Supercapacitors for Transportation Applications

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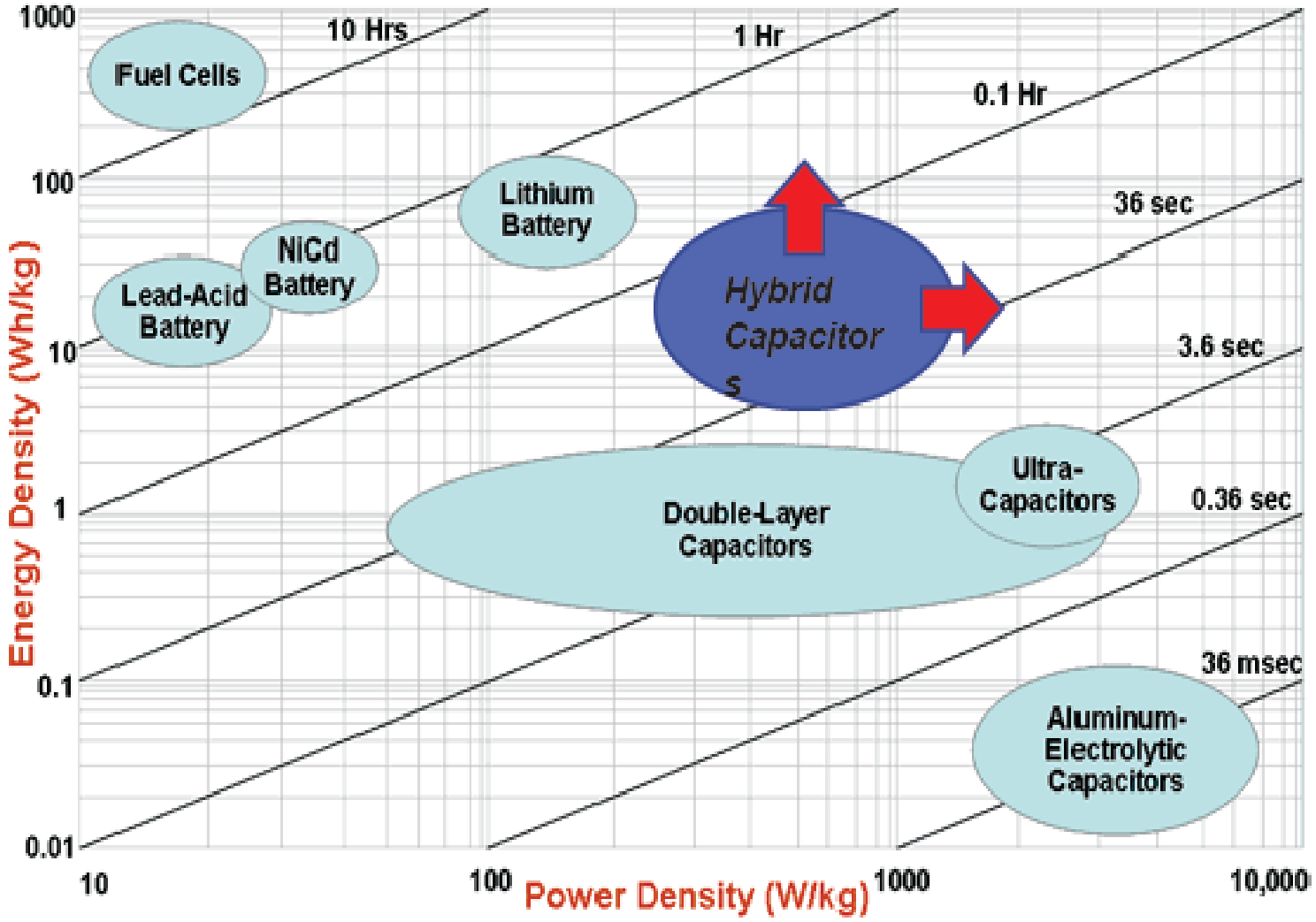
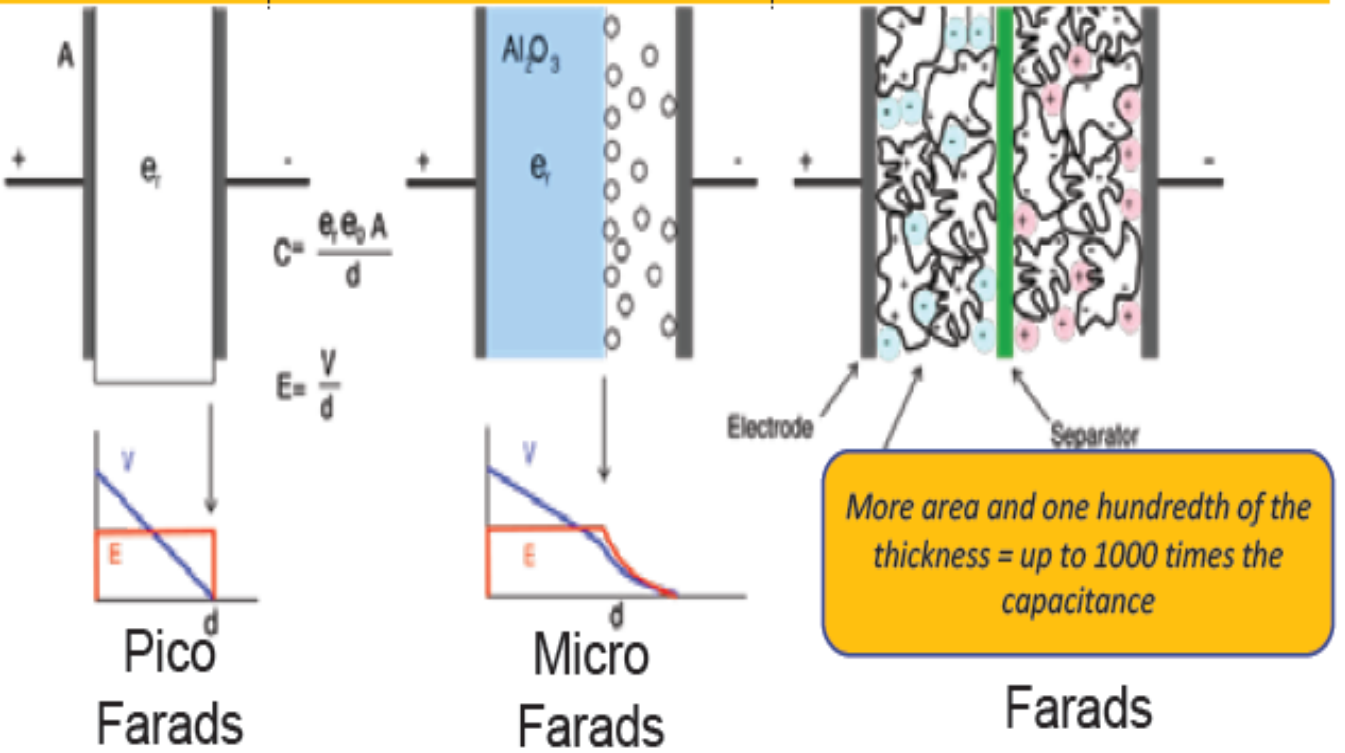
Ragone plot



