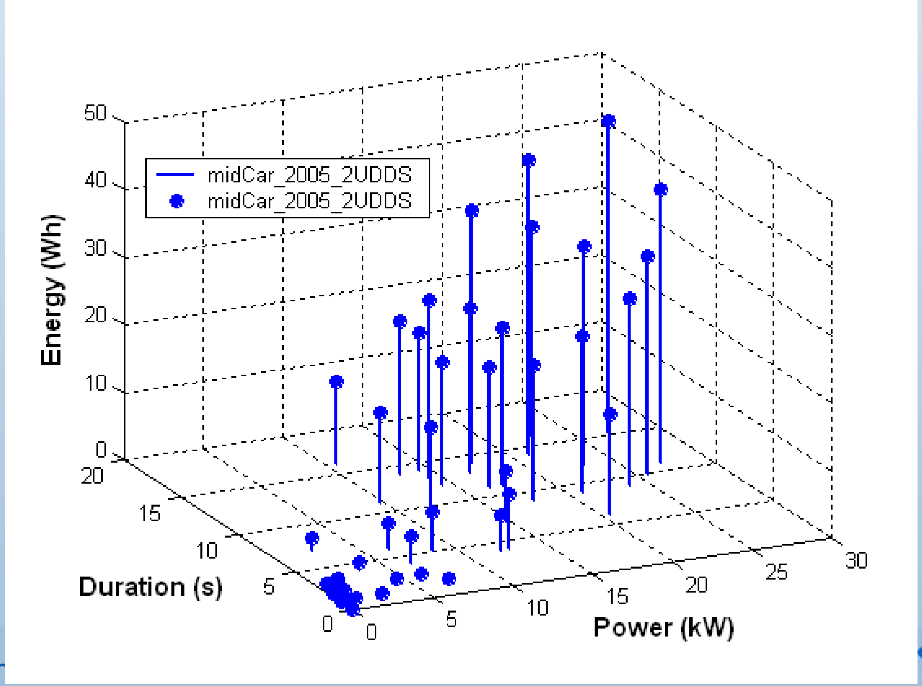
Typical Energy Storage System Assumptions

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 Energy Density	*W/L*	1600	2000	2800	4500
Energy Storage Specific Energy	*W/kg*	550	1000	1300	3500

