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Innovation for Our Energy Future
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Office of Energy Efficiency & Renewable Energy

EDLC Modeling and Integration for Hybrid Electric Vehicles

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Presented to
"*The 14th International Seminar on Double Layer Capacitors and Hybrid Energy Storage Devices*"
Deerfield Beach, Florida
December 6-8, 2004

Objectives of This Presentation

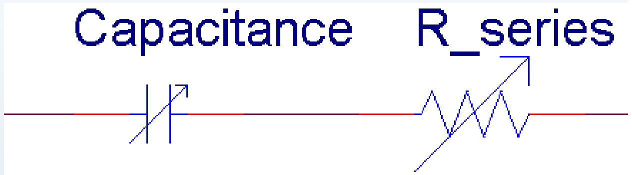
- Update on NREL's EDLC modeling and EDLC automated analysis program
- Update on EDLC roles in hybrid vehicles
- Overview of Heavy Hybrid EDLC initiatives

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

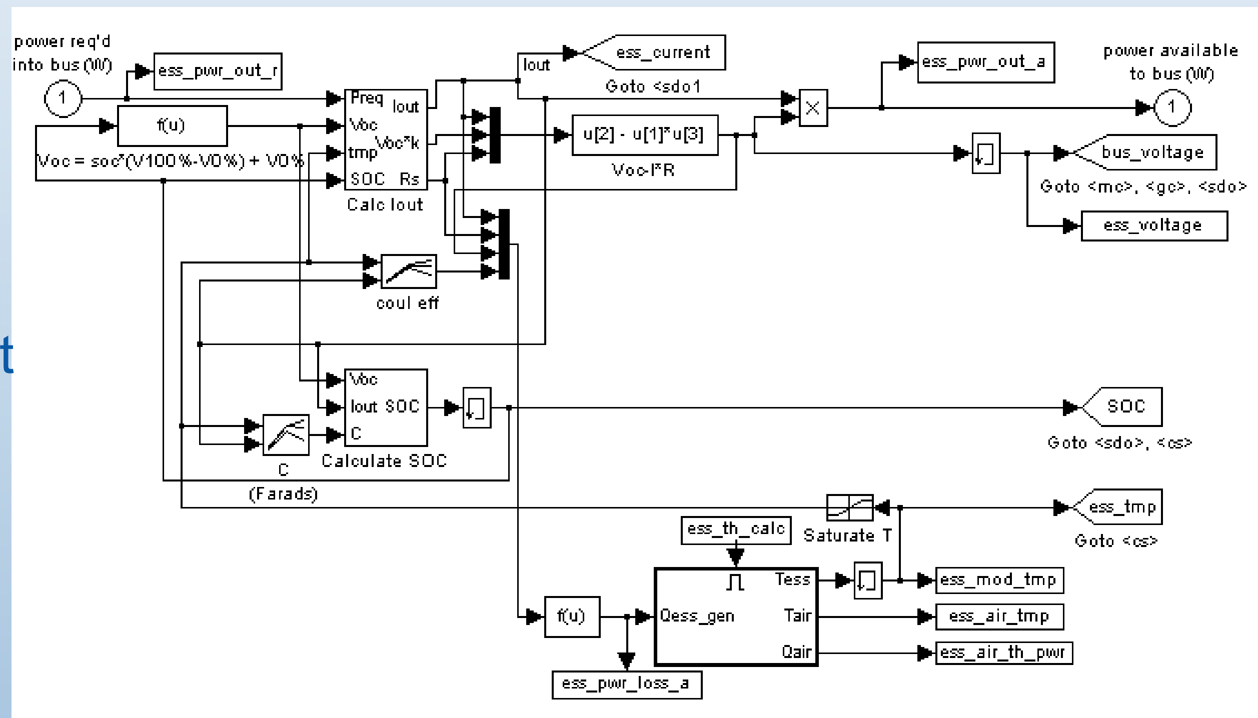
Equivalent Circuit Capacitor Model



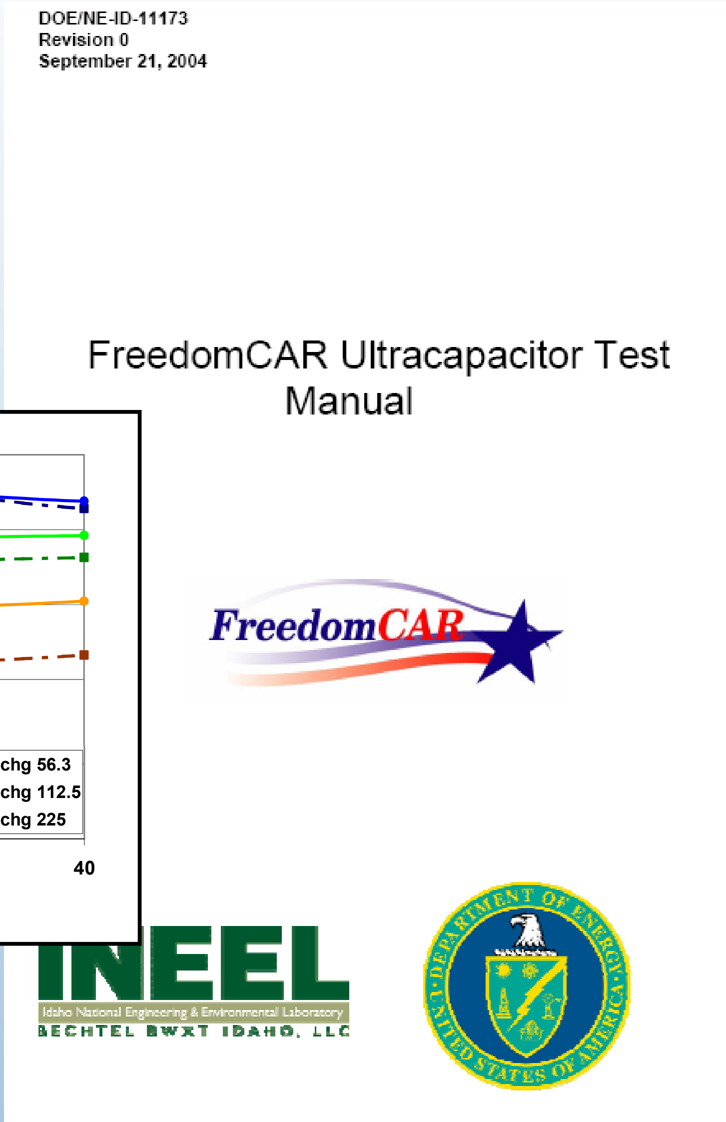
- C - mapped as a function of temperature & current
- R - mapped as a function of temperature & current