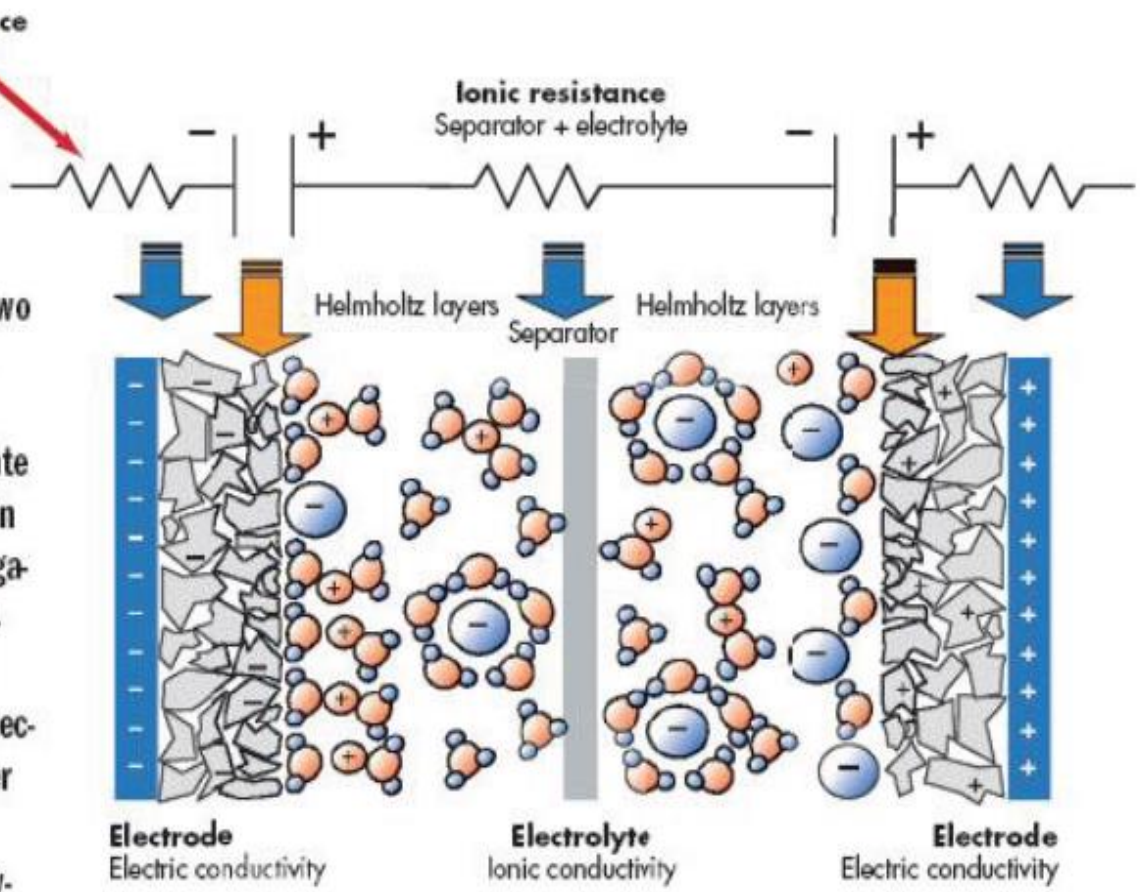
Source US Defence Logistics Agency

Types of capacitor

Traditional Capacitors Have a dielectric between the electrodes		Supercapacitors Have an electric double layer between electrolyte and each electrode (two capacitors in series)
No electrolyte	Electrolyte to contact/ heal thin dielectric on porous electrode	Has electrolyte to create double layer No dielectric



