

EDLC Modeling and Integration for Hybrid Electric Vehicles

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Objectives of This Presentation

- Update on NREL's EDLC modeling and EDLC automated analysis program
- Update on EDLC roles in hybrid vehicles
- Overview of Heavy Hybrid EDLC initiatives

Outline

EDLC activities overview

- **Modeling Review**
 - The New Manual's Modeling Implications
 - VBA Analysis Spreadsheet
 - Electrochemical Impedance Spectroscopy
- Light Duty Hybridization Analyses
 - Fuel Cell Efficiency Curve
 - Specific Fuel Cell ESS Requirements
- Heavy Hybrid EDLC Efforts

Equivalent Circuit Capacitor Model

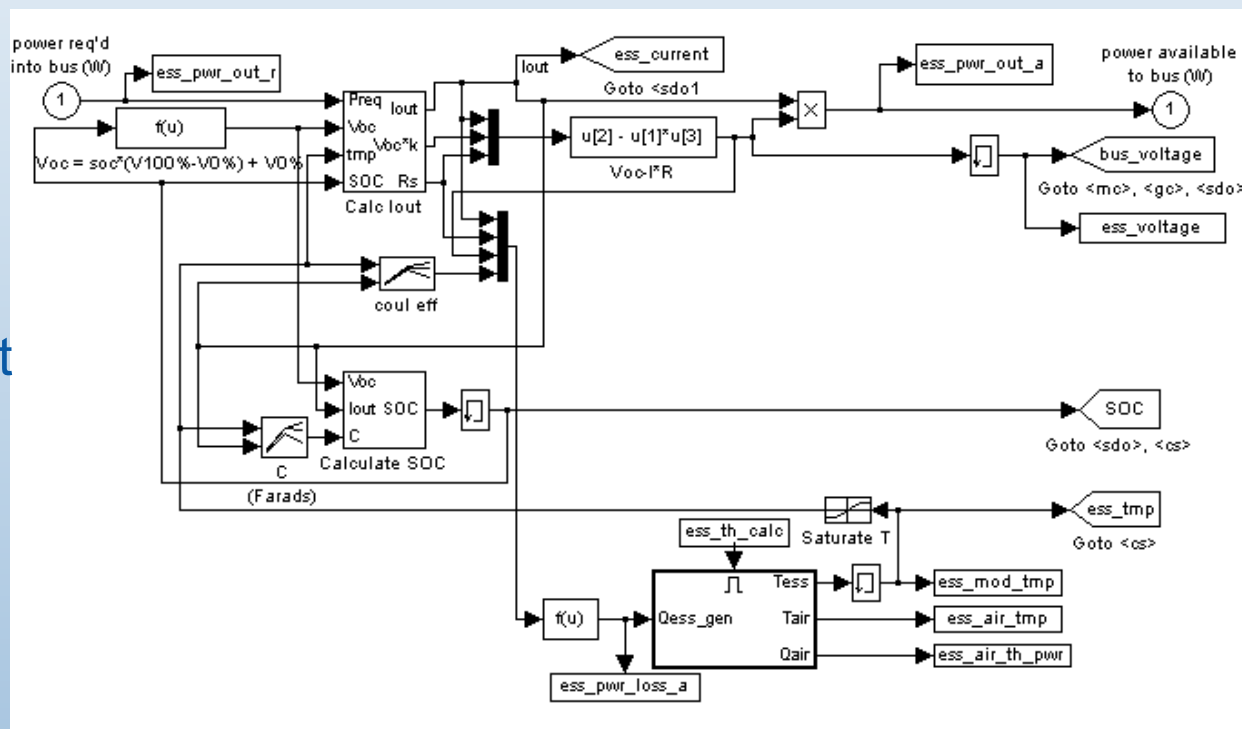
Capacitance R_{series}



- C - mapped as a function of temperature & current
- R - mapped as a function of temperature & current

Additional Attributes

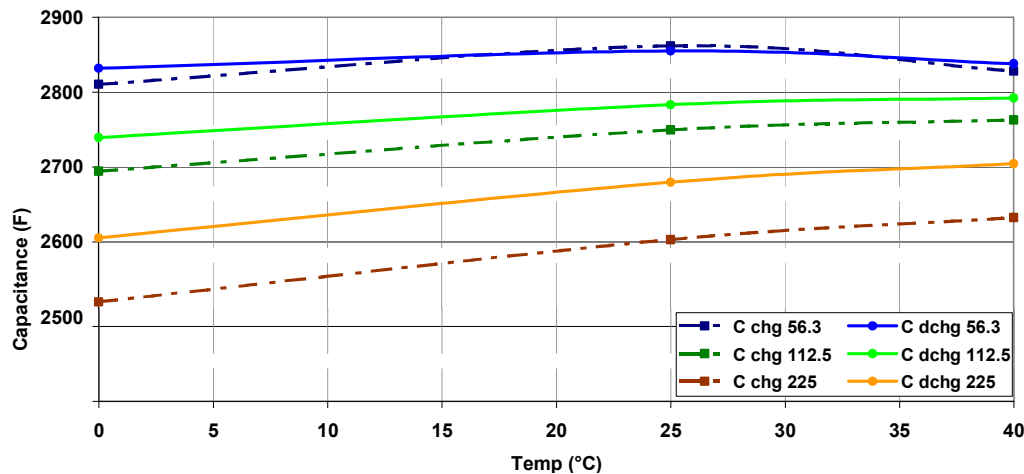
- Coulombic efficiency accounted for
- Thermal model: temperature rise predictions & thermostat temperature control
- Maximum power limitations
- Series and Parallel configurations



