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Supercapacitors Boosting Electrified Transportation

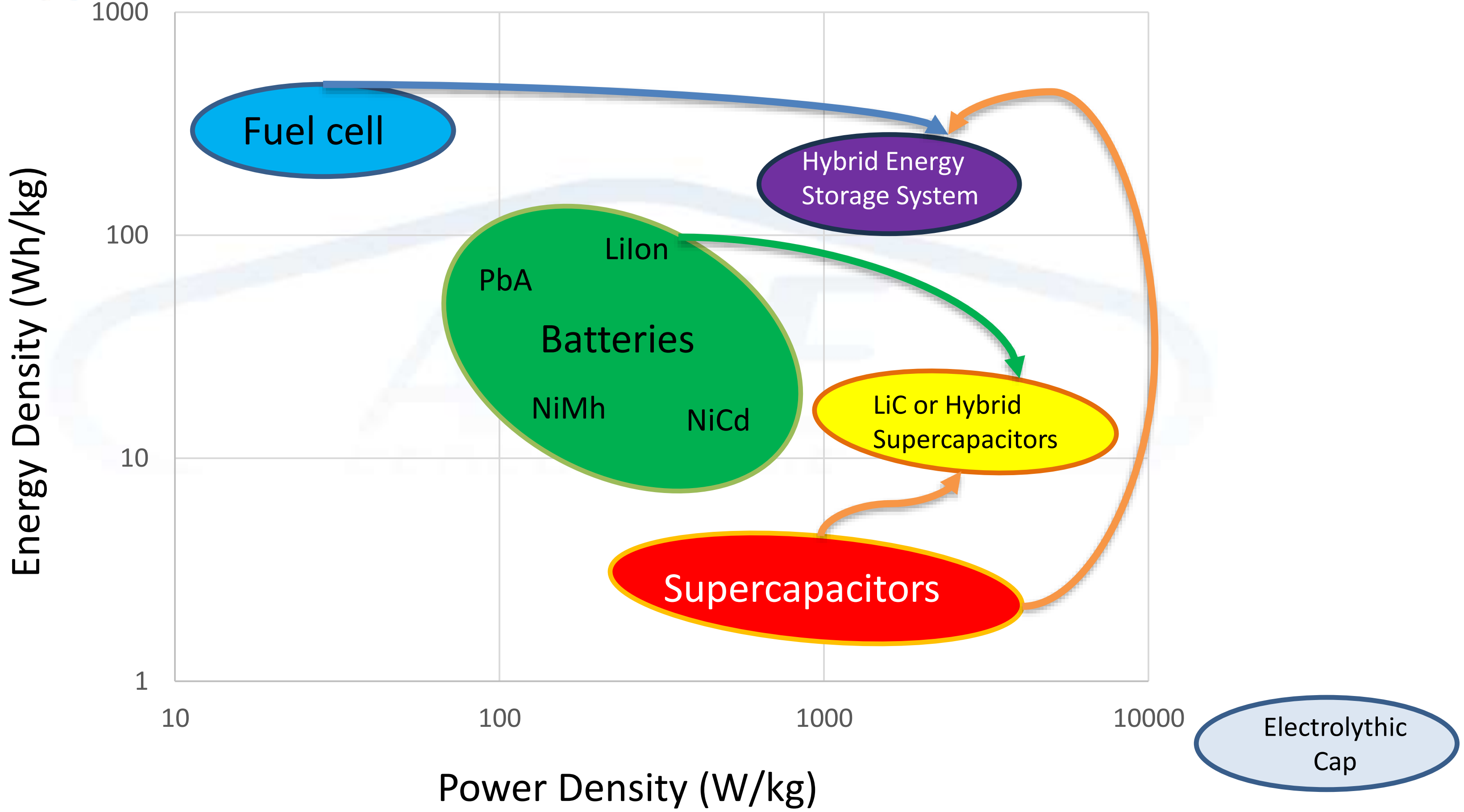
21 Jan 2025

Presentation agenda

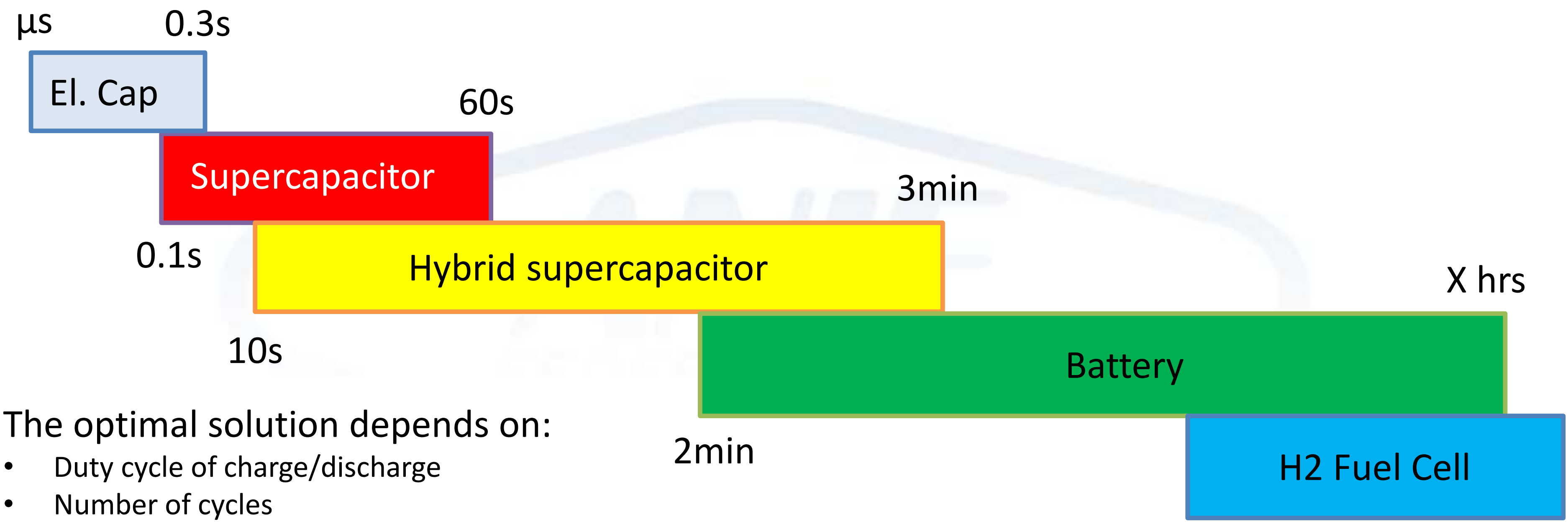
1. Electrical Energy Storage Methods
2. Hybrid Electrical Energy Storage Options
    1. LiIon + SC internal combination
    2. LiIon + SC external combination
3. Hybrid Power Systems
    1. Combustion/Fuel Cell + SC
    2. Application Examples
4. Takeaways
5. Q&A

Electrical Energy Storage Methods

Alternative Options For The Ragone-Plot



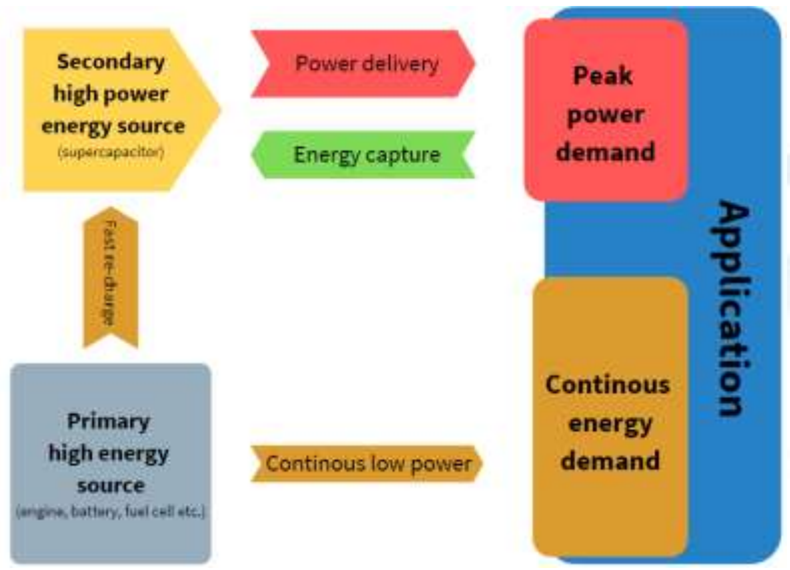
Energy Storage Selection Based On $/kWh



The optimal solution depends on:

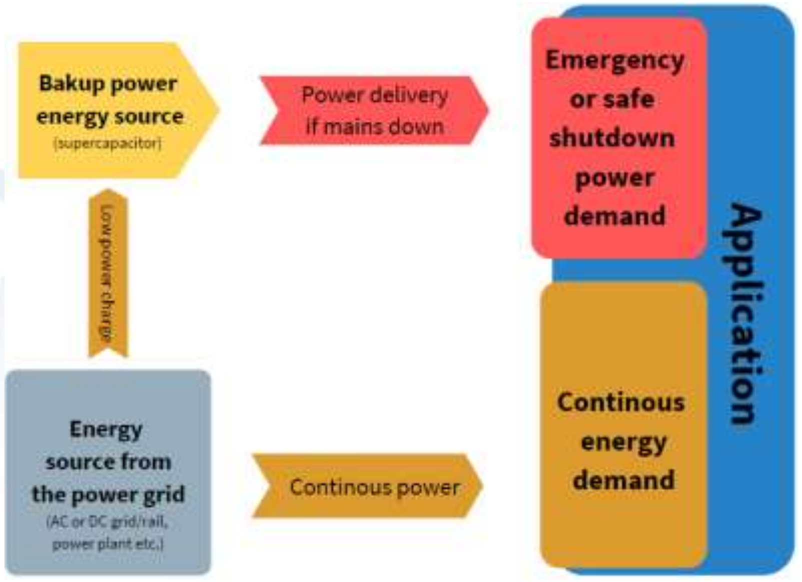
- Duty cycle of charge/discharge
- Number of cycles
- Ambient temperature level
- Discharge current
- Lifetime requirements

Major supercap application types



Peak/pulse power

- Battery powered IoT
- eMobility
- Grid stabilization



Back-up/hold-up power

- RTC backup
- Embedded brown-out prorection
- UPS for facilities

Supercap Constructions - Scaling

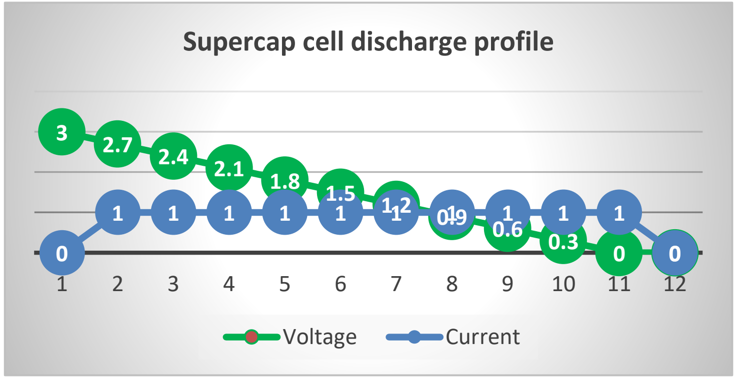
Coin Cells	Cylindrical Cells	Large Cells	Modules	Systems

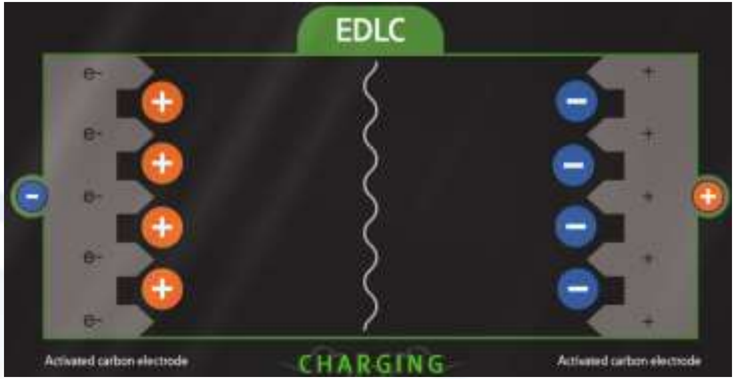
µW → kW → MW

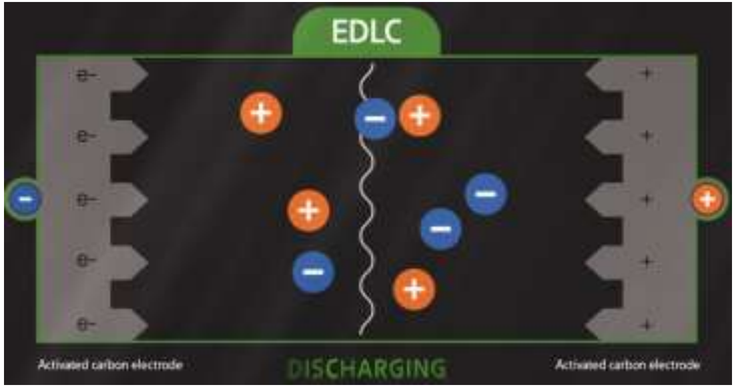
Hybrid Energy Storage - LiIon+SC internal combination -

EDLC aka. Supercaps

- Supercaps are symetrical devices comprised by activated carbon electrodes at both anode and cathode sides
- Charging and discharging are **electrostatic** processes – no chemical reactions
- Cycle life is practically unlimited
- Charge and discharge can be done at the same speed and fashion in seconds
- Voltage drops linerarly by the energy delivered
- Typical lifetime: 20yrs+ depending on voltage&temperature

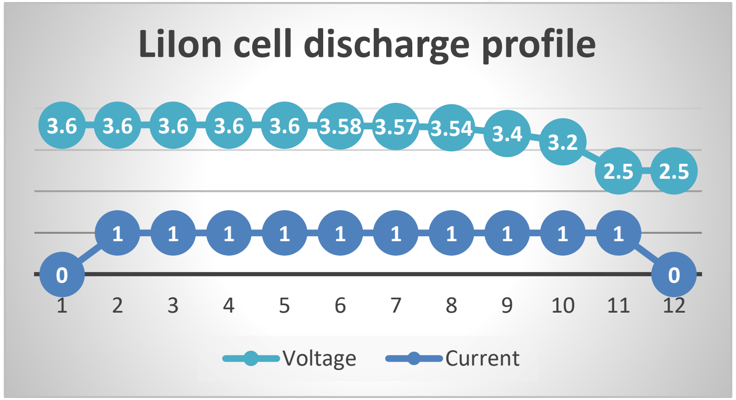


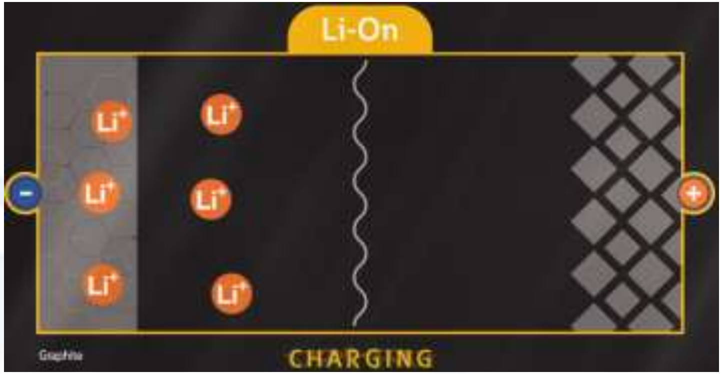


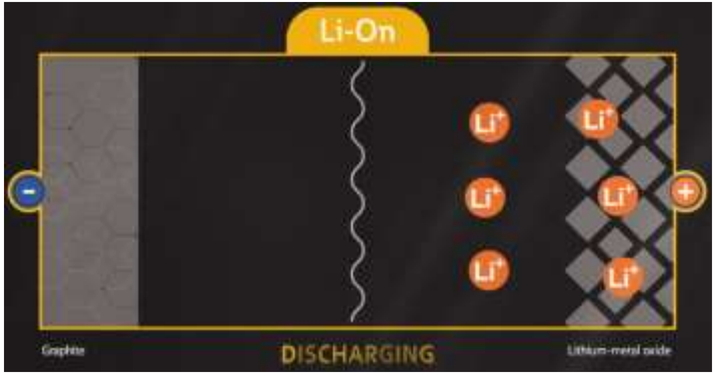


LiIon Batteries

- LiIon batteries are assymetric devices comprising of graphite anodes and metal oxide cathodes (Co, Mn, PO4, Fe, Ni combinations)
- Charge and discharge are **electrochemical** processes
- Cylce life is limited due to degradation (electrolyte oxidation, Li oxide buildup on anode and cathode surface, structural damage etc.)
- Discharge profile is flat, delivering quasi constant voltage
- Typical lifetime: 5-10yrs strongly depending on cycles

