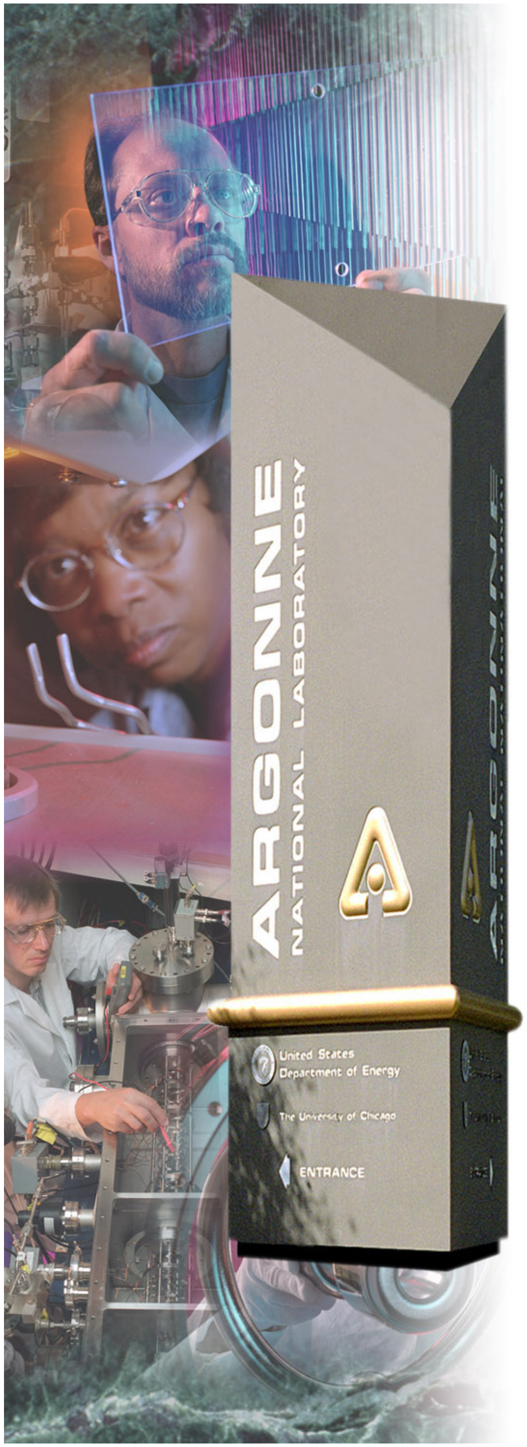

Optimization of Fuel Cell Vehicle Fuel Economy

Sponsored by Lee Slezak (U.S. DOE)

Aymeric Rousseau
Phil Sharer
Rajesh Ahluwalia
Argonne National Laboratory

Argonne National Laboratory

Office of Science
U.S. Department of Energy

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Fuel Cell Vehicle Fuel Economy Optimization

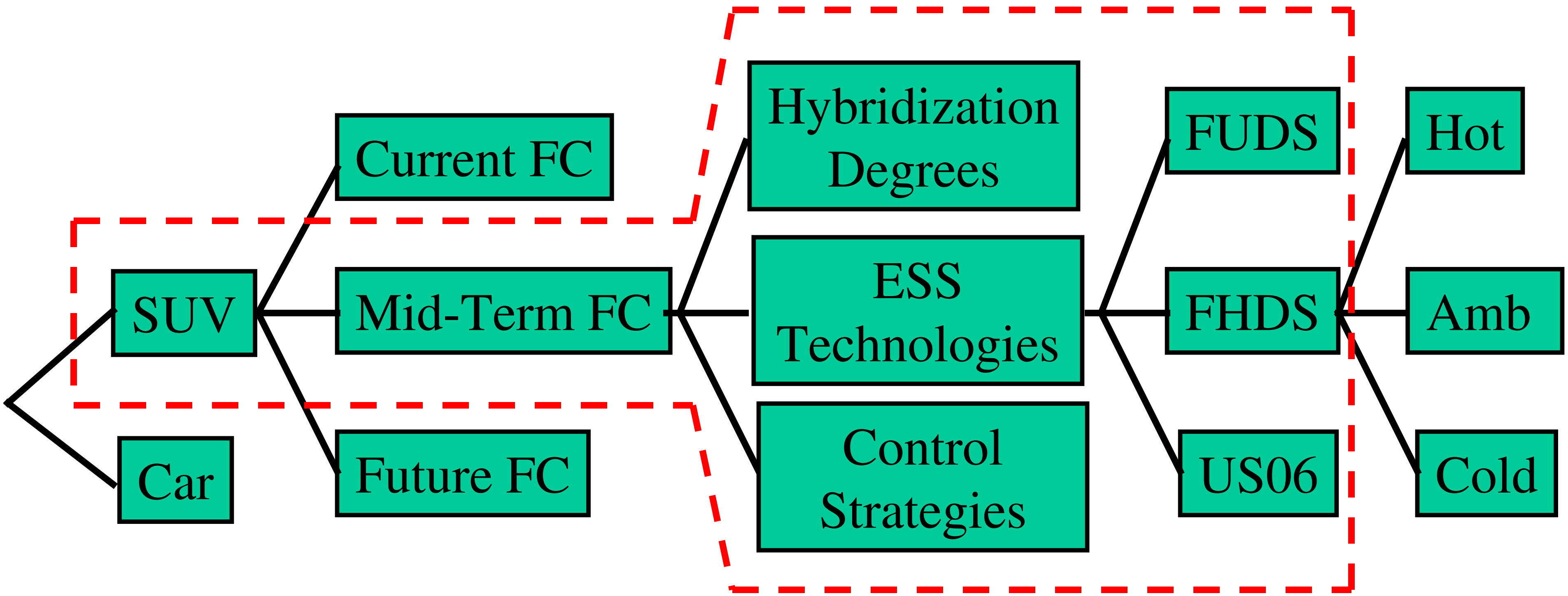
- **Study Scope**
- **Hybridization Degree**
- **Energy Storage Technology**
- **Control Strategy**
- **Perspectives**

FreedomCAR FCV Energy Storage Proposed Goals Spring 2003

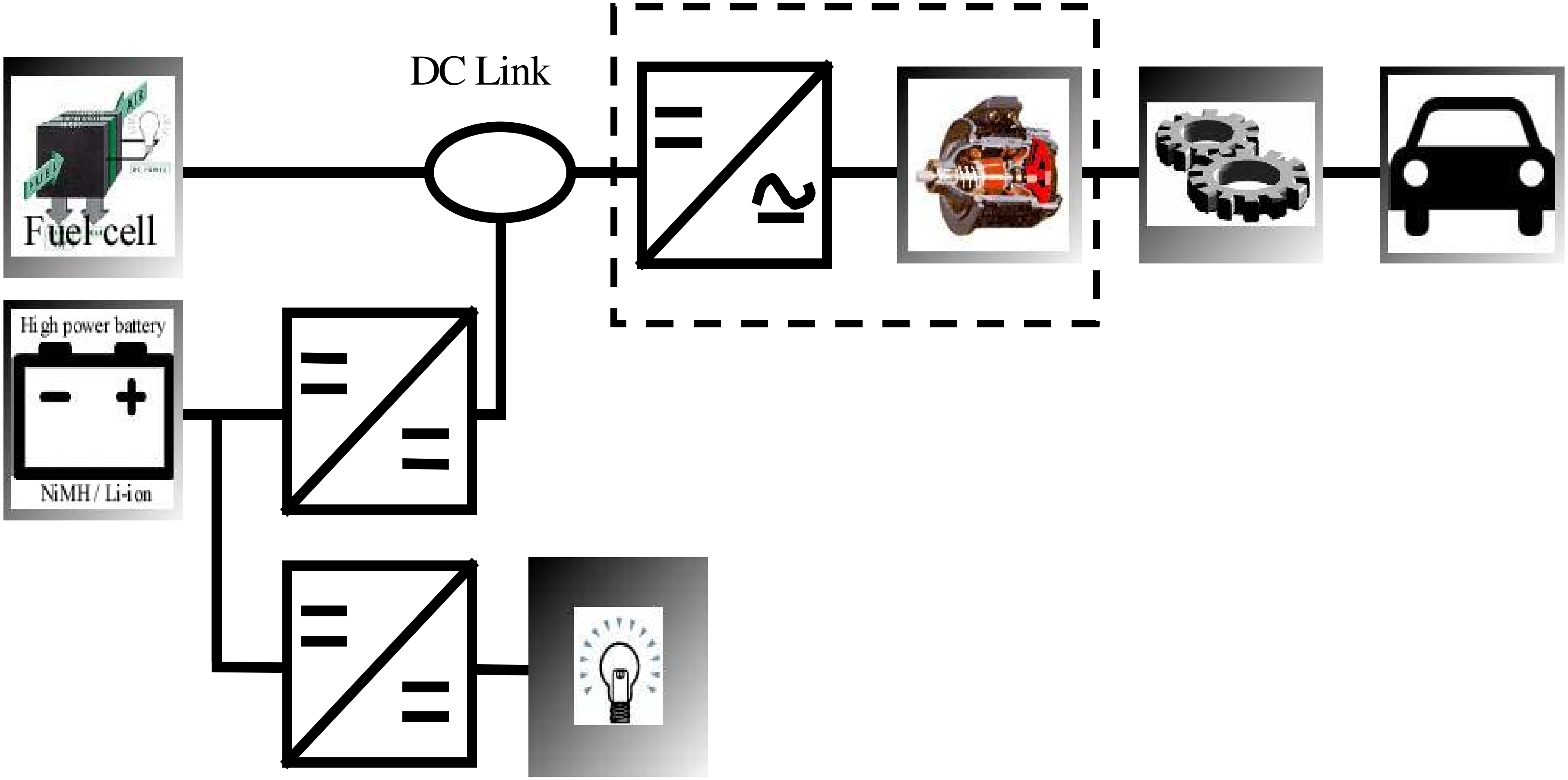
UNITED STATES ADVANCED BATTERY CONSORTIUM

FreedomCAR Goals Characteristics	Units	Low Power Energy Storage	High Power Energy Storage
Pulse Discharge Power (10s)	kW	25	50
Max Regen Pulse (5s)	kW	30	60
Total Available Energy	kWh	1.5	3
Round Trip Efficiency	%	>90	>90
Cycle Life	Cyc.	TBD (15 year life equiv.)	TBD (15 year life equiv.)
Cold-start at -30°C (TBD kW for TBD min.)	kW	5	5
Calendar Life	Yrs	15	15
Max Weight	kg	40	65
Max Volume	liters	32	50
Production Price @ 100k units/yr	$	500	1,000
Maximum Operating Voltage	Vdc	</= 440 max	</= 440 max
Minimum Operating Voltage	Vdc	>/= 0.5 x Vmax	>/= 0.5 x Vmax
Maximum Self Discharge	Wh/d	50	50
Operating Temperature	°C	-30 to +52	-30 to +52
Survival Temperature	°C	-46 to +66	-46 to +66