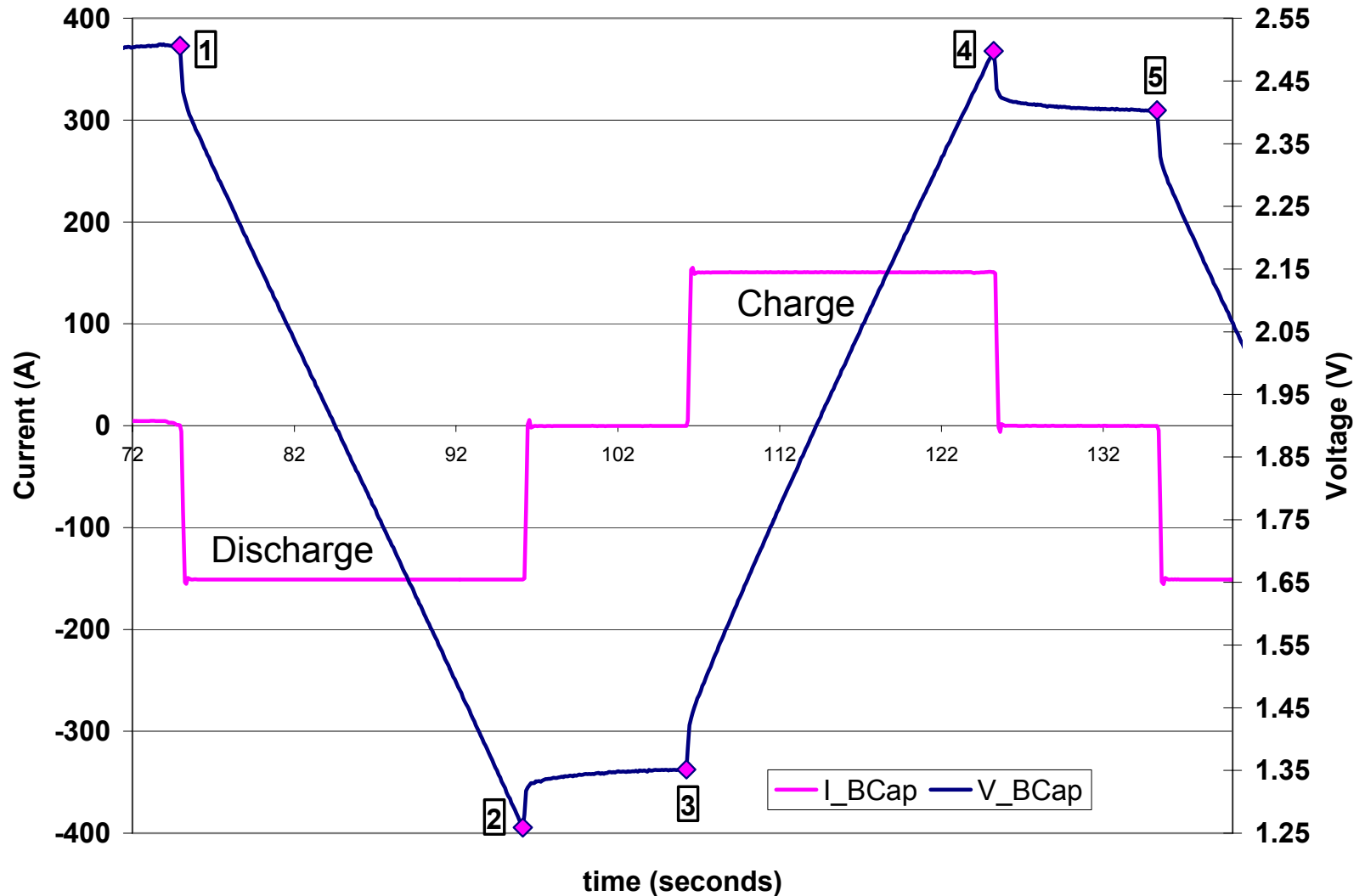
Most of NREL's Model Data is Generated from Standard Test Characterizations

DOE/NE-ID-11173
Revision 0
September 21, 2004

FreedomCAR Ultracapacitor Test Manual



There are Multiple Calculation Techniques used for obtaining Modeling Characteristics



Automated Analysis Program

Objective:

It is anticipated that the Excel VBA program will provide a simple, standard, user-friendly, and powerful tool to help industry perform automated test analyses and characterization for EDLC modeling

Demonstration:

The screenshot displays the user interface of the FreedomCAR Ultracapacitor Test Manual Modeling/Analyses Program. At the top, the NREL National Renewable Energy Laboratory logo is on the left, and the FreedomCAR logo (a blue star with a red and white swoosh) is in the center. To the right of the FreedomCAR logo is the seal of the Department of Energy, University of Illinois. Below the logos, the title "Ultracapacitor Test Manual Modeling/Analyses Program" is centered. The interface is divided into two steps:

Step 1: Specify Test Temperature

Temperature: °C comments:

Step 2: Choose Test-Type to Analyze

The interface features ten buttons for selecting test types, arranged in two rows:

- Reference Capacity
- Constant-Power Dschg
- Leakage-Current
- Hybrid Pulse Power Ch
- Thermal Performance
- Constant-Current
- Constant-Power Chg
- Self-Discharge
- Cold Cranking
- Energy Efficiency

1st Screen – Choose Test to Analyze

The screenshot shows a Microsoft Excel window titled "Microsoft Excel - EDLC_Analyses_Program.xls". The interface is a graphical user interface for an ultracapacitor test manual modeling program. It features the NREL logo and the "FreedomCAR" logo, which includes a stylized star. The text "Ultracapacitor Test Manual Modeling/Analyses Program" is prominently displayed. Below this, a section titled "Step 1 Choose Test-Type to Analyze" contains ten buttons for selecting different test types: Reference Capacity, Constant-Power Dschg, Leakage-Current, Hybrid Pulse Power Ch, Thermal Performance, Constant-Current, Constant-Power Chg, Self-Discharge, Cold Cranking, and Energy Efficiency. The Excel grid is visible in the background, with columns A through R and rows 1 through 31.