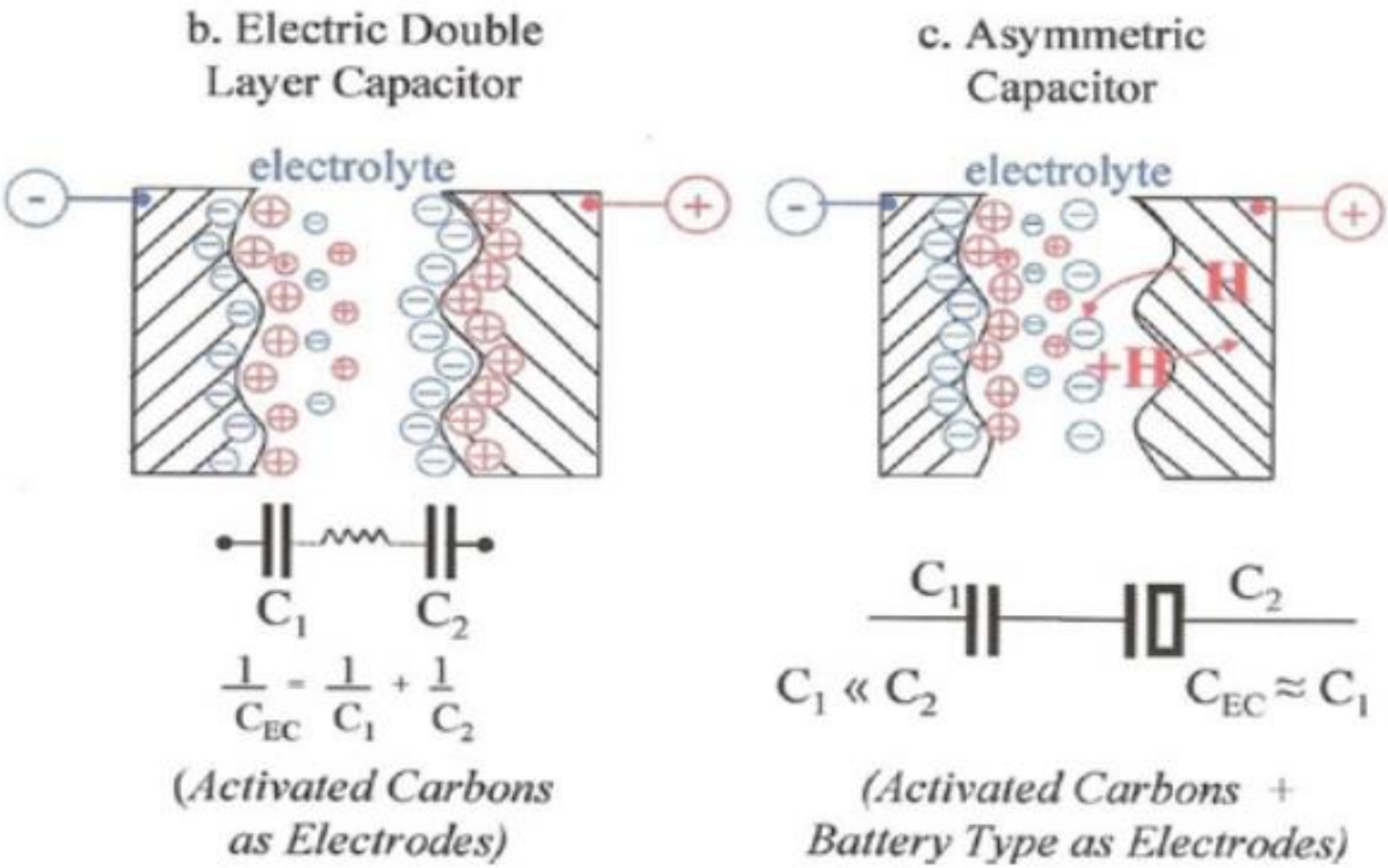
A supercapacitor (EDLC) is a symmetrical device



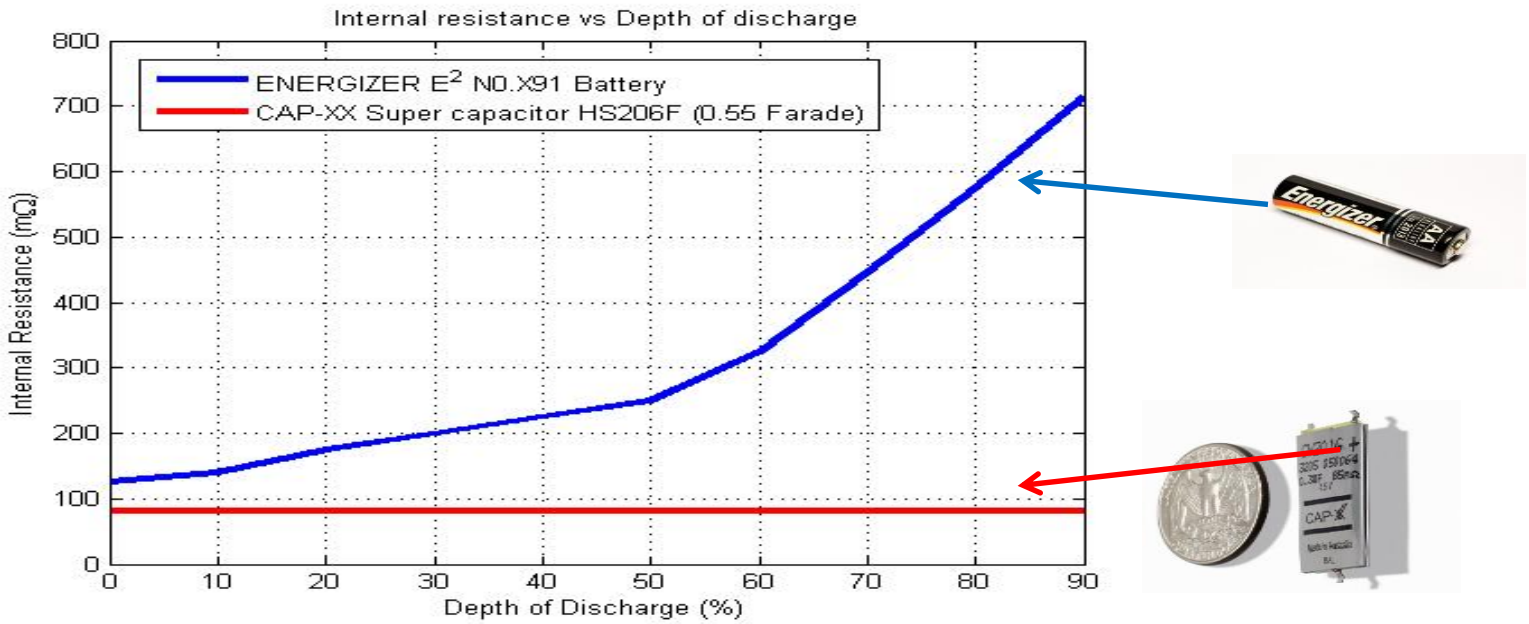
1. An ultracapacitor essentially comprises two plates and a separator suspended in an electrolyte. The positive plate attracts negative ions in the electrolyte. The negative plate attracts positive ions. This creates what is known as an electrochemical double-layer capacitor (EDLC), in which there are two layers of capacitive storage.

$$E = \frac{1}{2}CV^2 \qquad P = \frac{1}{4R}V^2$$

Hybrid SCs versus EDLC



Internal Resistance of Battery versus a SC



- In any battery the internal resistance keeps increasing with the depth of discharge
- In a supercapacitor equivalent series resistance is relatively constant over the depth of discharge
- Given this situation, the maximum current and power deliverable by a SC is only limited by its voltage.