Structure of the Study



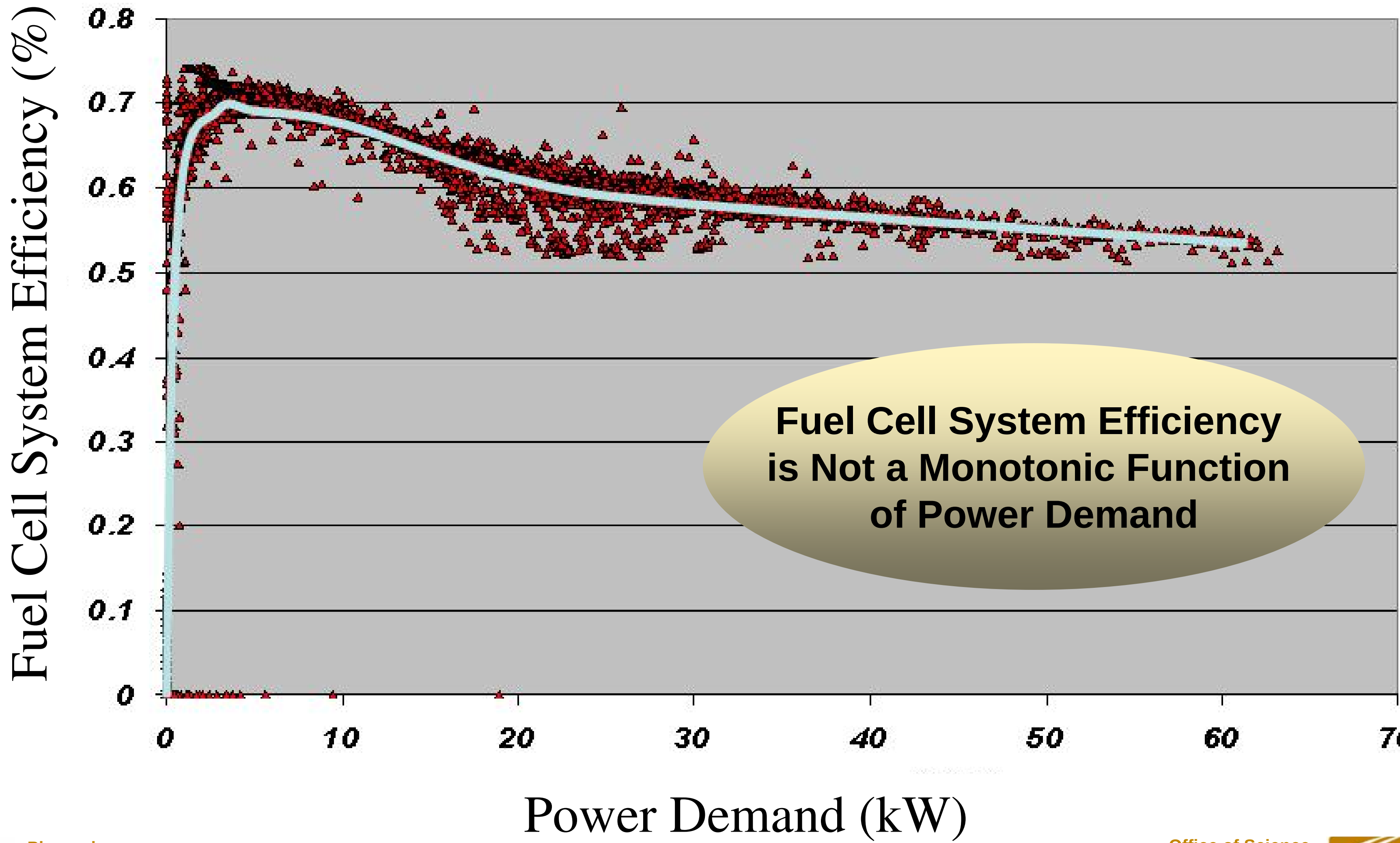
Fuel Cell HEV Configuration



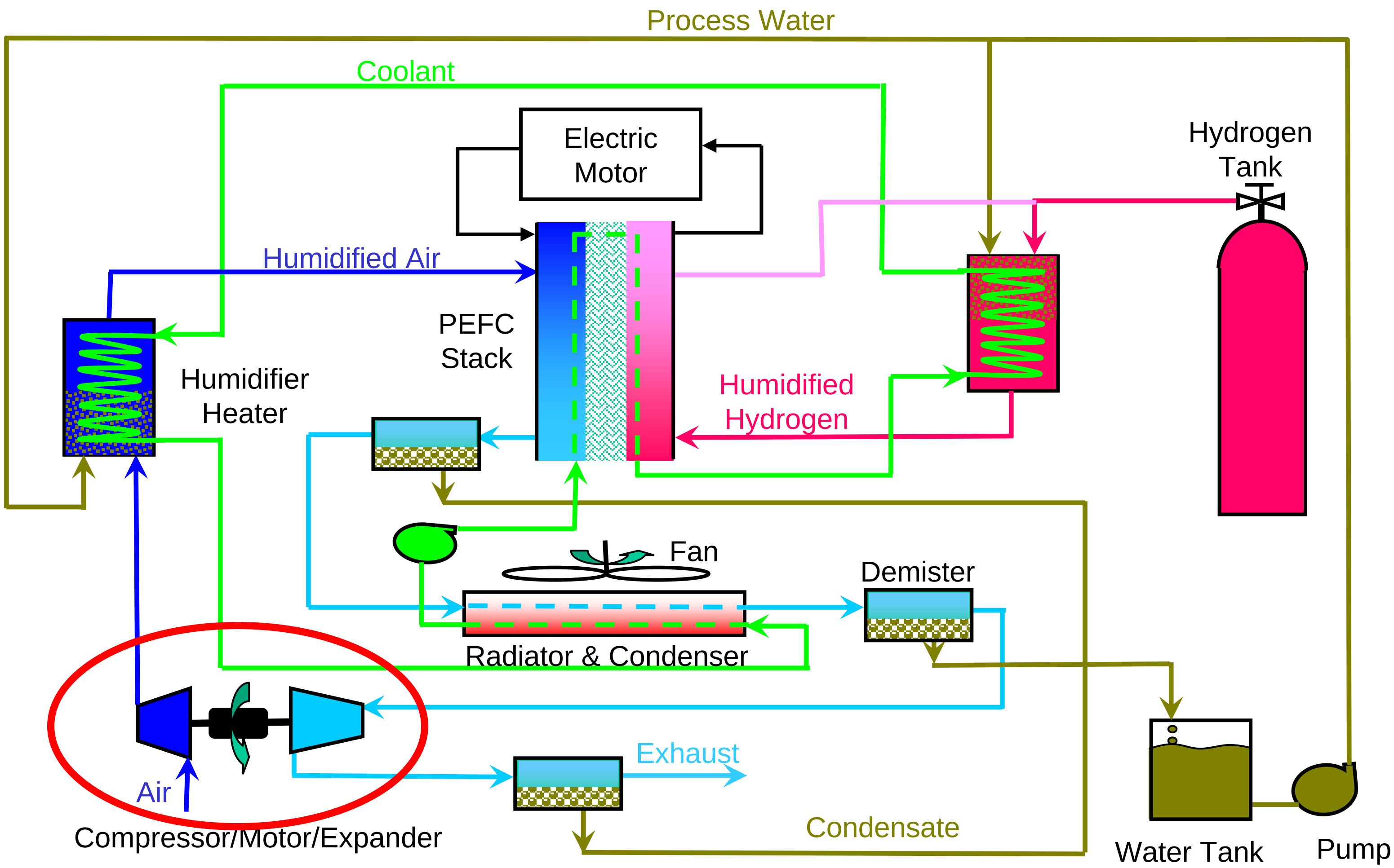
Major Assumptions

- **Vehicle and Performance**
  - Mid-size SUV (Explorer, Durango, Blazer)
  - Target 0-60 mph acceleration in 10.2 s
  - 55 mph at grade of 6.5% continuous (a least 20 minutes)
  - Top speed of 100 mph
- **Fuel Cell System Requirements**
  - Fuel cell should be sized to provide a least power for top speed and grade performance
  - FCS must have 1-s transient response time for 10% to 90% power.
  - FCS should reach maximum power in 15 s for cold start from 20C ambient temperature and in 30 s for cold start from -20C ambient temperature
- **Power Requirements (based on PSAT simulations)**
  - 160kW peak power for 0-60 mph acceleration
  - Minimum fuel cell power of 80kW for achieving speed at 6.5% grade
- **Default: tight SOC control, lithium-ion, FUDS**

