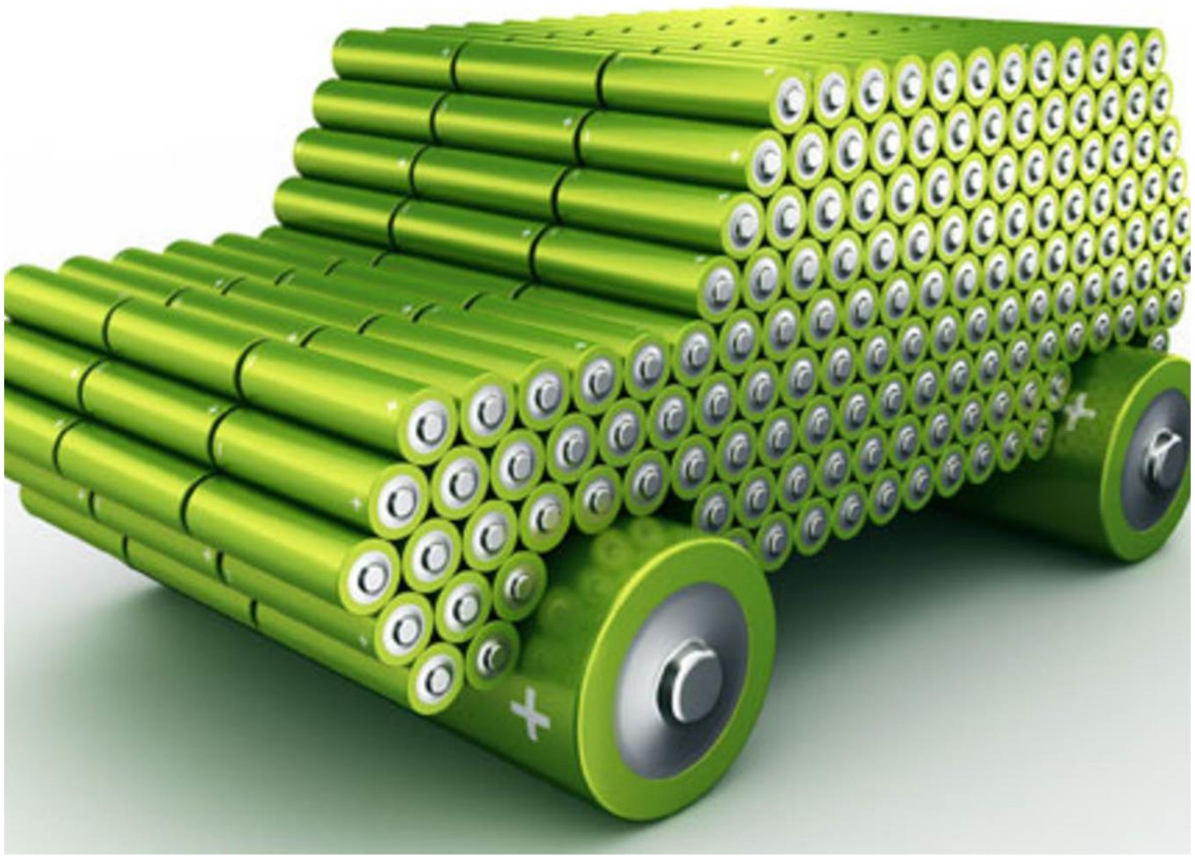
Hybrid Electric Vehicles: **EE 6435 D**

Module 3



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Overview of Batteries

From the electric vehicle designer's point of view the battery can be treated as a 'black box' which has a range of performance criteria. These criteria will include:

- ✓ **Specific energy**
- ✓ **Energy density**
- ✓ **Specific power**
- ✓ **Typical voltages**
- ✓ **Amp hour efficiency**
- ✓ **Energy efficiency**
- ✓ **Commercial availability**
- ✓ **Cost, Operating temperatures**
- ✓ **Self-discharge rates**
- ✓ **Number of life cycles**
- ✓ **Recharge rates**

The designer also needs to understand how energy availability varies with regard to:

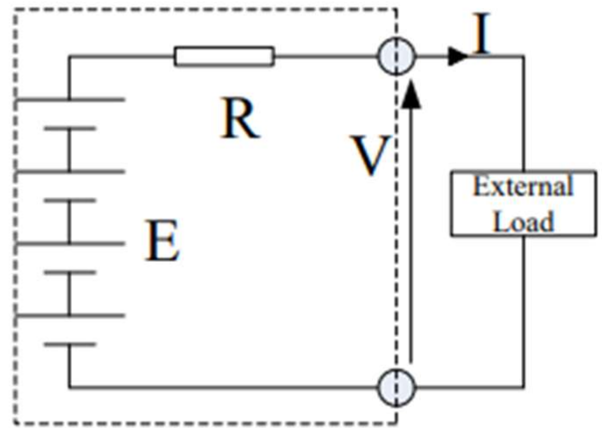
- ✓ Ambient temperature
- ✓ Charge and discharge rates
- ✓ Battery geometry
- ✓ Optimum temperature
- ✓ Charging methods
- ✓ Cooling needs

However, at least a basic understanding of the battery chemistry is very important, otherwise the performance and maintenance requirements of the different types, and most of the disappointments connected with battery use, such as their limited life, self discharge, reduced efficiency at higher currents.

Battery

Cell and battery voltages

All electric cells have nominal voltages which gives the approximate voltage when the cell is delivering electrical power. The cells can be connected in series to give the overall voltage required. The ‘internal resistance’ and the equivalent circuit of a battery .
The battery is represented as having a fixed voltage E, but the voltage at the terminals is a different voltage V , because of the voltage across the internal resistance R.



Charge (or Ahr) capacity

The electric charge that a battery can supply is clearly a most crucial parameter. The SI unit for this is the Coulomb, the charge when one Amp flows for one second. The capacity of a battery might be, say, 10 **Amp-hours**. This means it can provide 1Amp for 10 hours.

Energy stored

The energy stored in a battery depends on its voltage, and the charge stored. The SI unit is the Joule, but this is an inconveniently small unit, and so we use the Whr instead.
Energy in Whr = V*Ahr

Important Specifications of Battery for EV

Specific energy

Specific energy is the amount of electrical energy stored **for every kilogram of battery mass**. It has units of $Wh.kg^{-1}$.

Energy density

Energy density is the amount of electrical energy stored **per cubic meter of battery volume**. It normally has units of $Wh.m^{-3}$.

Specific power

Specific power is the amount of power obtained per kilogram of battery. It is a highly variable and rather anomalous quantity, since the power given out by the battery depends far more upon the load connected to it than the battery itself.

Ahr (or charge) efficiency

In an ideal world a battery would return the entire charge put into it, in which case the amp hour efficiency is 100%. However, no battery does; its charging efficiency is less than 100%. The precise value will vary with different types of battery, temperature and rate of charge. It will also vary with the state of charge.

Important Specifications of Battery for EV

Energy efficiency

This is another very important parameter and it is defined as the ratio of electrical **energy supplied** by a battery to the amount of electrical **energy required to return** it to the state before discharge.

Self-discharge rates

Most batteries discharge when left unused, and this is known as self-discharge. This is important as it means some batteries cannot be left for long periods without recharging. The rate varies with battery type, and with other factors such as temperature; higher temperatures greatly increase self-discharge.

Battery temperature, heating and cooling needs

Although most batteries run at ambient temperature, some run at higher temperatures and need heating to start with and then cooling when in use. In others, battery performance drops off at low temperatures, which is undesirable, but this problem could be overcome by heating the battery. When choosing a battery the designer needs to be aware of battery temperature, heating and cooling needs, and has to take these into consideration during the vehicle design process.

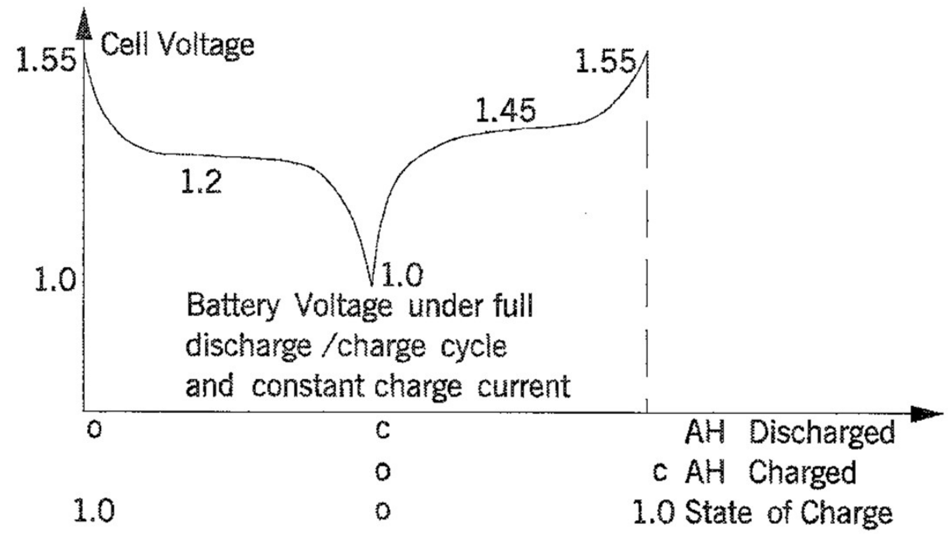
Battery life and number of deep cycles (DoD)

Most rechargeable batteries will only undergo a few hundred **deep cycles to 20%** of the battery charge. However, the exact number depends on the battery type, and also on the details of the battery design, and on how the battery is used. This is a very important figure in a battery specification, as it reflects in the lifetime of the battery, which in turn reflects in electric vehicle running costs.