Regen Capture Is the Primary Contribution of EES to Fuel Cell Vehicle Efficiency



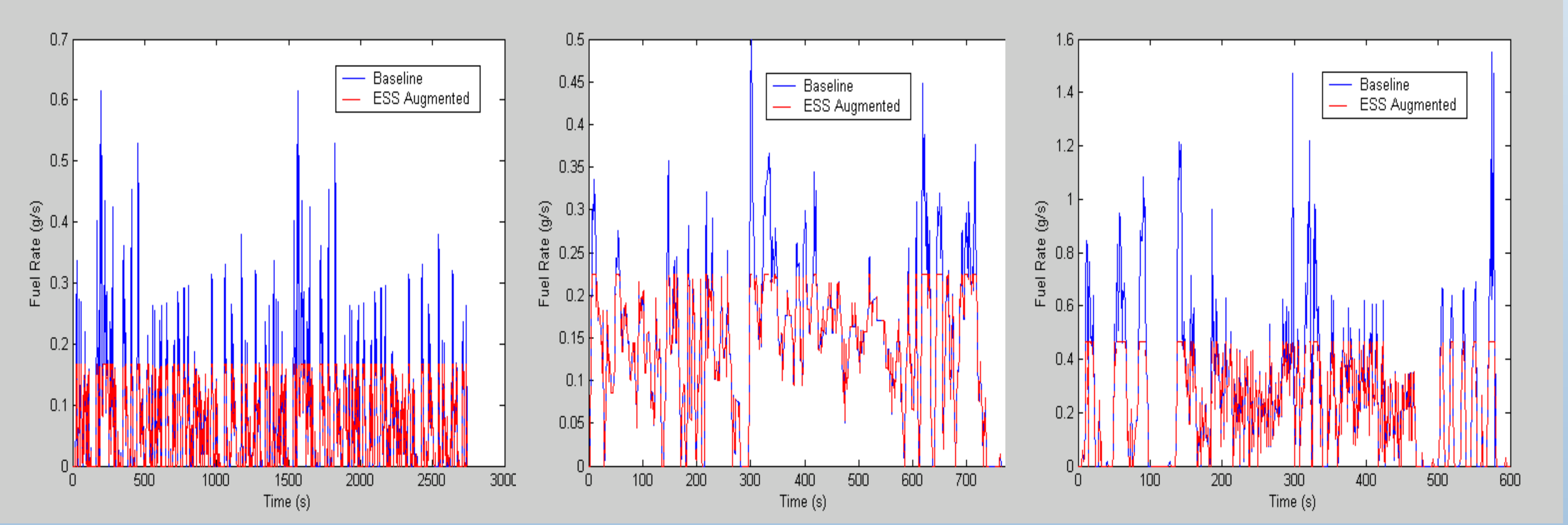




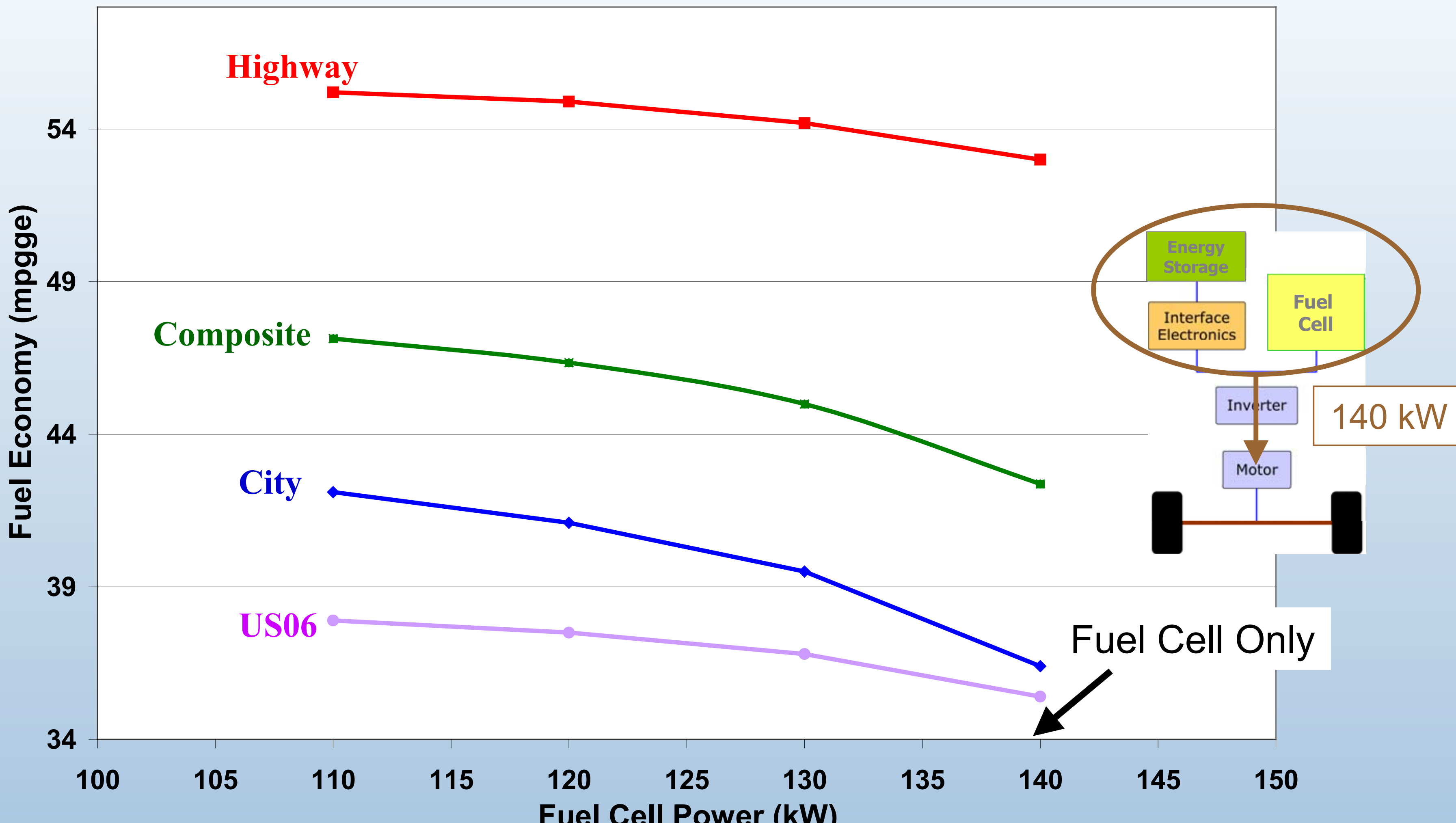
Maximum Fuel Savings Potential from Regen Energy Use

- Assumption: fuel cell power output is limited such that remaining peaks consume all regen energy.
- Assumed 100% efficiency for recovering regen energy.