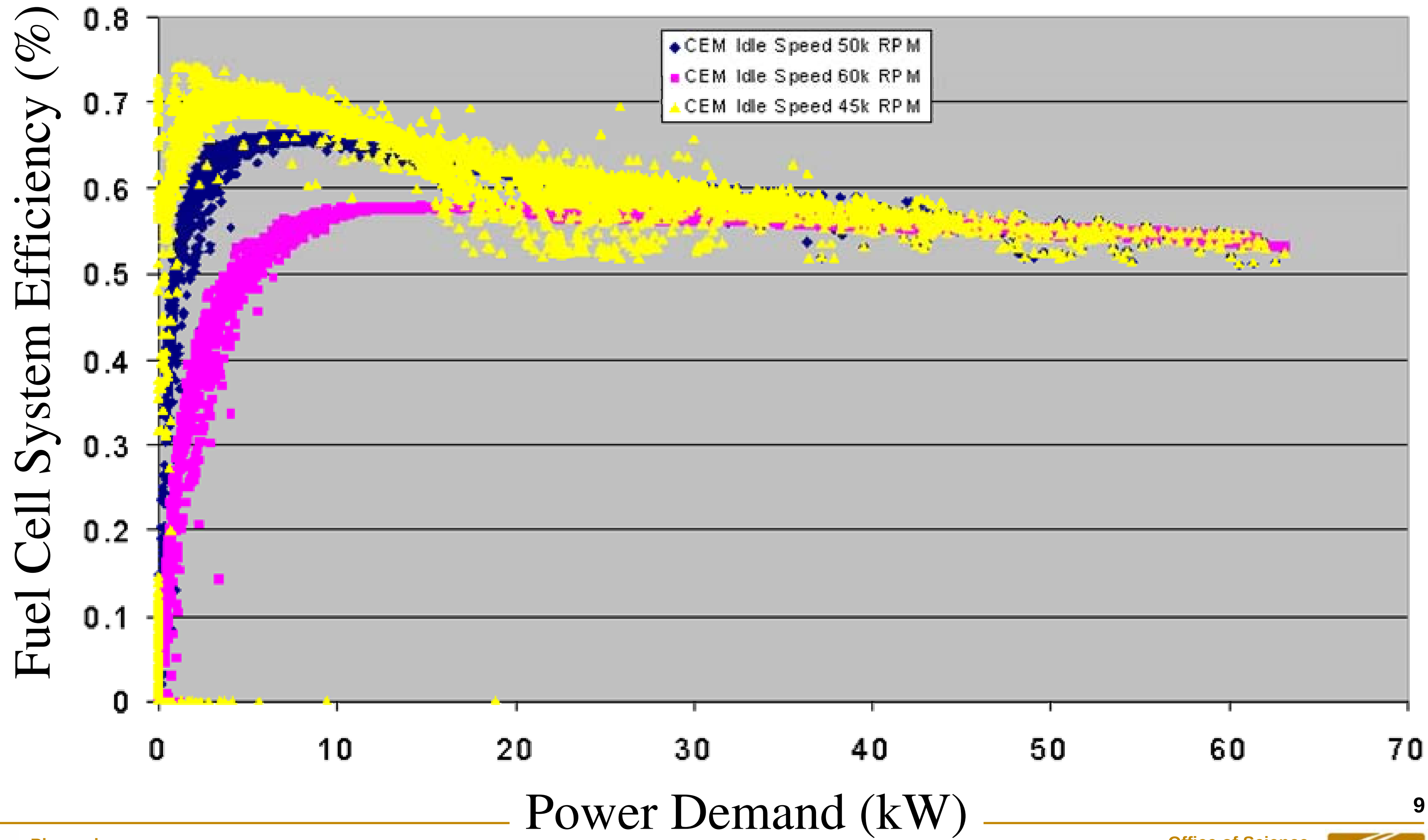
Detailed Models Necessary for Realistic Behavior



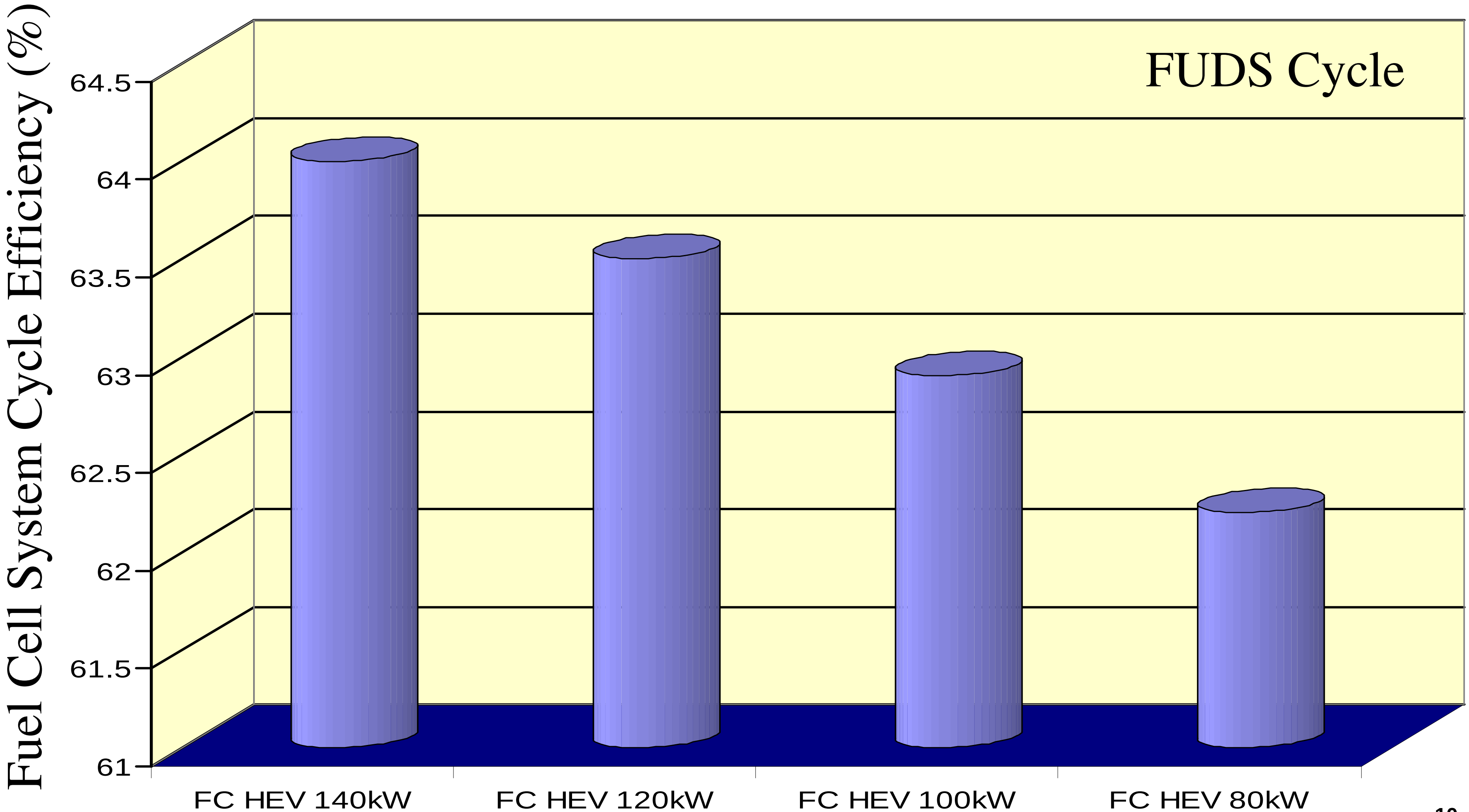
Design-Specific FC System Modeling Required to Assess Component Impact



Small Differences in Components Can Have Large System Implications



Design-Specific Models Required for Realistic FC Cycle Efficiency



Fuel Cell Vehicle Fuel Economy Optimization

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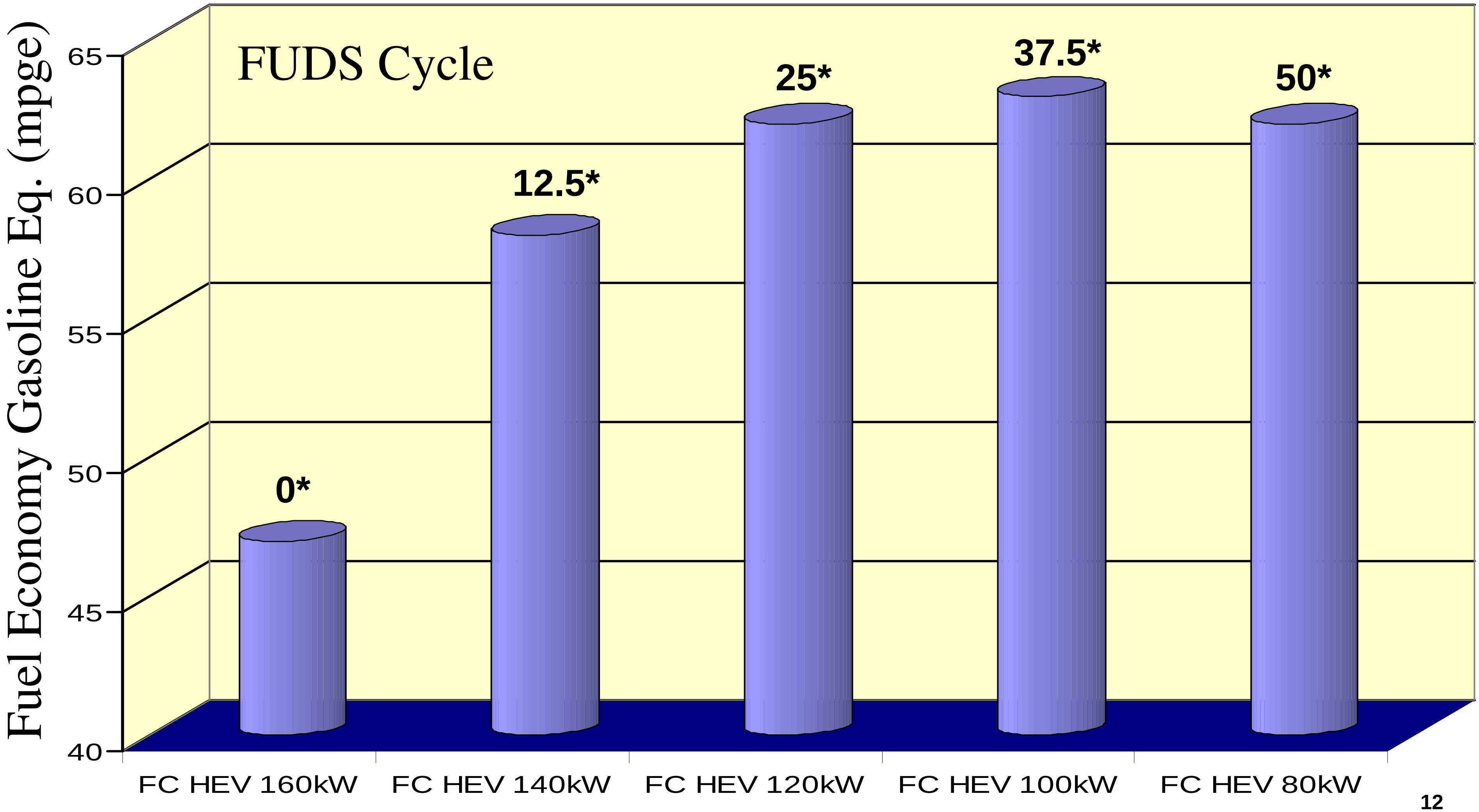
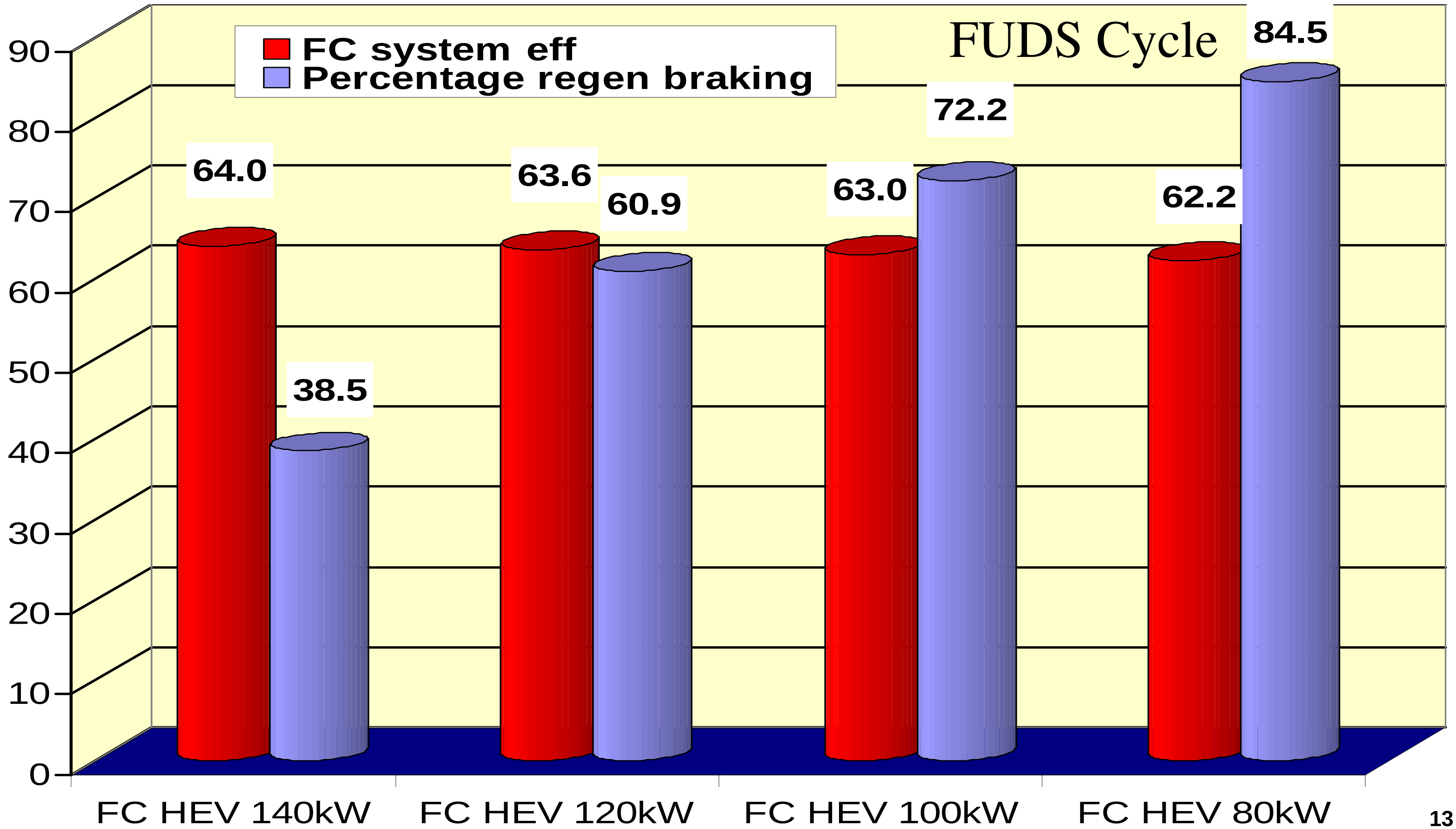
Increase in Hybridization Degree Can Lead to Decrease in Fuel Economy