Performance Characteristics of Batteries

The basic performance characteristics of the battery which influence the design are as follows:

1. **Charge/Discharge voltages.**
2. **Charge/Discharge ratio (c/d ratio).**
3. **Round trip energy efficiency.**
4. **Internal Resistance.**
5. **Charge efficiency**
6. **Self Discharge and Trickle Charging**
7. **Memory Effect.**



1. Charge/Discharge Voltages

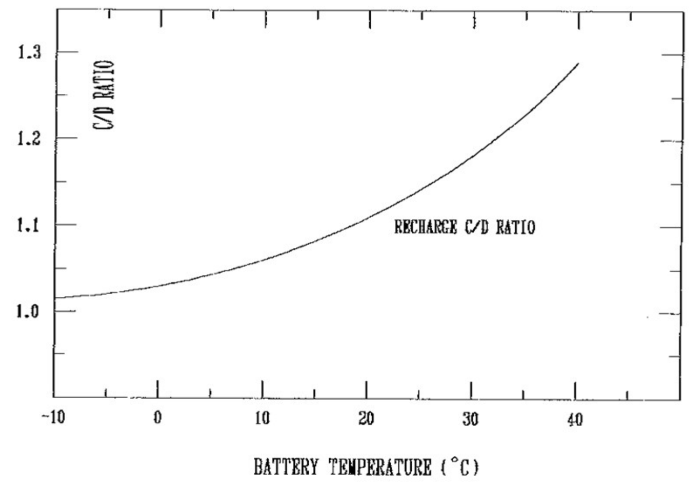
charge = 1.0, or Ah discharged = 0). As the cell is discharged, the cell voltage (Vc) drops quickly to a plateau value of 1.2, which holds for a long time before dropping to 1.0 at the end of its capacity (SOC = 0).

In the reverse, when the cell is recharged, the voltage quickly rises to a plateau value of 1.45 and then reaches a maximum value of 1.55 volts. The charge/discharge characteristic also depends on how fast the battery is charged and discharged.

Performance Characteristics of Batteries

2. Charge/Discharge ratios

After discharging certain Ah to load, the battery requires more Ah of charge to restore the full state of charge. The charge/discharge ratio is defined as the Ah input over the Ah output with no net change in the state of charge.



This ratio depends on the charge and discharge rates and also on temperature. At 20° C, for example, the charge/discharge ratio is 1.1, meaning the **battery needs 10 percent more Ah than what was discharged** for restoring to fully charged state.

3. Energy Efficiency

The energy efficiency over a round trip of full charge and discharge cycle is defined as the ratio of the **energy output over the energy input** at the electrical terminals of the battery. For a typical battery of capacity C with an average discharge voltage of 1.2 V, average charge voltage of 1.45 V and the charge/discharge ratio of 1.1, the efficiency is calculated as follows:

The energy output over the full discharge = 1.2*C

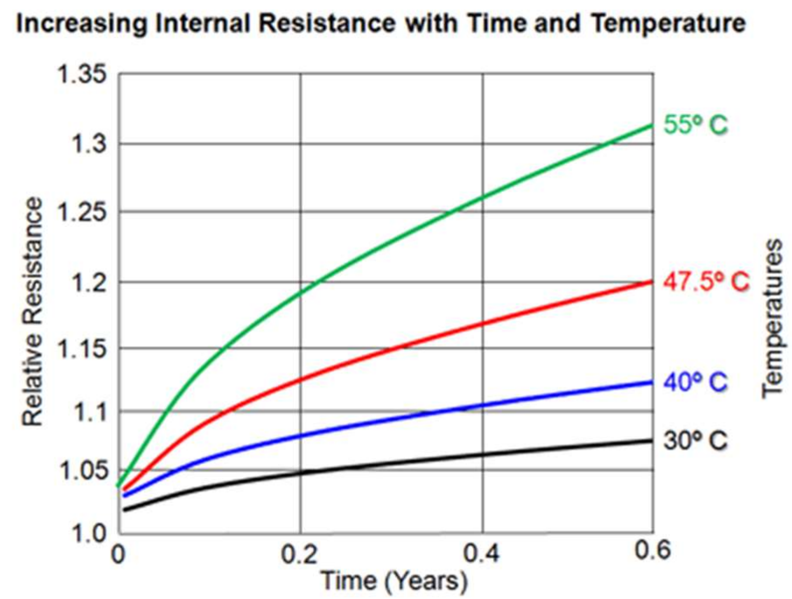
The energy input required to restore full charge = 1.45*1.1 C

Round trip energy efficiency??

Performance Characteristics of Batteries

4. Internal Resistance

The above efficiency calculations indicate that 25 percent energy is lost per charge/discharge cycle, which is converted into heat. This characteristic of the battery can be seen as having an internal resistance Ri. The value of Ri is a function of the battery capacity, operating temperature and the state of charge. The higher the cell capacity, the larger the electrodes and the lower the internal resistance. It also varies with temperature which is for a high quality 25 Ah NiCd cell.



5. Charge Efficiency

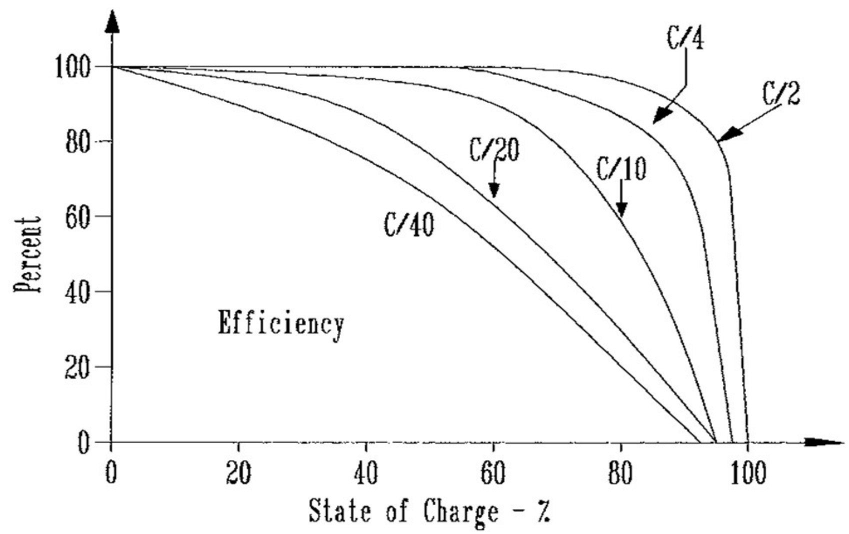
The charge efficiency is defined as the ratio of the Ah being deposited internally between the plates over that delivered to the external terminals during the charging process. It is different from the energy efficiency.

The **charge efficiency is almost 100 percent when the cell is empty of charge**, the condition in which it converts all Ah received into useful electrochemical energy. As the state of charge approaches one, the **charge efficiency tapers down to zero**. The knee point where the charge efficiency starts tapering off depends on the charge rate.

Performance Characteristics of Batteries

For example, at C/2 charge rate, the charge efficiency is 100 percent up to about 75 percent SOC. At a fast charge rate of C/40, on the other hand, the charge efficiency at 60 percent SOC is only 50 percent.