Additional Attributes

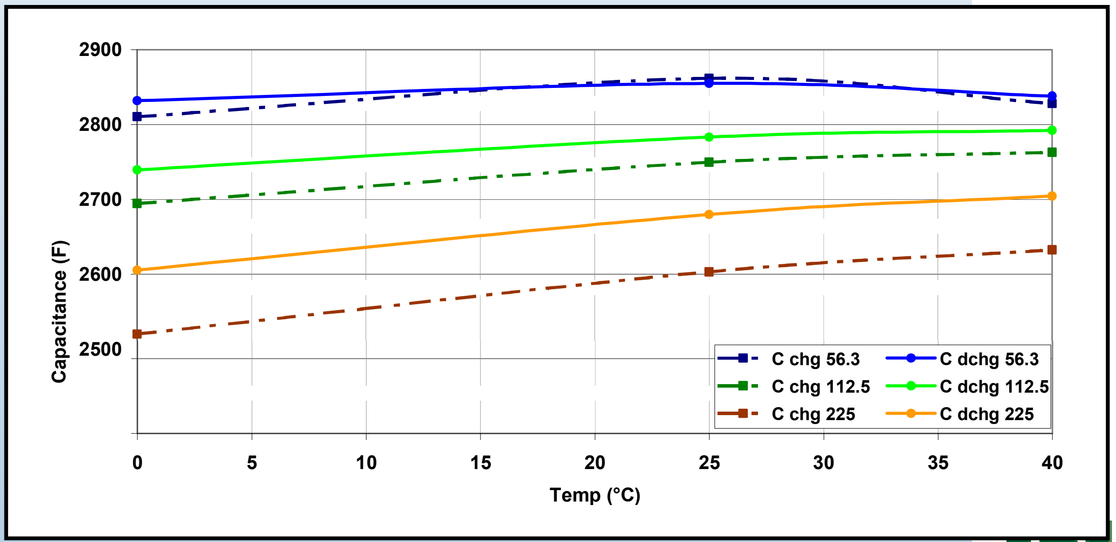
- Coulombic efficiency accounted for
- Thermal model: temperature rise predictions & thermostat temperature control
- Maximum power limitations
- Series and Parallel configurations



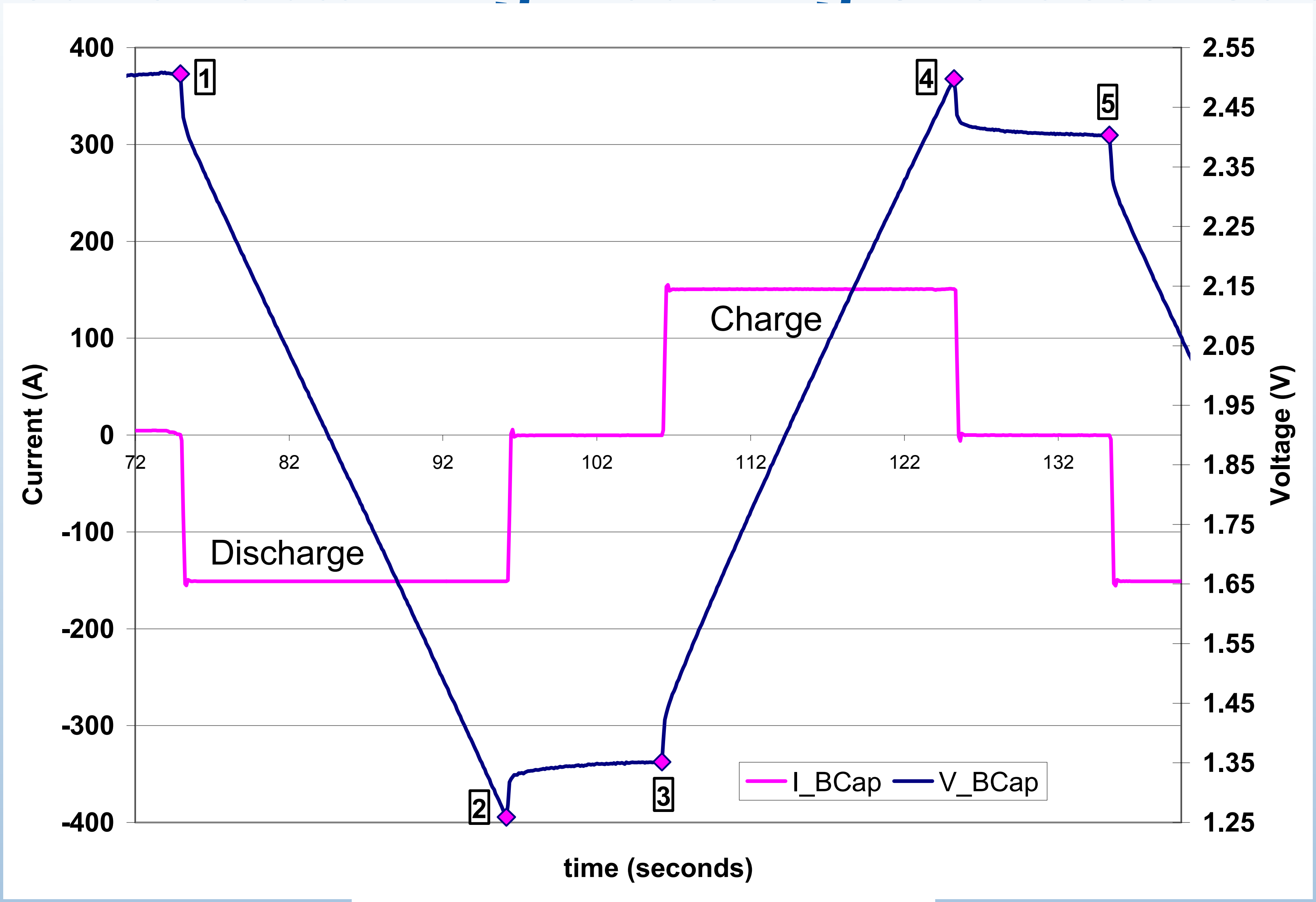
Most of NREL's Model Data is Generated from Standard Test Characterizations


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

FreedomCAR Ultracapacitor Test Manual



There are Multiple Calculation Techniques used for obtaining Modeling Characteristics