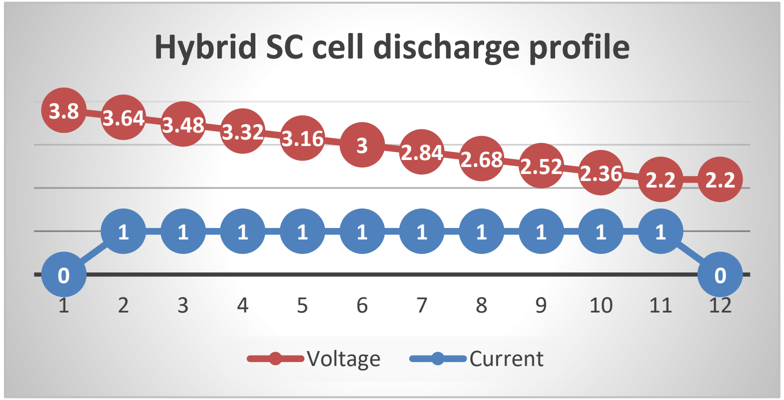


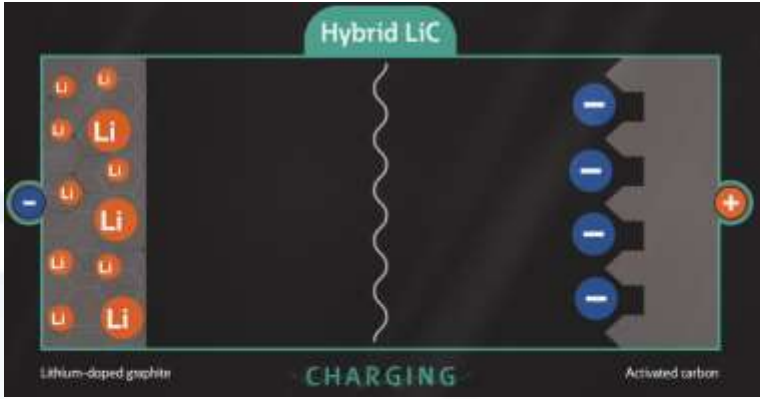


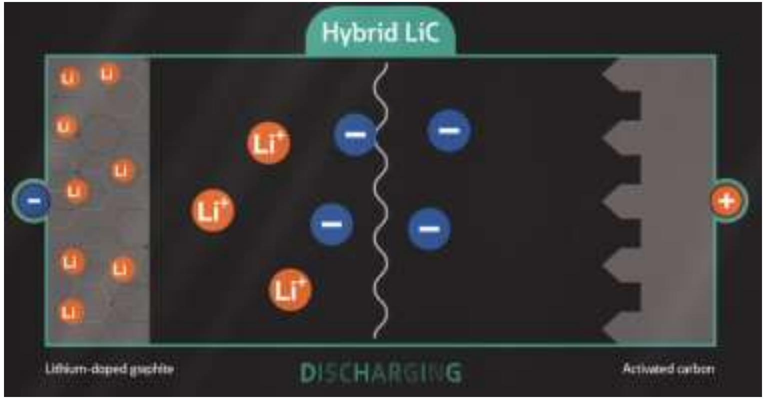


LiC aka. Hybrid Supercaps

- Hybrid supercaps are asymetric devices comprise of a Li doped graphite anode and activated carbon cathode
- The charge movement is done electrostatically mainly but in significantly lower depht as in case of the LiIon battery. This results a very high ~500.000x cycle life and very fast responsiveness to high C rate discharges
- As there are no metal oxides used the hybrid supercaps are not posing any risk of fire or thermal runaway
- Typical lifetime: 10yrs depending on voltage&temperature







Supercap vs. Hybrid Supercap vs. Batteries



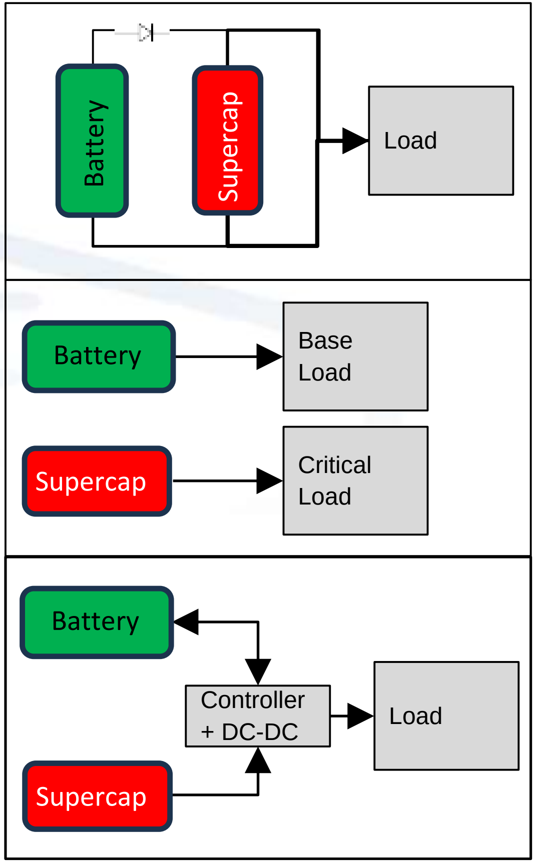

	16x25mm (25F/3V/5.3ccm)	16x25mm (220F/3.8V/5.3ccm)	AA size LiIon (3.7V, 1Ah, 8.5ccm)	AA size NiMh (1.2V, 2.45Ah, 8.3ccm)
Total stored energy	6 mWh/ccm	55 mWh/ccm	423 mWh/ccm max (load and temp dependent)	339 mWh/ccm max (load and temp dependant)
Peak power	125W	36W	10W	3W
Cylcle life	1M (unlimited)	500k	1k	500
Energy transfer life	25kWh	125kWh	3.6kWh	1.5kWh
Operating temp range	-40C/+65C (+85C with derating)	-15C/+70C (+85C with derating)	0C/+60C (discharge possible up to -20C with limited current)	(-4C/+50C)

Different performance aspects for different applications

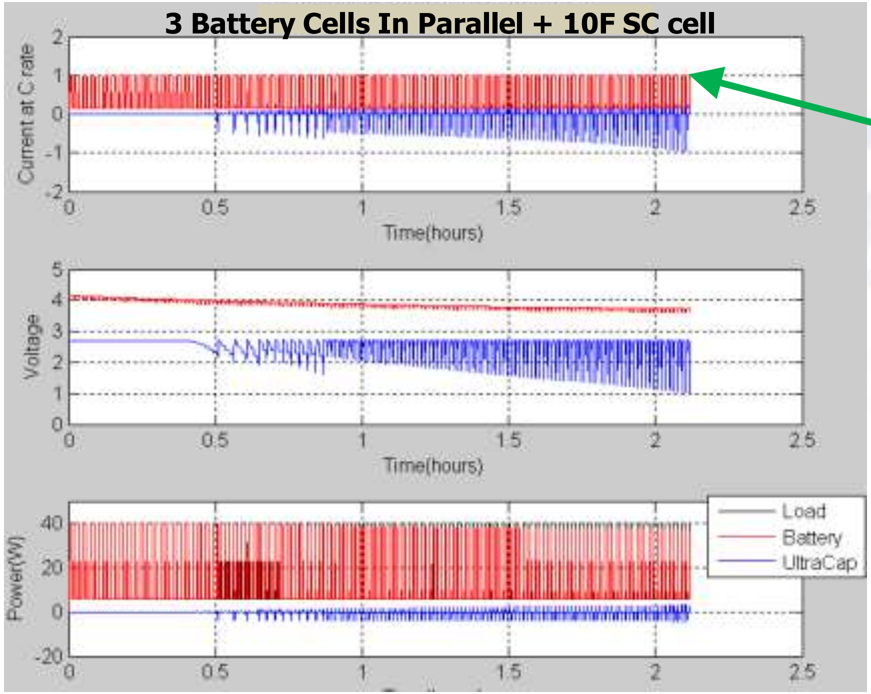
Hybrid Energy Storage - LiIon+SC external combination -

Battery&Supercap Parallel Configurations

- Parallel
  - Low cost
  - Simple
  - Supercap not optimized – fixed to battery voltage
  - Mostly common for IoT
- Separated
  - Low cost
  - Simple
  - Depends upon loads
- Smart
  - Optimizes use of battery and supercap
  - Maximize life time and run time
  - Mostly common for transportation power units



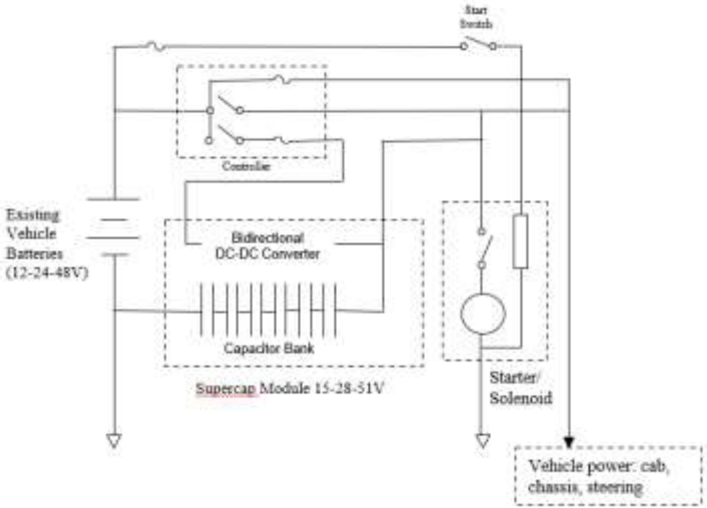
Parallel Example – 6W 40sec 40W 10sec cycle