Microsoft Excel - EDLC_Analyses_Program.xls


File Edit View Insert Format Tools Data Window RCS Help Adobe PDF


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 **NREL** National Renewable Energy Laboratory

FreedomCAR 

Ultracapacitor Test Manual Modeling/Analyses Program



Step 1 Choose Test-Type to Analyze

Reference Capacity Constant-Power Dschg Leakage-Current Hybrid Pulse Power Ch Thermal Performance

Constant-Current Constant-Power Chg Self-Discharge Cold Cranking Energy Efficiency

2nd Screen – Choosing Data

Microsoft Excel - EDLC_Analyses_Program.xls

File Edit View Insert Format Tools Data Window RCS Help Adobe PDF

100% Arial

NREL National Renewable Energy Laboratory

FreedomCAR

Ultracapacitor Test Manual Modeling/Analyses Program

Department of Energy
UNITED STATES OF AMERICA

Convention: Discharge Current (-) Negative, Charge Current (+) Positive

Step 1 Select file for analysis at: °C

Choose Constant Current File 07232004_BCap77523_CCTestA2at30C001.xls

Back to "Main" Return to Test Selector Sheet

Step 2 Select data columns:

Select Time (s) Data	Cell	Value	Select Current (A) Data	Cell	Value	Select Voltage (V) Data	Cell	Value
Select Beginning Time	B\$43203	72.000418	Select Current Column	\$F\$43203	-0.161987	Select Voltage Column	\$E\$43203	2.490959
Ending Time:	B\$50403	84.000418	Ending Current:	\$F\$50403	-0.192505	Ending Voltage:	\$E\$50403	2.479744

Select Different Ending Time min time units

Step 3 Data Analyses Feedback:

Graph & Pick Pt.s

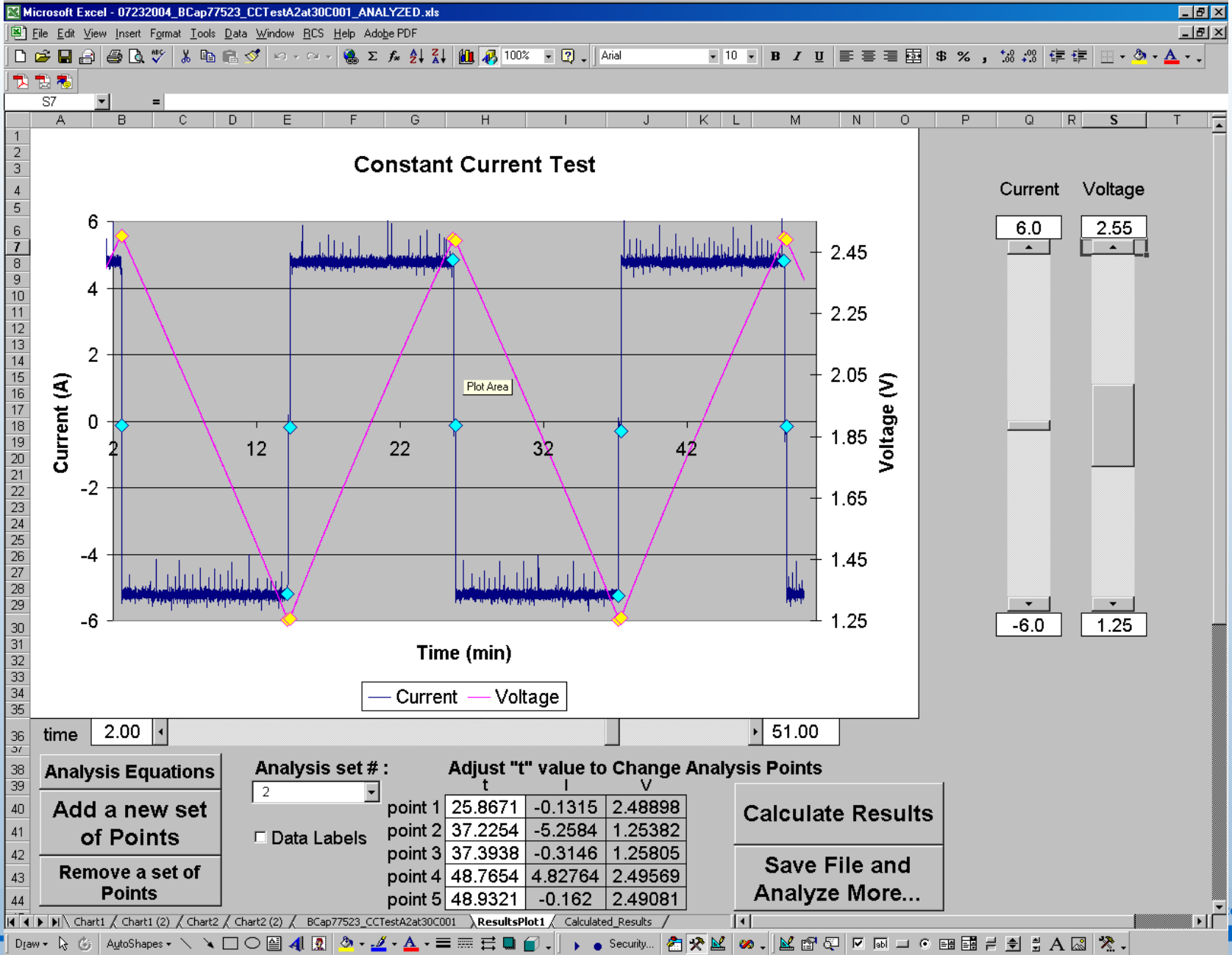
Plot Results are located in file specified in step 1, and in tab: **ResultsPlot1**

CC Interface

Draw AutoShapes

Security...

3rd Screen – Analyzing Data (Self Documenting)



4th Screen – Analysis Results

Microsoft Excel - 07232004_BCap77523_CCTestA2at30C001_ANALYZED.xls

File Edit View Insert Format Tools Data Window RCS Help Adobe PDF

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A1 = t (s)

	A	B	C	D	E	F	G
1	t (s)	I (A)	V (V)	Dischg Capacitance (F)	Chg Capacitance (F)	Dischg Resistance (mOhm)	Chg Resistance (mOhm)
2	156.825	-0.116211	2.504272				
3	849.825	-5.197388	1.252403				
4	859.92504	-0.192505	1.255875				
5	1541.925	4.842896	2.492867				
6	1552.02504	-0.13147	2.488976				
7				2897.201017	2649.110057	0.66524498	0.812357003
8	1552.02504	-0.13147	2.488976				
9	2233.52502	-5.258423	1.253815				
10	2243.62506	-0.314575	1.258049				
11	2925.92502	4.827637	2.495689				
12	2935.92504	-0.161987	2.490807				
13				2887.076864	2651.232368	0.811943962	1.019172034
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Chart1 Chart1 (2) Chart2 Chart2 (2) BCap77523_CCTestA2at30C001 ResultsPlot1 Calculated_Results

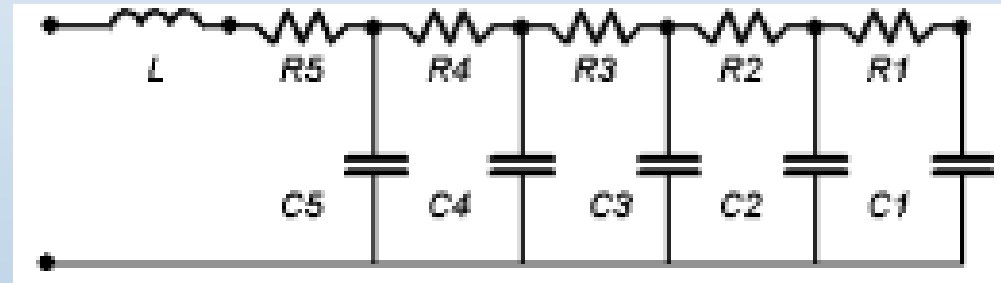
Draw AutoShapes Security...