C-Rate indicates the rate at which the battery is being charged or discharged relative to its capacity. Charge – discharge curves typically show steady performance of the batteries excepting close to the fully charged and fully discharged conditions

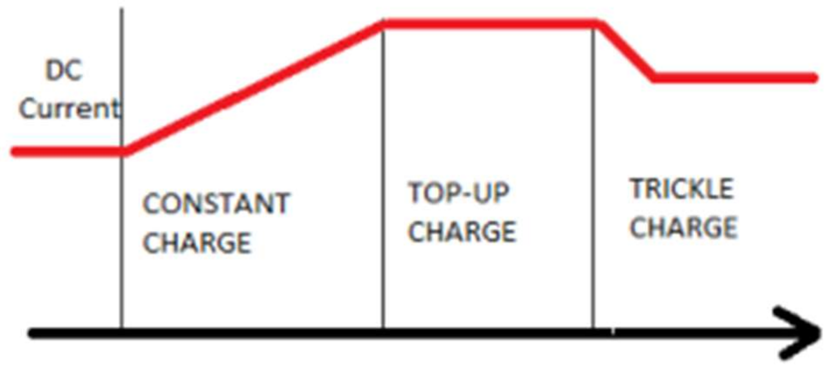


6. Self-Discharge and Trickle Charge

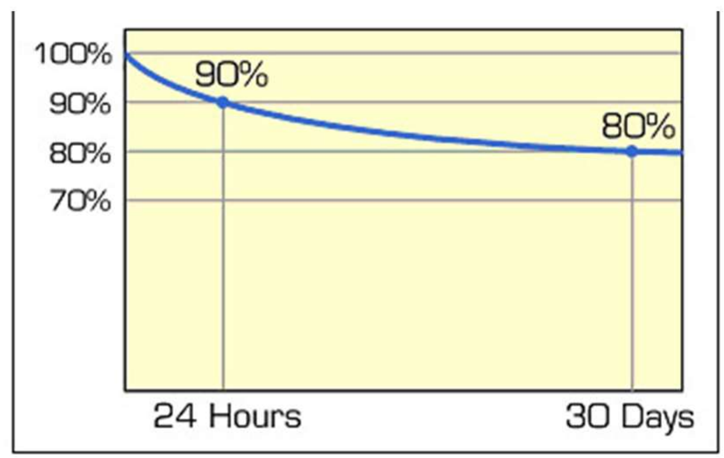
- ✓ Even with open-circuit terminals, the battery slowly self-discharges. In order to maintain the full state of charge, it is continuously trickle-charged to counter the self-discharge rate. This rate is usually **less than one percent per day** for most electro chemistries in normal working conditions.
- ✓ After the battery is fully charged, the charge **efficiency drops to zero**. Any additional charge will be converted into heat.
- ✓ If overcharged at higher rate than the self-discharge rate for an extended period, the battery would overheat posing a safety hazard of potential explosion.

Performance Characteristics of Batteries

For this reason, battery charge should have a regulator, which cuts back the charge rate to the tricklerate once the battery is fully charged. Any excessive **overcharging will produce excessive gassing**, which scrubs the electrode plates.



Continuous scrubbing at high rate produces excessive heat, and wears out electrodes leading to shortened life. The trickle charging produces a controlled amount of internal gassing. It causes mixing action of the battery electrolyte, keeping it ready to deliver full charge.



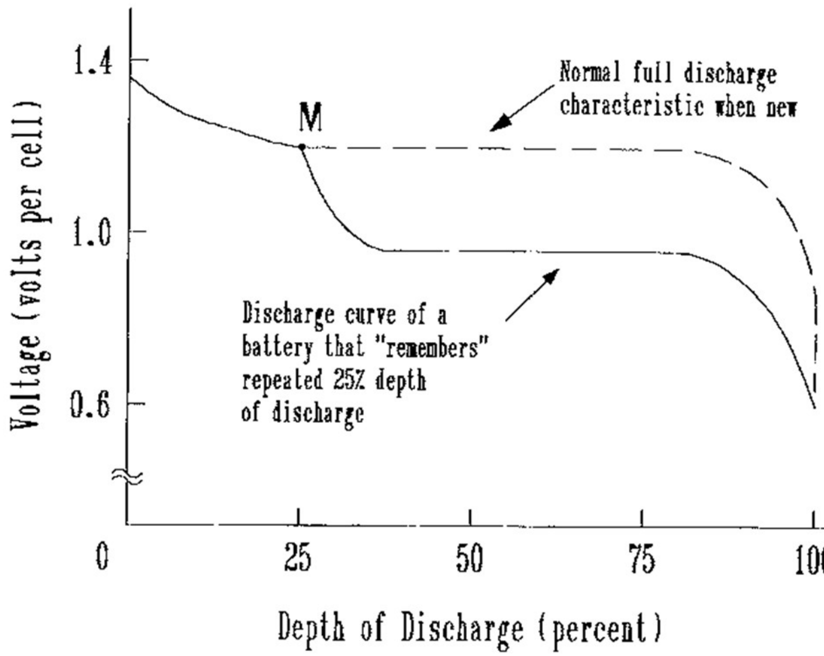
7. Memory Effect

- ✓ One major disadvantage of the battery is the memory effect. It is the tendency of the battery to remember the voltage at which it has delivered most of its capacity in the past.
- ✓ For example, if the battery is repeatedly charged and discharged 25 percent of its capacity to point M, it will remember point M.

Performance Characteristics of Batteries

- ✓ Subsequently, if the battery is discharged beyond point M, the cell voltage will drop much below its original normal value. The end result is the loss of full capacity after repeatedly using shallow discharge cycles.

- ✓ The phenomenon is like losing a muscle due to lack of use over a long time. A remedy for restoring the full capacity is “reconditioning”, in which the battery is fully discharged to almost zero voltage once every few months and then fully charged to about 1.55 volts per cell. Other types of batteries do not have the memory effect.



Lifetime and Sizing Considerations

Time and charge/discharge cycles

One of the characteristics of electrochemical cells is that the ability to store charge degrades with time. Repeated deep charge/discharge cycles can even more significantly result in a reduced lifetime.

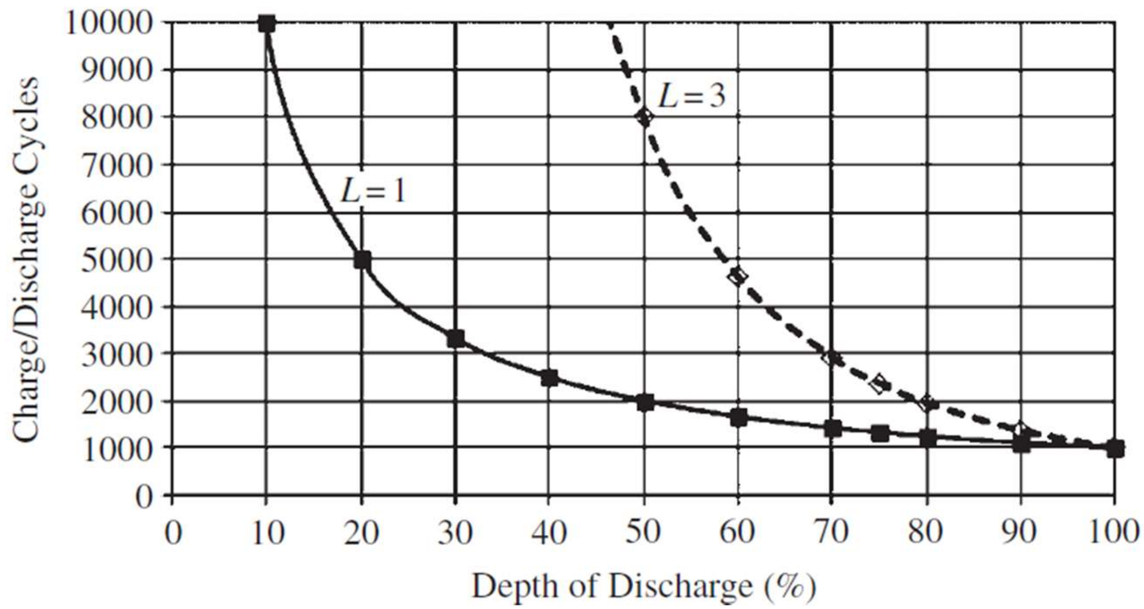
Lifetime: The lifetime of a battery can be described using time (years) or repeated cycles. Automotive batteries may have an additional requirement expressed as range in miles or kilometers.

Beginning of life (BOL): The beginning-of-life parameters are typically the values for the capacity and the internal resistance of the battery when it is initially manufactured.

End of life (EOL): The end-of-life parameters are the values of critical components once they degrade with time or usage. A typical end-of-life criterion is for the battery energy storage capacity to drop to 80% of the BOL value or for the internal resistance to increase by 50%.

Battery life testing can be very complex and time consuming. Typical testing involves a series of partial and full charges and discharges on multiple identical battery packs to determine the number of cycles from BOL to EOL. A representative set of curves of charge/discharge versus DOD is plotted. The plots are based on the number of charge/discharge cycles until the capacity drops to the EOL capacity, typically specified as 80%.

Design Analysis of BSU



For the solid line curve (L = 1), we assume that the energy throughput of the battery is constant. Thus, if the battery can sustain 1000 cycles at 100% DOD, then it will sustain 2000 cycles for a 50% DOD and 10,000 cycles for a 10% DOD. In equation form:

$$N = N_{100\%} \times \frac{100\%}{\text{DOD}} \quad \text{or} \quad \text{DOD} = \frac{N_{100\%}}{N} \times 100\%$$

where N100% is the number of cycles for a 100% DOD, and N is the number of cycles for a given DOD

Design Analysis of BSU

The assumption of a constant energy throughput is a reasonable starting assumption when sizing a battery for a BEV.

However, battery lifetimes can be significantly higher than the numbers just outlined for HEV batteries, which are designed for shallower discharges and a very high cycle life. Representative lifecycle numbers for HEV batteries can range from 3000 cycles for a DOD of 75% (from a 95% SOC to a 20% SOC), to 9000 cycles for a DOD of 50% (from 95% SOC to 45% SOC). Smaller charges and discharges can result in the hundreds of thousands of cycles necessary for a HEV.