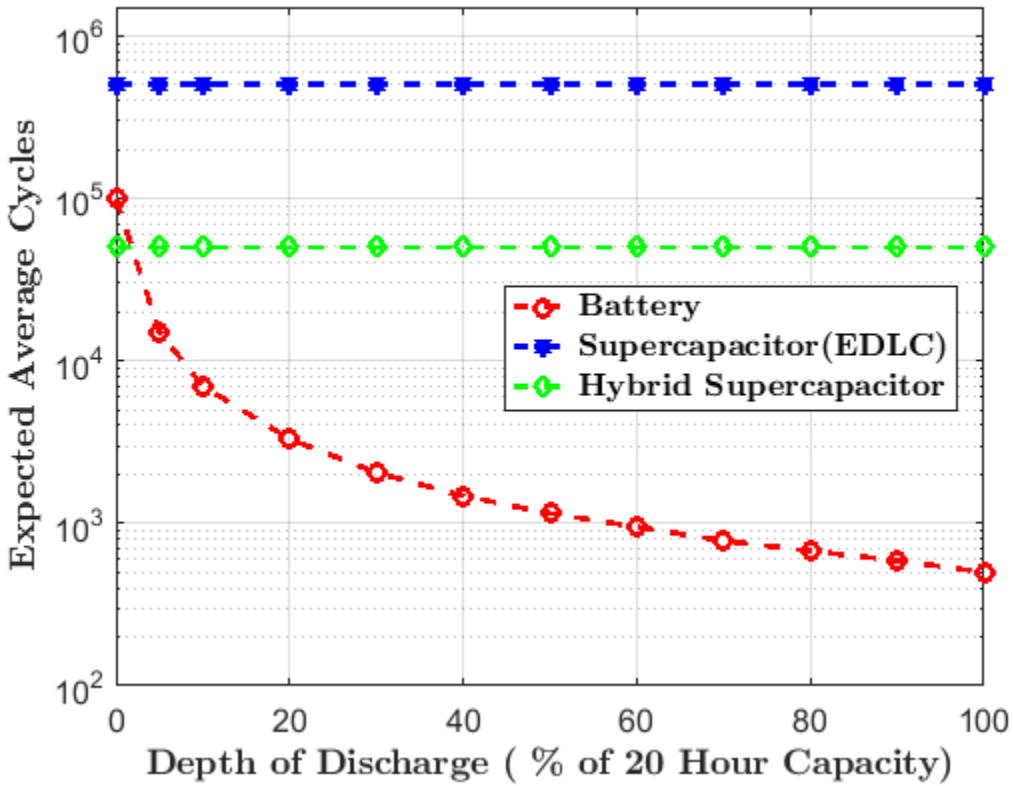
Comparison of practical devices

Image	Device Type	Manufacturer	Capacitance	Voltage Rating	ESR (mΩ)	Total Energy Storage Capability	Maximum possible output power (load resistance=ESR)
	Supercapacitor	LS Mtron	3000 F	2.7 V	0.36	10.9 kJ	6.07 kW
	Electrolytic capacitor	Cornell-Dubilier	2200 µF	50 V	71	2.75 J	8.8 kW
	Hybrid supercapacitor	Samwha Electric	7500 F	2.8 V	0.8	29.4 kJ	2.45 kW
	Disposable energizer cell –C type	Energizer	8.35 Ah	1.5 V	324 mΩ	45.1 kJ	1.73 W
	Li-ion cell	Panasonic	3.4 Ah	3.6 V	50 mΩ	11.52 kJ	64.8 W

An overall comparison – Key specifications based

	Power density max	*Energy density max*	*Cycles*	*Low temperature range*
Li-ion battery	3 kW/kg	200 Wh/kg	500 - 1000	0°C to 60 °C
Supercapacitor	10 kW/kg	10 Wh/kg	1 000 000	-40°C to 80 °C
Hybrid supercapacitor	5 kW/kg	25 Wh/kg	>10 000	-20°C to 60 °C

Depth of discharge and cycle life



Battery and Supercapacitor – Pros and Cons

Supercap Pros

- **High Power → Low Cost/KW**
- **Fast charge acceptance**
- **High Cycle Life (1million) → LowCost/cycle**
- **>95% Charge Efficient** and **Charge Acceptance for life**
- Wide temp operating range -40oC to 80oC
- Extends Battery Life
- DOD/SOC do not affect life

Supercap Cons

- High Cost per Whr (when not sized properly)
- DC/DC converter required
- Self discharge
- Low ultracap literacy rate
- Full value proposition requires crossing silos