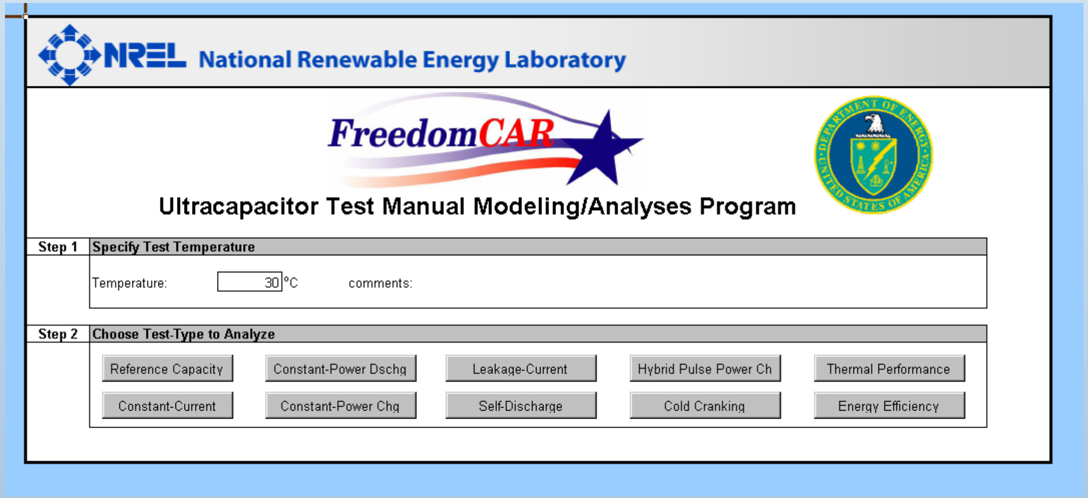


Automated Analysis Program

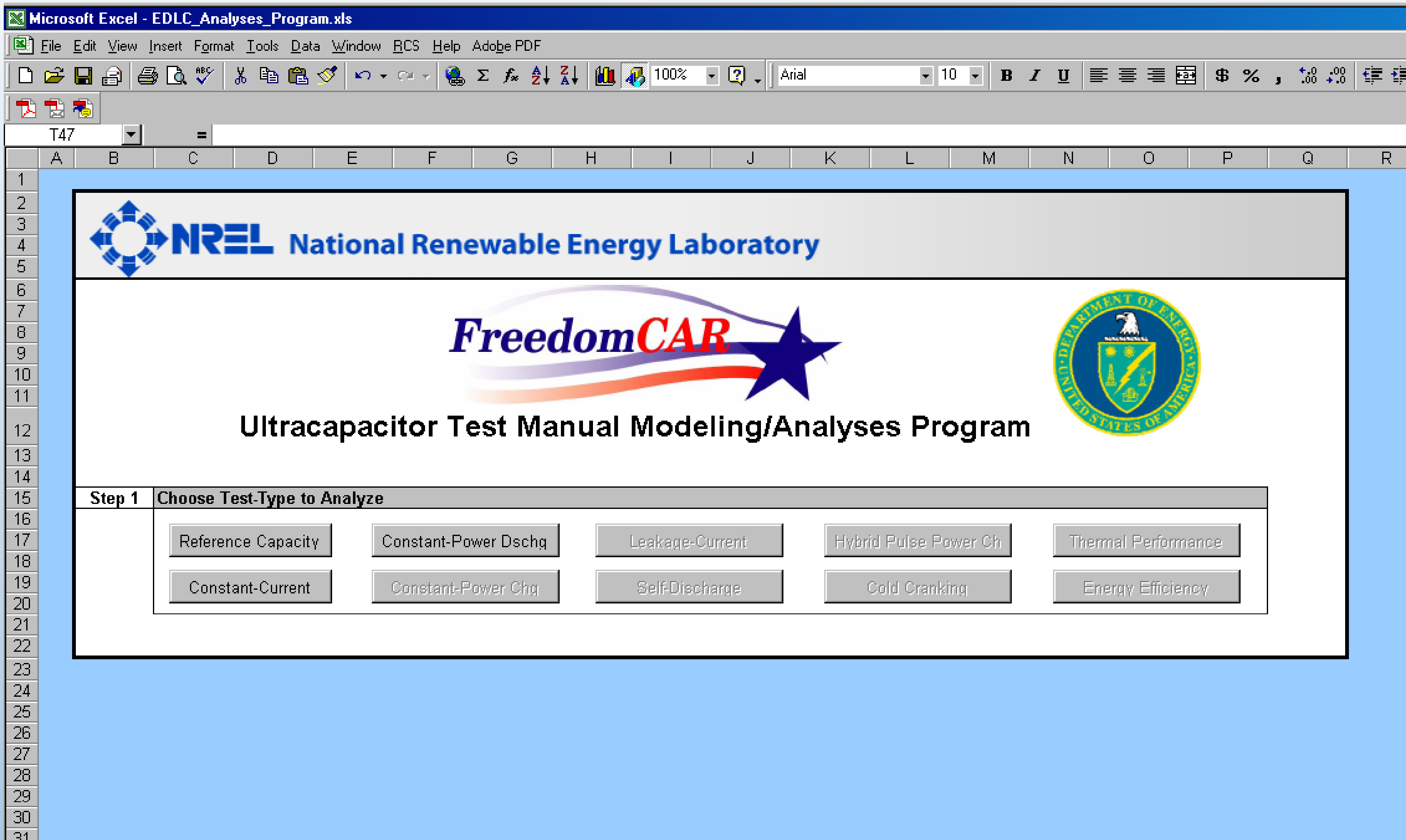
Objective:

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

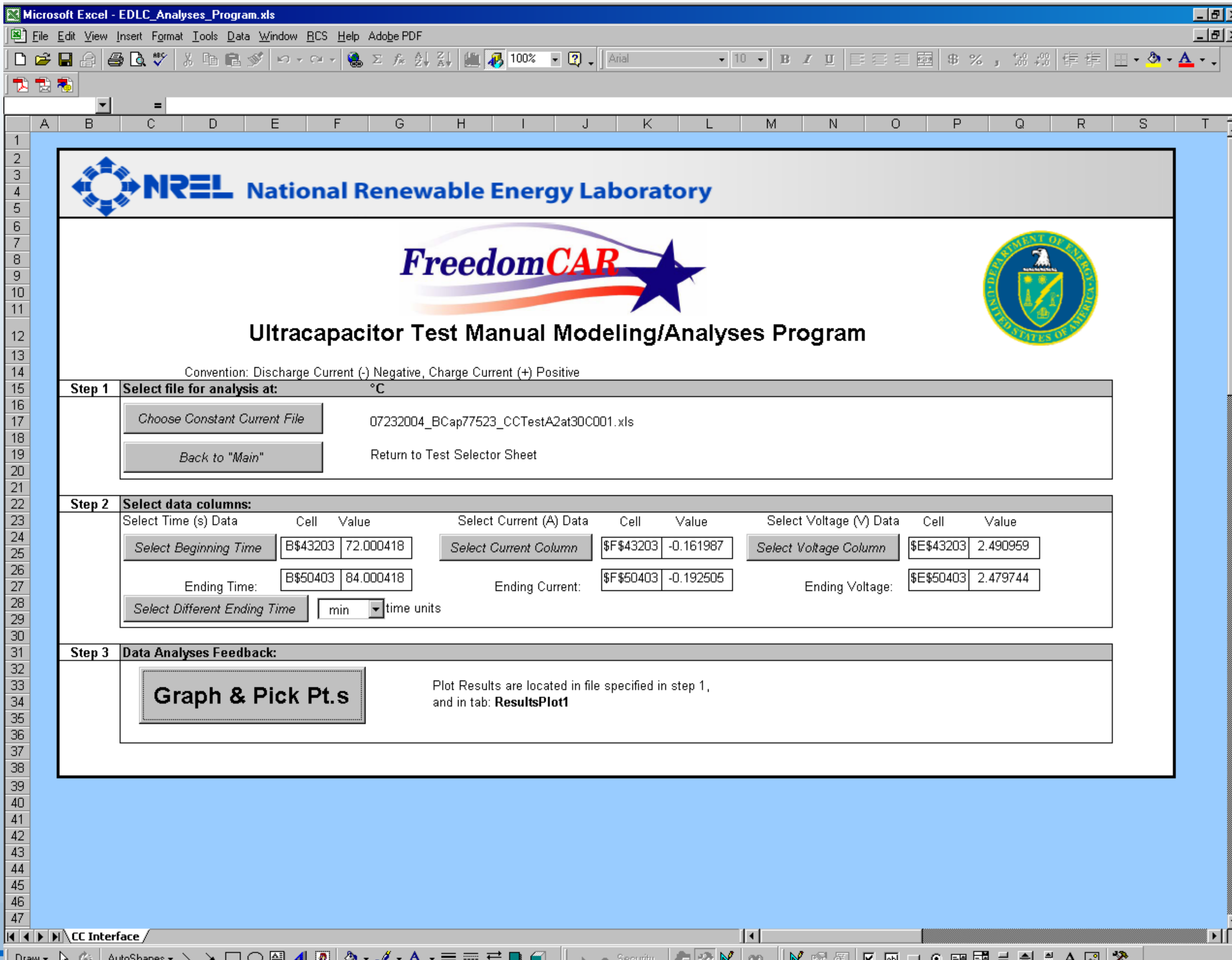
Demonstration:



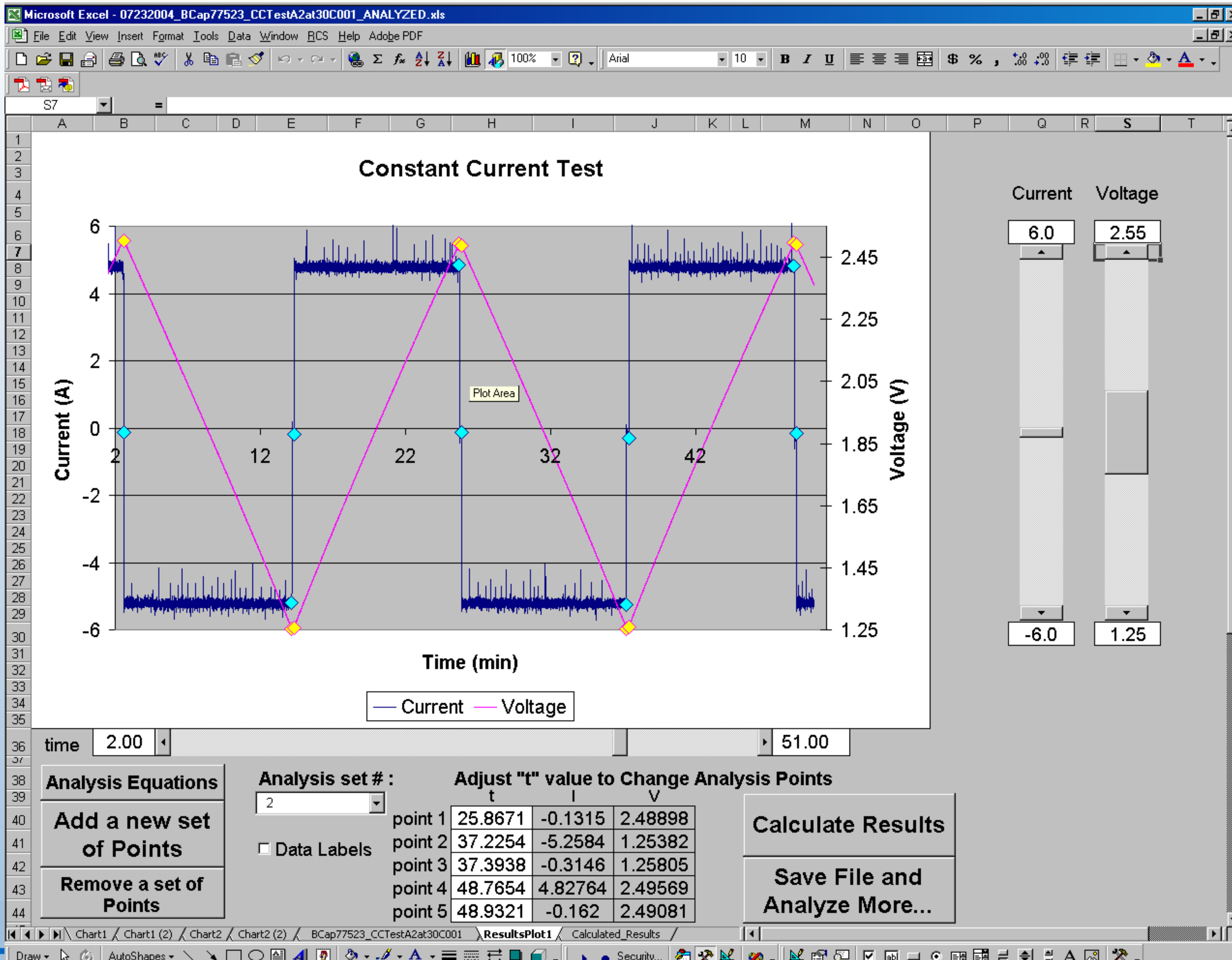
1st Screen – Choose Test to Analyze



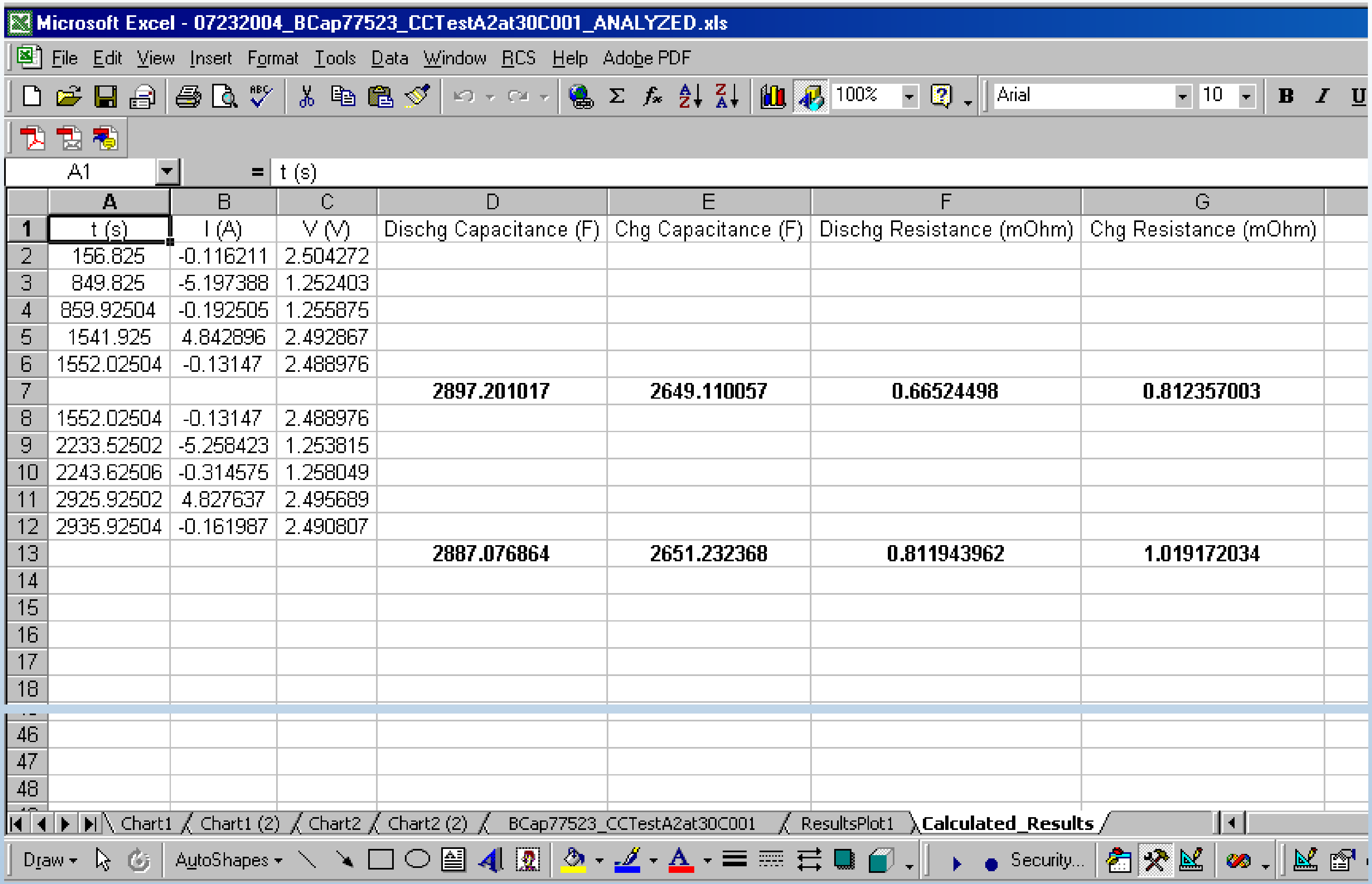
2nd Screen – Choosing Data



3rd Screen – Analyzing Data (Self Documenting)



4th Screen – Analysis Results



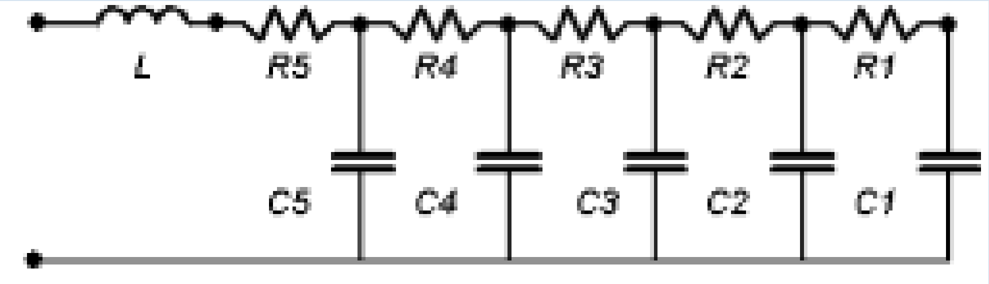
	A	B	C	D	E	F	G
1	t (s)	I (A)	V (V)	Dischg Capacitance (F)	Chg Capacitance (F)	Dischg Resistance (mOhm)	Chg Resistance (mOhm)
2	156.825	-0.116211	2.504272				
3	849.825	-5.197388	1.252403				
4	859.92504	-0.192505	1.255875				