Thus, a **cycle lifetime index** L is introduced here as a novel concept, and is used in this section as a parameter to quantify battery life.

Equation is modified to include index L as follows:

$$N = N_{100\%}\left(\frac{100\%}{\mathrm{DOD}}\right)^{L} \quad \text{or} \quad \mathrm{DOD} = \left(\frac{N_{100\%}}{N}\right)^{1/L} \times 100\%$$

Problem 1: Determine the beginning-of-life kilowatt-hour storage required in a BEV battery pack based on the following requirements: eight years of operation, an average of 48 km of driving per day sday over the 365 days of the year, daily charging, and an average battery output energy per kilometer Ekm = 180 Wh/km. Assume L = 1 and N100% = 1000. Assume two parallel battery strings with 96 Li-ion cells per string, with a total number of cells Ncell = 192, and a nominal voltage of 3.75 V per cell. Determine the ampere-hours per cell. What are the vehicle ranges at BOL and EOL?

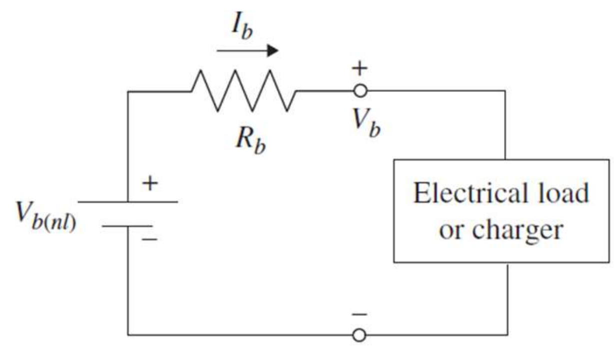
Design Analysis of BSU

Solution:

N = 2920 Cycles; E_{day} = 8 64 kWh; DoD = 34.25 % ; E_{BOL} = 25 23kWh; E_{EOL} = 20 18kWh; Ah_b = 35 04Ah; Range BOL = 140 2km; Range EOL =112 1km

Problem 2: A 24 kWh battery pack can be fast charged from 0% to 80% SOC in 30 min. Determine the approximate charge current and power in order to achieve this charge time.

Solution: 107 A



Determining the Cell/Pack Voltage for a Given Output\Input Power

If the DOD is known, then the cell voltage is simply

$$V_b = V_{b(nl)} - R_b I_b$$

as the no-load voltage Vb(nl) is a function of the DOD. The current is positive for discharging and negative for charging. If the battery input or output power Pb is known, as often is the case, then the current and terminal voltage are easily determined by solving the following quadratic equation:

$$P_b = V_b I_b = V_{b(nl)} I_b - R_b I_b^2$$

$$\Rightarrow R_b I_b^2 - V_{b(nl)} I_b + P_b = 0$$

$$I_b = \frac{V_{b(nl)} - \sqrt{V_{(b)nl}{}^2 - 4R_b P_b}}{2R_b}$$

$$I_b = \frac{V_{b(nl)} - \sqrt{V_{b(nl)}{}^2 - 4R_b(-P_b)}}{2R_b}$$

Design Analysis of BSU

Problem 3: A battery has 96 cells in series per string with two parallel strings. Each cell has a no-load voltage of 4.18 V and an internal resistance of 2.8 mΩ.

i) Determine the pack current and voltage under a 80 kW discharge if the battery is fully charged.

ii) Determine the discharge efficiency of the battery.

Solution:

$I_{bp} = + 214\ 8A$; $\eta_{dis} = 92\ 8\ \%$

Problem 4: Determine the pack current and voltage under a 50 kW charge if the battery is fully discharged. The cell voltage drops to 2.5 V when fully discharged. How efficient is the charging of the battery at this power level?

Solution:

$\eta_{dis} = 90.\ 5\ \%$

Cell Energy and Discharge Rate

The usable battery capacity drops as the C rate increases. This is basically due to the increased resistive losses at the higher discharge rates. Note that the following approach to estimating the cell energy of a battery works for the Li-ion cells presented but is not generally applicable to other battery chemistries.

The Ah value for an automotive BEV battery is typically specified at a low rate,

for example, the C/3 rate. The total energy stored within the cell prior to discharge Ecell is equal to the rated capacity times the rated voltage plus the resistive losses for the rated condition:

Design Analysis of BSU

$$E_{cell} = \mathrm{Ah}_{rated} \cdot V_{rated} + R_b I_{rated}{}^2 \cdot \frac{\mathrm{h}}{C_{rated}}$$

where "h" is one hour.

The nominal voltage V_{xC} at other C rates, designated xC, can be approximated by subtracting the internal resistance voltage drop from the rated voltage:

$$V_{xC} \approx V_{rated} - R_b(I_{xC} - I_{rated})$$

where x is the coefficient of the C rate.

The available output energy at xC is then approximated by

$$E_{xC} \approx E_{cell} - R_b I_{xC}{}^2 \cdot \frac{\mathrm{h}}{x}$$

The efficiency of the discharge (and also of charge) is also a function of the C rate;

$$\eta_{dis} = \frac{E_{xc}}{E_{cell}}\,(\%) \text{ for discharge, } \eta_{ch} = \frac{E_{cell}}{E_{xc}}\,(\%) \text{ for charge}$$

Design Analysis of BSU

Problem 5: The capacity of the cell is approximately 33.3 Ah at C/3 with a rated voltage of 3.75 V. Assume R= = 2.8 mΩ. Summarize the following parameters for C/3, 1C and 3C.

Parameters	C/3	1C	3C
x	1/3	1	3
V	**3.75**	**3.69**	**3.5**
Ah	**33.3**	**33.3**	**33.3**
Wh	**124.88**	**122.8**	**116.6**
Efficiency	**99.2**	**97.5**	**92.6**

Problem 6: An EV battery has a 100% SOC of 85 kWh. The battery can be charged at high power when the battery DOD is maintained within a range of 20% to 100%. The pack has 96 cells in series per string with 74 parallel strings. Each cell has an average no-load cell voltage during charge of 3.64 V and an internal resistance of 65 mΩ.

i) Determine the battery terminal voltage, current, and efficiency for a 120 kW charge.

ii) What approximate time is required to charge the battery from a DOD of 100% to 20%?

Ans: −318.9 A, 376.3 V, 92.9%, 30–40 min

Problem 7: A Li-ion cell is rated at 3.6 V, 3.4 Ah at 0.2C and has an internal resistance of 65mΩ. Determine the cell Wh, Ah, and efficiency for the 4C rate.

Ans: 9.38 Wh, 3.4 Ah, 75.7%

Design Analysis of BSU

Problem 8: A BEV has the following requirements: eight years of operation at an average of 24,000 km per year, averaged out over 365 days per year. Assume an average battery output of 204 Wh/km and a rated cell voltage of 3.6 V, a capacity of 3.4 Ah, and a lifetime index of L = 1.

i) Determine the BOL kWh storage.
ii) How many cells do you need and what is the BOL range?
iii) What is the BOL storage and how many cells are required for a larger pack in order to increase the BOL range to 425 km?
iv) How many parallel strings are required if the pack has 96 cells in series?
v) What is the battery pack mass, assuming a battery with a pack density of 150 Wh/kg?
vi) If the peak power is 325 kW, what is the P/E ratio of the battery for the larger pack?

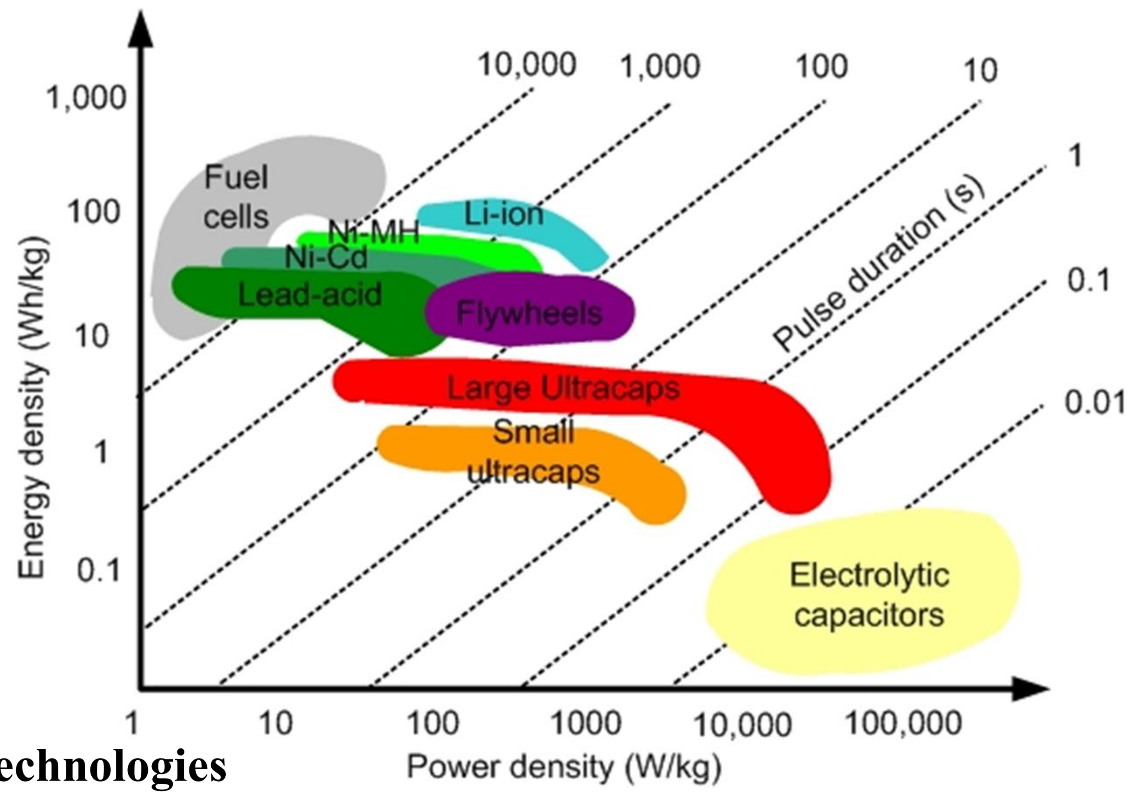
Ans: 39.16 kWh, 3,200, 192 km, 86.7 kWh, 7,083, 74, 578 kg, 3.5