2UDDS	Highway	US06
19%	7%	18%

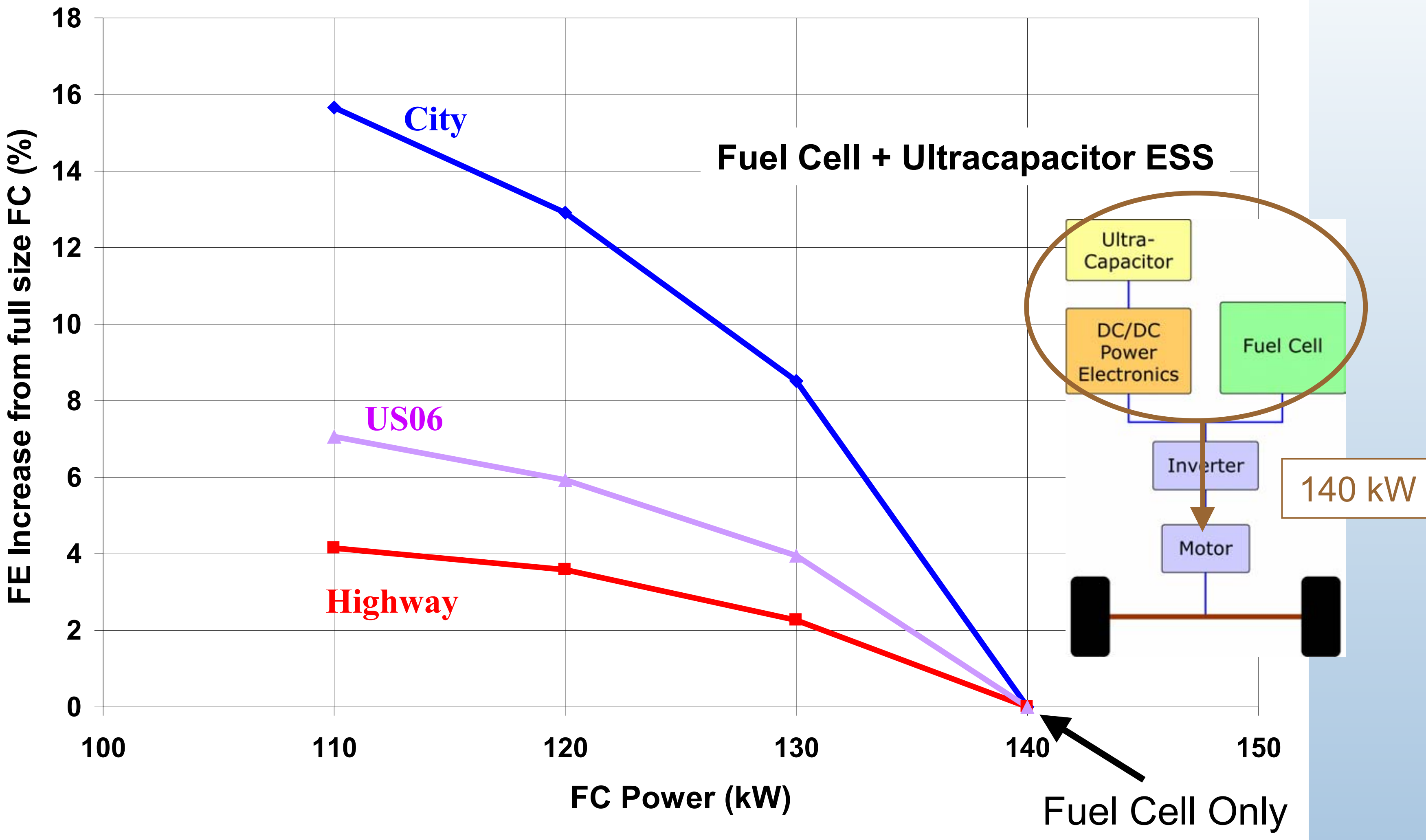


Fuel Economy Depends on Driving Cycle and Degree of Hybridization

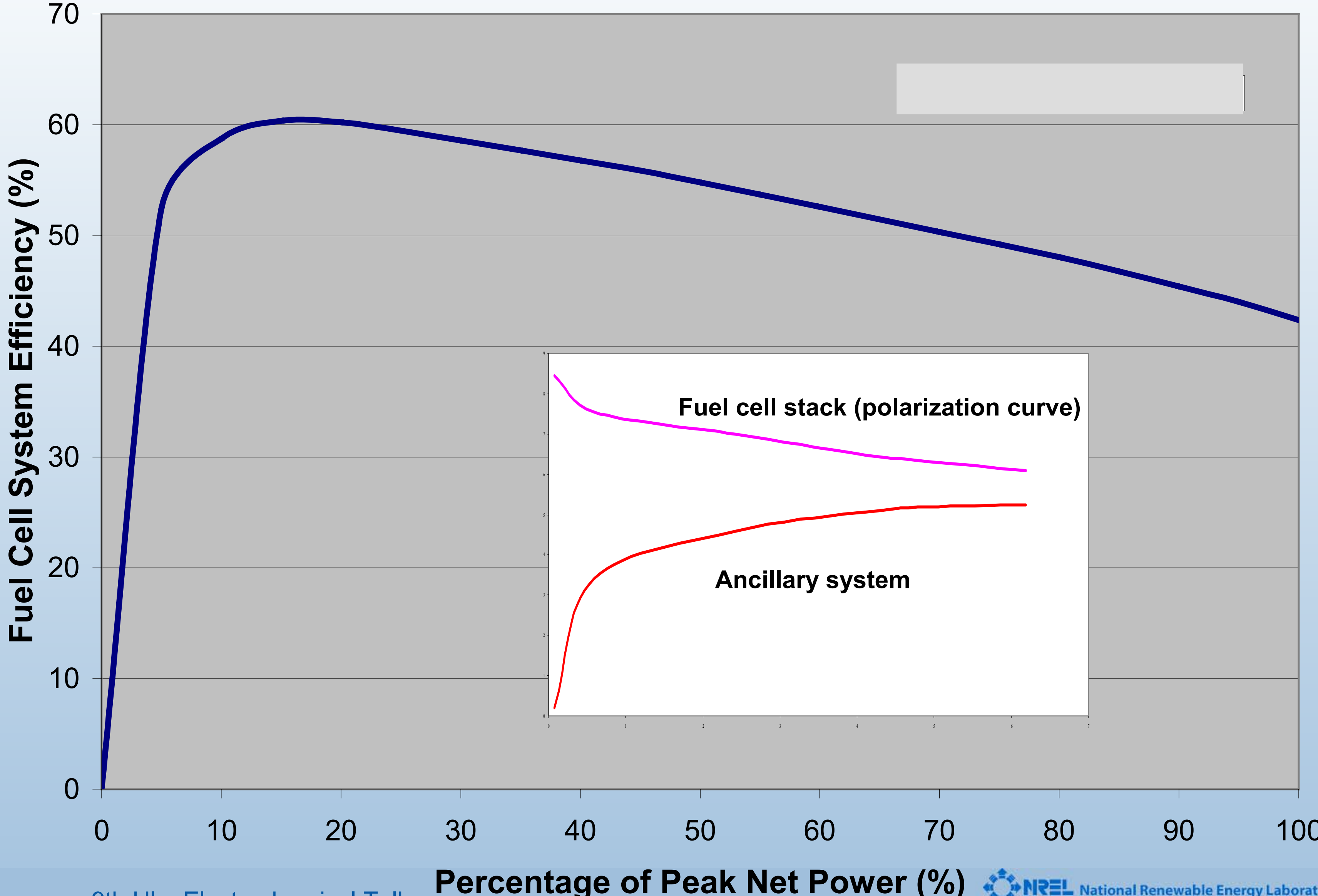