Battery Pros

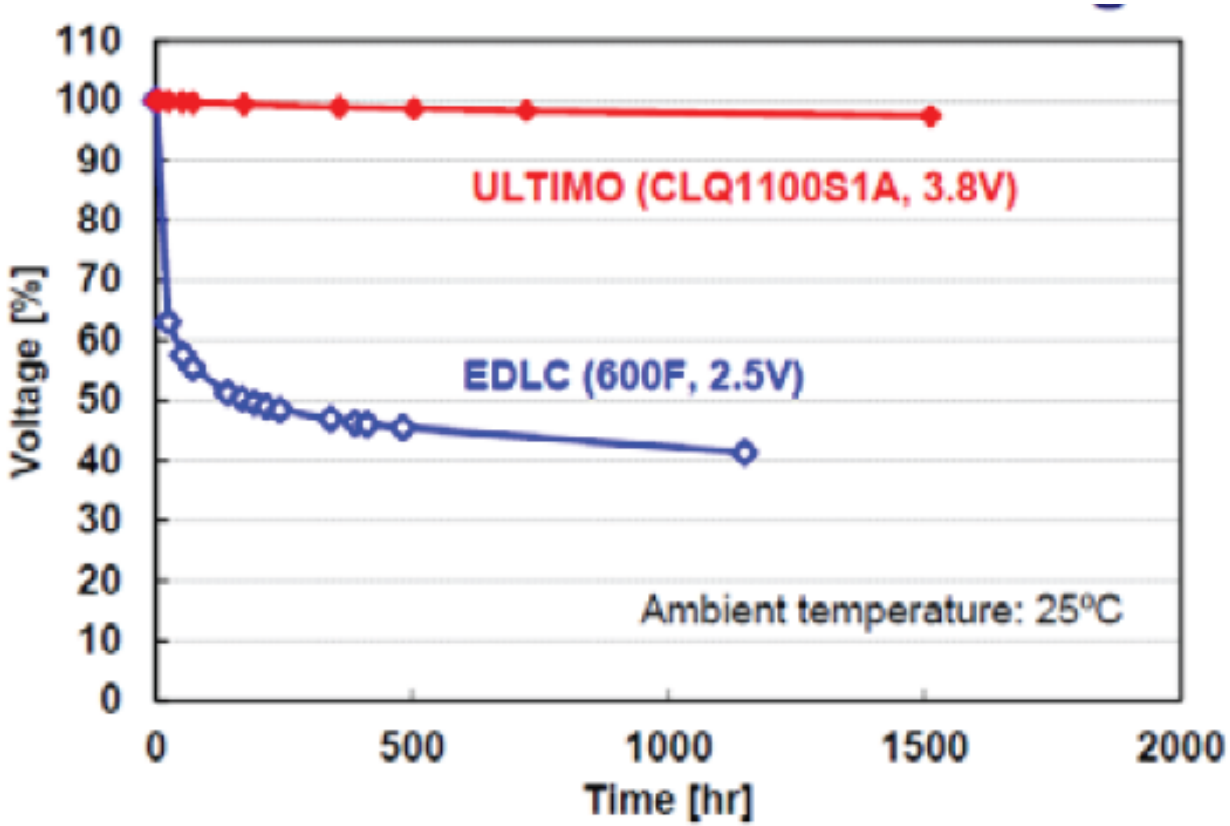
- **High Energy**
- **Low Cost / Whr**
- **Widely Available**
- **People know batteries**

Battery Cons

- Low Power
- High Cost / KW
- Close attention to DOD/SOC required
- Recycling/safety issues
- Poor low temp performance
- 70-80% Efficient
- Charge acceptance quickly falls based on battery age and DOD