Problem 9: A NiMH HEV battery pack is sized based on the following requirements: 10,000 cycles of 60 Wh per year for ten years, a 6.5 Ah cell with a rated voltage of 1.2 V and an index of L = 1.5.
i) What is the BOL battery pack energy storage?
ii) What is the total number of cells required?
iii) What is the pack voltage if the cells are all in series?
iv) If the peak power is 30 kW, what is the P/E ratio of the battery?

Ans: 1.29 kWh, 166, 199.2 V, 23

Alternative Energy Storage in Developing Stage

- ✓ Batteries are suitable for applications where we need an energy delivery profile. For example, to feed a load during the night when the only source is PV modules.
- ✓ However, batteries are not suitable for applications with power delivery profiles. For example, to assist a slow load-following fuel cell in delivering power to a constantly and fast changing load.
- ✓ For this last application, two technologies seem to be more appropriate:
  - ✓ Ultracapacitors (electric energy)
  - ✓ Flywheels (mechanical energy)



Power vs. Energy delivery profile Technologies

Power vs. Energy delivery profile Technologies

	Lead-Acid	Ni-Cd	Ni-MH	Li-ion
Cell voltage (V)	2	1.2	1.2	3.6
Specific energy (Wh/kg)	1-60	20-55	1-80	3-100
Specific power (W/kg)	< 300	150 – 300	< 200	100 – 1000
Energy density (kWh/m^3)	25-60	25	70-100	80-200
Power density (MW/m^3)	< 0.6	0.125	1.5 – 4	0.4 – 2
Maximum cycles	200-700	500-1000	600-1000	3000
Discharge time range	> 1 min	1 min-8 hr	> 1 min	10 s-1 h
Cost ($/kWh)	125	600	540	600
Cost ($/kW)	200	600	1000	1100
Efficiency (%)	75 - 90	75	81	99

	Flywheel	Ultracapacitor
System power ratings (kW)	2 – 500	5 – 1000
Specific energy (Wh/kg)	15 – 150	0.5 – 4
Specific power (W/kg)	900 - 20000	50 – 3000
Energy density (kWh/m^3)	6 – 100	0.8 – 4
Power density (MW/m^3)	0.3 – 40	0.3 – 1
Maximum cycles	> 100 000	> 100 000
Discharge time range	4 - 60 s	1 – 60 s
Life expectancy (hours)	175 000	100 000
Cost ($/kW)	300	500
Efficiency (%)	90 – 93	90 – 95

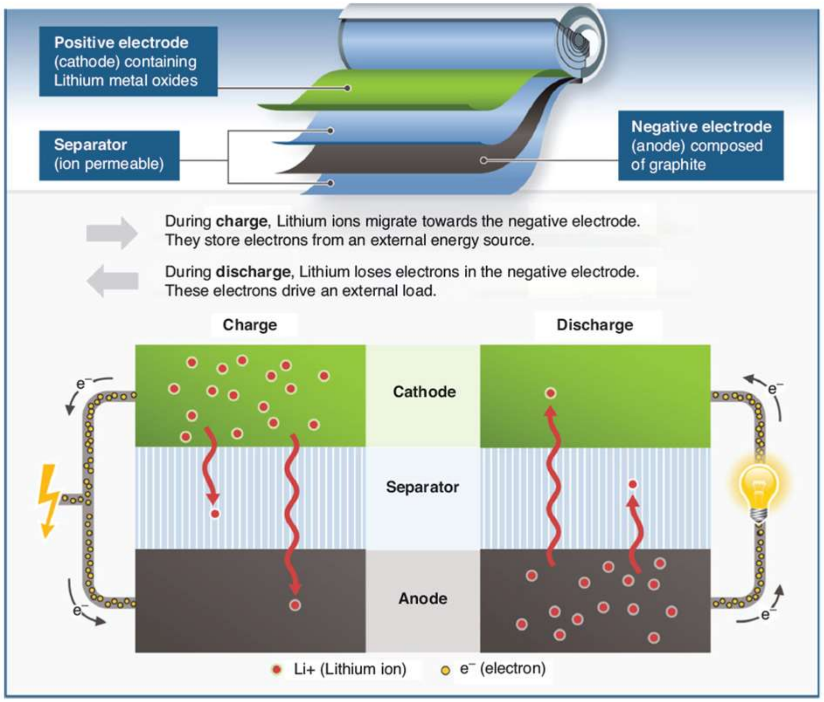
Basic operation of a lithium-ion battery

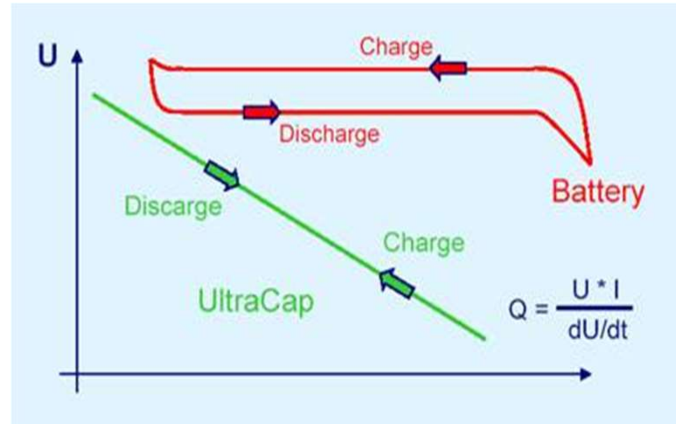
Lithium-ion technology is becoming the battery technology of choice, but it still has plenty of potential to offer. Today's batteries have an energy density of up to 140 Wh/kg or more in some cases, but have the potential to go as high as 280 Wh/kg. Much research in cell optimization is taking place to create a battery with a higher energy density and increased range. Lithium-ion technology is currently considered the safest.

Today's batteries have an energy density of approximately 140 Wh/kg or more in some cases, but have the potential to go as high as 280 Wh/kg.

R&D team is working on post-lithium-ion batteries, such as those made using lithium–sulphur technology, which promises greater energy density and capacity. The company estimates that the earliest the lithium–sulphur battery will be ready for series production is the middle of the 2025s.

Basic operation of a lithium-ion battery





Super-capacitor versus Battery charge and discharge characteristics.

While the battery is discharging and providing an electric current, the anode releases lithium ions to the cathode, generating a flow of electrons from one side to the other. When plugging in the device, the opposite happens: Lithium ions are released by the cathode and received by the anode.

A battery is made up of an anode, cathode, separator, electrolyte, and two current collectors (positive and negative). The anode and cathode store the lithium. The electrolyte carries positively charged lithium ions from the anode to the cathode and vice versa through the separator. The movement of the lithium ions creates free electrons in the anode which creates a charge at the positive current collector

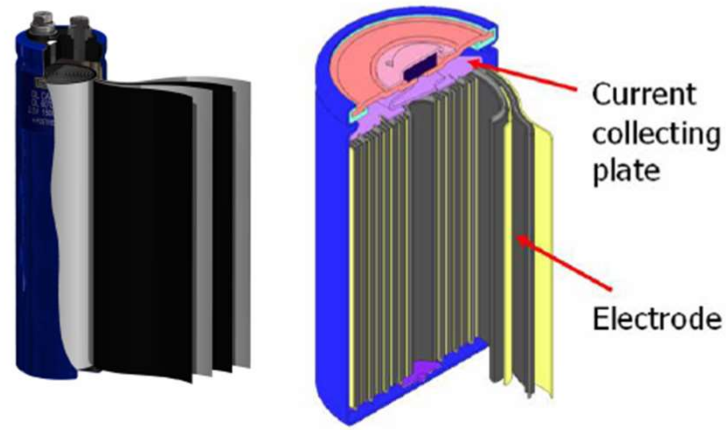
If the separator of the lithium-ion batteries gets damaged, they are susceptible to fire hazards and relatively expensive.