(Fuel Cell + Energy Storage) combination provides total 140 kW for Max SUV Power Requirements

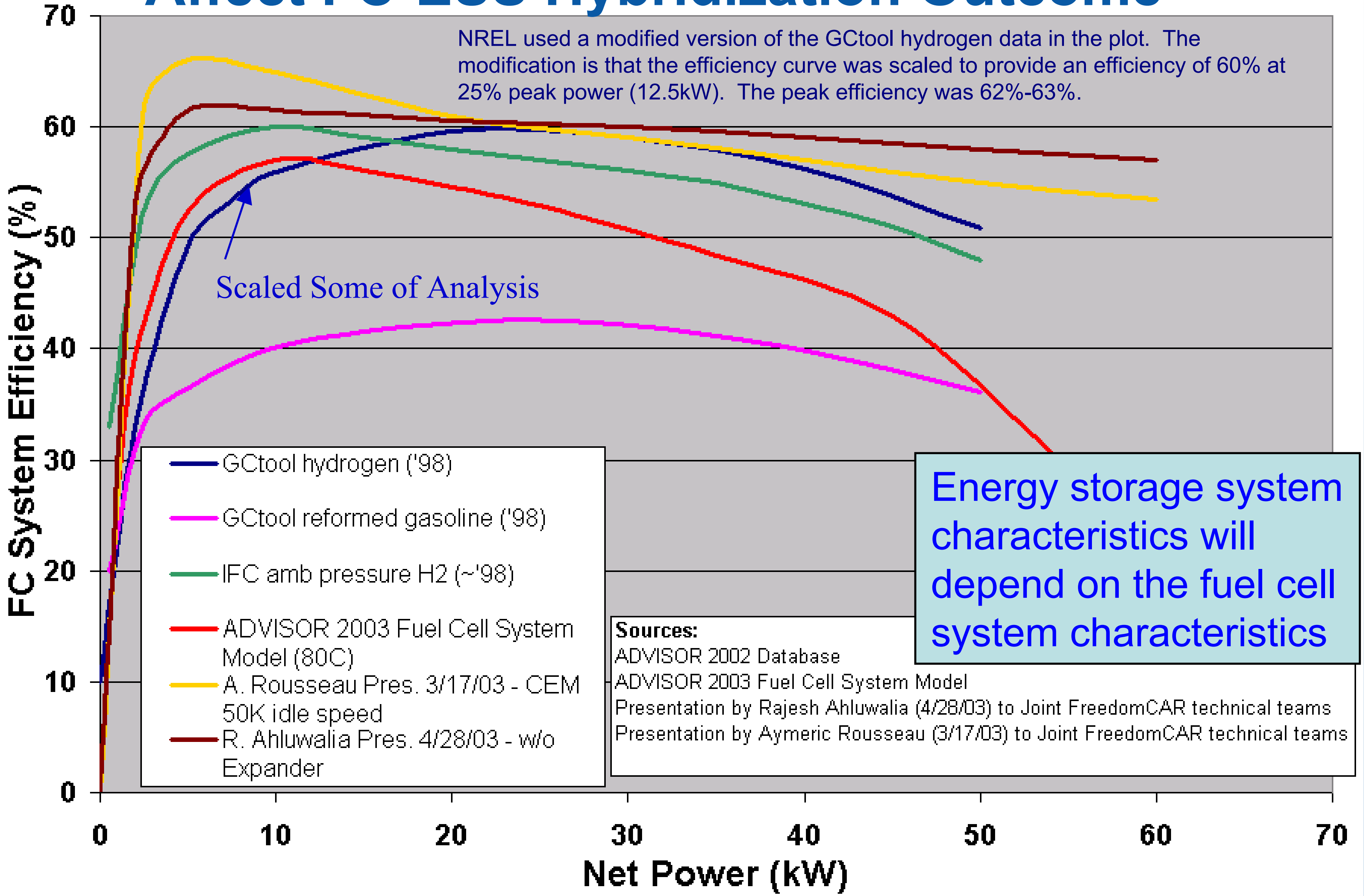
Key Benefit of Hybridization Is Fuel Economy Increase for Urban Cycles