The system's run time is 2.12 hours (more than 400% longer than battery only). Supercaps are taking over the higher pulses (peak shaving)

Parallel Example: Peak Shaving In Start-Stop Systems

- Start-Stop SC module rated at 150F at 14V, with an ESR of 4.5mΩ for New European Drive Cycle at 23°C
  - Battery - failed after 44,000 starts
  - Battery + Supercapacitor – ran for 120,000 starts
- Mazda battery charge acceptance test at 23°C
  - Battery - failed after 981 starts
  - Battery + Supercapacitor - Ran for 9,553 starts



Engine Starter

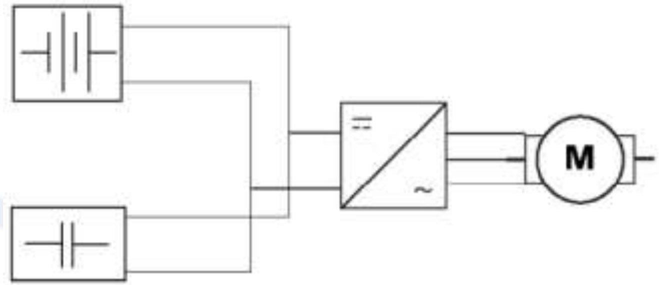
Supercap Pack

Battery Pack

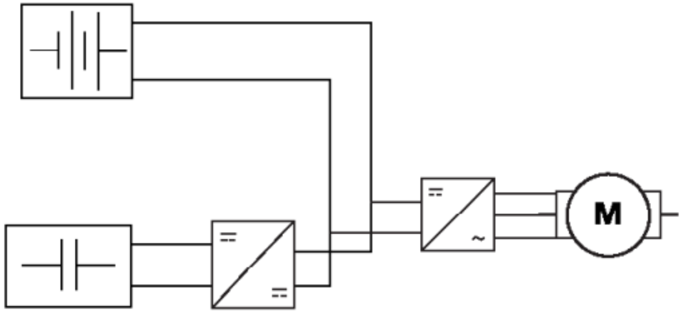
EV Battery Life Extension By Supercapacitor

Three factors that can extend the battery life

- Peak current reduction,
- Depth-of-Discharge (DoD) level reduction,
- Reduction in number of DoD cycles due to charge and discharge.



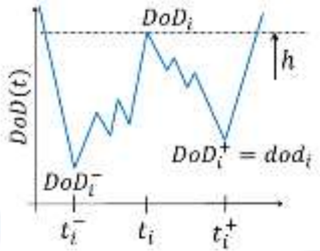
Passive HESS



Active HESS

Battery Life Extension: Depth-of-Discharge

- Methodology is developed to predict the battery life with SC
  - Provided validated battery and SC model available
  - Battery supplied provided cycles-to-failure data available.
  - Gives a relatively fair estimate of battery life extension given battery life of current system is known
- Published in IEEE APEC 2017 Conference - Battery Life Estimation Model and Analysis for Electric Buses with Auxiliary Energy Storage.
- Can be used for gain customer confidence for their applications.



$$EN(N_f) = \sum_{1}^{k} n_i\, p_i \approx \sum_{1}^{k} \frac{n_i}{N_{fi}} = 1$$

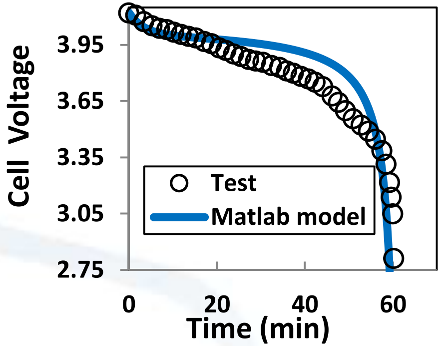
$$L = \frac{1}{EN\; D_N\; 365}$$

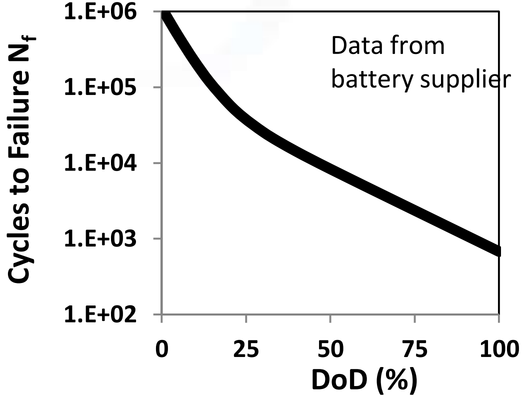
n_i Expected cycles of charge/discharge for peak DoD_i by Rainflow counting

$$p_i = \frac{1}{N_{fi}}$$

Probability of incremental damage measure

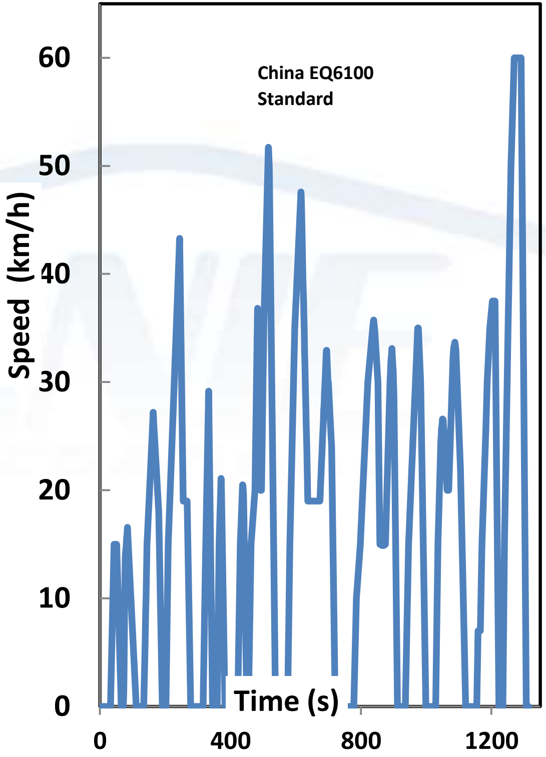
If D_N is number driving cycles per day, life in years

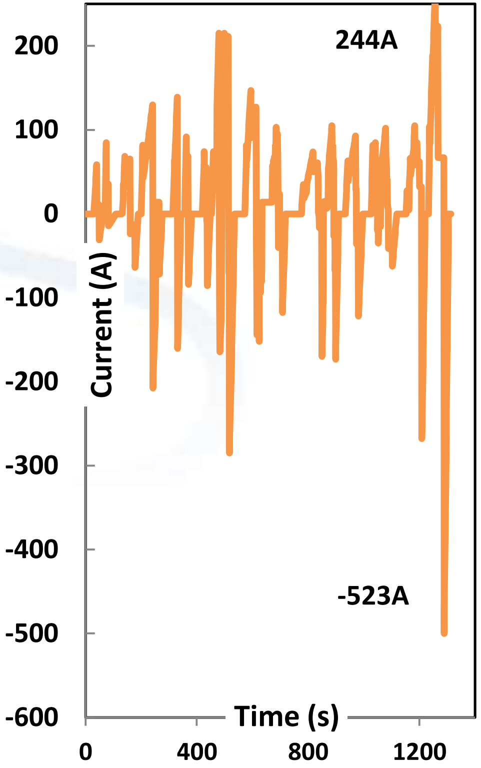




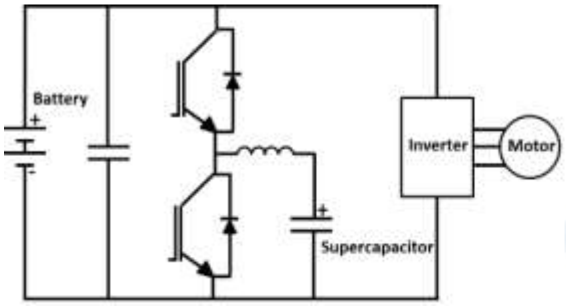
Battery life Extension for Electric Bus

- „W" city driving cycle
- Crowded street, vehicles and uneven roads.
- Distance 6 km.
- Duration 1314 sec
- Idle time 28.4%.
- Peak power discharging 137 kw
- Peak power charging 277kW
- Average battery life 4 years.
- Maximum speed 62 km/h
- Average speed 16.5 km/h
- Average acceleration 0.39m/s^2
- Average braking −0.48m/s^2
- 530V Lithium-ion battery system