Ultra-capacitors

• Capacitors store energy in its electric field.

• In ideal capacitors, the magnitude that relates the charge generating the electric field and the voltage difference between two opposing metallic plates with an area A and at a distance d, is the capacitance:

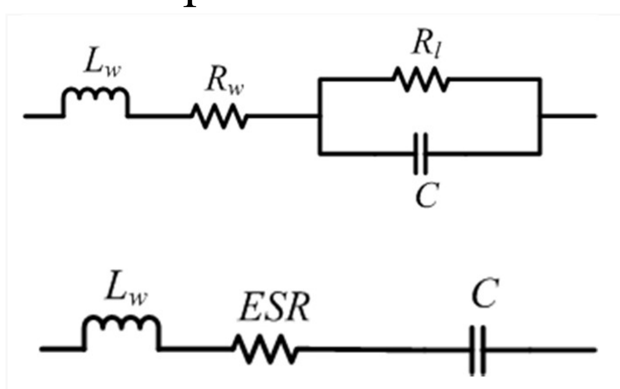
$$C = \frac{Q}{V}$$



• In ideal capacitors:

$$C = \varepsilon \frac{A}{d}$$

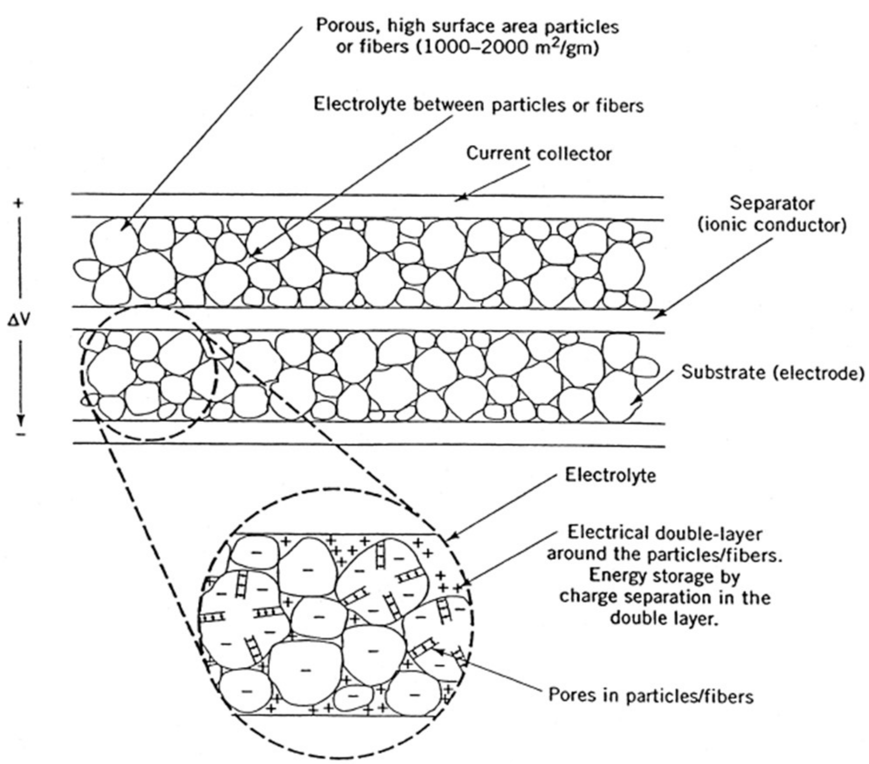
• Equivalent model of real standard capacitors:

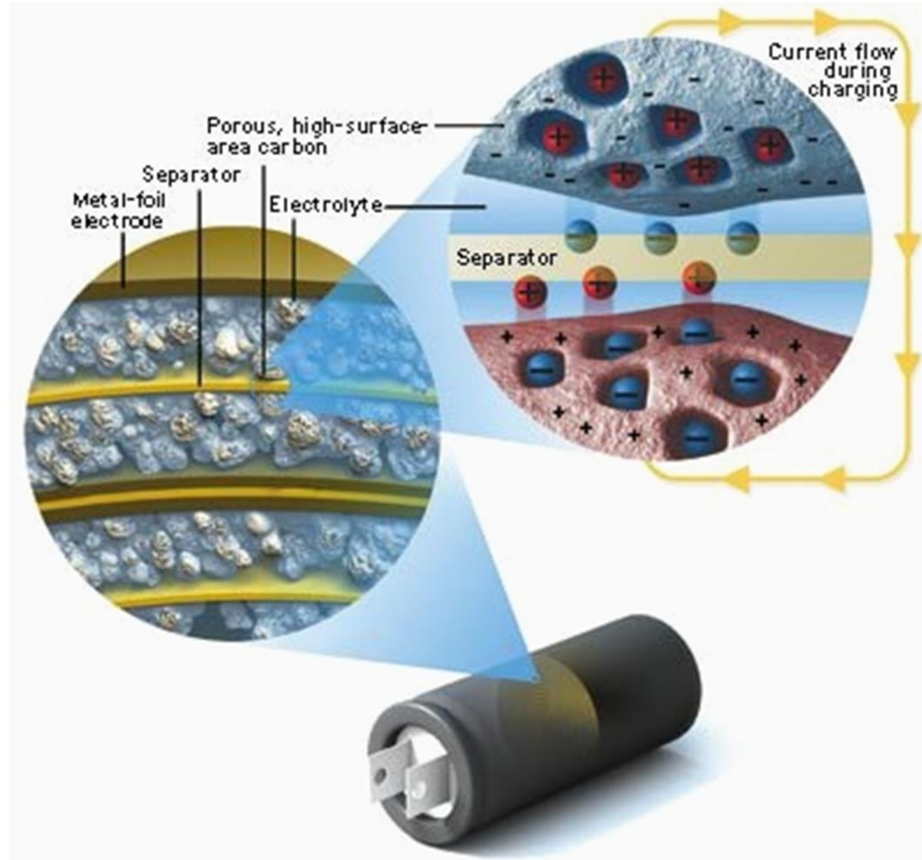


$$ESR = R_w + \frac{1}{\omega^2 R_l C^2}$$

Ultra-capacitors

- Ultracapacitors technology: construction
  - Double-layer technology





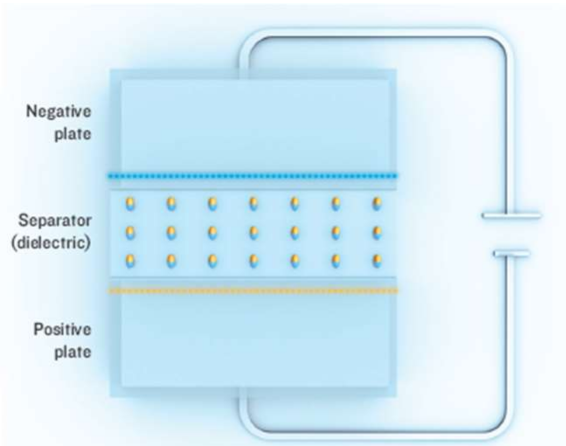
•Electrodes: Activated carbon (carbon cloth, carbon black, aerogel carbon, particulate from SiC, particulate from TiC)

• Electrolyte: KOH, organic solutions, sulfuric acid.

Ultra-capacitors

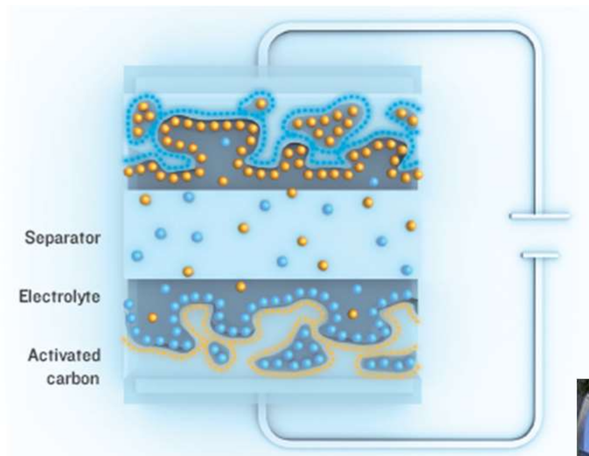
- Ultracapacitors technology: construction

Traditional standard capacitor



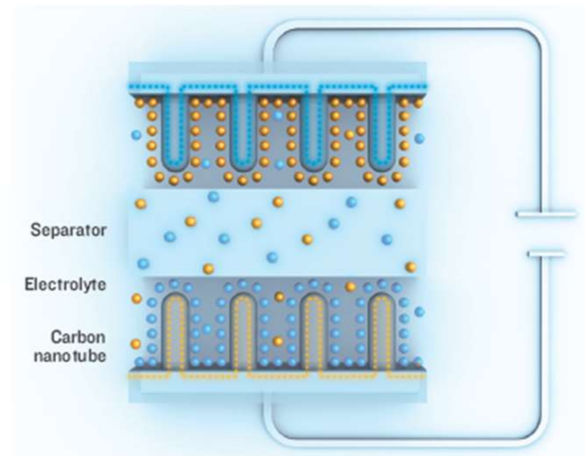
The charge of ultracapacitors, IEEE Spectrum Nov. 2007

Double layer capacitor (ultracapacitor)



$$C = \varepsilon \frac{A}{d}$$

Ultracapacitor with carbon nano-tubes electrodes



- Key principle: Area is increased and distance is decreased

- There are some similarities with batteries but there are no reactions here.