Typical System Efficiency Characteristics from Fuel Cell Model

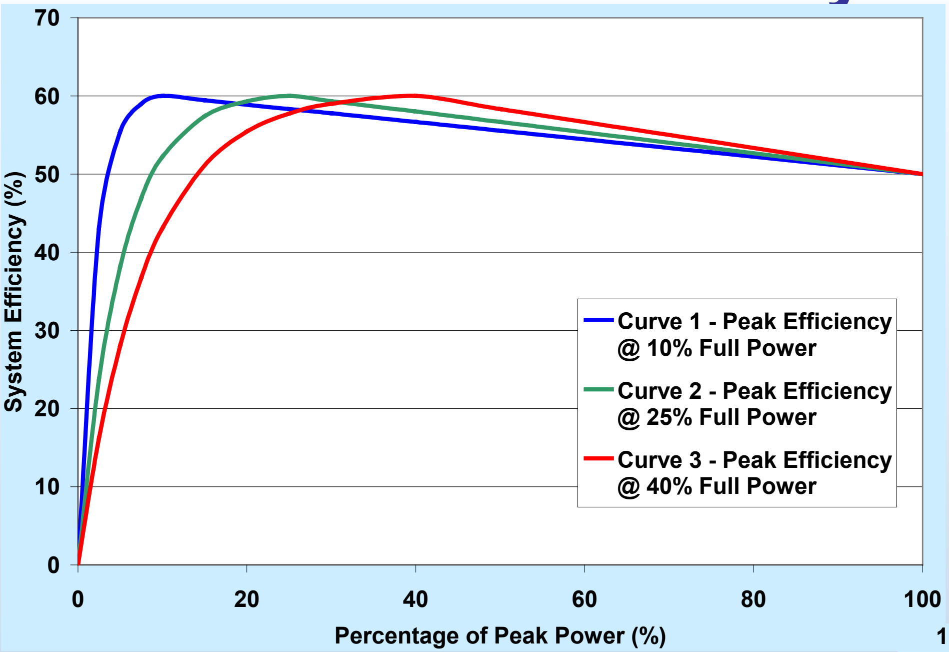


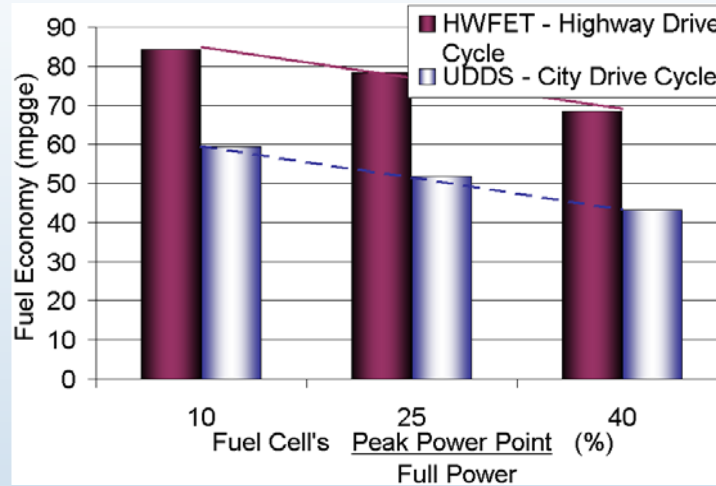
Fuel Cell System Efficiency Variability Could Affect FC-ESS Hybridization Outcome