*Hybridization Degree

Because the Regen Energy Increase is Nullified by the FC Efficiency Decrease



Hybridization Results

- **Key benefit of hybridization is fuel economy increase for FUDS thanks to regenerative braking**
- **Increasing the hybridization degree is interesting until the additional gain is nullified by the decrease in fuel cell efficiency**

→ For Li-ion, it is better to limit the ESS power to 40kW to preserve FC system efficiency while capturing most available regen energy

Fuel Cell Vehicle Fuel Economy Optimization

- Study Scope
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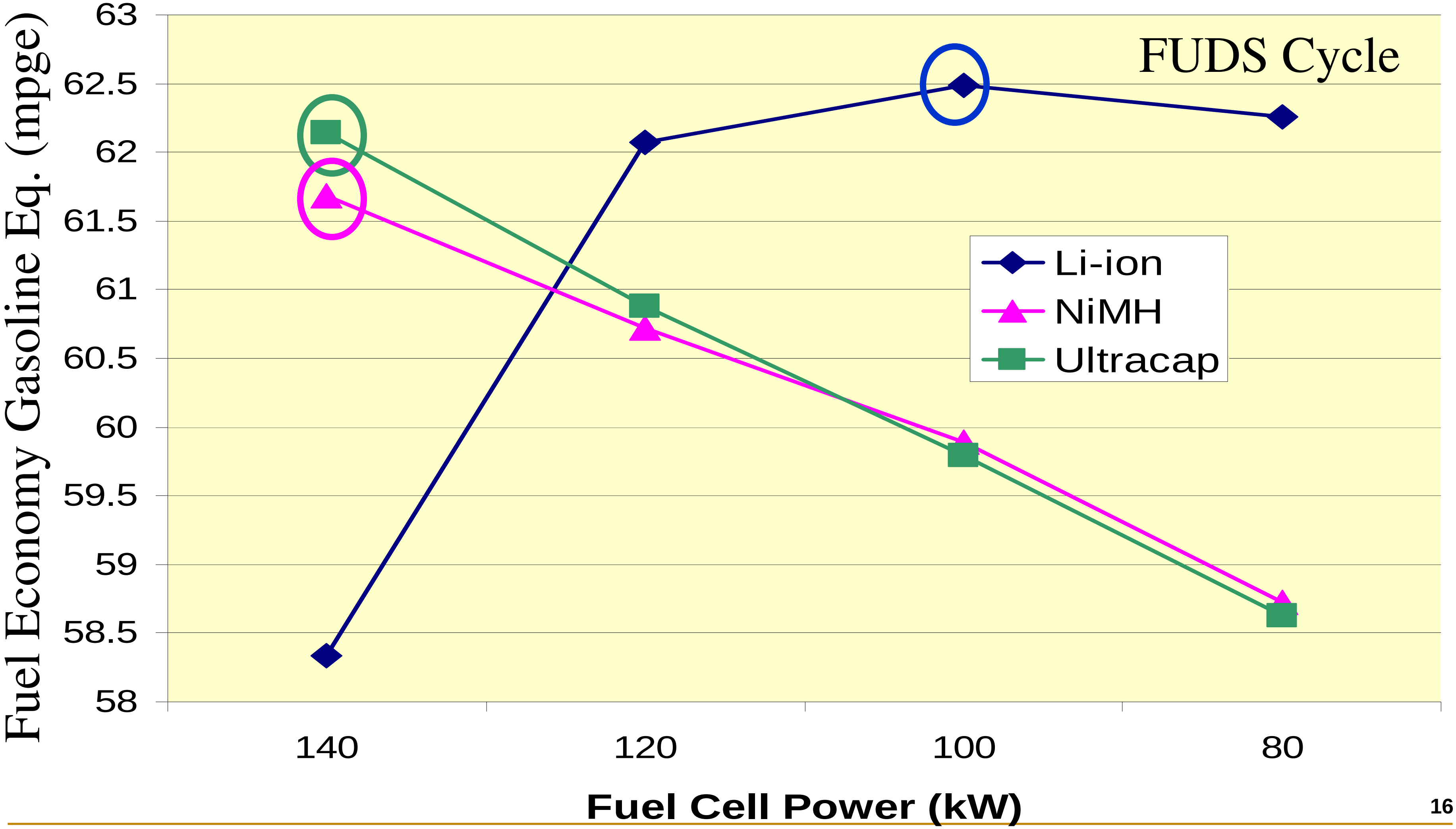
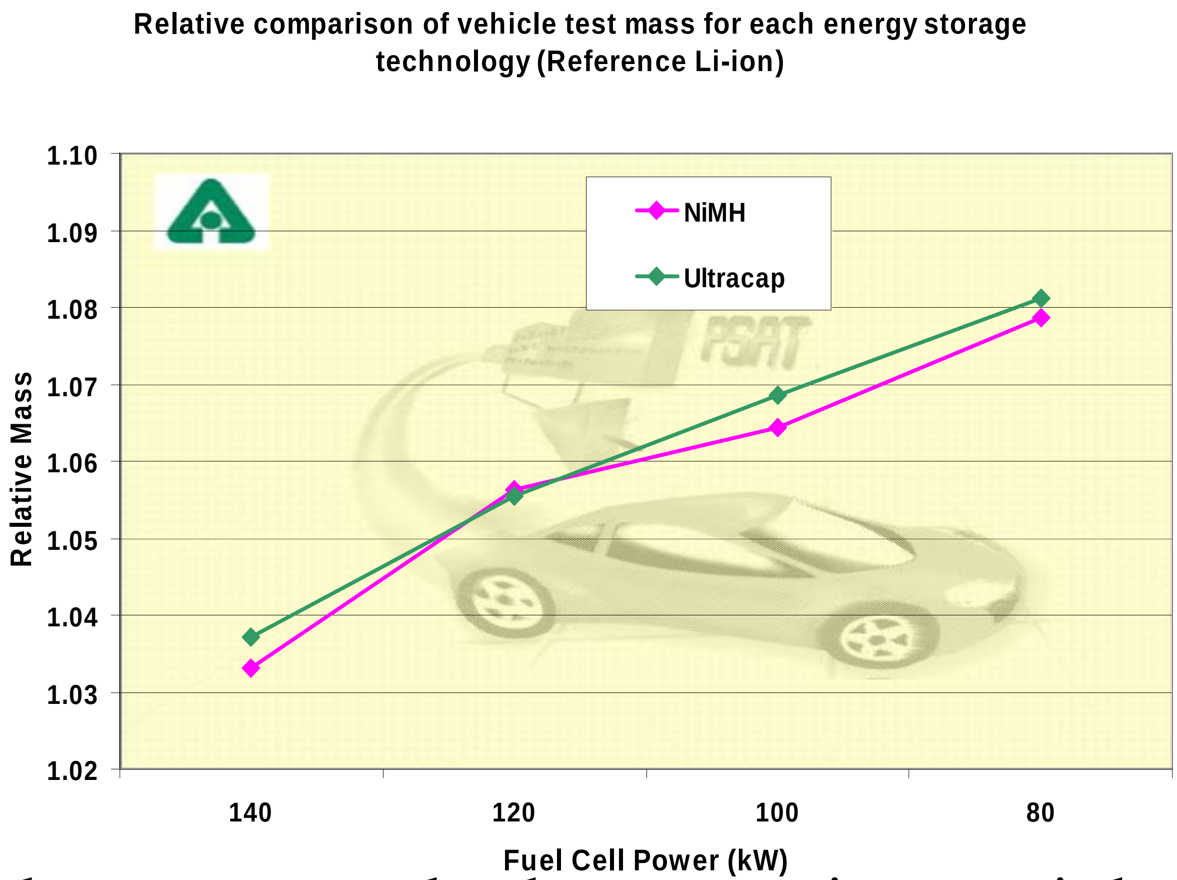
Optimum Hybridization Degree Depends upon the ESS Technology