Electrochemical Impedance Spectroscopy (EIS) Applications

- Material Characterization & Modeling
- Battery SOC predictions
- Battery SOH predictions

Proposed:

- EDLC modeling



Rigorous Test Procedures are Required for Device-Level Modeling with EIS Data

- More rigorous test procedure details are to be included in the new testing manual:
 - (1) Insure small AC amplitude injection signal.
 - (2) Use true four lead measurement.
 - (3) A low resistance, consistent, & repeatable connection must be made **between** the four leads and **the cell** under test.
 - (4) Use equipment with adequate current drive rating.
 - (5) Specify consistent and stable SOC(s) at which to perform readings.
 - (6) Wait sufficient time to allow for device to equilibrate after charging to said SOC.
 - (7) Connect “reference” leads directly to the cell under test (not “working” and “counter” leads) – If connectors don’t allow same location of connection point.

More Rigorous Definition of Details for EIS Analyses

The **CNLS fitting method is not as straightforward as would be desired for a procedure outlined in a manual.** It involves:

- (1) Evaluate quality of lab data for glitches/anomalies that will prevent proper fitting.
- (2) Estimate initial values from which to begin the fitting process.
- (3) Fix some values (necessary for high order circuits, like the 5-stage ladder) & iterate through by fitting different circuit sections.
- (4) Adjust weighting or the weighting method used between real & imaginary impedance values (depending on fitting software).
- (5) Simulate the model for comparison to the data.

Many steps need: (A) researchers' **heuristic feedback**, (B) **measurements iterations** to obtain a working circuit diagram. Additionally, **it may be difficult to provide a consistent basis by which fittings can be compared from different sources.**

Modeling Summary

- We are looking for EDLC community feedback on:
 - Level of interest and those interested in Beta testing the automated analysis program for the FreedomCAR EDLC test manual
 - Level of interest for EIS based system modeling and feedback on consistent techniques to incorporate EIS into standardized device testing/modeling.

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There are Various Vehicle Applications/Needs for Energy Storage

Addressing requirements of energy storage in vehicles with different strategies

42-Volt (Start/Stop, Mild HEV, Power-assist HEV)



Power Assist HEV (Low Power, High Power)



Fuel Cell Hybrids (Power)