5	1541.925	4.842896	2.492867				
6	1552.02504	-0.13147	2.488976				
7				**2897.201017**	**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**
14							
15							
16							
17							
18							
46							
47							
48							

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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  - Specific Fuel Cell ESS Requirements
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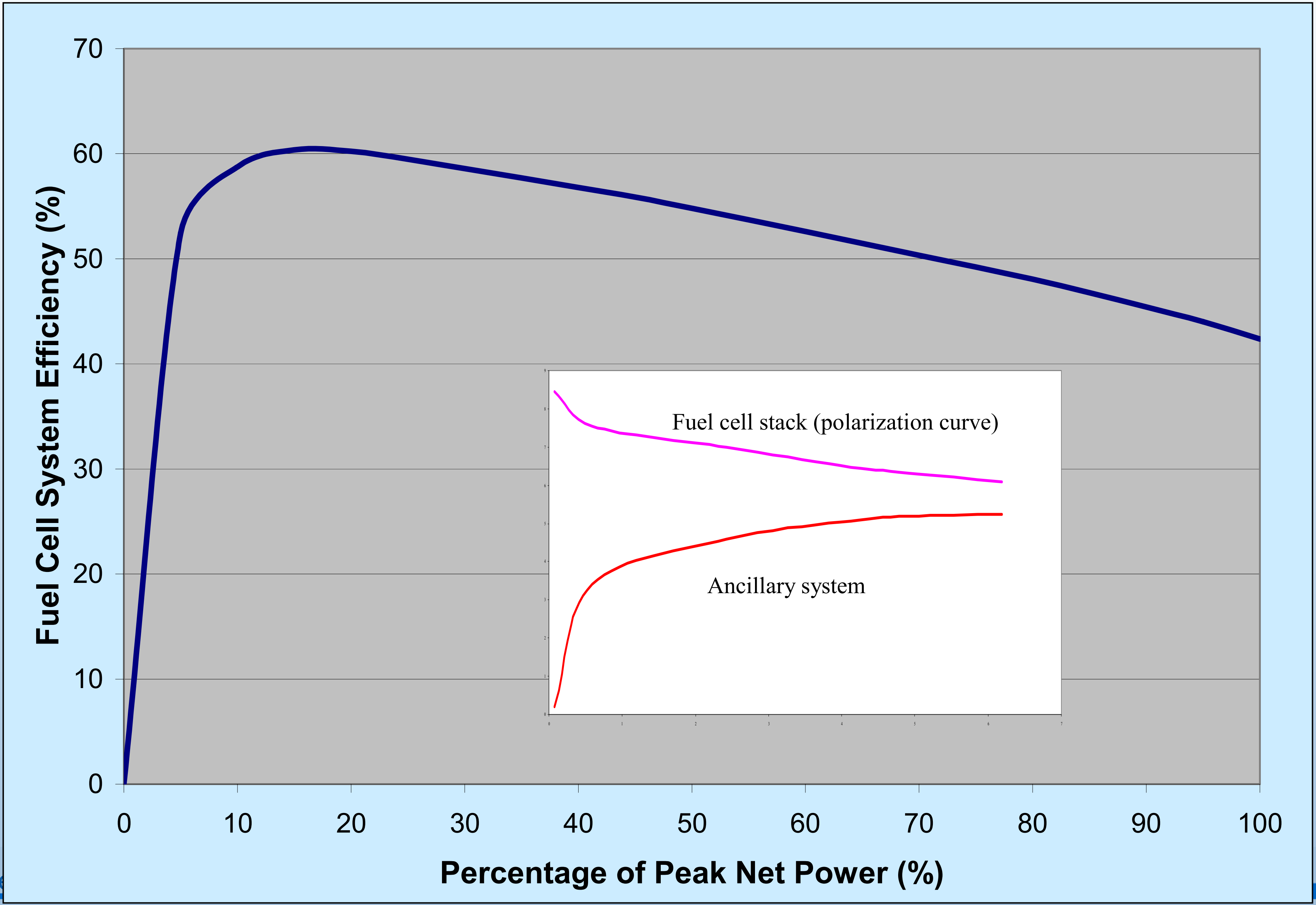
There are Various Vehicle Applications/Needs for Energy Storage