Supercapacitor powered electric buses have been used in China for nearly a decade

Ultra-capacitors

• Some typical Maxwell's ultracapacitor packages:

C =	650	1200	1500	2000	2600	3000	F
ESRac =	0.6	0.44	0.35	0.26	0.21	0.20	mΩ
ESRdc =	0.8	0.58	0.47	0.35	0.31	0.30	mΩ
τ =	0.52	0.696	0.705	0.700	0.806	0.900	s
I_{rms} =	105	110	115	125	130	150+	A_{rms}

www.ansoft.com/firstpass/pdf/CarbonCarbon_Ultracapacitor_Equivalent_Circuit_Model.pdf

• At 2.7 V, a BCAP2000 capacitor can store more than 7000 J in the volume of a soda can.

• In comparison a 1.5 mF, 500 V electrolytic capacitor can store less than 200 J in the same volume.

Sizing the EVs drive system

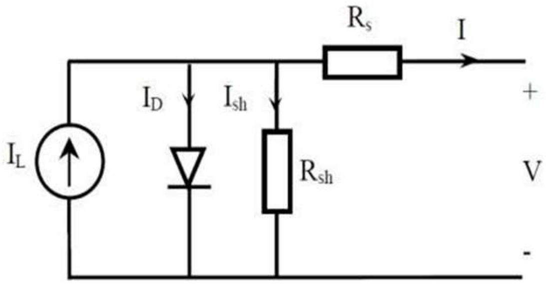
1. 1250 CC capacity of IC engine car is having 14 inches of wheel diameter. It can run the maximum speed of 240 kmph with 170 Nm. If it is modified as battery operated vehicle, what is the required motor sizing (BHP) and also estimate the number of battery pack to run 8 hrs continuously while driving consistently 60 kmph. 70 cells are connected in series in a pack with the rating of 3.6 V, 100 Ah.

2. Design a medium duty electric vehicle to run 60 kmph with 50 Nm. It should run at least 3 hrs continuously while the wheel diameter of 10 inches. (Ah rating, Motor sizing, suitable motor, power converter circuit for regeneration and power devices rating). Consider 48 V motor and BLDC hub motor drive.

3. Design a light duty e-scooter to run 30 kmph by carrying 100 kg of pay load (other than 75 kg of body weight). It should run at least 100 km for one shot charge. (Ah rating for 48 V motor)

Solar PV Assisted EV

Mathematical Model of Solar Cell



$$I = I_L - I_o\left(e^{\frac{q(V+IR_s)}{kT}} - 1\right) - \frac{V + IR_s}{R_{sh}}$$

Where:

I is the cell current (A).
I_L is the light generated current (A).
I_o is the diode saturation current.
q is the charge of electron $= 1.6\text{x}10^{-19}$ (coul).
K is the Boltzman constant (j/K).
T is the cell temperature (K).
R_s, R_{sh} are cell series and shunt resistance (ohms).
V is the cell output voltage (V).

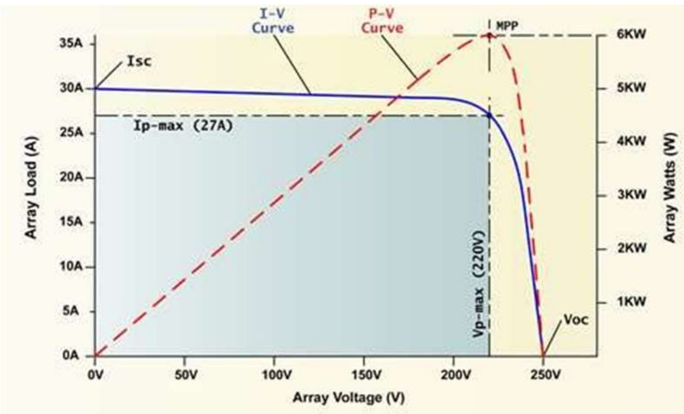
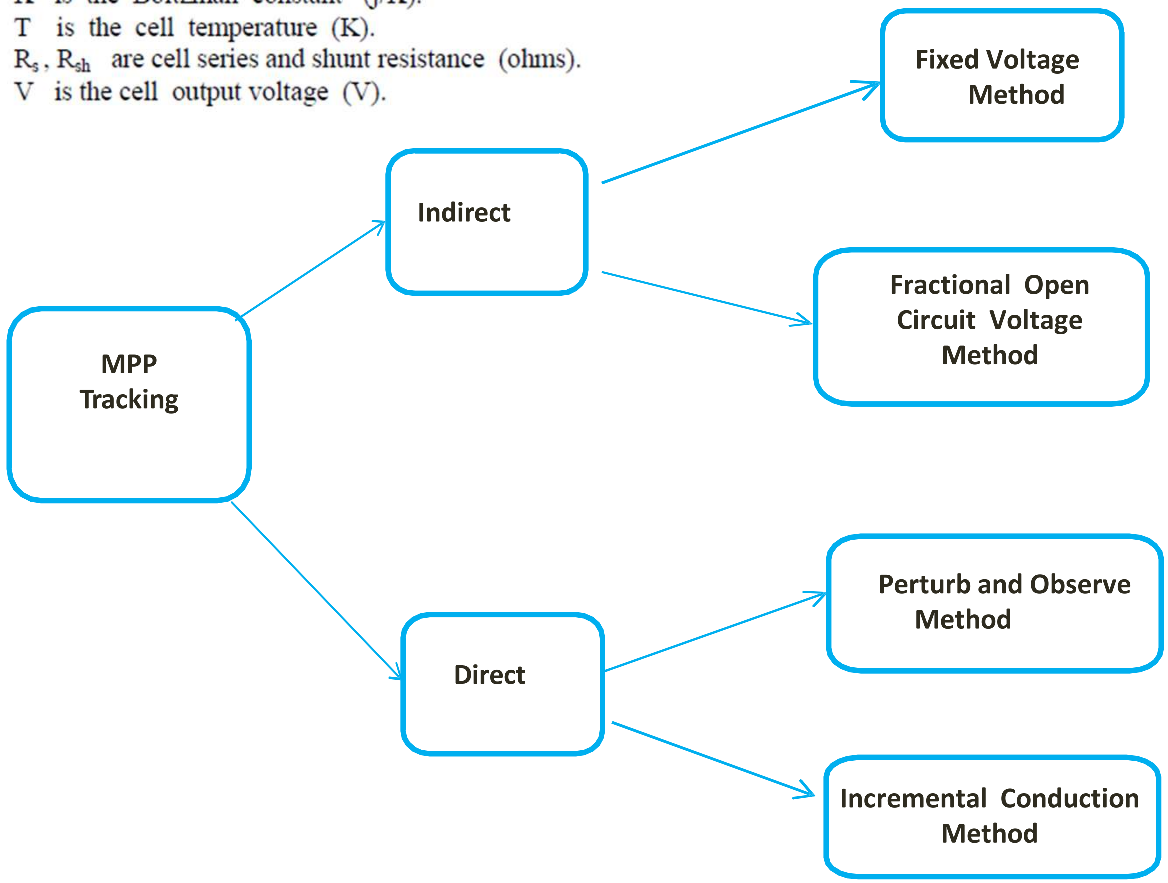
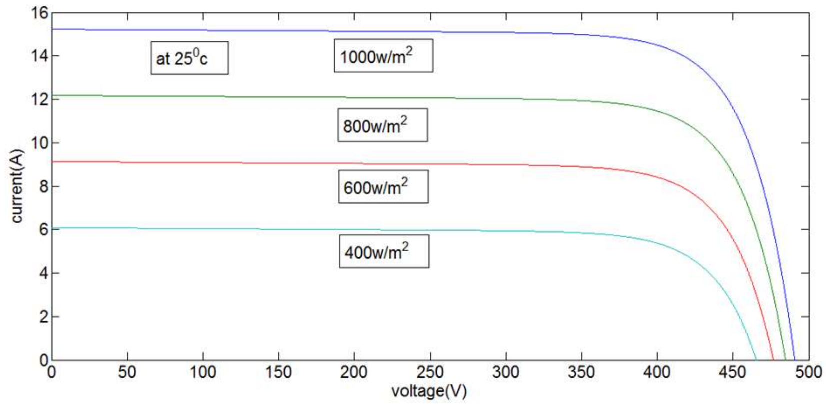