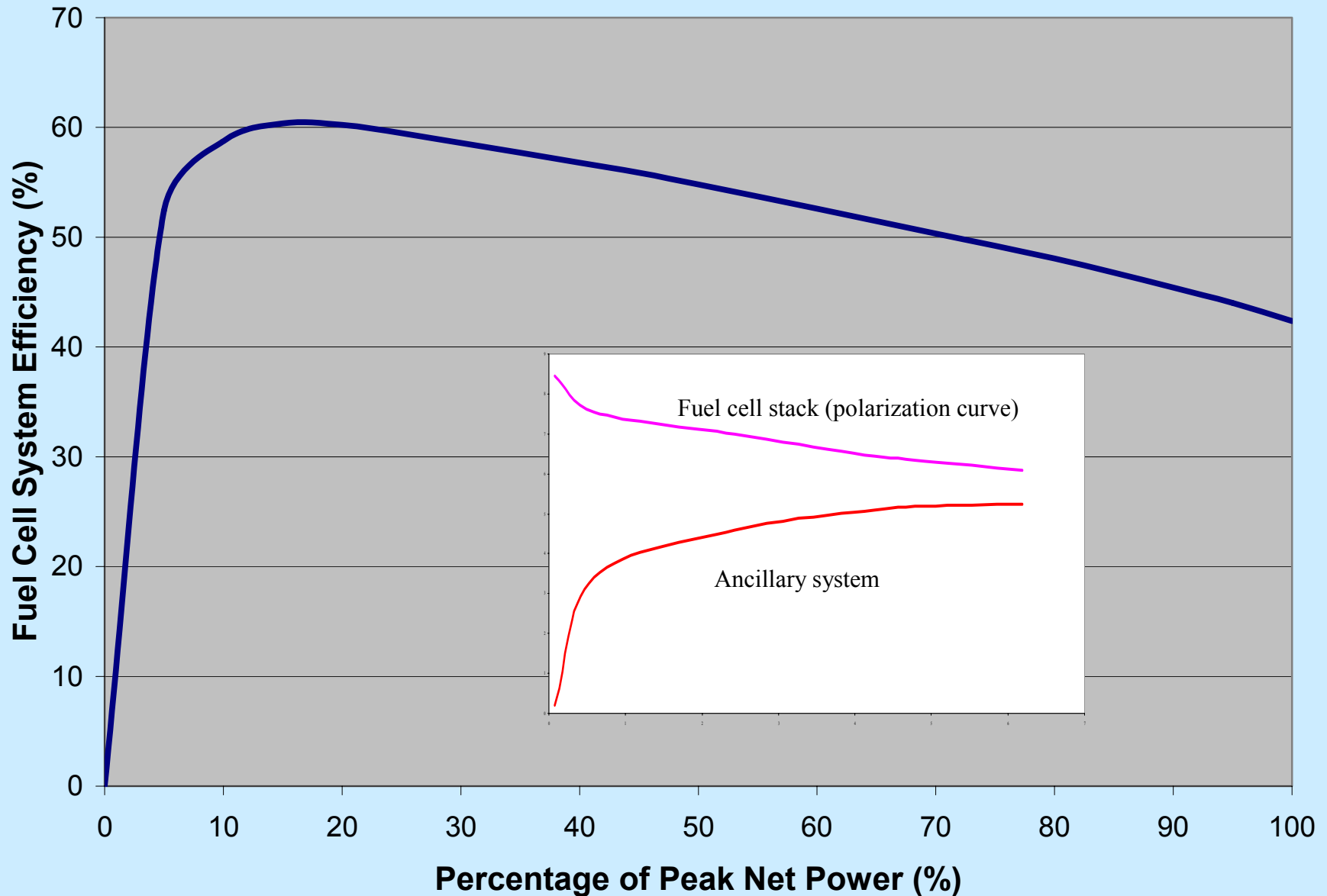


Battery EV

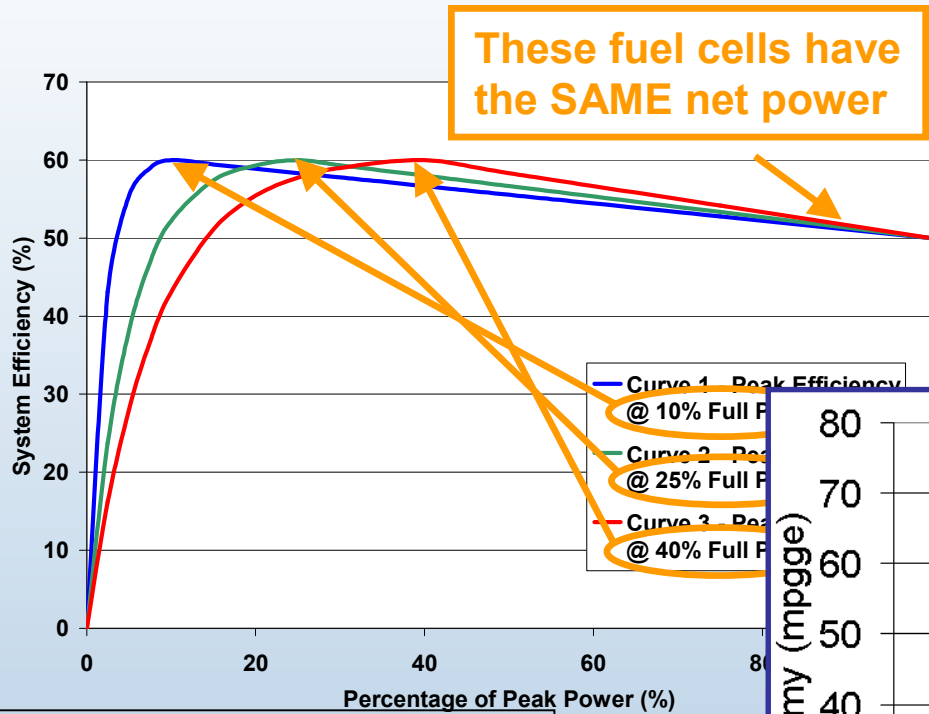


This Presentation's Focus

Variability in Fuel Cell System Efficiency Will Affect FC-ES Hybridization, so System Design is Key