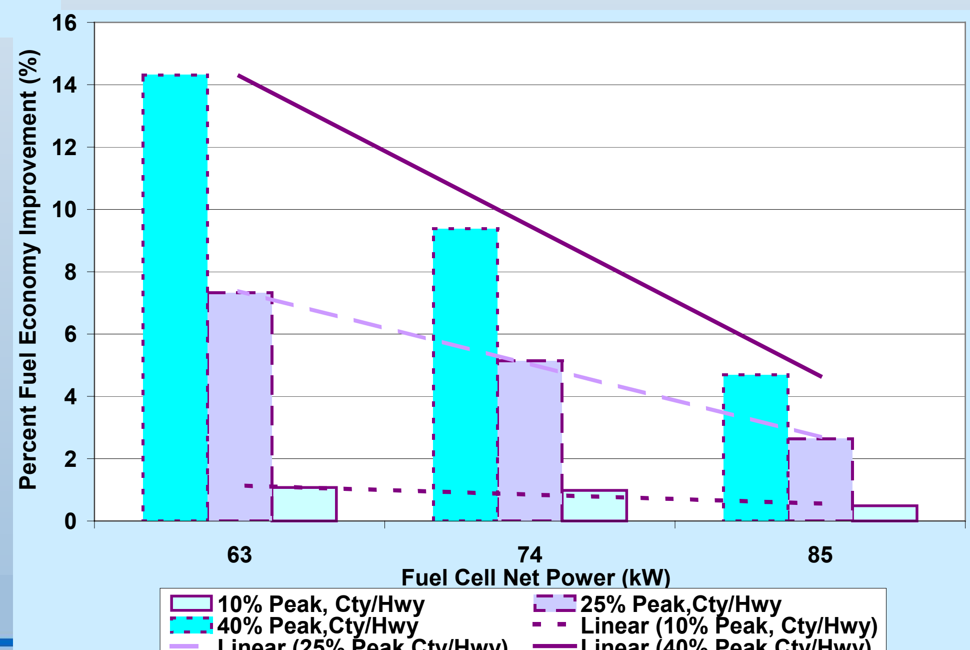
Energy storage system characteristics will depend on the fuel cell system characteristics