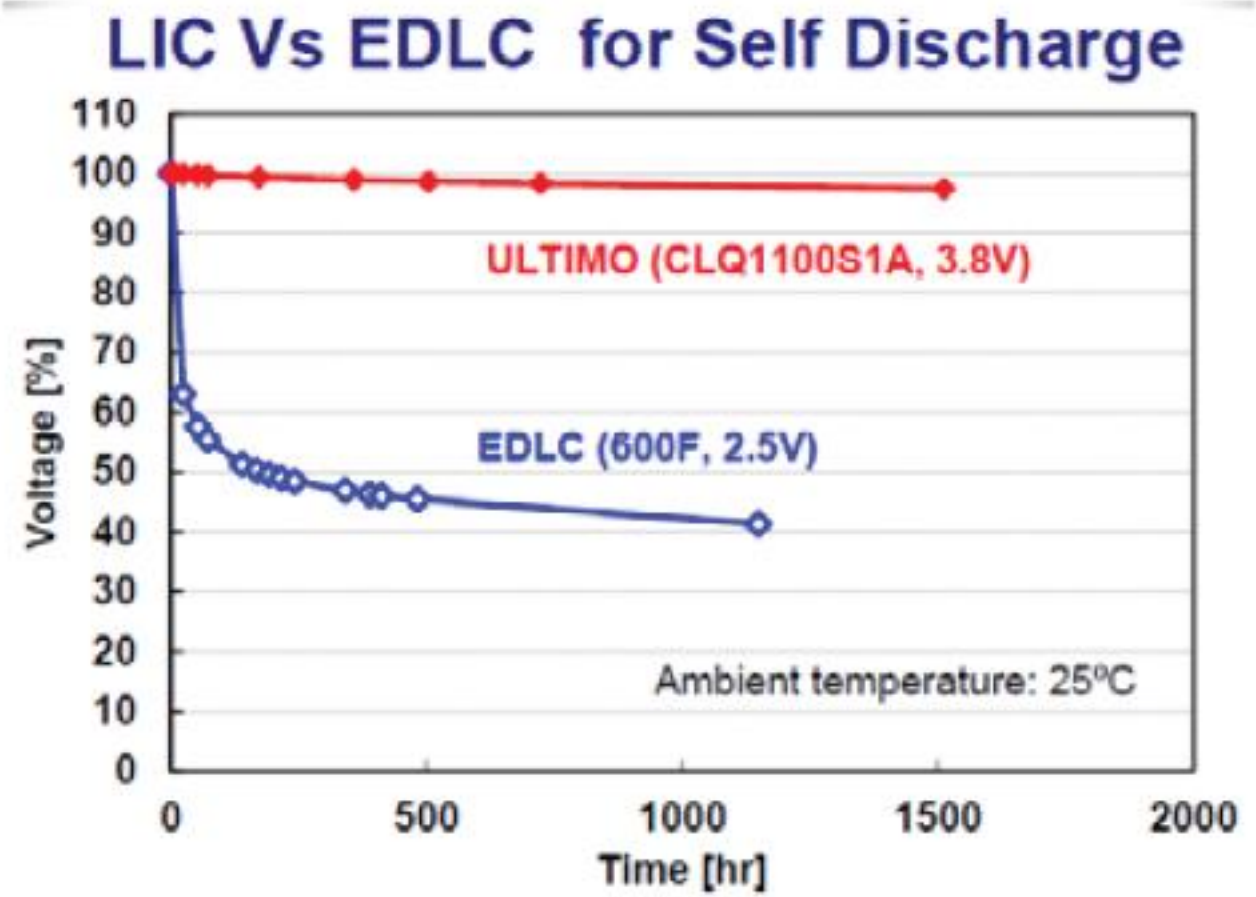
Self-discharge of supercapacitors

- All types of supercapacitors have higher self discharge compared to Li-ion batteries
- However, if you design a system for short-term use of pre-stored energy SCs are still ok.
- Hybrid types have better performance than symmetric devices



Source: JSR Micro

Self Discharge



Source: JSR Micro

SCs versus electrolytics

TABLE 2. COMPARISON OF TYPICAL ELECTROLYTIC CAPACITORS AND SUPERCAPACITORS FOR THEIR ESR VALUES AND OTHER USEFUL SPECIFICATIONS						
ENERGY STORAGE LIMIT	CAPACITOR TYPE	MANUFACTURER	PARAMETERS			
			CAPACITANCE (μF/F)	TERMINAL VOLTAGE (V)	SHORT CIRCUIT CURRENT (A)	ESR (m Ω)
Less than 1J	Electrolytic	RSS	2200 μF	16	104	153
1-5 J	Supercap	Maxwell	1 F	2.7	3.85	700
		Cap-xx	2.4 F	2.3	115	20
	Electrolytic	Cornell Dubilier	2200 μF	50	704	71
5-50 J	Supercap	Maxwell	10 F	2.5	14	180
		Cap-xx	1.2 F	4.5	112.5	40
		Nesscap	10 F	2.3	33	70
	Electrolytic	Cornell Dubilier	82,000μF	16	1441	11.1
		VICOR	270 μF	200	325	614
Above 50 J	Supercap	Maxwell	350 F	2.7	840	3.2
		Nesscap	120 F	2.3	144	16

In general, SCs have lower ESR than the electrolytic capacitors, but their DC voltage rating is very low.

Nomenclature

Traditional Capacitors	Supercapacitors (symmetrical – usually carbon on a metal electrode on either side)	Hybrid supercapacitors (one supercap electrode + one battery electrode)	Batteries
	Electrochemical Double Layer Capacitors EDLC	Asymmetric Electrochemical Double Layer Capacitors AEDLC	
	Ultracapacitors	When based on a lithium-ion battery – "lithium capacitor" or "Lithium-ion capacitor"	
		When based on a lead acid battery – trade name	

STORES MORE ENERGY Wh/kg or Wh/l

DELIVERS MORE POWER W/kg or W/l

Traditional Applications of Supercapacitors

•In general supercapacitors have much less energy density than batteries

•But their power delivery capability (Watts/kg) is quite high compared to batteries

•Large supercapacitors have very low ESR in the range of few mΩs to fractional mΩs

Common supercapacitor applications are in

- UPS systems
- Wind turbine systems
- Electric vehicles/ Fork lifts/ Hybrid buses
- Utility voltage stabilizer systems
- Photo voltaic systems
- Memory back up systems

- In many of these applications battery-supercapacitor hybrid systems are used

Which characteristics of ESS are useful in transportation?

- All transportation systems have several essential engineering components
  - A prime mover
  - An energy storage system (ESS) to drive the prime mover
  - A transmission system
- When the systems become electrically driven we require
  - An energy storage system
  - Electric wheel motors and the controller units
  - Charging system
- In EVs, HEVs and PHEVs energy storage systems can be in few common forms
  - Battery packs
  - Battery –SC hybrids
  - Supercapacitors
  - Fuel cells
- **Given the above, following primary specifications matter in [an electrical] energy storage system**
  - **Energy density –** dependent on the device technology
  - **Power density-** dependent on the open circuit voltage and the internal resistance
  - **Useful temperature range -** dependent on the device technology
  - **Cycle and calendar life -** dependent on the device technology
  - **Self discharge -** dependent on the device technology

In supercapacitors, power density is very high, and the operational temperature range in wider and cycle life is very much larger than batteries

Three main market segments for supercapacitors

Consumer
- Burst Power
- Battery Life Extension
- Quick Charge

Industrial
- Burst Power
- Regenerative Power
- Back up Power

Transportation
- Burst Power
- Regenerative Power

In addition there are many new and non traditional applications – i.e SCA Techniques

Supercapacitors in transportation systems

- In transportation systems, energy source should be as large as possible
- An internal combustion engine (ICE) and the fuel tank combination still wins- due to high energy density of fossil fuels
- In electric vehicle arena, electrical specifications of the ESS come into play
- Very high power density (result of lower ESR) of a SC bank, it helps in quick acceleration
- However, lower energy density means a lower driving range
- Batteries are having much lower cycle life than SCs
- Internal resistance of battery keeps increasing
  - With the age
  - With the depth of discharge
- (Internal resistance increases internally dissipated heat in the ESS)
- In SCs, due to constant ESR, heat dissipation due to ESR does not matter
- Very long life cycle of SCs is a definite advantage.
- **Only major disadvantage of SCs is the high manufacturing cost**

SCs in Transportation - Three major application areas

- Hybrid –electric transit buses [In USA and China]
- Electric braking systems in passenger cars
- Stop-go hybrid vehicles

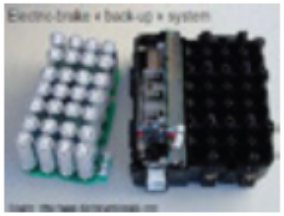
Stop-Start Systems

Engine shuts off when car stops (red light). SC provides braking power. AGM lead acid batteries broadly adopted. SC perform better in operational lifetime. Cost parity between AGM and SC will be reached soon. AGM 70% charge acceptance in 8 month (Ioxus,2014).