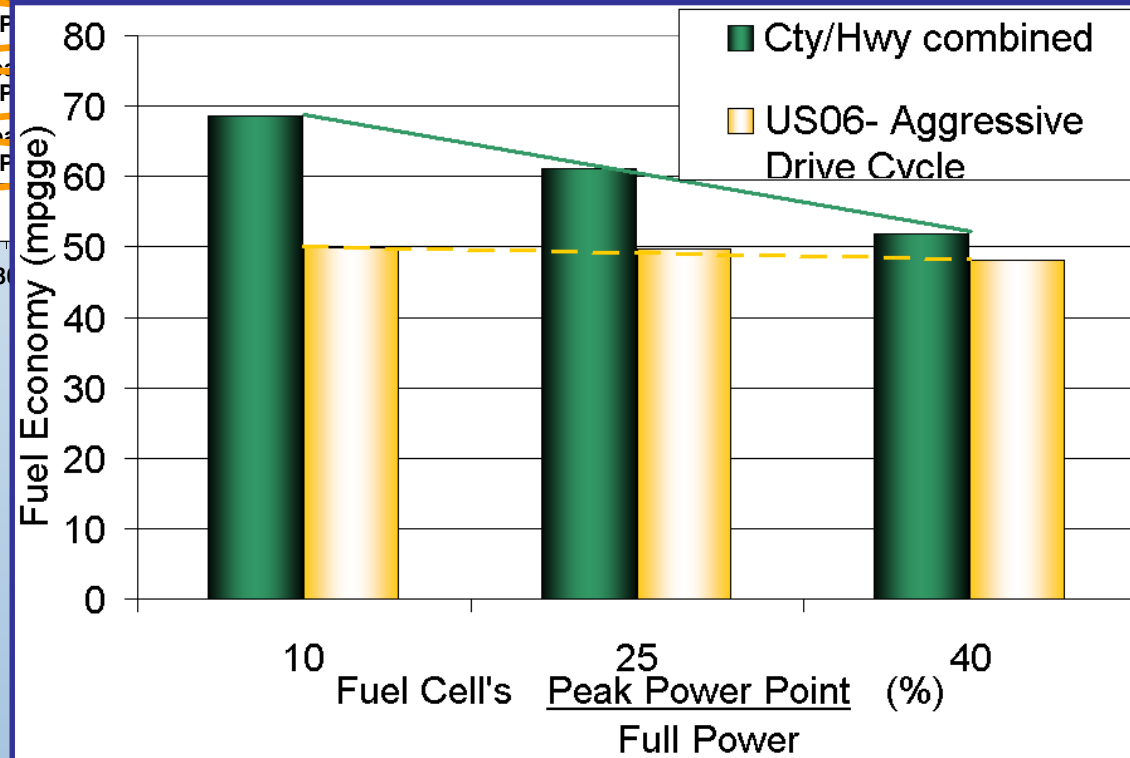


Fuel Economy is Affected by the Position of FC Peak Efficiency

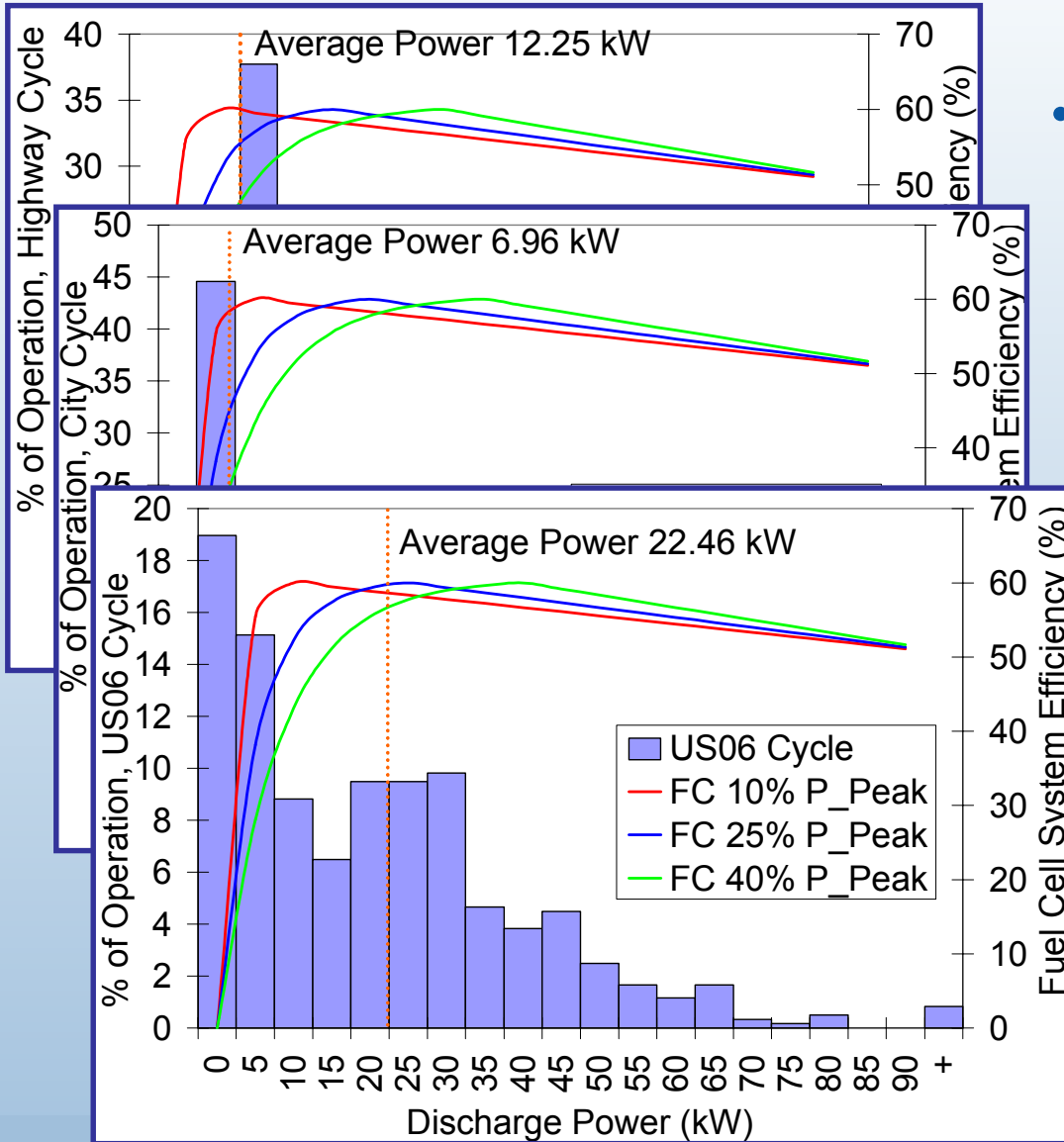


Vehicle with fuel cell only (96 kW)