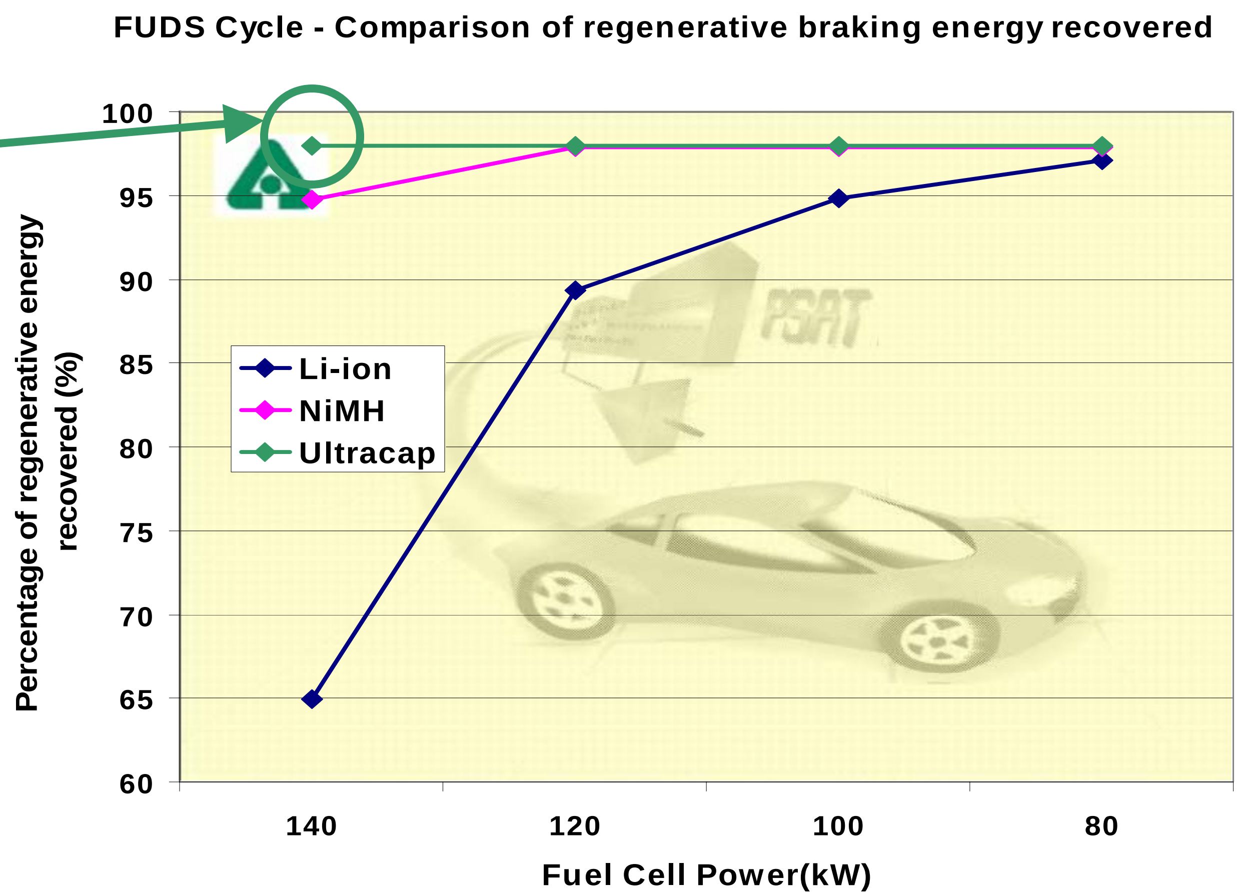
NiMH and Ultracap have lower specific power than Li-ion



The fuel economy penalty due to mass increase is lower for a low hybridization degree

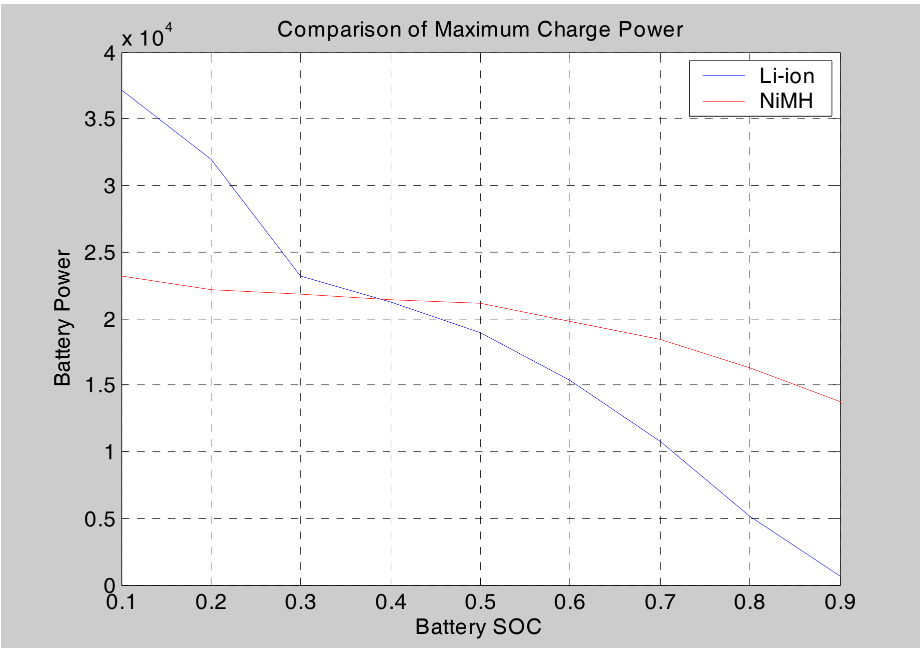
NiMH and Ultracap allow better regenerative braking recovery at low hybridization degree

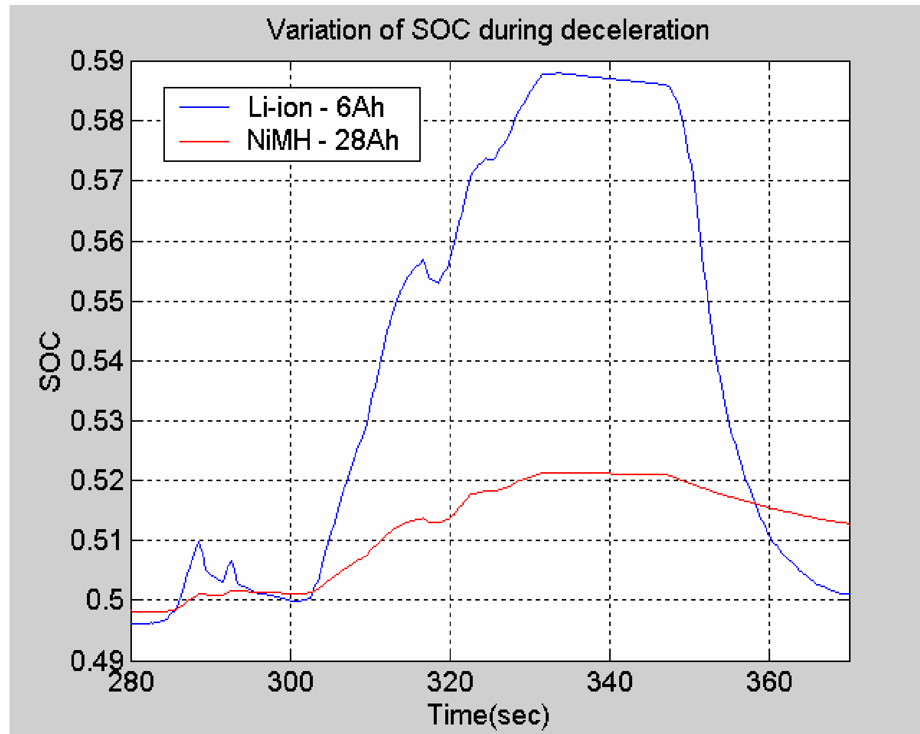
Due to the need to size the ultracap for Z60 for energy



Small ess strategy ; SOCtarget = 0.5

The SOC varies more for the Li-ion 6Ah, decreasing the maximum charge power





Energy Storage Technology Results

- **Optimum hybridization degree depends on energy storage technology**

- **Specific power and specific energy characteristics are key to optimum fuel economy**

→ For Li-ion a higher hybridization degree is necessary while both NiMH and ultracapacitors achieve best results at very low hybridization degrees

Fuel Cell Vehicle Fuel Economy Optimization

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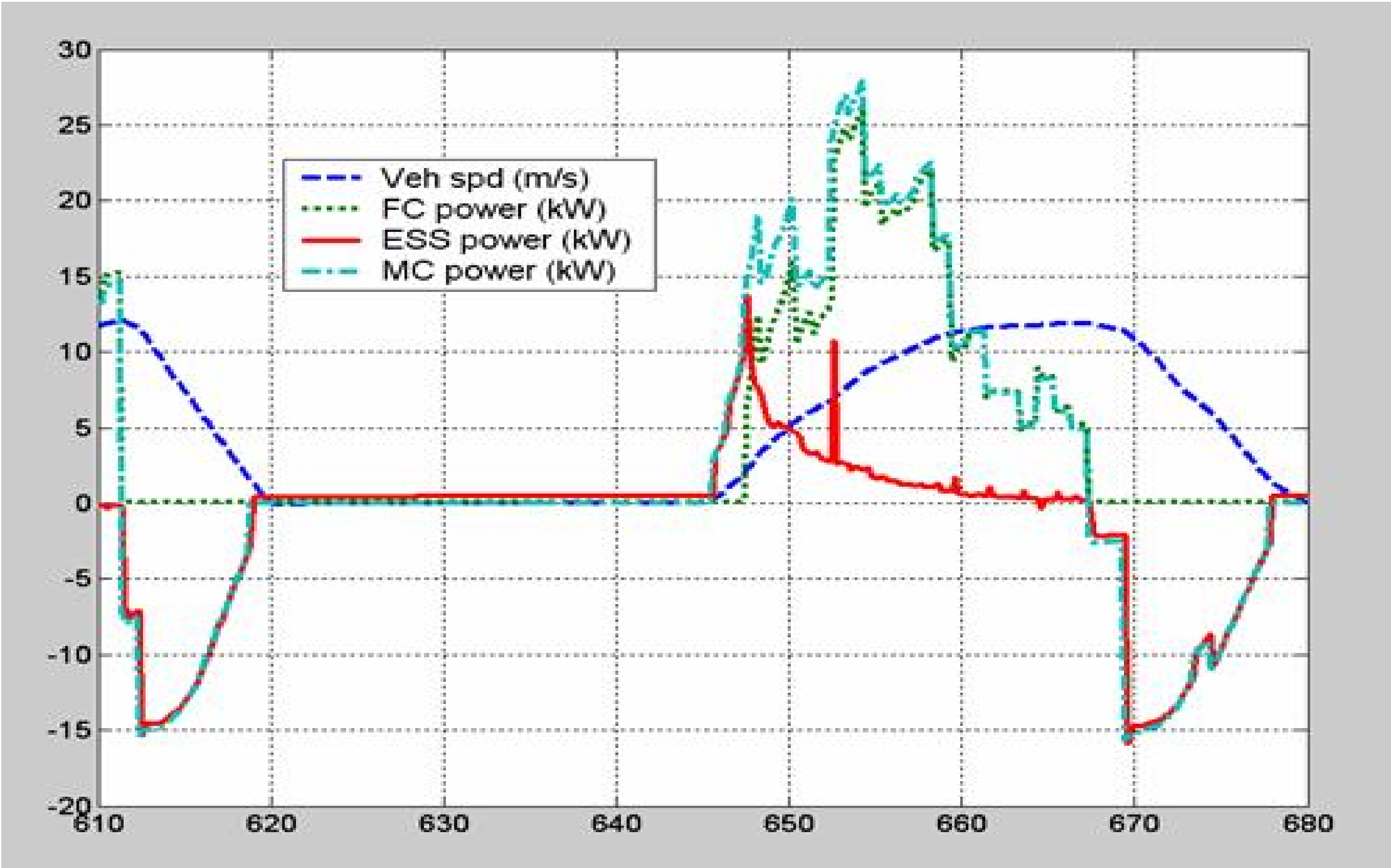
Default Control Strategy Maximizes Fuel Cell System Use