Addressing requirements of energy storage in vehicles with different strategies

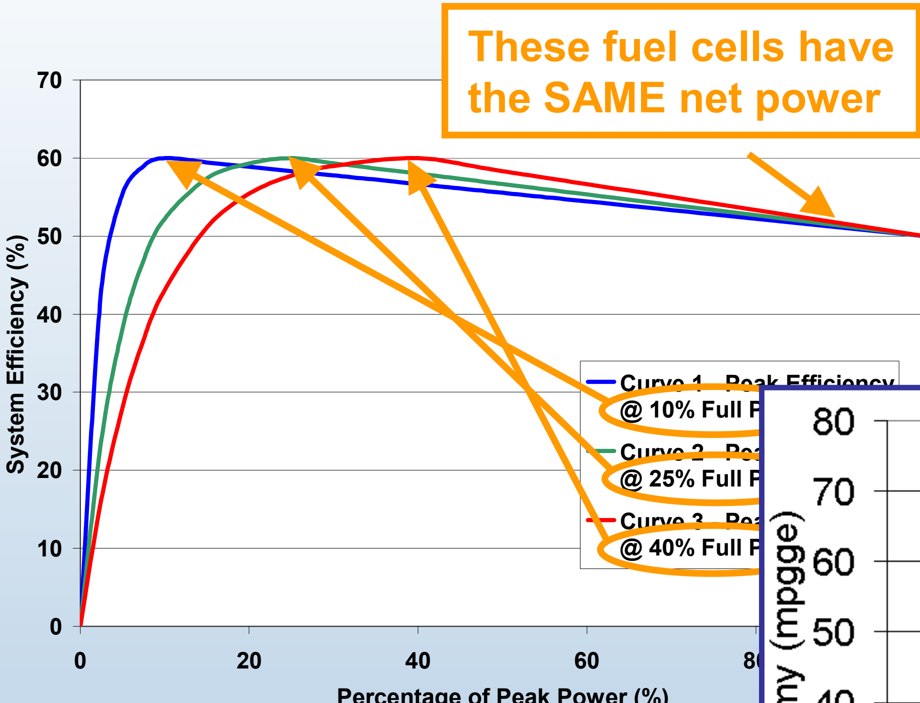
42-Volt (Start/Stop, Mild HEV, Power-assist HEV)	
Power Assist HEV (Low Power, High Power)	
Fuel Cell Hybrids (Power)	
Battery EV	