Theoretical FC efficiency curves are based on DOE Targets



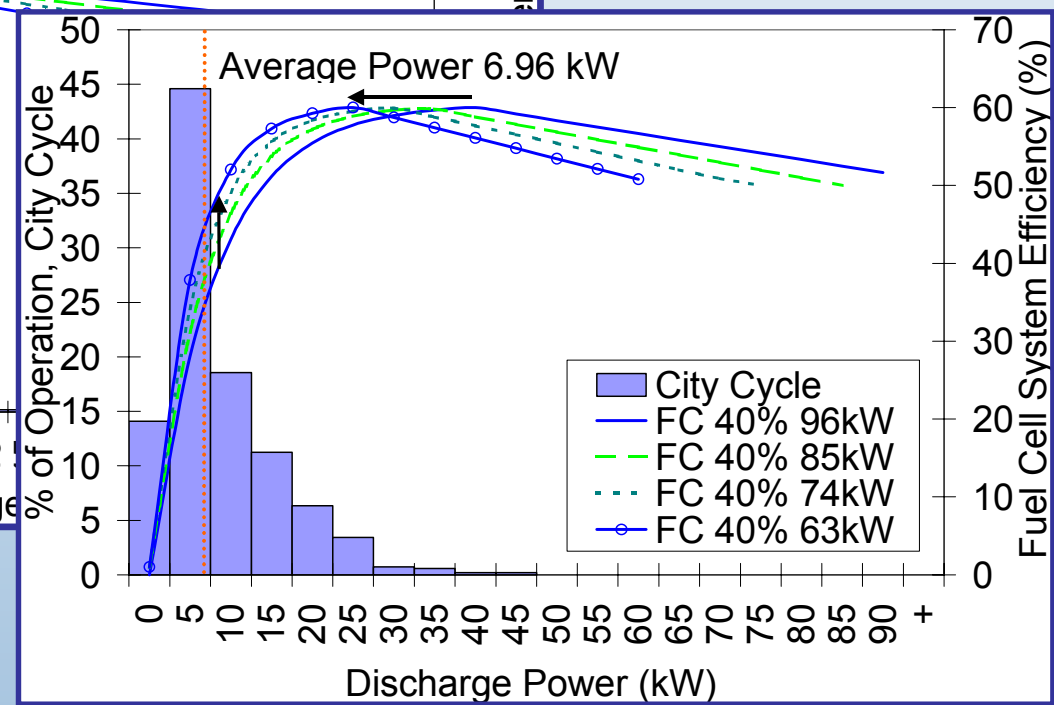
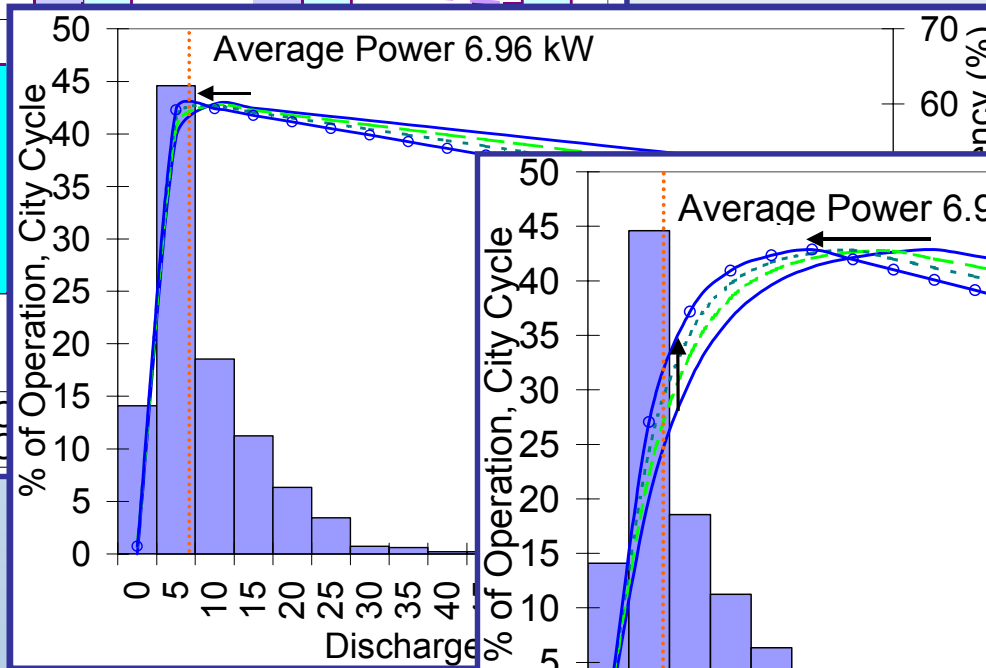
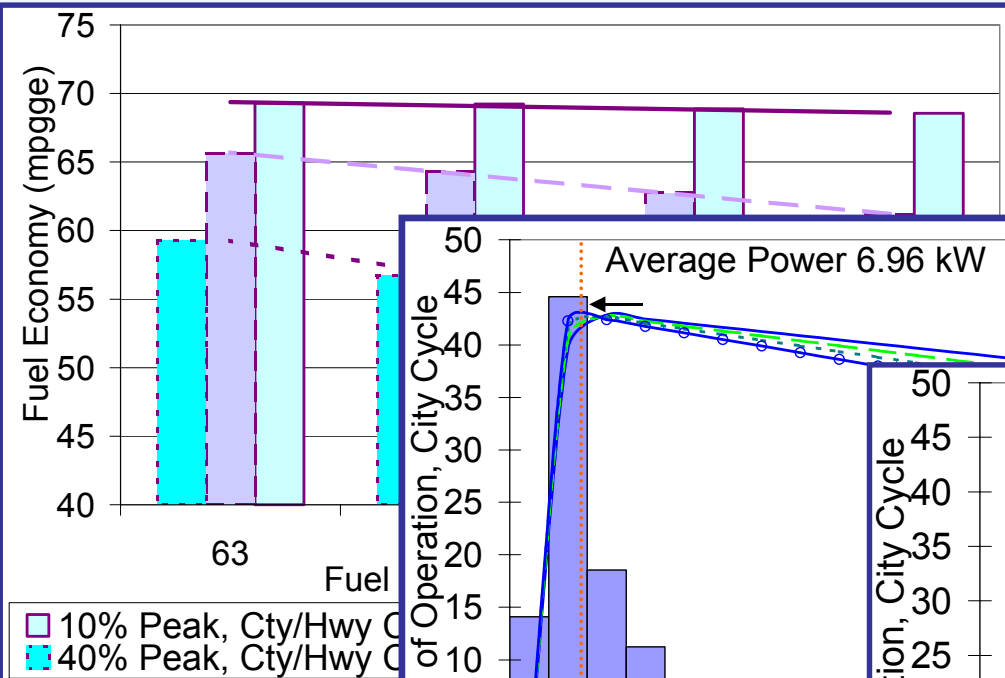
Drive Cycle Power Output Histogram Helps Explain 10% Peak Power Benefits



- 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}

Vehicle with fuel cell only

The Benefit of Downsizing Tied to Fuel Cell Efficiency Characteristics



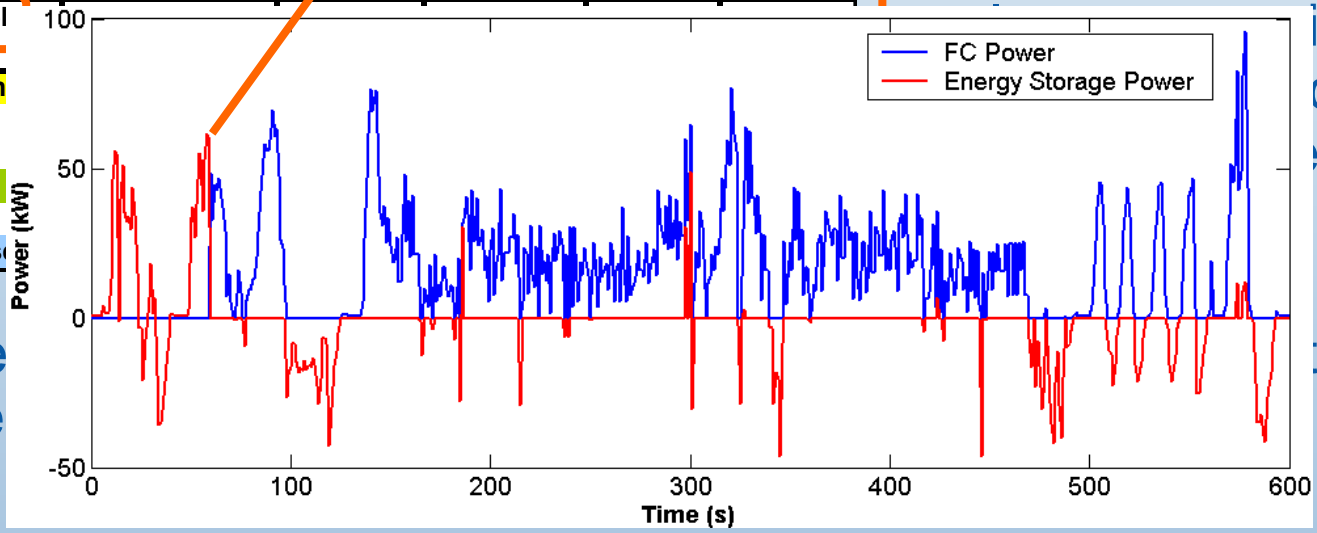
What kind of Energy Storage is Required for Minimum Supplementation of a Downsized FC?