Advantages of Downsizing Tied to Fuel Cell Efficiency Characteristics

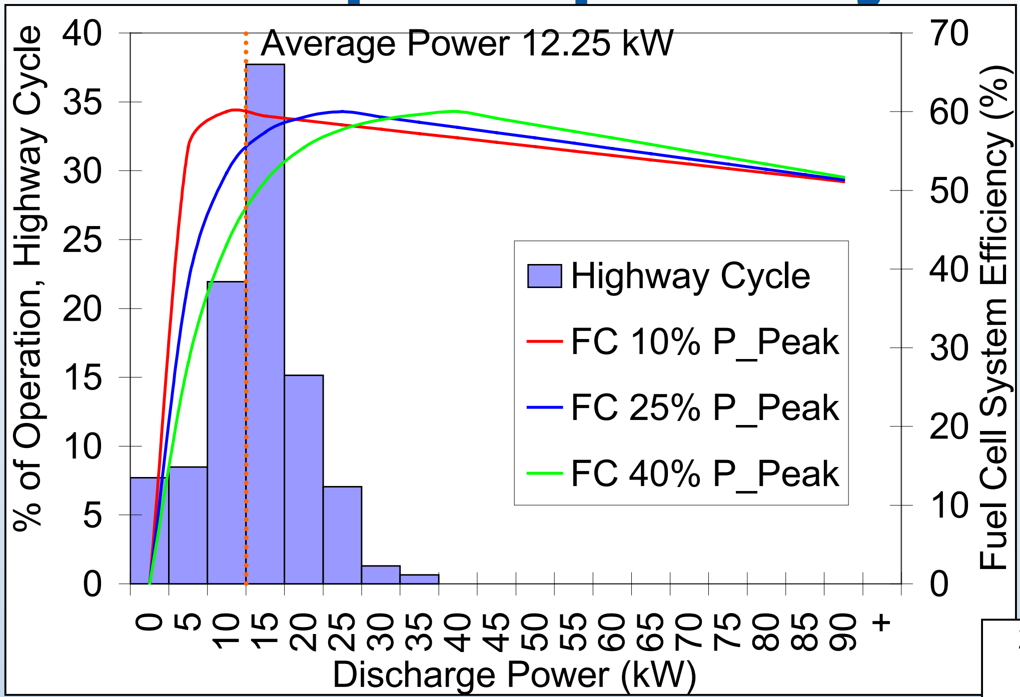


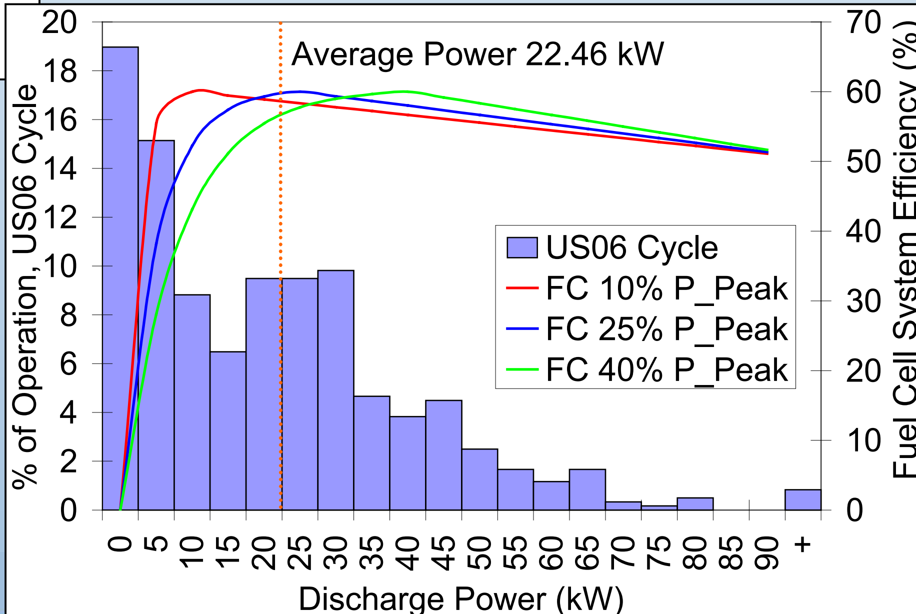


Proposed theoretical FC efficiency curves for current analysis due to lack of data

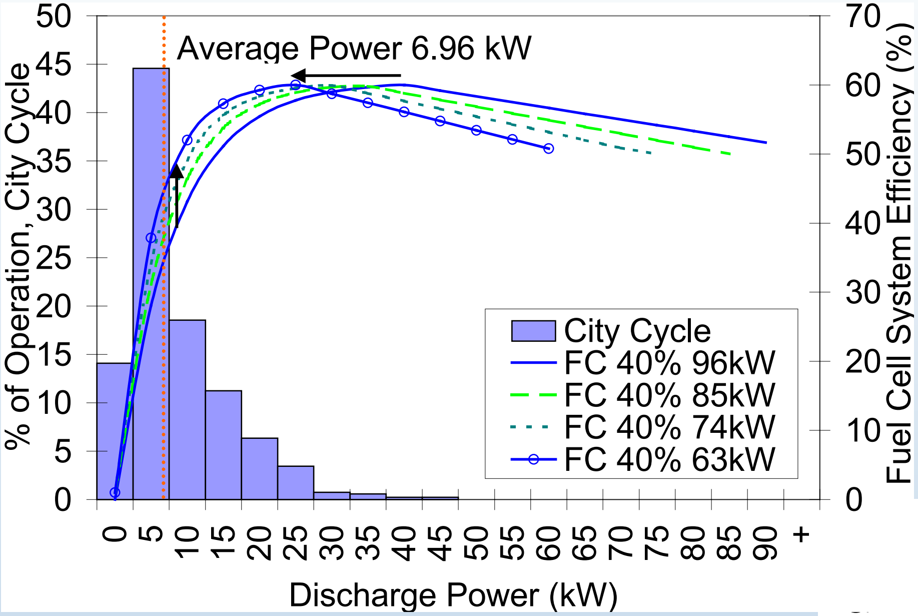


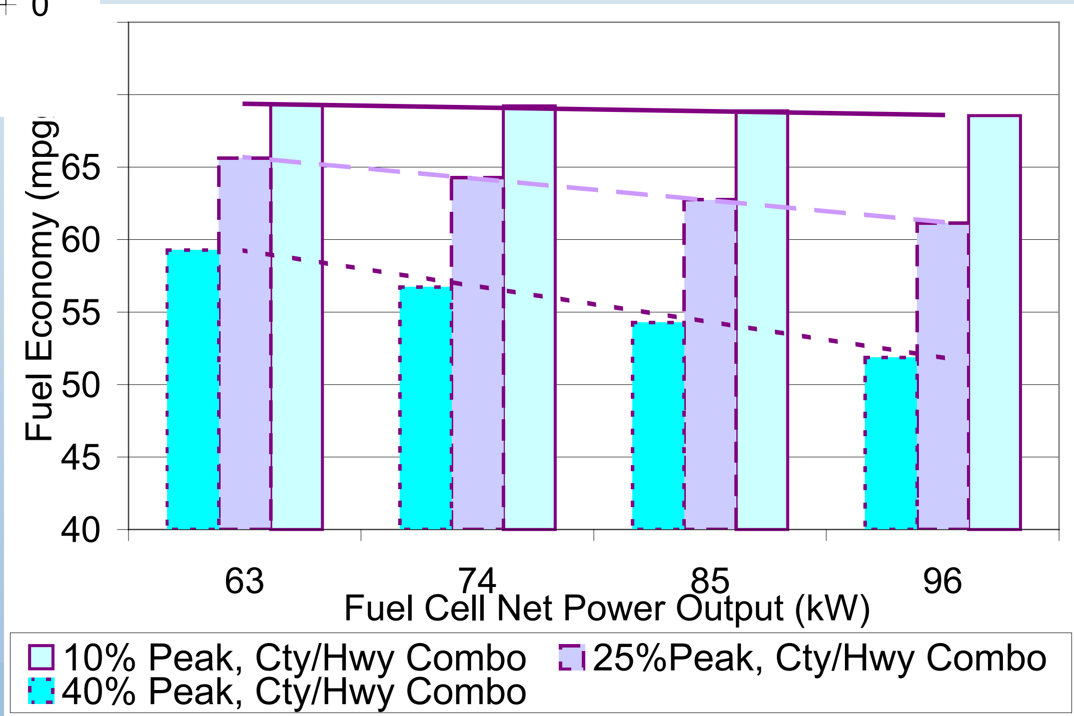
Drive Cycle Power Output Histogram Helps Explain Hybridization Benefits