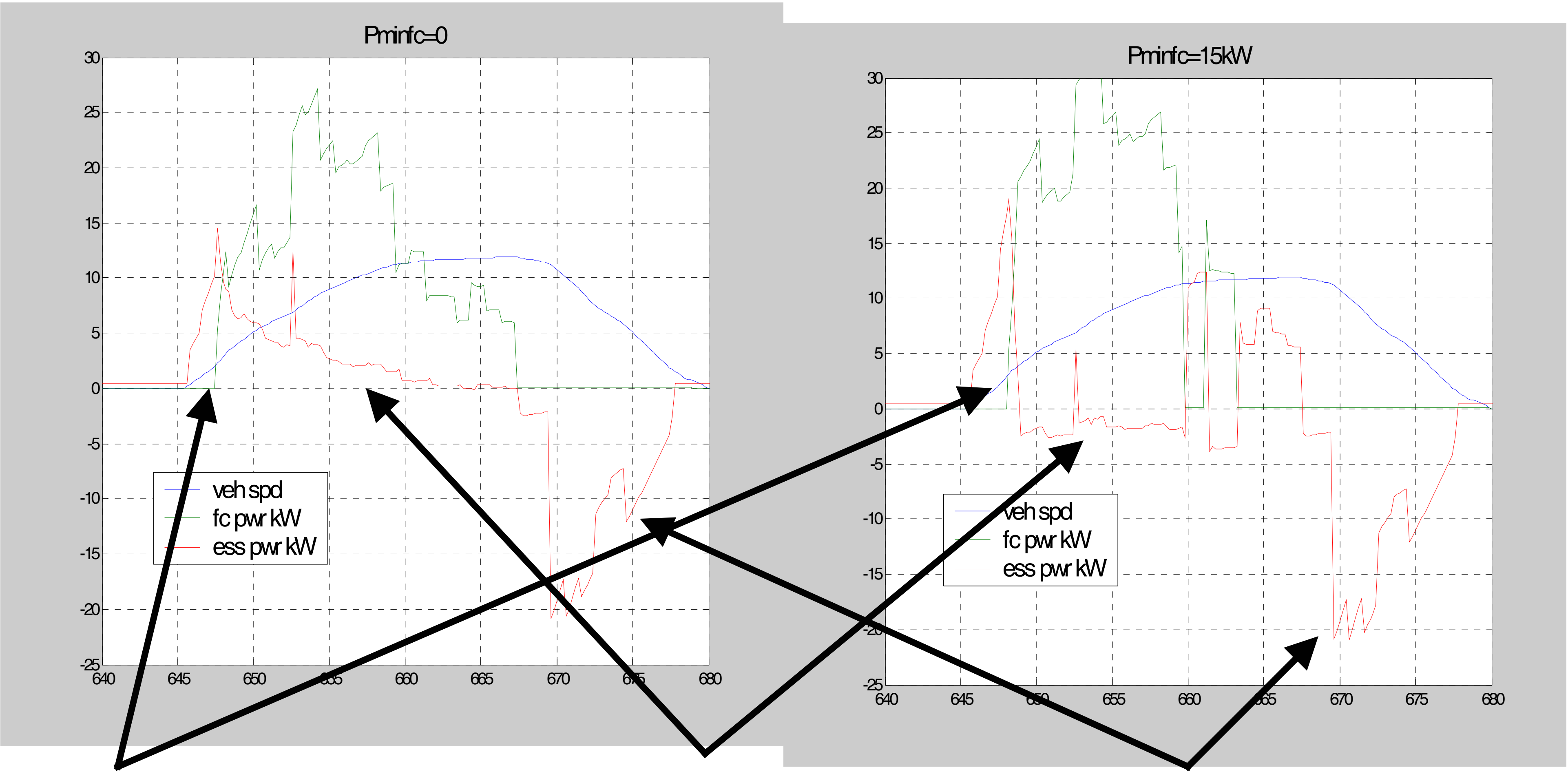


Control Strategies Options Considered

- **Use the fuel cell as main power source**
  - SOCtarget = 0.7
    - *Min fuel cell power demand = 0 (Default Control)*
    - *Min fuel cell power demand = 5kW*
    - *Min fuel cell power demand = 15kW*
  - SOCtarget = 0.5
    - *Min fuel cell power demand = 0*
    - *Min fuel cell power demand = 15kW*
- **Use the battery as main power source**
  - SOCtarget = 0.7
  - SOCtarget = 0.5

With min fuel cell power demand = Pwheel + P(SOC)