Energy Recovery

SC perform better than lithium batteries. 80% energy can be recovered as opposed to 30% in batteries. Energy stored can be released when accelerating.

Power Back-up



Last resource for power in electronically-controlled back

Need for rapid discharge

22 x 100F ultracaps are used in the Toyota Prius II's electronically controlled brake.

Production began 2007

Power Buffering

Fuel cells and battery degrade faster when exposed to frequent high power demands. Fuel cells efficient operation point is at constant power. 17% efficiency over a pure FC system Addresses of PEMFC degradation (Imperial College 2013) .

Source credit: ID TechEx

Automotive sector companies utilizing supercaps

GM	*Continental Automotive Systems' Maxwell-powered voltage stabilization system (VSS) will be a standard feature on 2016 Cadillac ATS and CTS sedans and ATS coupes, excluding the ATS-V, CTS-V and CT6 models.*
PSA PEUGEOT CITROËN	*Peugeot 308 and other diesel platforms use supercapacitors in stop start systems*
BOSCH BoschEngineering	*Supercaps have become the cheapest high power energy storage technology for power discharges below 13 seconds and below 25oC , that means all sports cars and cold weather countries.*
TOYOTA BMW	*Toyota's TS040 winner racing car integrates supercapacitor technology. BMW-Toyota sports car partnership may integrate the technology in the future.*
LAMBORGHINI	*Automobili Lamborghini S.p.A., incorporated support a stop-start idle-elimination system in all Lamborghini's Aventador cars*
HONDA The Power of Dreams	*Honda developed a supercapacitor system to buffer high power in their FCX fuel cell car platform.*
mazda	*Mazda uses supercapacitors in their i-Eloop energy recovery system.*

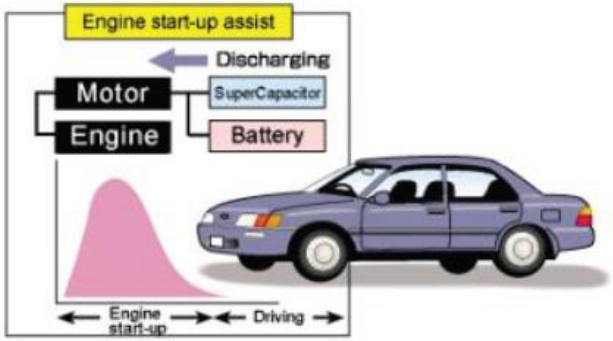
Source credit: ID TechEx

Transportation Applications

Truck starters which allow replacing several lead acids and operating down to -40 ^{0}C

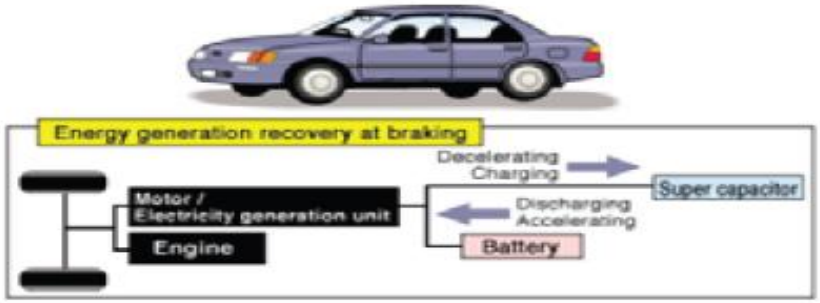
8. Maxwell's BMOD series modules offer capacitance values up to 500 F at 16.2 V dc and 63 F at 125 V dc.

Start stop systems in micro hybrid cars – ie Citroen / Continental



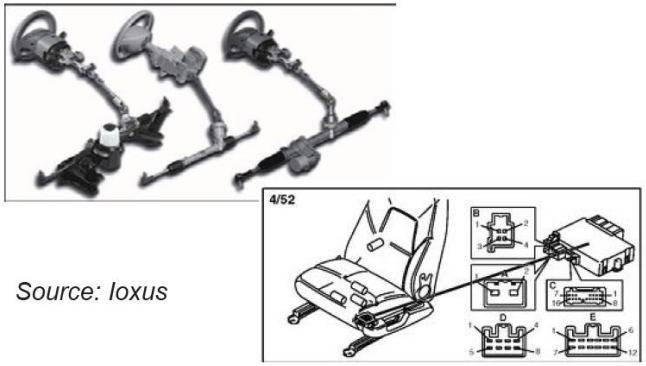
Source: NEC-Tokin

Energy recovery in hybrid cars – 80% recoverable by SC compared to 30% by batteries



Transportation Applications – contd..

Power at the point of demand



Source: Ioxus

Electronic Controlled Brake

22 x 100F ultracaps are used in the Toyota Prius II's electronically controlled brake. Production began in 2007

Souce: Ioxus

Sportscars use supercaps

Made to run without an onboard starter for reasons of saving mass. Instead a supercapacitor system will be used.

"The combined mass reduction from removing the starter and using the supercapacitor system has roughly the same impact on the car performance as the switch to the significantly more powerful race engine!"

Benoît Dupont
Renault-Sport's circuit Technical Manager

Bombardier light rail and others use supercapacitor energy harvesting recovering up to 35% of electricity on braking of trains and trams. This used to be done with lithium-ion batteries

Tolerates faster charging. Fit and forget. Space/cost not a problem.

Hybrid energy systems

Supercapacitors assist fast charging in ABB's TOSA bus charging system in Geneva

Hybrid Bus - USA

Hybrid Electric Bus Drive Trains
Several 100 buses in operation
→ ISE Research, CA – leader in advance energy systems

→ Diesel-electric
→ Gasoline-electric

Source: Maxwell Technologies

Any hybrid bus is capable of running on the electrical energy stored aboard in supercaps or batteries, for a range going from about **400m** (supercaps) to **2km** (batteries), but in a degraded mode (limited acceleration, influence on lifetime for batteries…).

