BATTERIES FOR ENGINEERING APPLICATIONS

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BORN INNOVATIVE

TOPICS

1. INTRODUCTION (terminology, battery construction and operation characteristics)
2. BATTERY TECHNOLOGIES (lead acid, Ni-MH, lithium ion, zebra, metal-air)
3. APPLICATIONS: Portability, renewal sources, Smart Grid, battery sizing, modeling and testing
4. NEXT GENERATION (battery challenges, new technologies, the future of energy storage)

Batteries and Portability

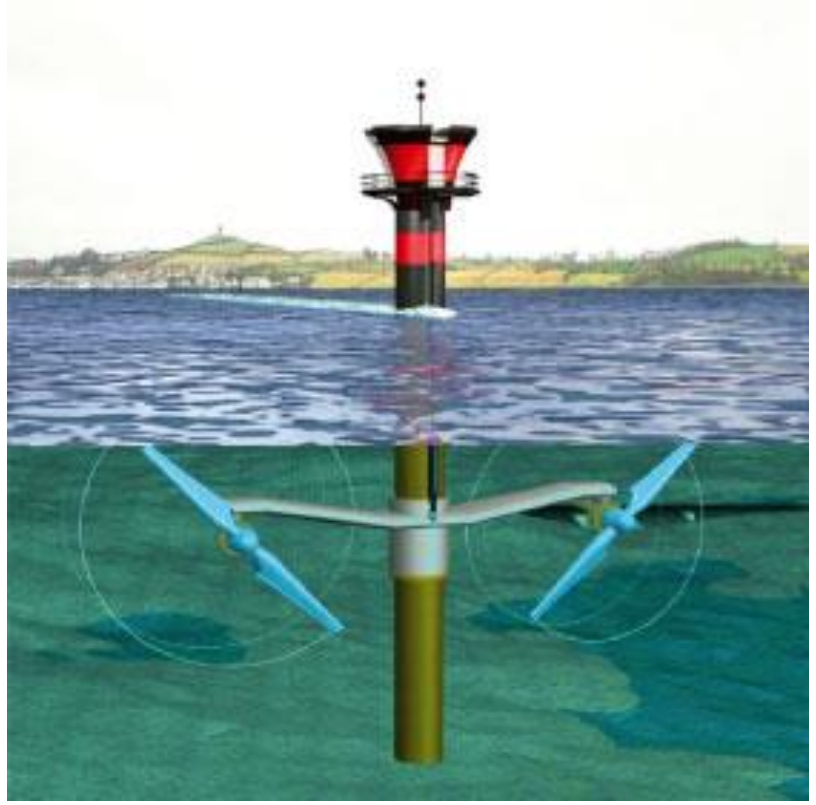
Portability central problem…..

...energy storage systems!!!

Batteries and renewable energy

Renewable energy sources utilization problem…..

...energy storage systems!!!



Batteries and Electric Vehicles

China...