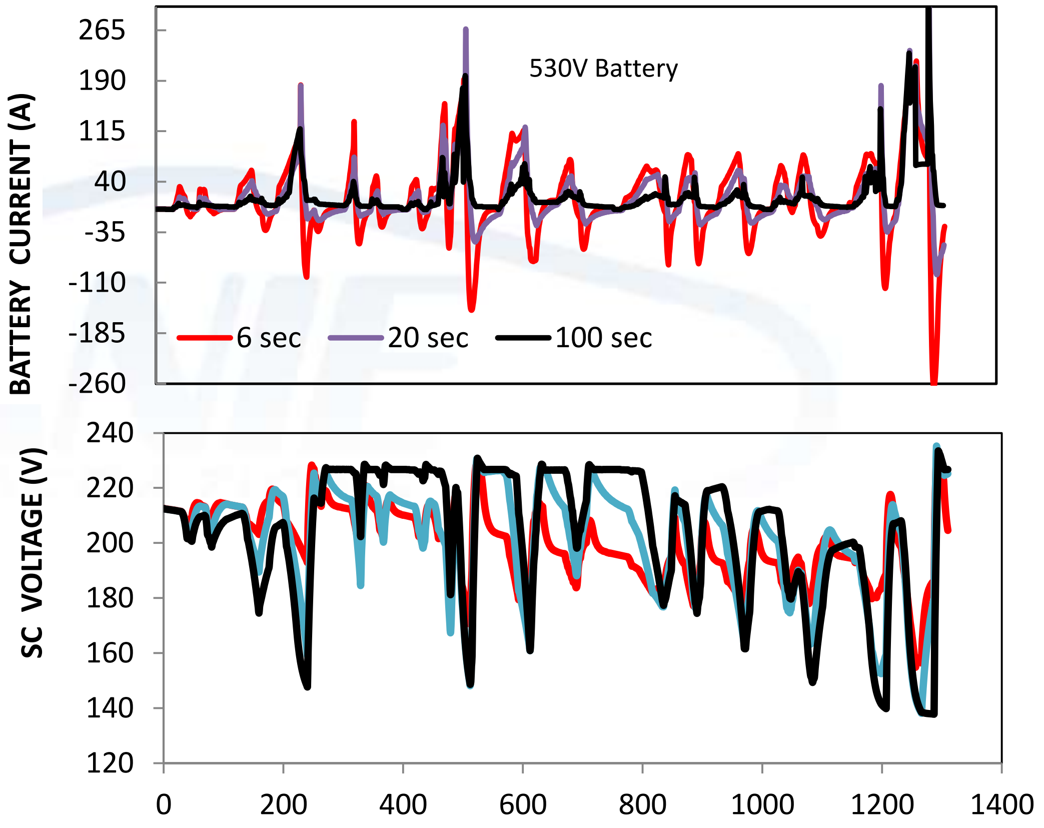


Hybrid Energy Storage with Supercapacitors

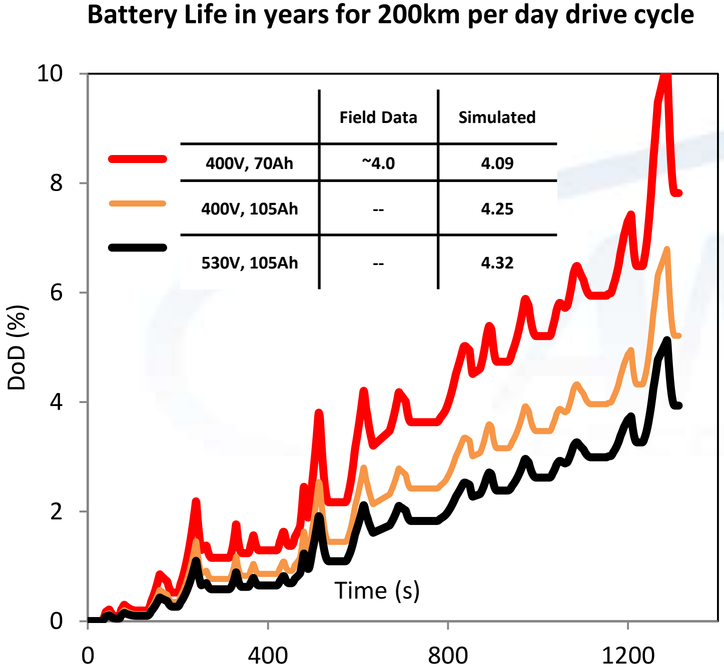


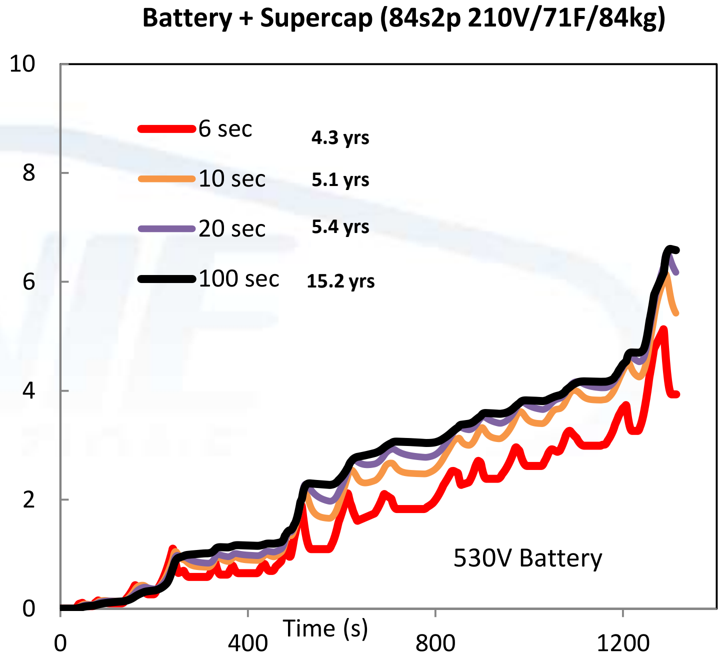
Hybrid Energy Storage System Topology

- SC module responds to faster dynamics
- Battery current peaks are reduced substantially during charging
- With increase in time constant of low pass filter, battery charging cycles are reduced



Electric Bus Battery Life Extension





Life extension can be as high as 3x with supercapacitors

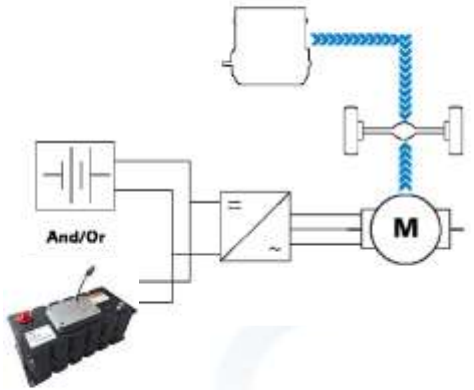
Hybrid Energy Storage
- ICE/FC+SC external -

Motivation For Electrification – Commercial Vehicles

- Higher efficiency than hydraulic systems
- Better control on the load side using electric motors
- Less maintanance
- Cleaner solution
- Change for load leveling and energy regeneration

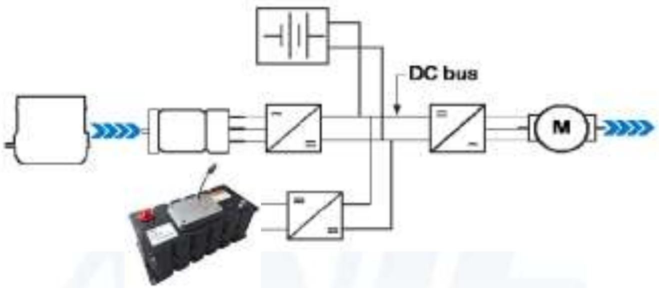
- 25-30% combustion engine downsizing
- 30% fuel efficiency improvement
- xx% SOx, NOx reduction
- Much longer engine lifetime!!!! (normally 2yrs per major maintanance otherwise)

Electrified Hybrid Vehicle Powertrain Topologies



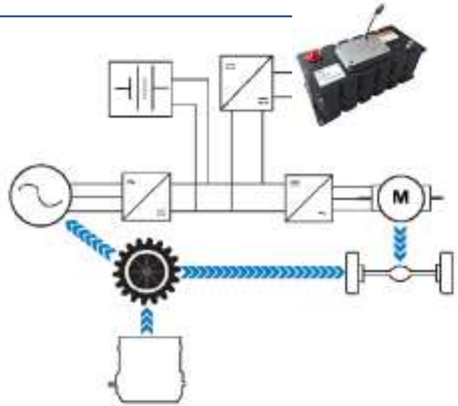
Parallel Hybrid (µHEV)

- 48V normally
- 10-50kW charge/discharge
- Allows combustion engine downsizing
- Fuel efficiency improvement of cca 20%



Series Hybrid (FHEV)