This Presentation's Focus

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

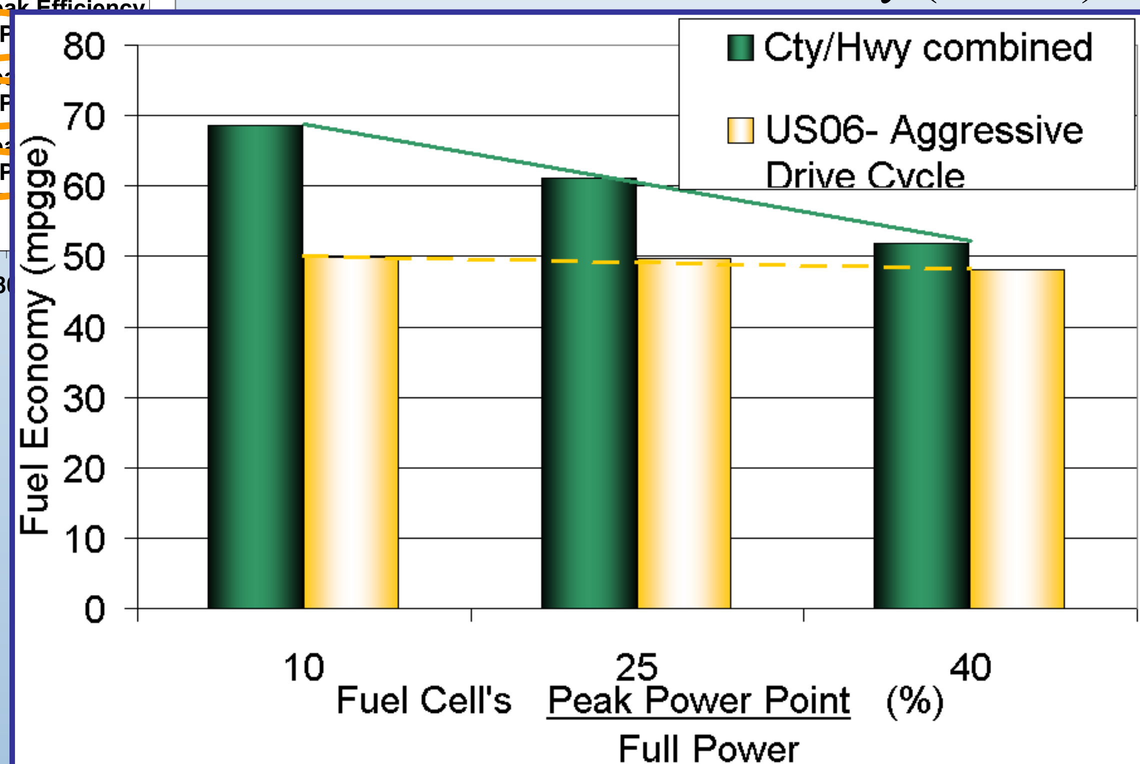


Fuel Economy is Affected by the Position of FC Peak Efficiency

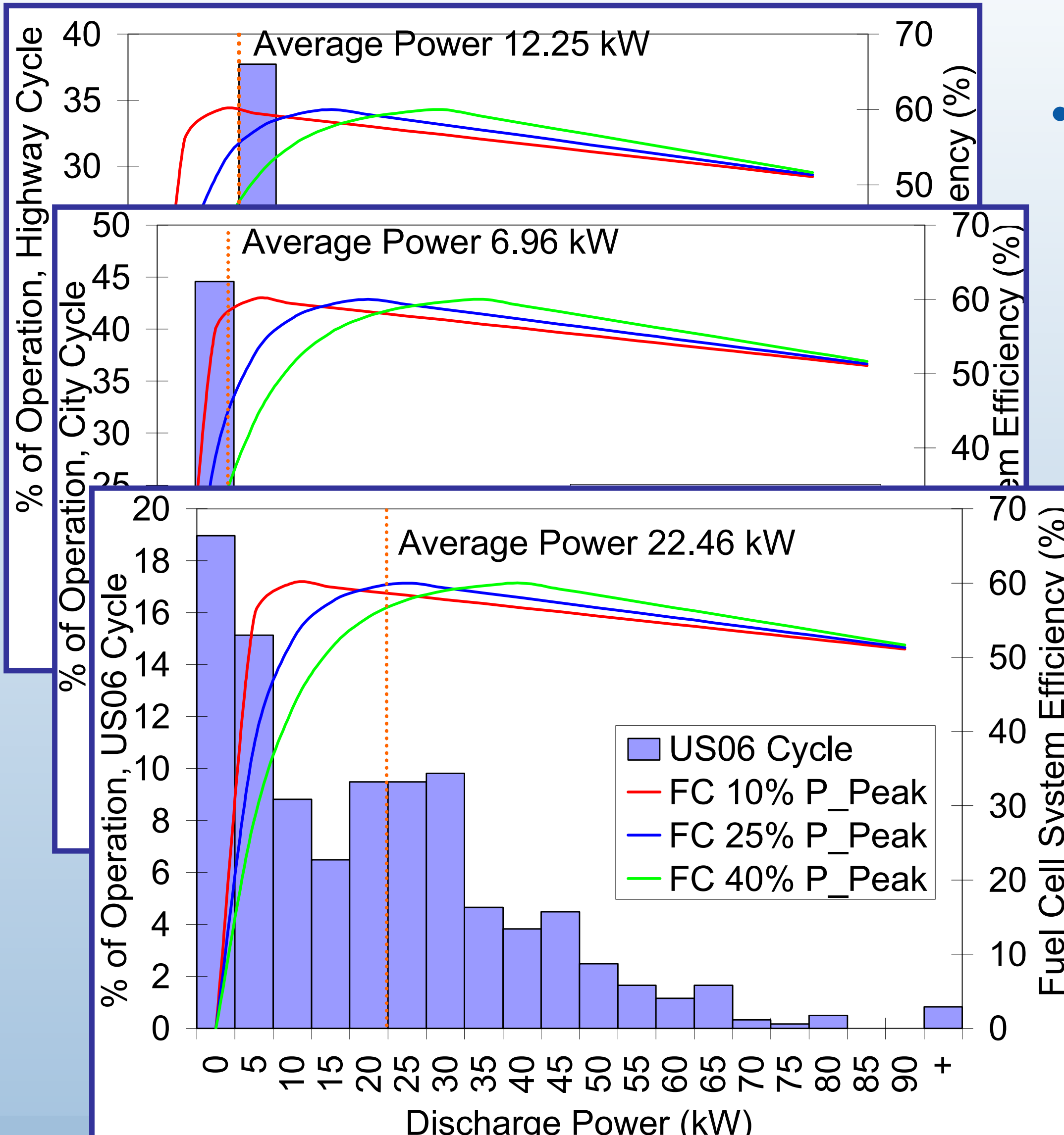


Theoretical FC efficiency curves are based on DOE Targets

Vehicle with fuel cell only (96 kW)



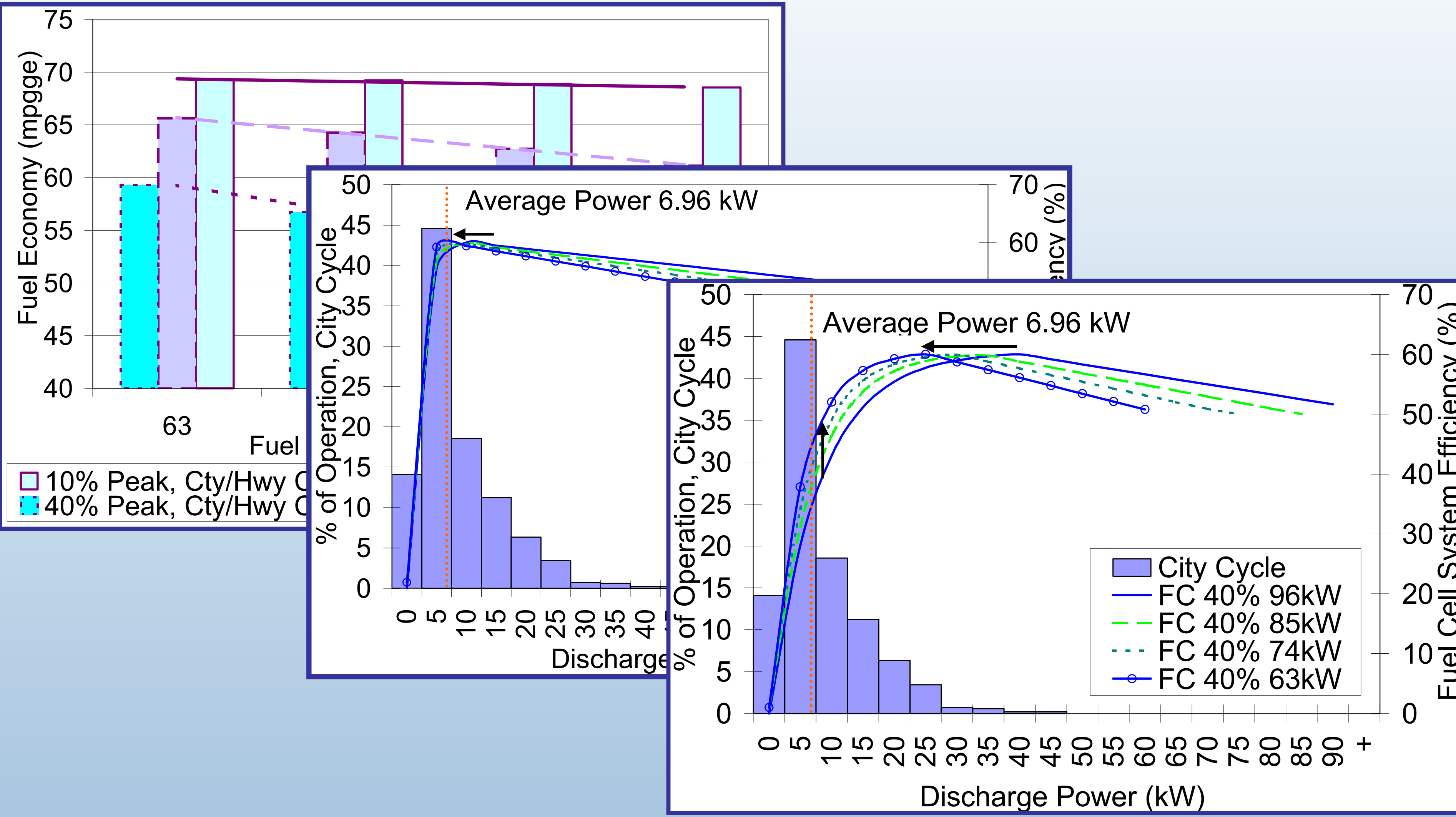
Drive Cycle Power Output Histogram Helps Explain 10% Peak Power Benefits