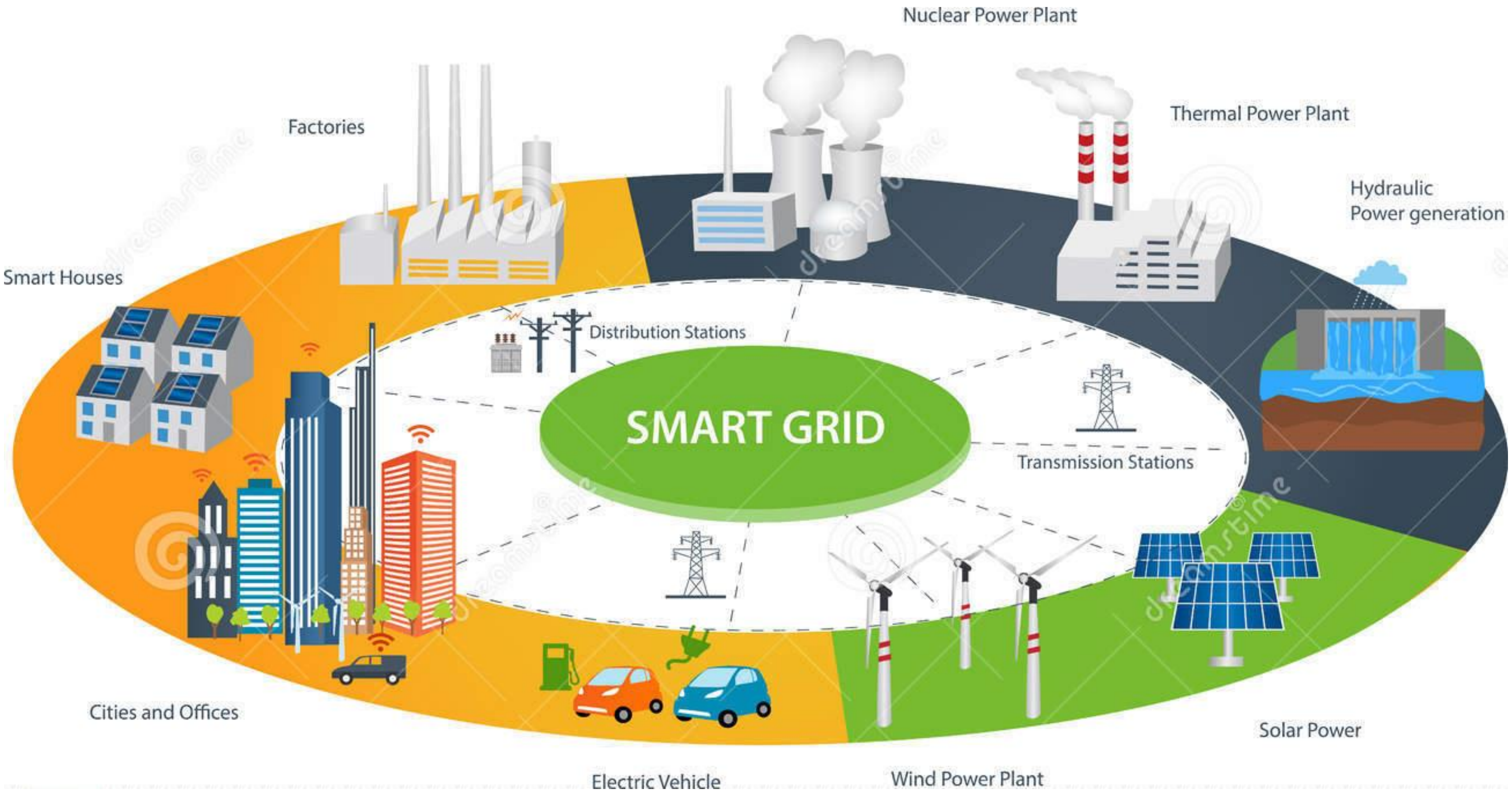
Electric vehicles central problem…..

...energy storage systems!!!

São Paulo...

Índia...

Batteries and Smart Grids



Smart Grids and EV´s

The Battery Central Problem

Batteries are at the center of many technological developments

Let see a little about battery sizing for any application

Battery Sizing

Step 0: remembering some unit definitions

Ampere definition: 1 Coulomb/second

Capacity [C] = I [A] ∗ t [s] or Capacity [Ah] = I [A] ∗ t [h]

And Energy? Energy [J] = Voltage [V] ∗ Current [A] ∗ Time [s] or

Energy [Wh] = Voltage [V] ∗ Current [A] ∗ Time [h] = Capacity [Ah] ∗ Voltage [V]

Power [W] = Voltage [V] ∗ Current [A] = Energy [Wh] / Time [h]

Battery Sizing

Step 1: how much battery capacity do you need to run your application or device?