- 200V-400V normally
- 100+kW electric covering part of the drivecycle
- Allows combustion engine downsizing significantly
- Supercap supports battery current shaving (20-30%) to extend range (5-10%) and improve battery life



Power Split Hybrid (PHEV)

- 400V normally
- 100+kW electric covering part of the drivecycle
- Normally used for passanger cars
- Very complex

Economically Beneficial SC Integrations

1. Combustion engine parallel hybrids:
   - Mild hybrid city buses
2. Combustion engine series hybrids:
   - Tractors/Agricultural
   - Wheel loaders
   - Crushers
   - Mining equipments
   - Offshore building vessels
3. Fuel cell drives:
   - Boats
   - HD trucks
   - LD trucks/delivery vehicles

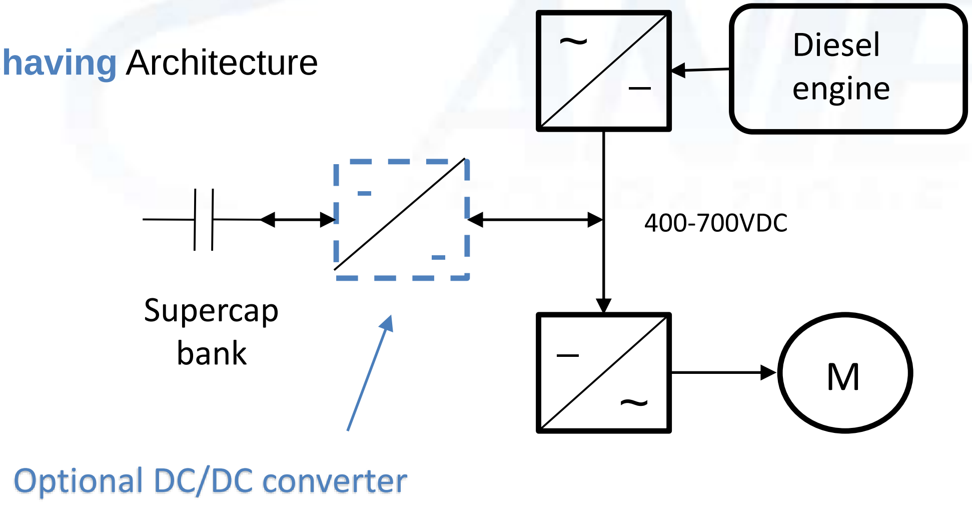
Combustion engine – SC hybrid example

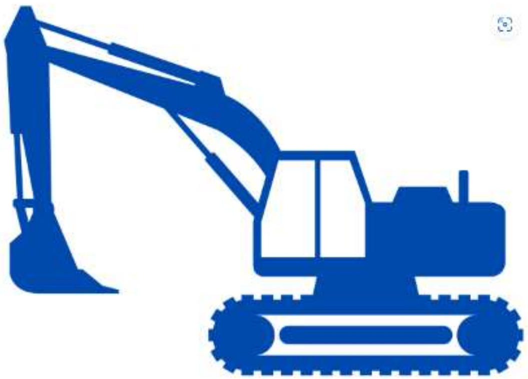
Example: Diesel-Hybrid Excavator

Example: hybrid diesel excavator

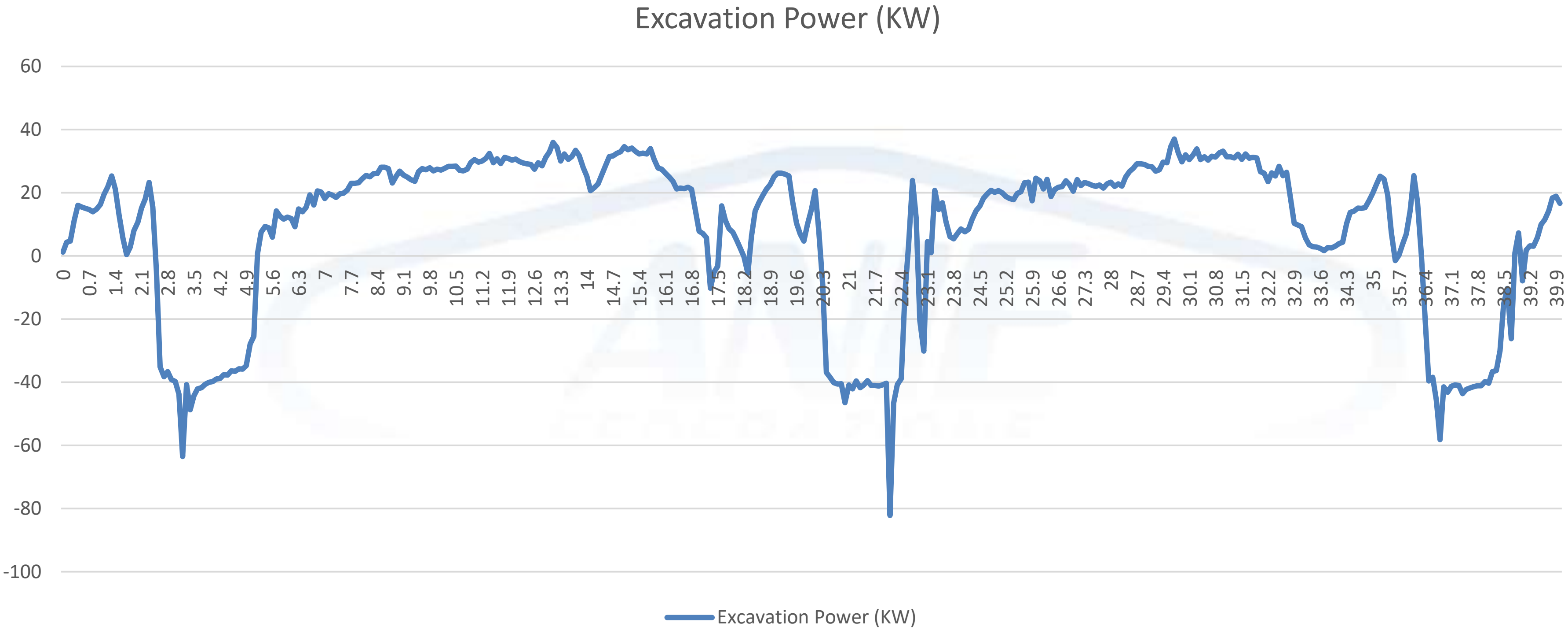
- Engine: 250kW max – goal to downsize to 200kW
- Powetrain DC-rail: 650V nominal
- Peak shaving as per load fluctuations using supercapacitors

DC peak shaving Architecture





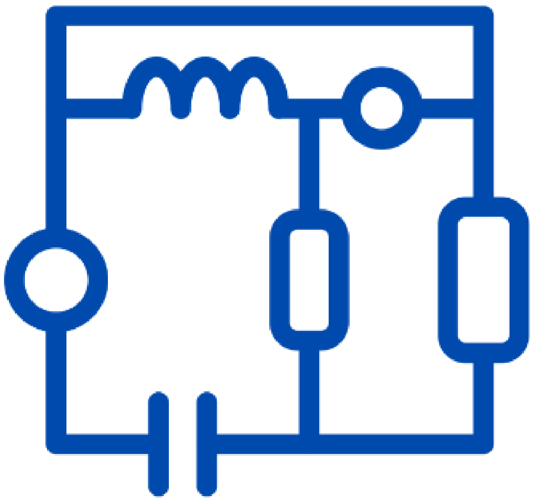
Example: Diesel-Hybrid Excavator



Example: Diesel-Hybrid Excavator

Supercap design considerations:

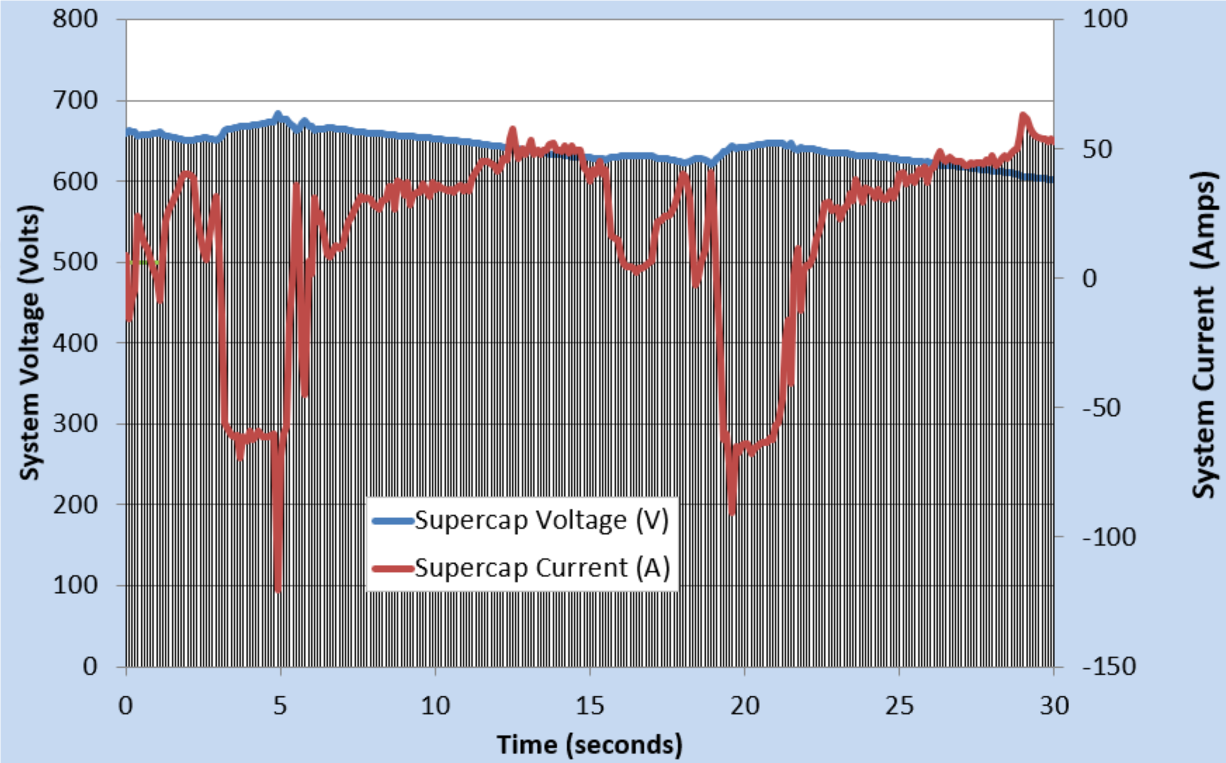
- Design lifetime: 10yrs min without maintanance
- Ambient temperature up to +45C => internal temp rise +5C => max allowed supercap temp rise +15C = +65C max supercap temperature
- Ruggedized construction
- Agency certificates preferred: ECE UN R10/R100, UL, CE

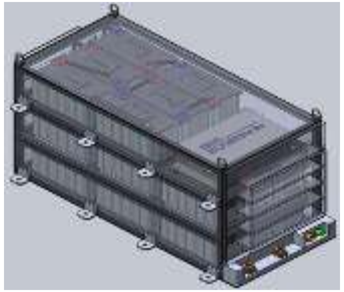


Example: Diesel-Hybrid Excavator

Solution:

- 15pcs series connected 51V rated supercap modules
- C =12.5F new/10F EOL
- ESR=75mΩ/150mΩ EOL
- Irms = 40A
- Trise = 3.5°C/7°C EOL
- Total mas = 225kg
- Total volume = ~250L
- Peak power = 1.9MW

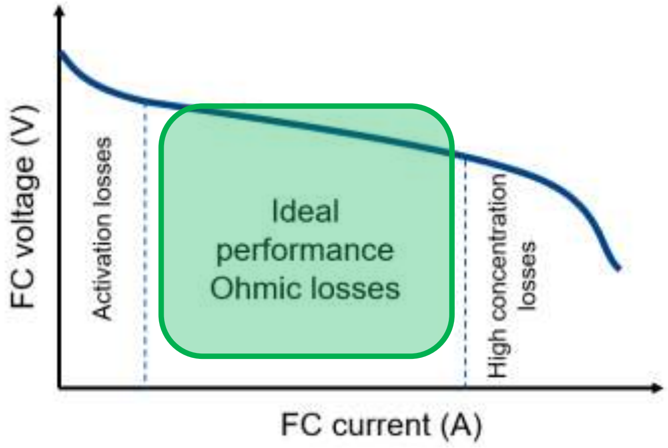




H2 fuel cell SC hybrid example

Necessity for supercapacitor/battery in FC drive

1. Fuel cell lifetime improvement:
   1. Lifetime is very dependent on load fluctuations => energy storage is a must for load balancing
   2. FC membrane is extremely sensitive for air pollution => periodic short circuiting helps to clear pores (x00ms per every x0 seconds => energy storage to provide load backup
2. Fuel cell performance improvement:
   1. Startup: fuel cells startup takes time 30-60s, not ready instantly, but supercap can help to speed it up
   2. Energy absorbtion: supercap is being charged. It's a must, very critical for safety and lifetime of fuel cell
   3. Power boost: rapid changes in power can only be followed by an external boost source = supercap or battery

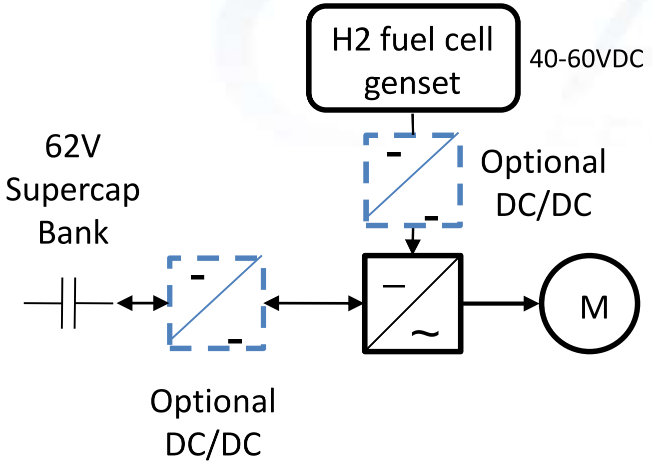


Example – H2 FC Engine

Fuel cell engine:

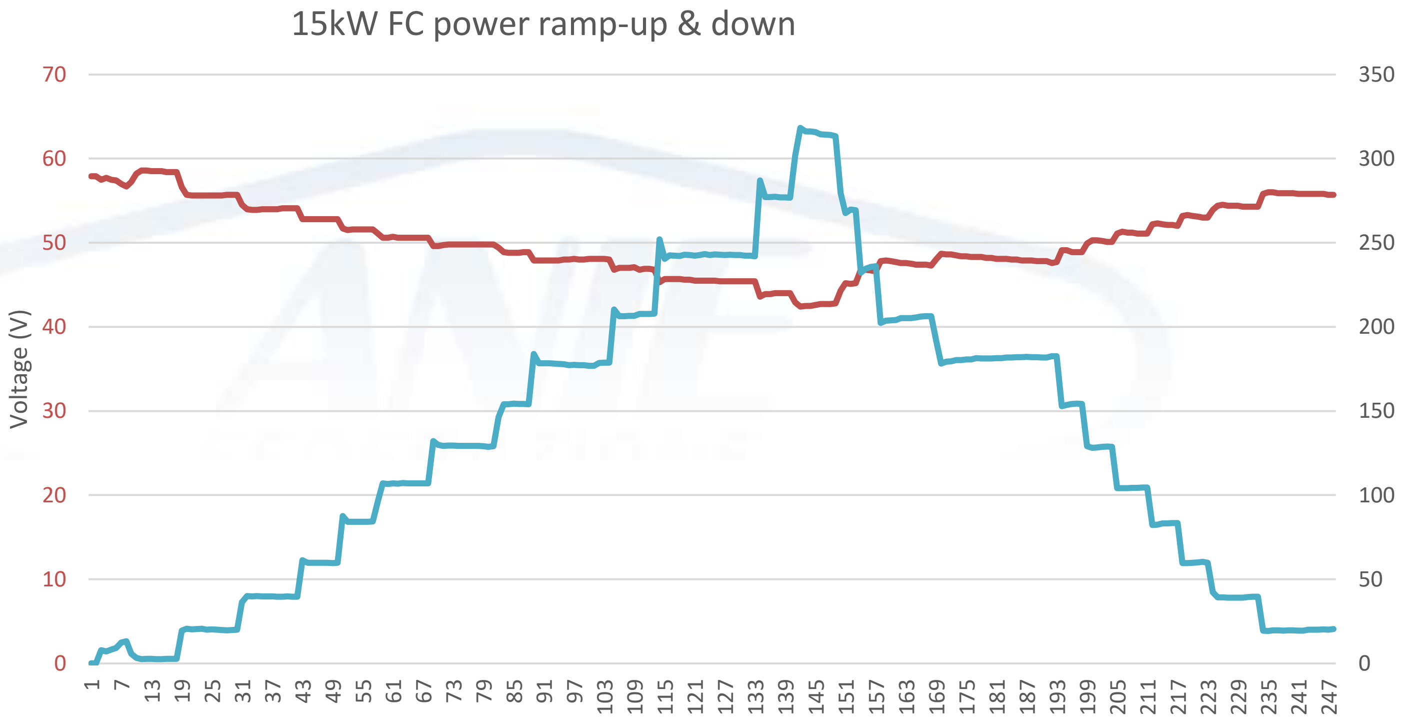
- 15kW max power
- 60V max output voltage
- 1kW/s max load fluctuation