- 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

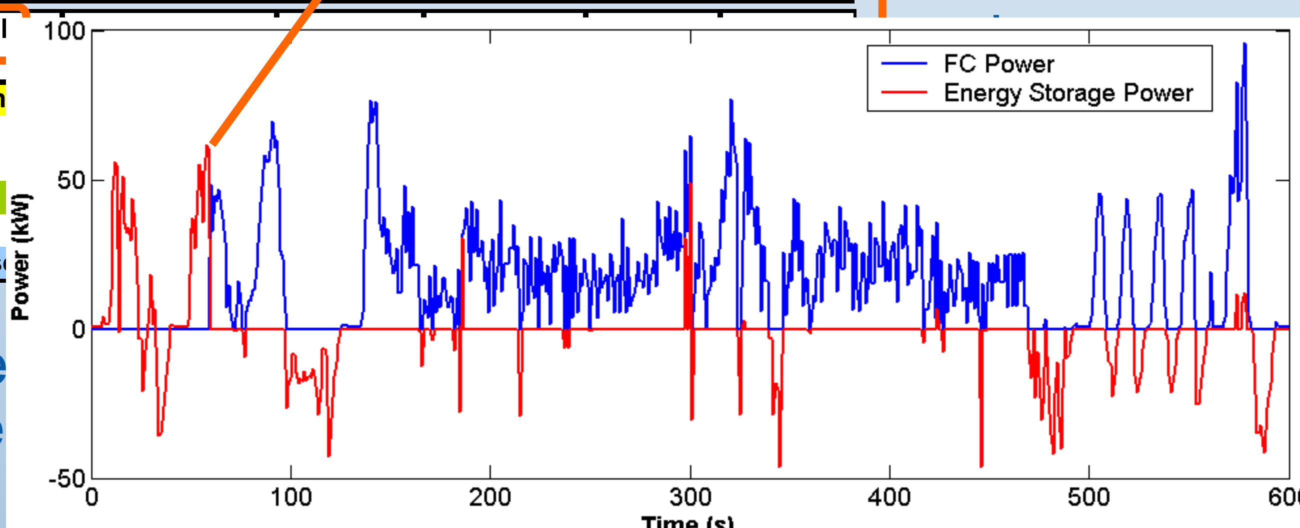


What kind of Energy Storage is Required for Minimum Supplementation of a Downsized FC?

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 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 Cel
Today's Perfoman
2010 Target
"Ideal" 63 kW Cas



- Minimal ESS roles require high power and relatively little energy.
- ESS needs significantly ... in "2010 ... cell ... e.
- The ... tle to no affe...

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

@

EVS 21
MONACO
2 - 6 April 2005

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

AH²PS

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

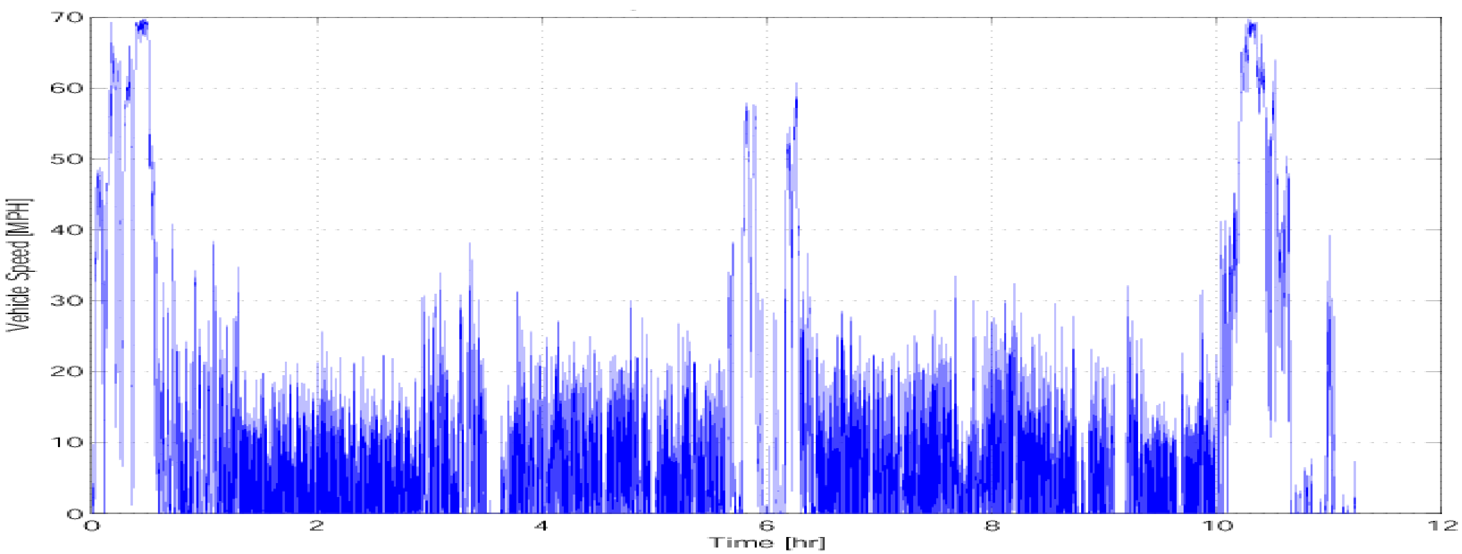
- 3-year Research & Development Effort (FY 03-05)
- 50%-50% Government / Industry Cost-Share
- Design, Develop, Characterize, and Show Feasibility of Energy & Fuel Saving Heavy Vehicle Hybrid Propulsion Technologies
- Targeting Wide Range of Class 3 – Class 8 Heavy Vehicles

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.
  - Energy Storage Program
  - Vehicle Systems Program
- We appreciate the support and technical guidance from USABC/FreedomCAR ES Technical Team
  - Harshad Tataria
  - Cyrus Ashtiani
  - Franco Leonardi

www.ctts.nrel.gov/BTM

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