Calculate de current needed and the time duration for your application, then you will know the capacity…

For example, let suppose a water pump.
If your pump is drawing 5 A and you want it to run for 5 hours a day

$$C = 5\ A * 5\ hours = 25\ Ah$$

If your pump works at 100-140 V level then you will need:

Energy = $C * V = 25 * (100\ V\ or\ 140\ V) = 2500 - 3500\ Wh$…..let assume 3000 Wh

Now we know…we need 25 Ah and 3000 Wh

Battery Sizing

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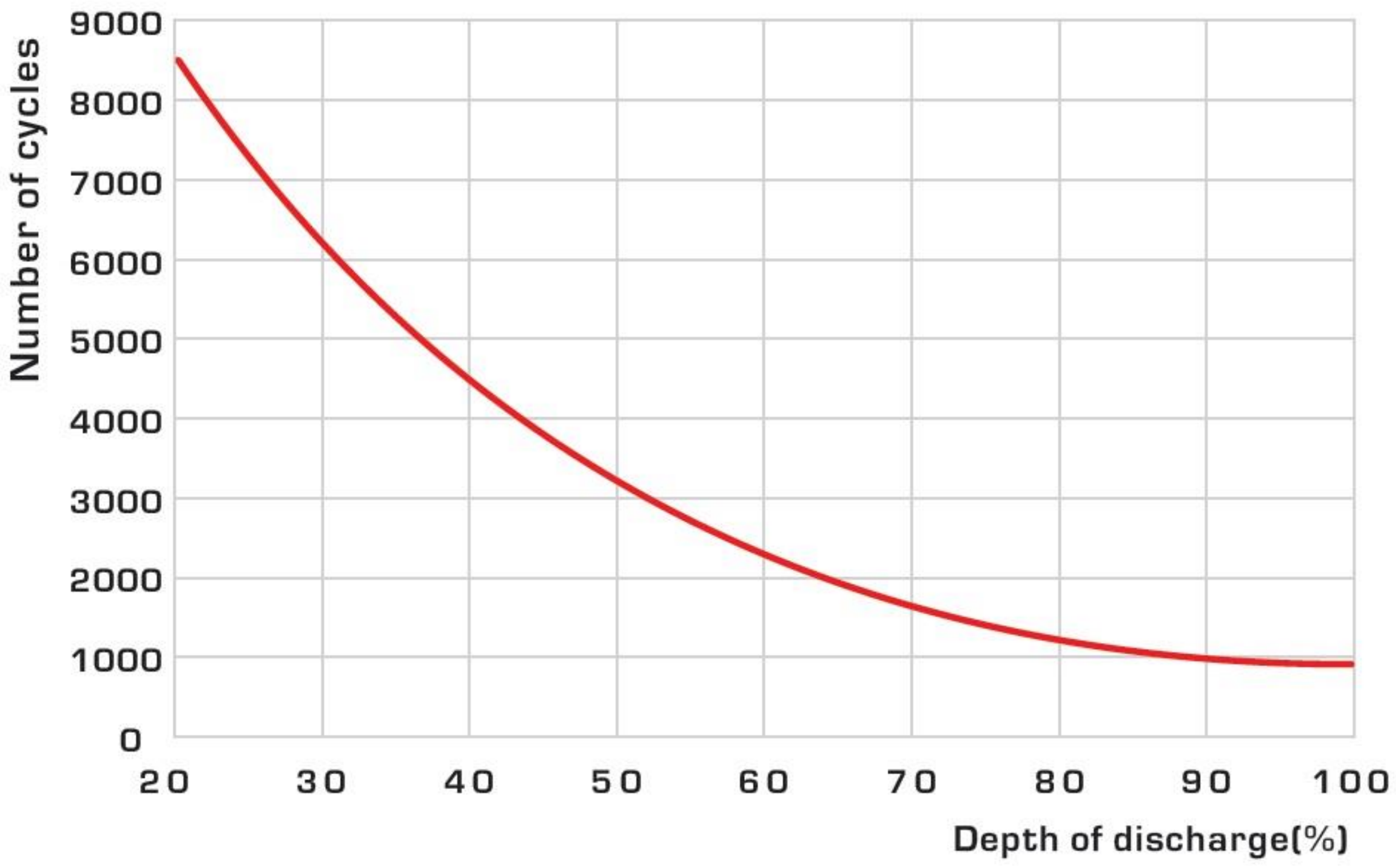
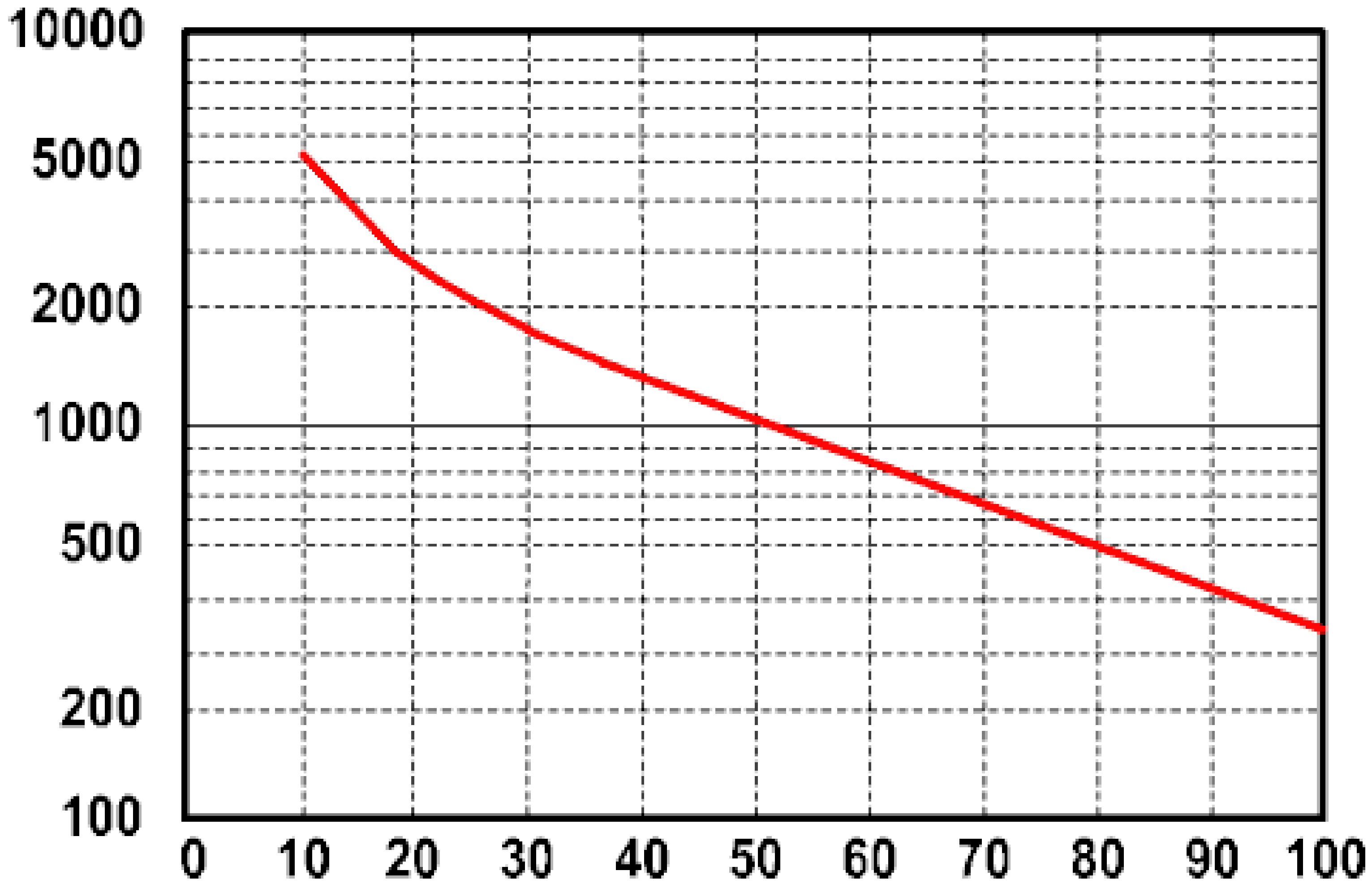
Step 2: Cycle life considerations