Fig-2 The I-V & P-V CURVES

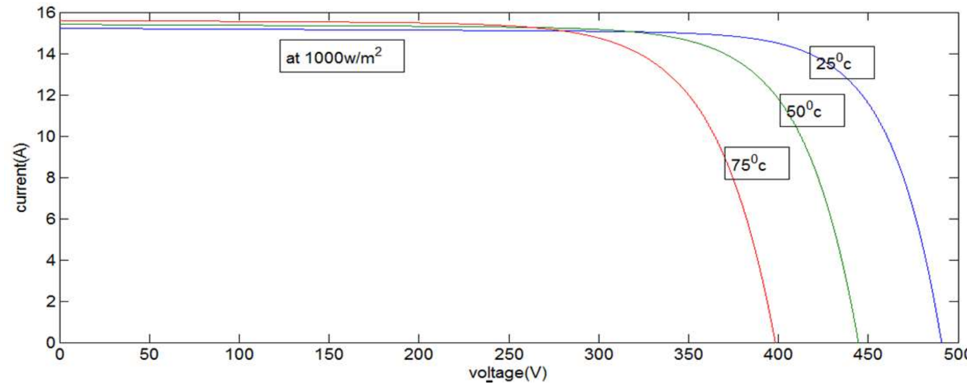


Solar PV Assisted EV

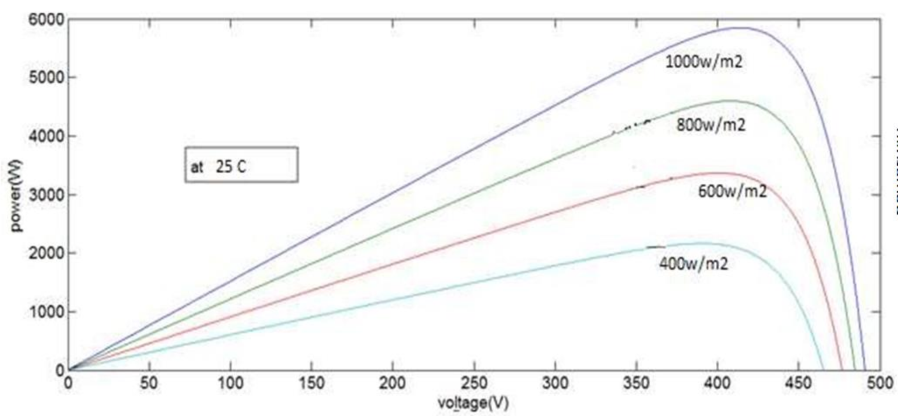
V-I and P-V characteristics of a solar cell



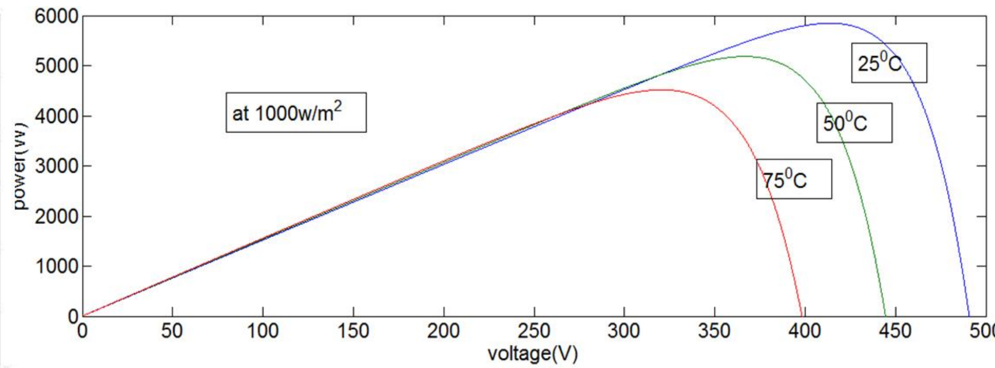
Variation of I-V curve with solar irradiation



Variation of I-V with temperature



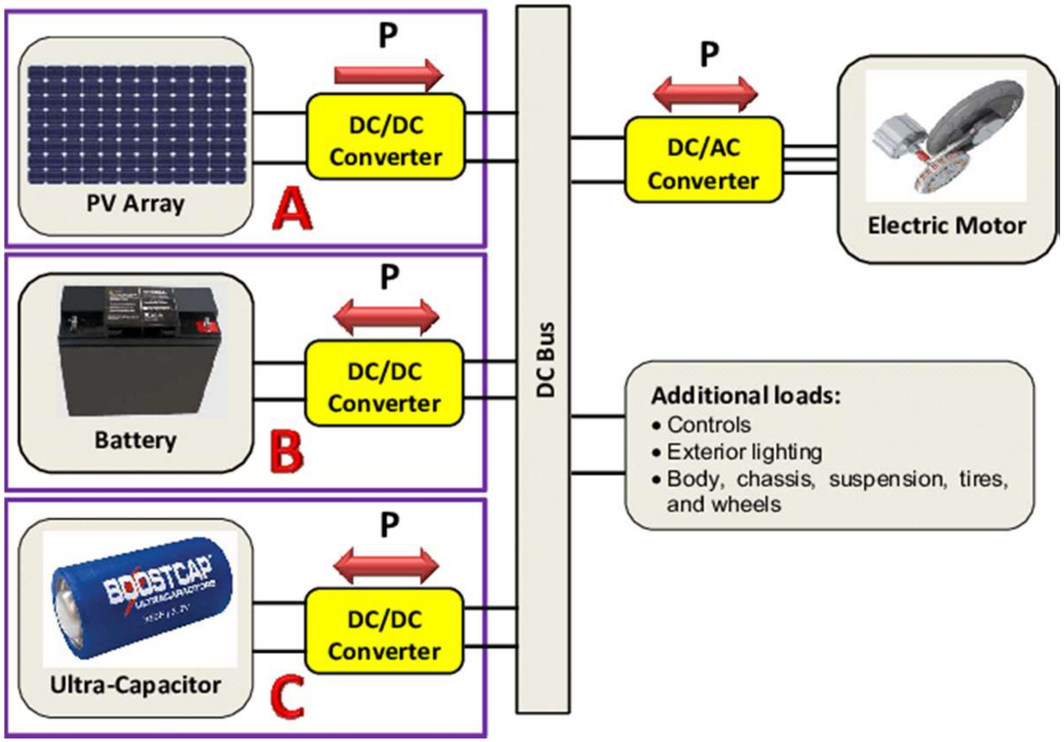
Variation of P-V curve with solar irradiation



Variation of P-V curve with temperature

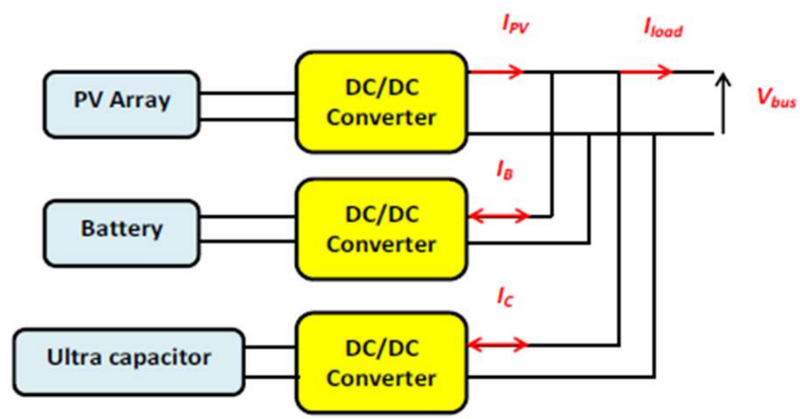
Solar PV Assisted EV

Power Management of Solar PV assisted EV



Different conditions of the power flow according to the load conditions

Cases	K_{Load}	K_{PV}	K_B	K_C
Case 1	+1	+1	+1	+1
Case 2	+1	0	+1	+1
Case 3	-1	+1	-1	-1
Case 4	-1	0	-1	-1



The flow of power from the PV array is varying depending on the environmental conditions; this power value expresses the quantity of solar energy converted into electrical energy.

Solar PV Assisted EV

Power Management of Solar PV assisted EV

The energy is managed based on the current situations during the race, where many circumstances should be taken into considerations such as:

1) *Acceleration conditions:* At high speed, PV modules will not be able to work only without the need of another storage device, since increasing the speed will lead to more power consumption by the motor. Thus, more power should be generated to drive the car by the battery and/or the ultra capacitor as shown in Table IV in case 1.

2) *Deceleration conditions:* In braking conditions, it is a must to draw the power back to the ultra capacitor and if the ultra capacitor is fully charged, then the battery could be used to store the rest of the energy. In other words, if the load current is negative, then it is recommended to store the energy in the ultra capacitor, rather than the battery, and to store the PV energy in the battery as shown in case 3 in Table IV.

3) *Time: It is* an important factor that should be taken into consideration, if it is night, then the power drawn from the PV is zero, and here where the energy storage devices should work efficiently to deliver the required power to the load as shown in case 2 and case 4 in Table IV.

4) *Route: T*he road conditions also play an important role in how the energy is managed. If the driver is away 500 m from a turn, then the ultra capacitor should be discharged so that when decelerating the energy is stored in the ultra capacitors.