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 Performance	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 Performance	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

- Minimal ESS roles require high power and relatively little energy.
- ESS needs significantly

63 kW Fuel Cell
Today's Performance
2010 Target
"Ideal" 63 kW Case



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Additional Fuel Cell Hybridization Work to be presented:

**Objective: Evaluate Energy Storage System (ESS)
Requirements for a Fuel Cell Vehicle
with an Aggressively controlled ESS**

Using 2010+ Vehicle and Fuel Cell Assumptions

@



Light-Duty Hybridization Summary

- Downsizing the fuel cell in a vehicle provides improvement in:
 - Fuel economy, especially for FC systems with peak efficiency as a high percentage of net power
 - Fuel cell costs
 - Has little to no affect on ESS sizing [in minimal control case].

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DOE's Advanced Heavy Hybrid Propulsion Systems Program



Program Goals:

- Next generation technologies for commercially viable heavy-hybrid vehicles
- 100% Increase in fuel efficiency (target)
- Meet EPA's 2007 emissions standards

Phase I - Underway

- 3-year Research & Development Effort (FY 03-05)
- 50%-50% Government / Industry Cost-Share
- Design, Develop, Characterize, and Show Feasibility of Energy & Fuel Saving Heavy Vehicle Hybrid Propulsion Technologies
- Targeting Wide Range of Class 3 – Class 8 Heavy Vehicles

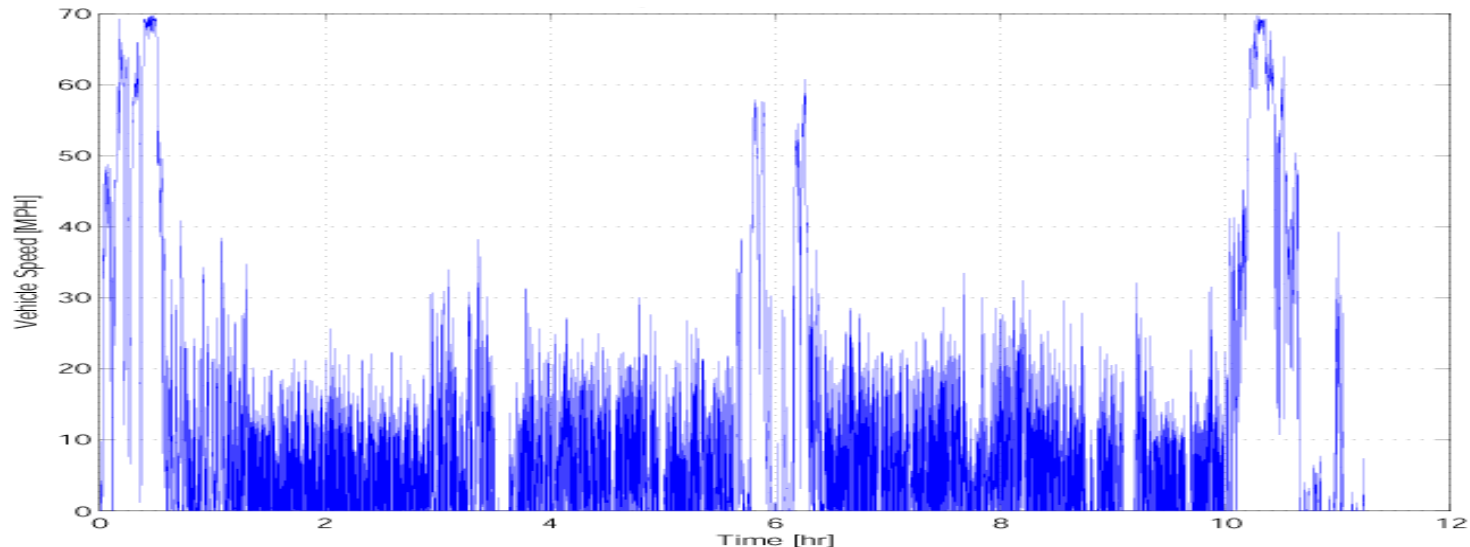
EDLC's may be Well Suited to some Heavy Vehicle Applications



Demanding Vehicle Requirements:

- 8 to 12 hours of continuous stop-and-go duty cycle
- 34,500 lb vehicle, 17,000 lb payload
- Fully loaded highway speeds / grades
- Much higher traction / regen power requirements
- Durability, reliability, and cost are critical fleet concerns

Actual Heavy Vehicle Duty Cycle with > 1000 starts/stops



AHHPS EDLC

System Development Activities



Vehicle Systems Modeling (FY04)

- Fuel economy prediction, system sensitivity, optimization

Technology Characterization (FY04)

- Review / down-select of available technologies

Reliability testing (FY05)

- Bench testing of 3-4 selected technologies

Thermal management (FY04 – FY05)

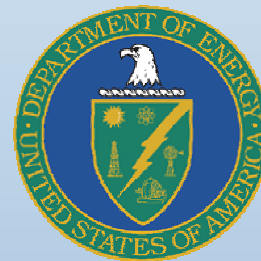
- Conjugate thermal / flow analysis of module thermal management

Model validation (FY04 – FY05)

- Module and thermal management system bench tests
- Chassis dynamometer and field testing of vehicle

Acknowledgements

- Sponsored by U.S. Department of Energy's Office of FreedomCAR and Vehicle Technologies.
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 - Vehicle Systems Program
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 - Cyrus Ashtiani
 - Franco Leonardi



www.ctts.nrel.gov/BTM
www.ctts.nrel.gov/analysis