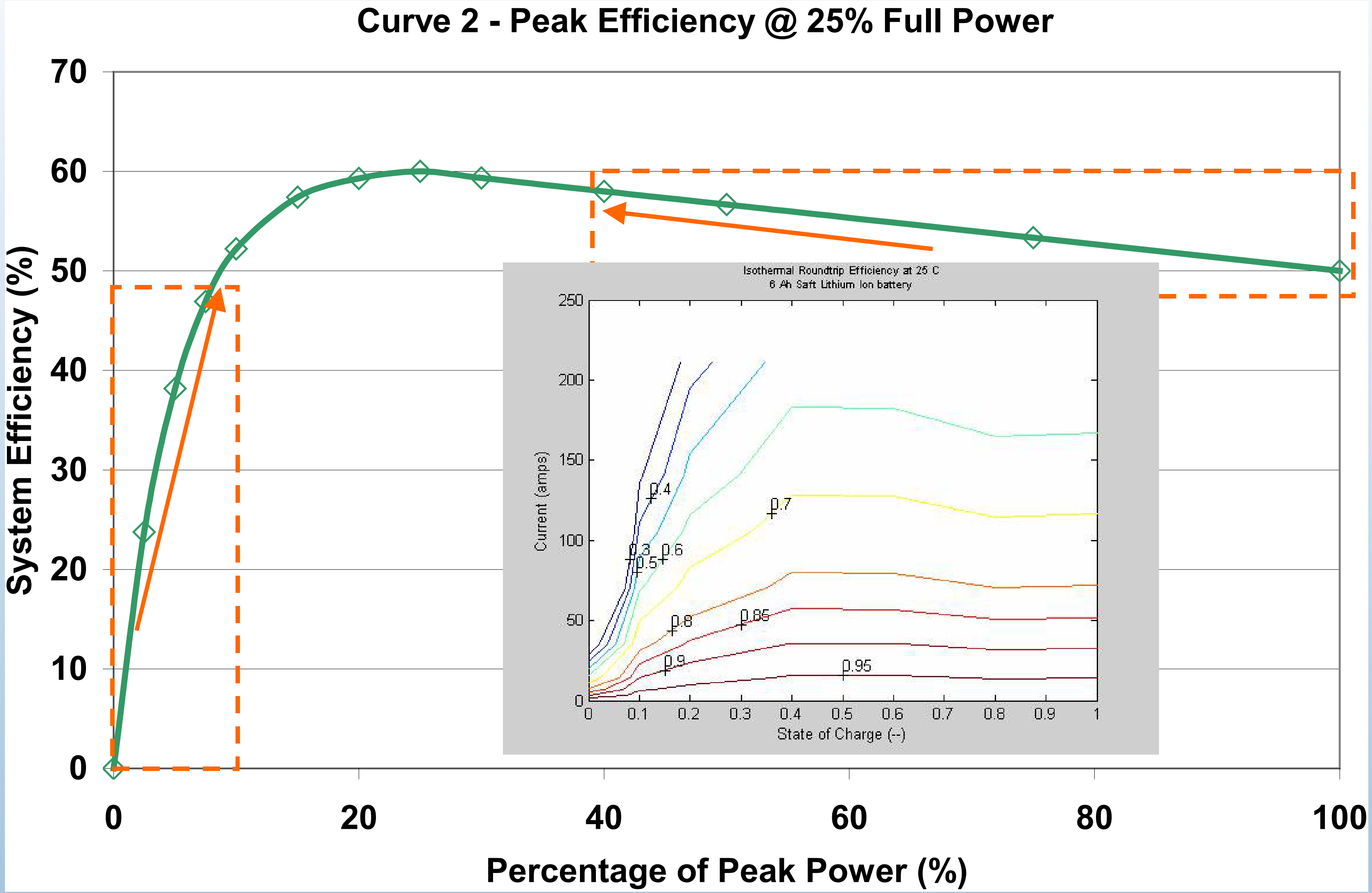


Benefit of Downsizing Fuel Cell as a Function of Peak Efficiency Position





Potential Active Roles for Supplementing Fuel Cell Operation



Concluding Observations

- Vehicle performance specifications can significantly influence ESS requirements.
- Fuel cell operating characteristics can significantly influence ESS requirements.
- Regen capture is the key contribution of the ESS to fuel cell vehicle efficiency.
- A key benefit of hybridization is an increase in fuel economy for urban cycles.
- Maximizing fuel economy depends on drive cycles and fuel cell system characteristics (efficiency curve).
- Ultracapacitors can recapture a significant portion of the regen energy and thus improve fuel economy. However, because of their limited energy storage capability, they provide less potential for fuel cell system downsizing.

Acknowledgments

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