DC peak shaving Architecture



Example – H2 FC Engine

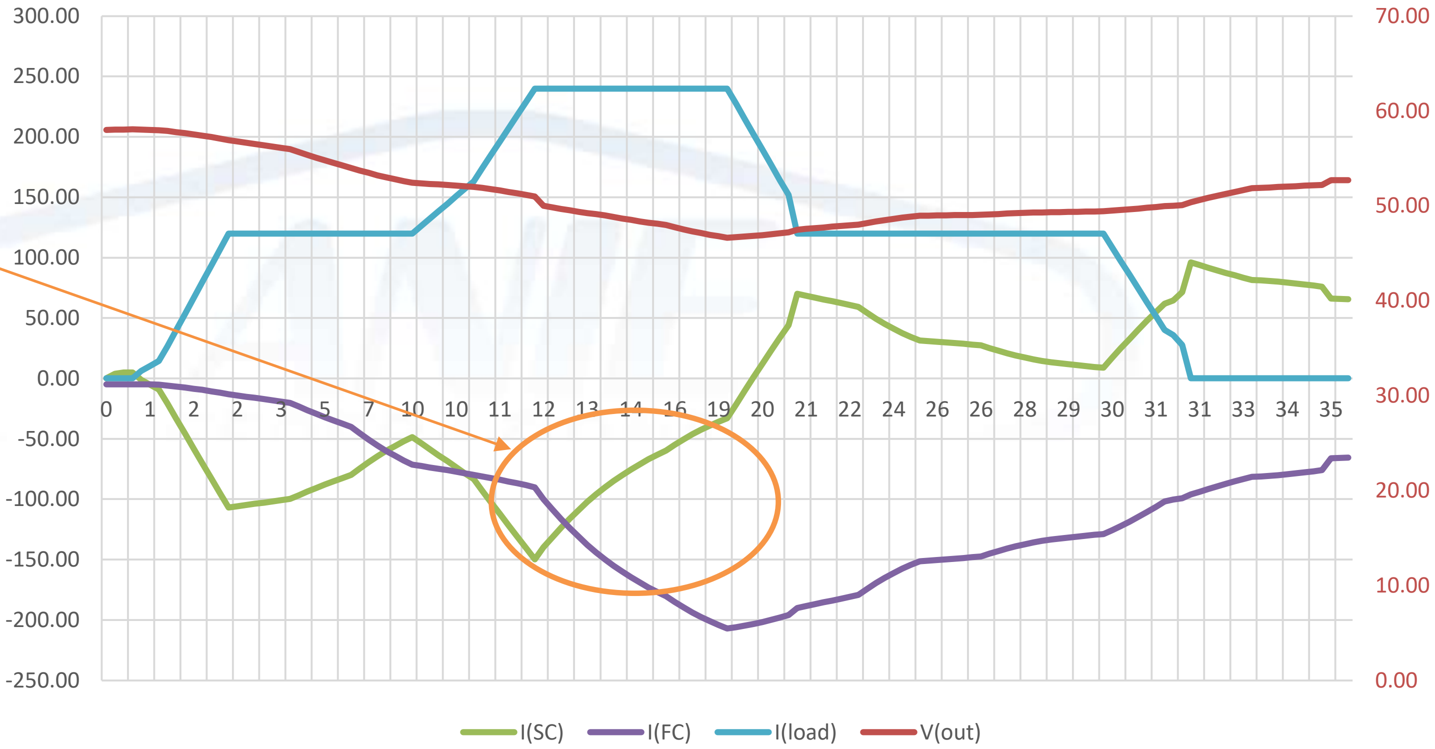
- 1kW/s rampup&down rate respected
- Limited performance for load changes especially for vehicles

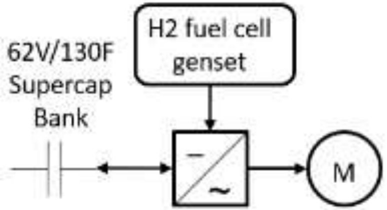


FC+SC Direct Parallel Connection

- The FC ramp rate is difficult to control in case the SC is being discharged too deep => Pout is dropping
- SC charge power is not controlled => Pout is dropping due to the heavy load request from the capacitors

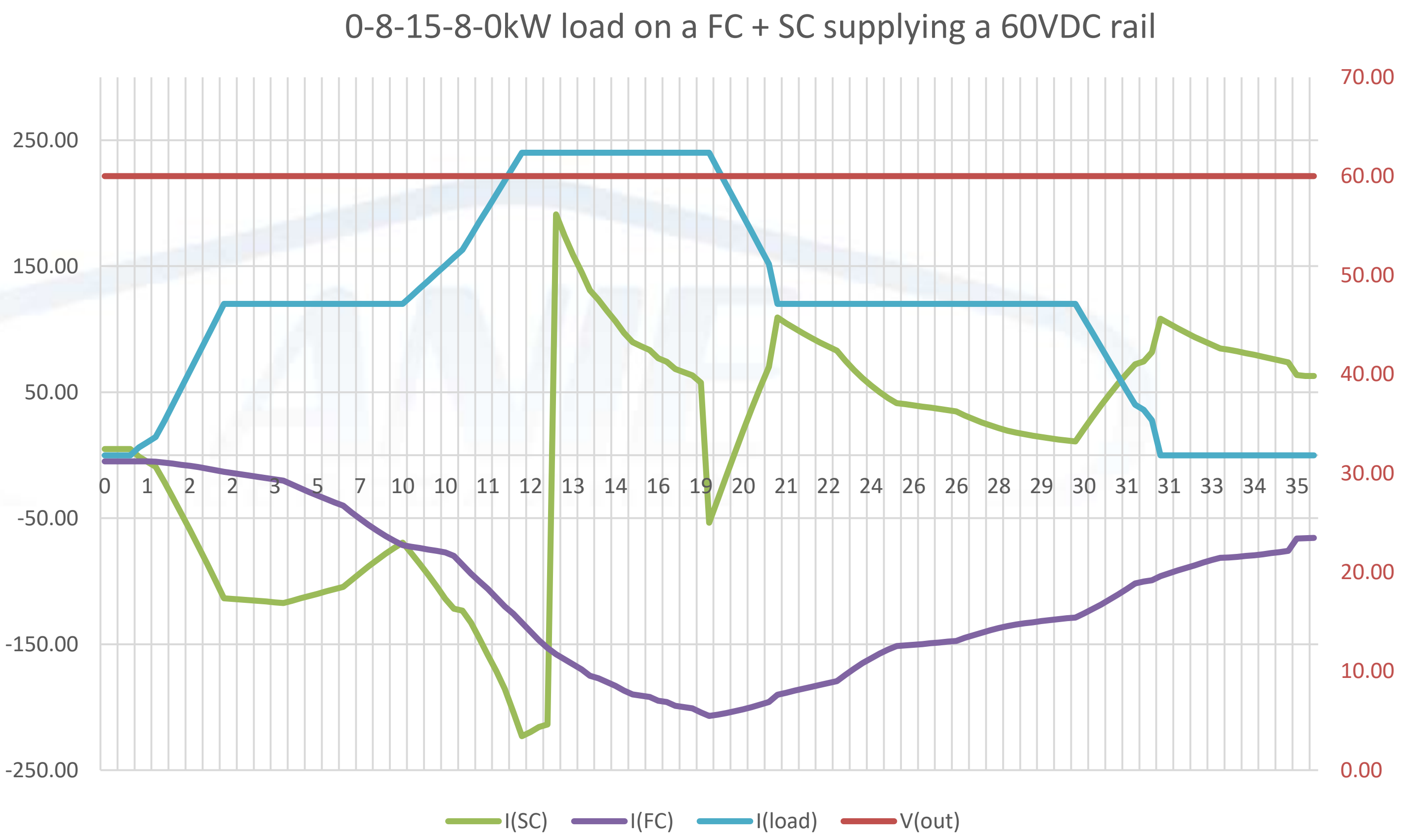
0-8-15-8-0kW load on a FC + SC direct parallel drive

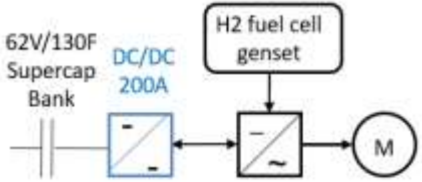




FC+SC Connected Through DC/DC Converters

- Pout can be maintained at all situation
- SC is excersized much more to stabilize the output





Takeaways

1. Hybrid energy storage systems in predictible duty cycle vehicles makes sense
2. Using DC/DC converters and smart architectures allows optimized system sizing (weight, cost, performance & efficiency)
3. Supercapacitor technology can support to act as a power booster/filter in a scaleable way to support 0.5-30s peak power demands very effectively and cost efficiently for even megawatt systems

Q&A

THANK YOU!