For example, the HESS 24m vehicle can ride up to **500m** on supercaps

Source: Maxwell Technologies

CSR China – Hybrid Electric Bus

Aka: TEG (Times Electric Group)

48V modules per bus

10 series for Series-Parallel Hybrid

15 series for Series Hybrid

2009: 300 buses ~ 3800 modules

2010: 500 buses ~ 6,000 modules

2011: 750 buses ~ 9,000 modules

Source: Maxwell Technologies

Fork lifts to Aircrafts

Forklifts

- Increase usable time per battery charge by 33%
- Increase battery life by 2x – 4x

Not replacing

SC in Lifting operations + Energy Recovery from Short Trips

- Not practical to run only on SC
- Dinamic Duty Cycle Several vertical and horizontal acelerations
- Max Power demand during 30 s
- Opportunity for the capture regenerative of energy

Source: Ioxus

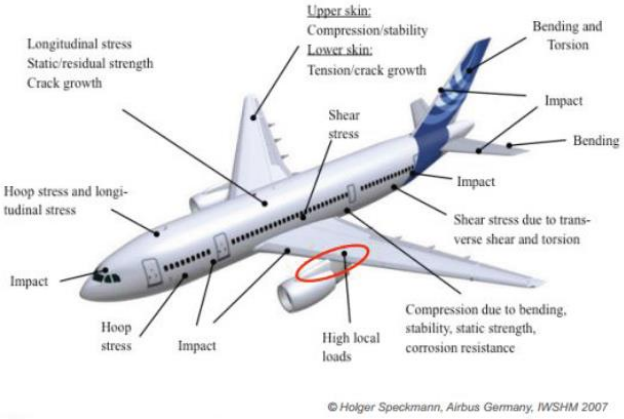
Supercapacitors applications in Aerospace

Promising applications include:

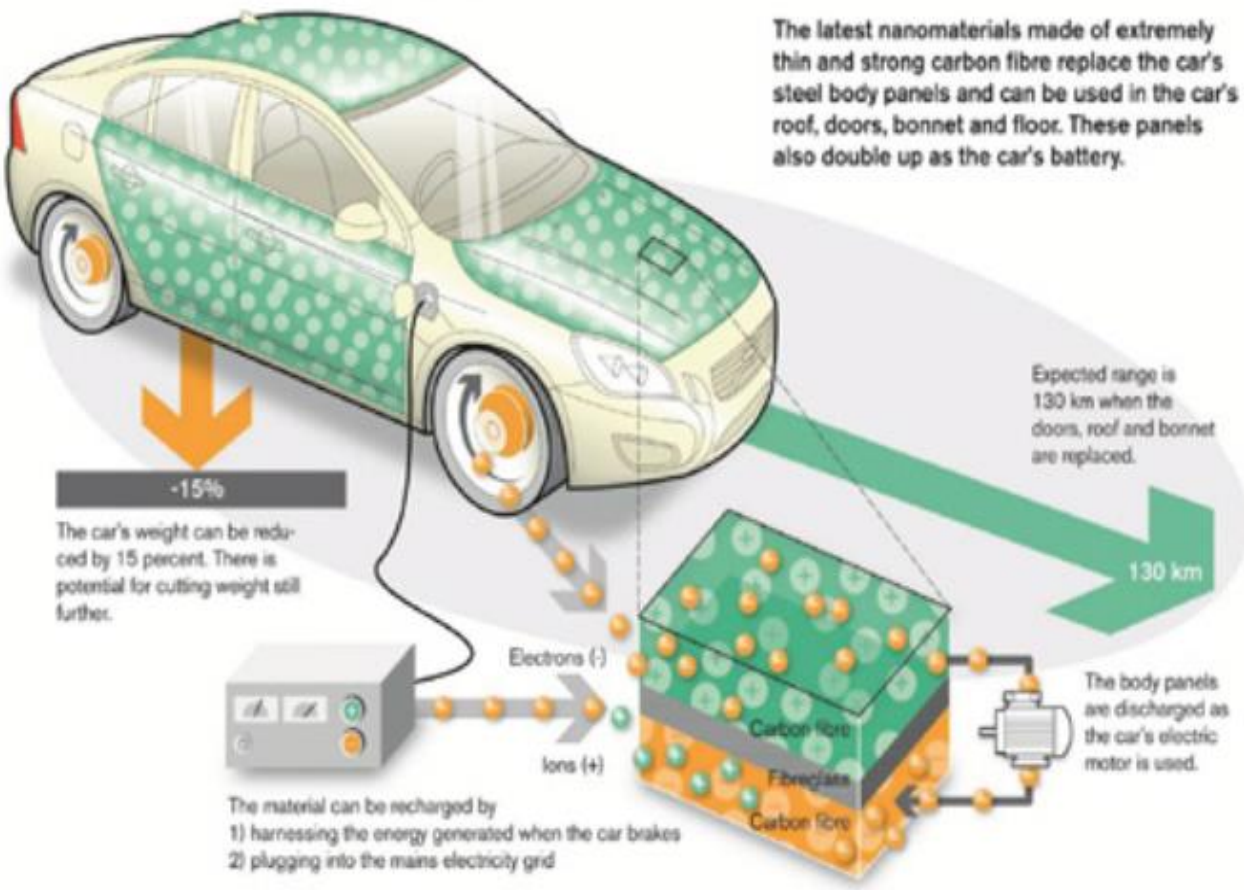
- Autonomous Wireless Sensors Networks (on-ground tests and flight)
- High power radar
- Energy reserve for calculator
- Simplification of the pyrotechnics chain
- High power actuators for the control of attitude
- Activation of electromechanical conduits
- Robot supply for exploration missions

<u>As well as using supercapacitors to compensate the battery for power and energy applications (hybridization)</u>

Source: Airbus Defence&Space



Supercapacitors in the future- Structural Energy Storage



Thank you…..

Question Time…

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