Impact of fuel cell power min on battery power

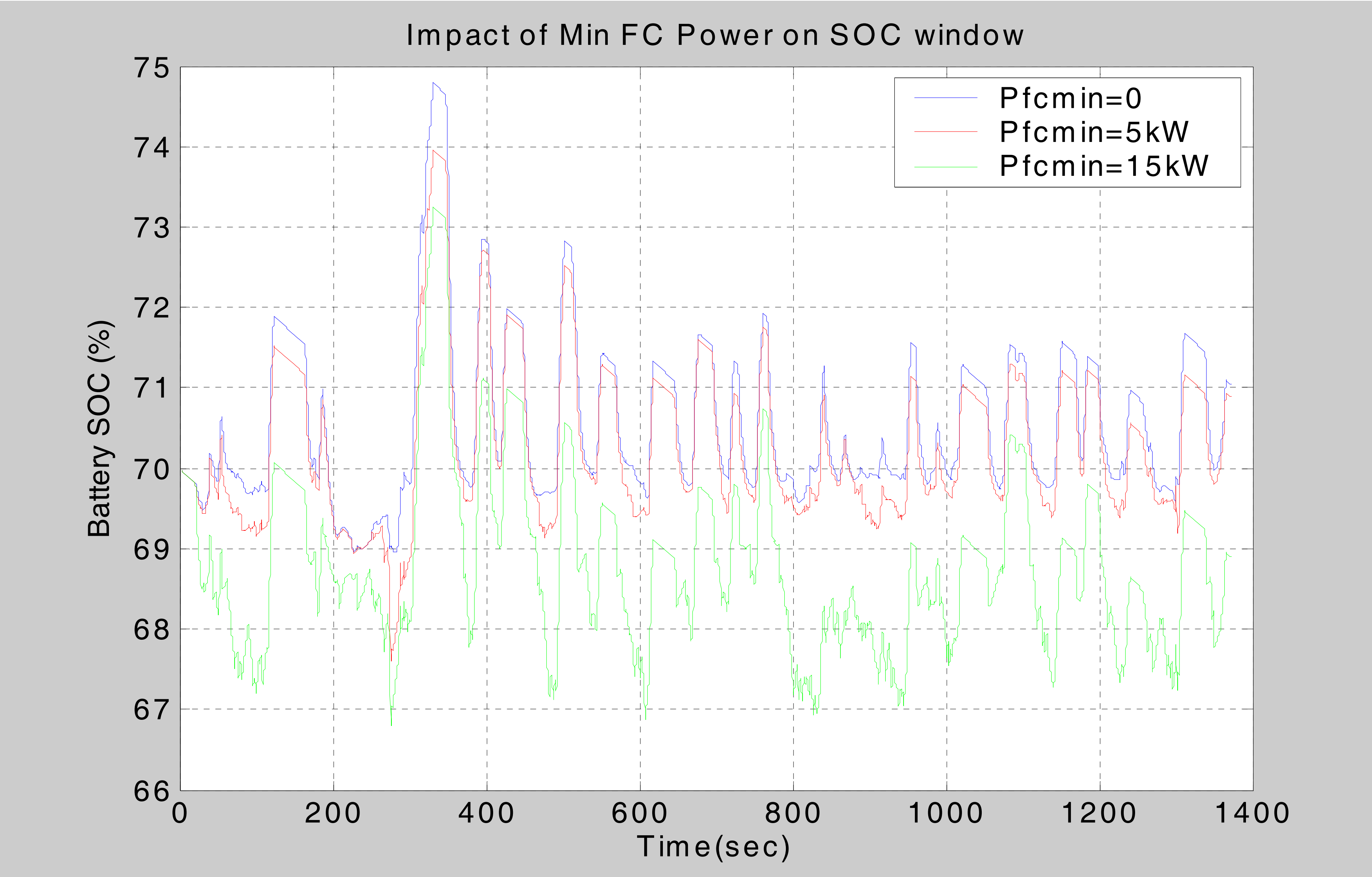


1 – Battery provides more power during a longer period

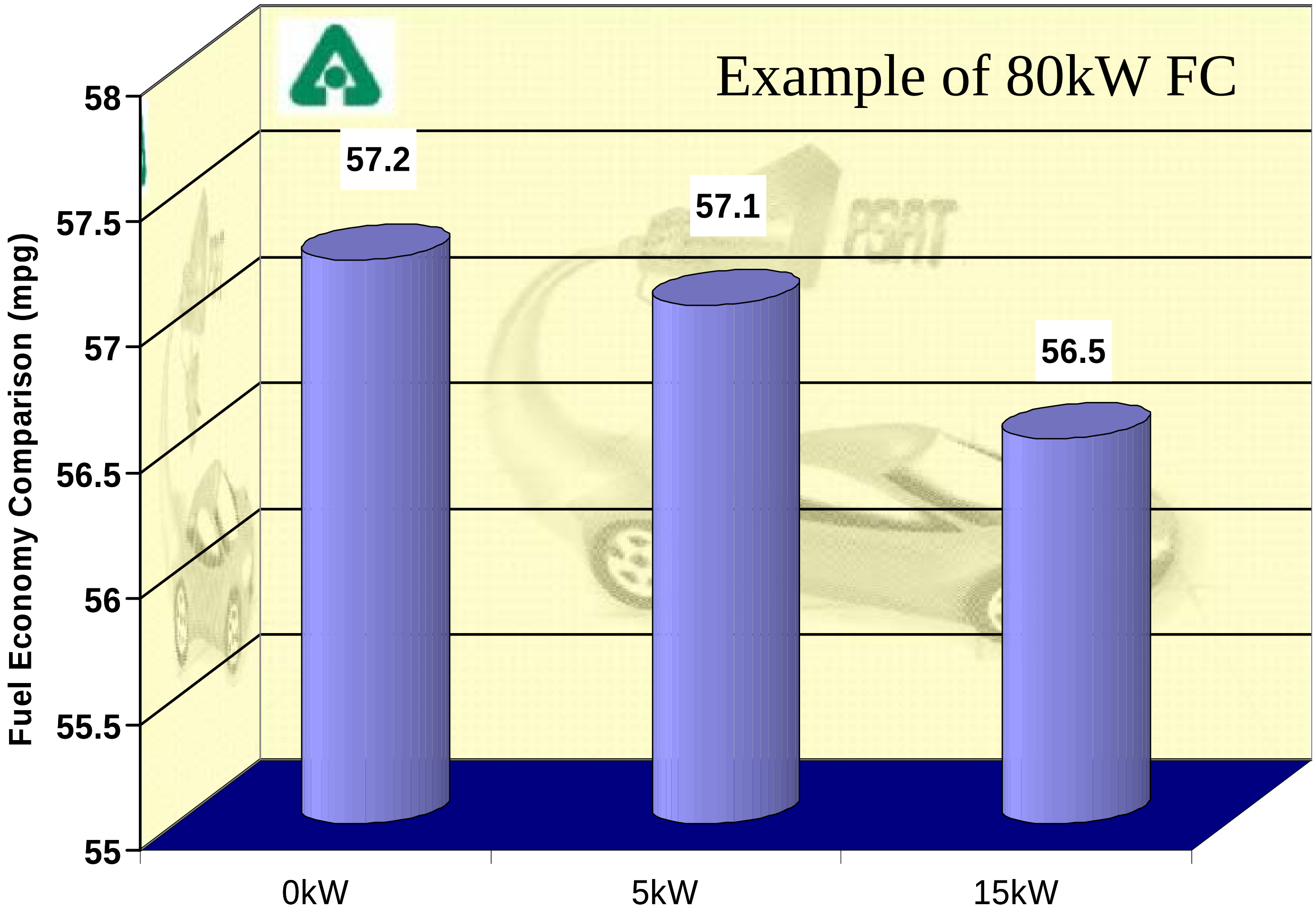
2 – FC provides more power to recharge the battery

3 – Regen amount in unchanged

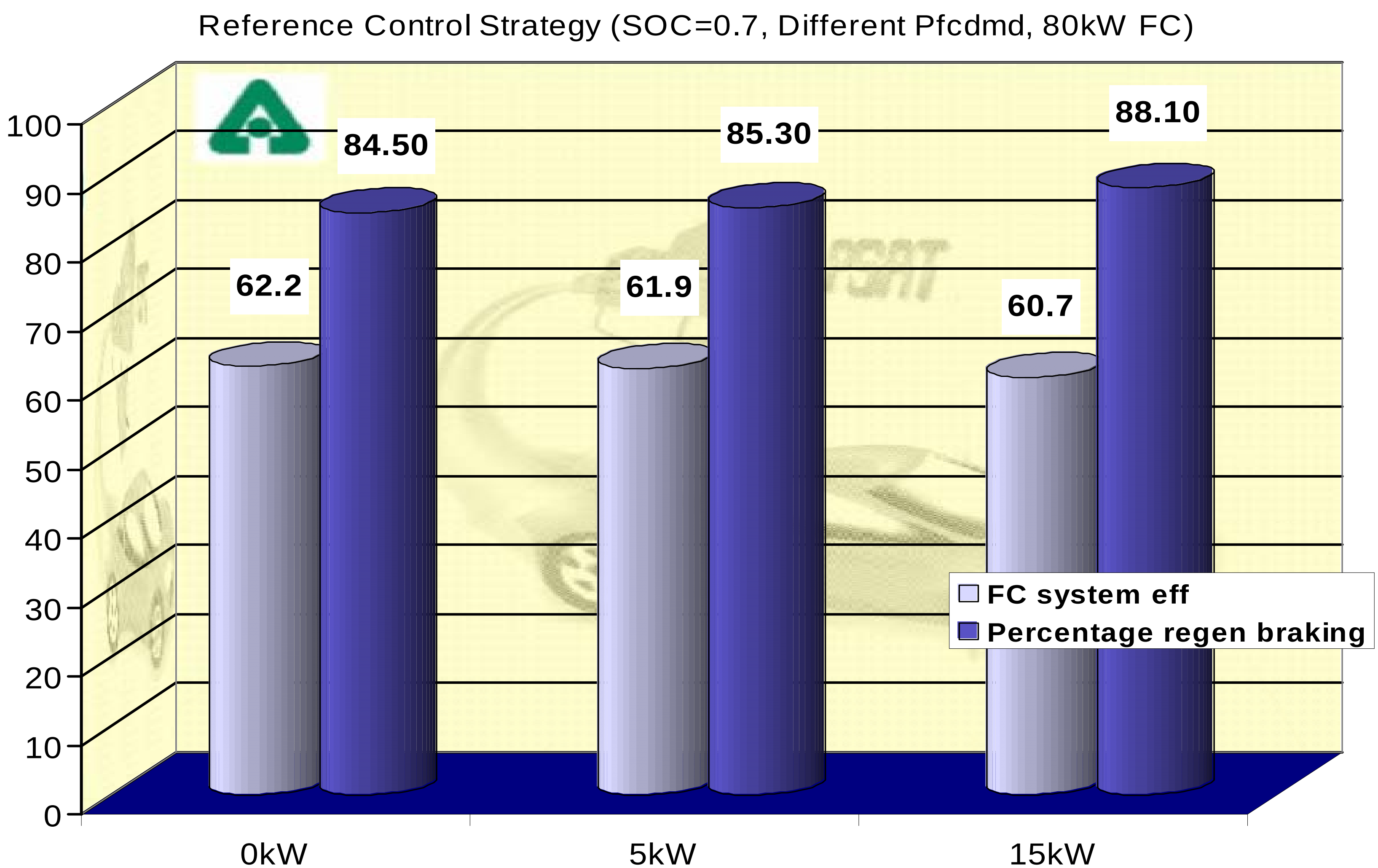
Impact of fuel cell power min on battery SOC



Increasing the min fuel cell power demand leads to fuel economy penalty



Because the increase in regen energy is nullified by the decrease in fuel cell efficiency



Summary Table – Example of 80kW fuel cell system (SOCtarget = 0.7)

	Units	0kW	5kW	15kW
Mech. Braking Energy Loss	Wh	106	100	76
Fuel Cell Energy Loss	Wh	1818	1839	1906
Difference	Wh		14.9	57.7

Control Strategies Options Considered

- **Use the fuel cell as main power source**
  - SOCtarget = 0.7
    - *Min fuel cell power demand = 0 (Default Control)*
    - *Min fuel cell power demand = 5kW*
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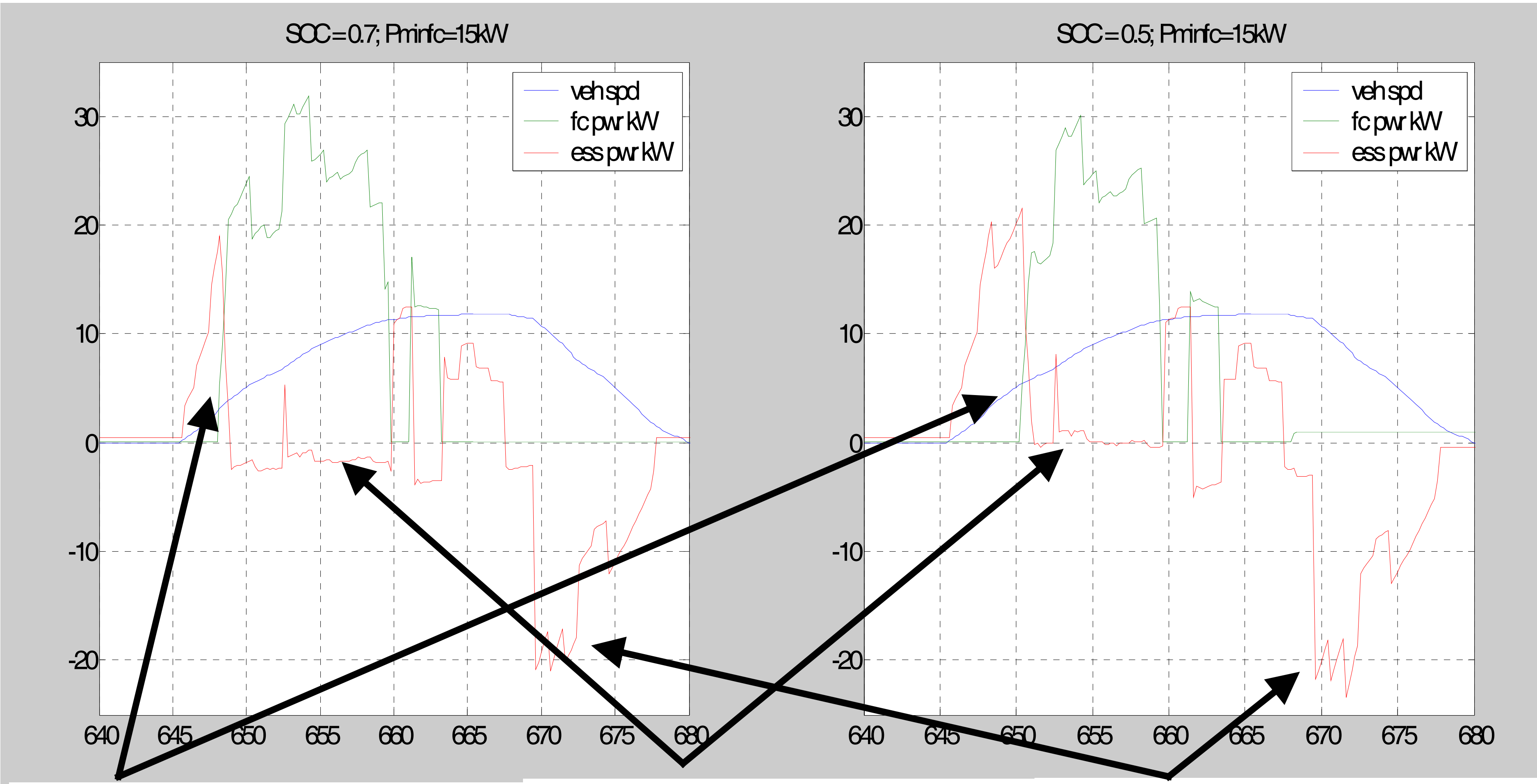
  - SOCtarget = 0.5
    - *Min fuel cell power demand = 0*
    - *Min fuel cell power demand = 15kW*
- **Use the battery as main power source**
  - SOCtarget = 0.7
  - SOCtarget = 0.5

With min fuel cell power demand = Pwheel + P(SOC)

Impact of target battery SOC on battery power

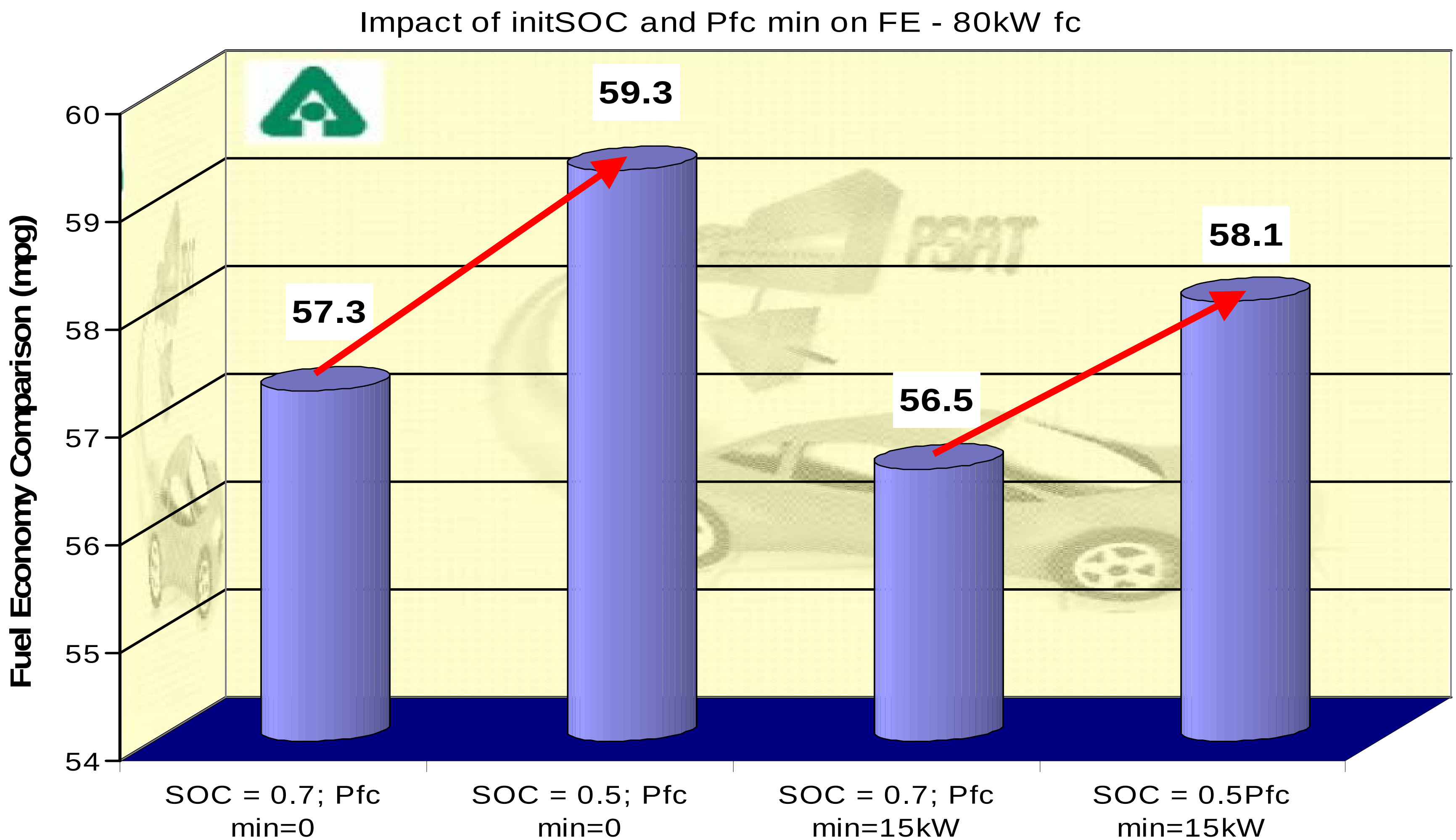


2 – Battery provides more power during a longer period

3 – FC does not need to recharge the battery

1 – Increased regen amount

A smaller target SOC (0.5) leads to fuel economy benefits



Control Strategies Options Considered

- **Use the fuel cell as main power source**
  - SOCtarget = 0.7
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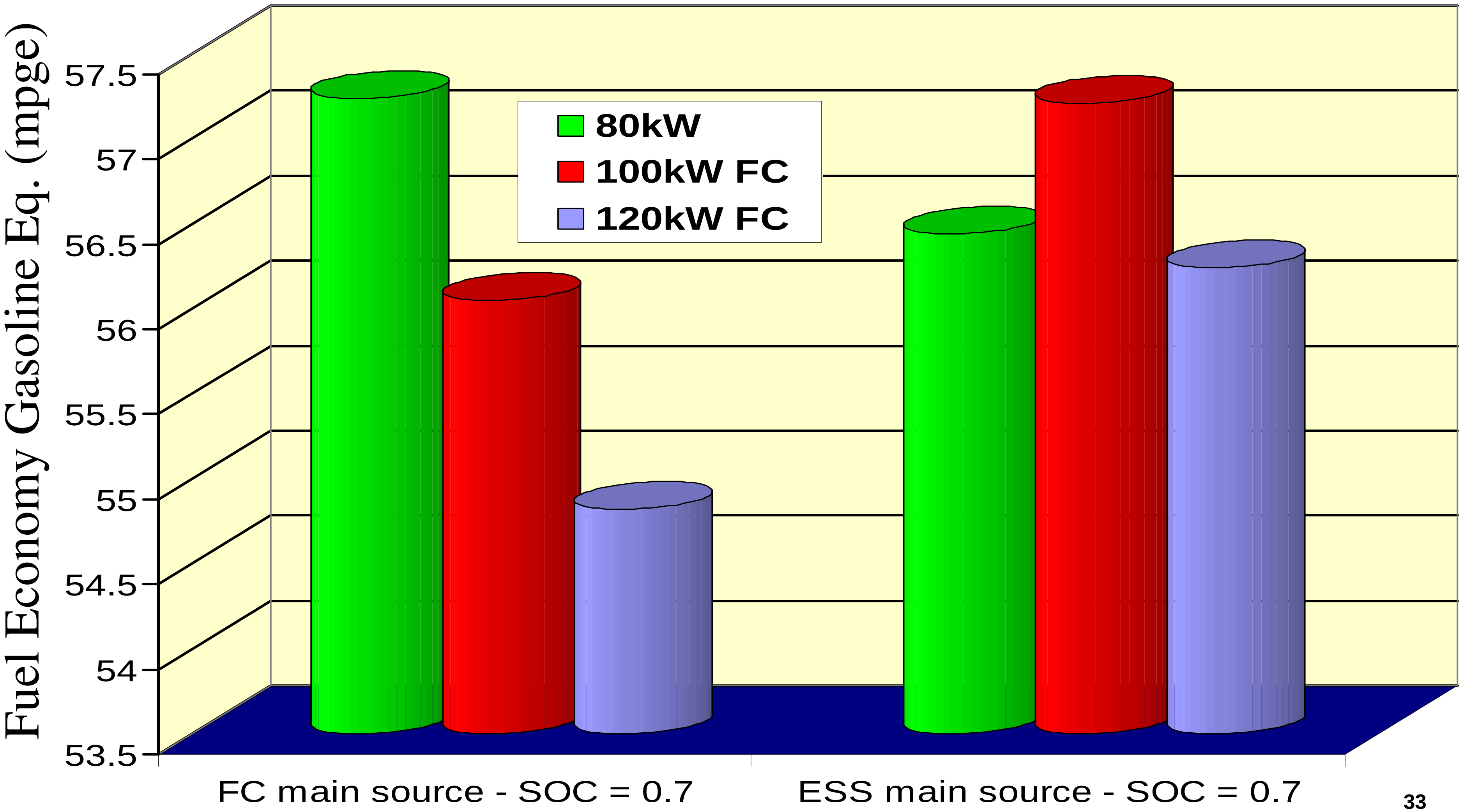
    - *Min fuel cell power demand = 15kW*
  - SOCtarget = 0.5
    - *Min fuel cell power demand = 0*
    - *Min fuel cell power demand = 15kW*
- **Use the battery as main power source**
  - SOCtarget = 0.7
  - SOCtarget = 0.5

With min fuel cell power demand = Pwheel + P(SOC)

US06 Cycle Could Benefit From Using More The Battery



Use more the battery

Control Strategy Results

- **For the same control strategy, it is possible to increase losses by increasing the regenerative braking due to fuel cell efficiency**
- **Rather than increasing the minimum fuel cell power demand, minimizing the target SOC is a better way to increase the regenerative braking**

1 - Low SOC should be targeted to increase regen capture
2 – Optimum control strategy philosophy depends upon driving cycle: For FUDS, it is better not to use the battery too much, whereas it is the opposite for US06

System Approach is Needed to Achieve Optimum Fuel Economy

- **Key benefit of hybridization is fuel economy increase for FUDS thanks to regenerative braking**
- **Optimum hybridization degree is energy storage technology dependant**
- **Fuel cell system efficiency and regenerative braking trade-off is key to optimum fuel economy**
  - Increasing hybridization degree and SOC window can lower fuel economy
  - Minimizing SOC target is a good way to increase the regenerative braking

Aymeric Rousseau	**arousseau@anl.gov**
Philip Sharer	**psharer@anl.gov**
Rajesh Ahluwalia	**walia@anl.gov**

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