It isn’t good to run a battery all the way down to zero during each charge/discharge cycle…because…..





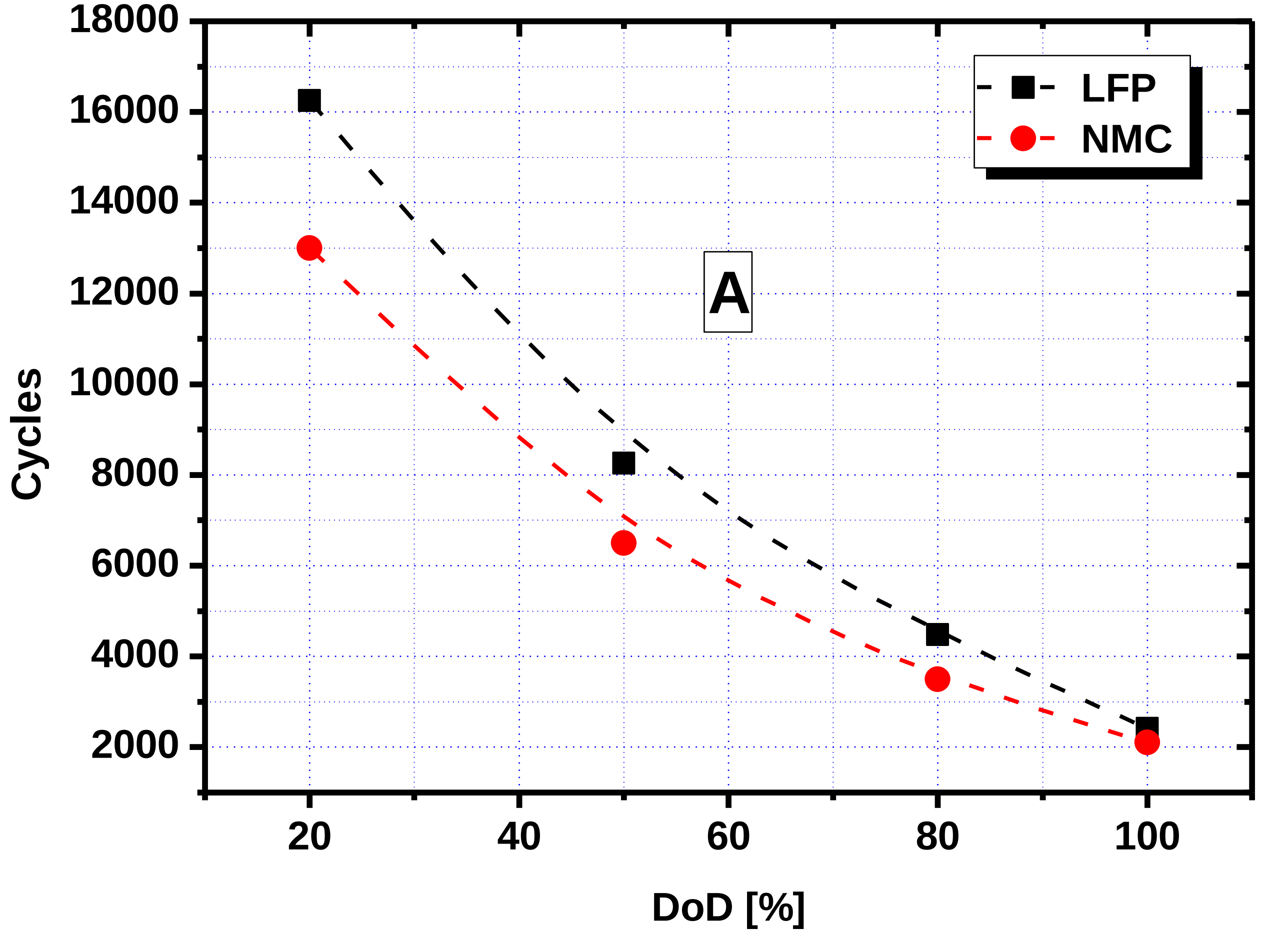
Battery Sizing

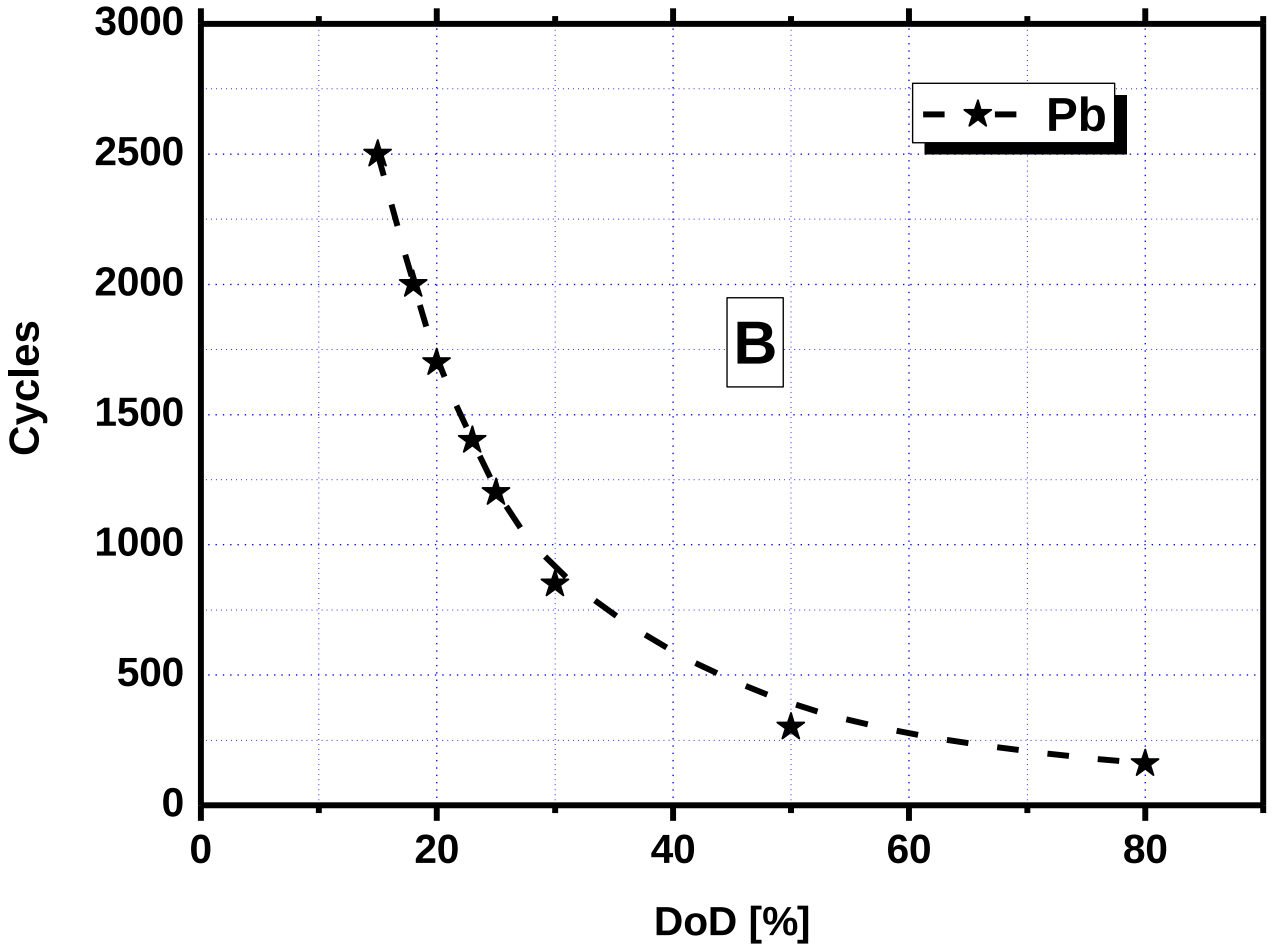
Step 2: Cycle life considerations

But at low DoD you will need more batteries to assist the same demand….here the energy throughput is the key...

Let see an example with three batteries: Pb-acid, LFP e NMC…

Technology	Capacity	Voltage
NMC	40 Ah (C_5)	3.2 V
LFP	45 Ah (C_5)	3.2 V
Lead-acid	180 Ah (C_5)	12 V





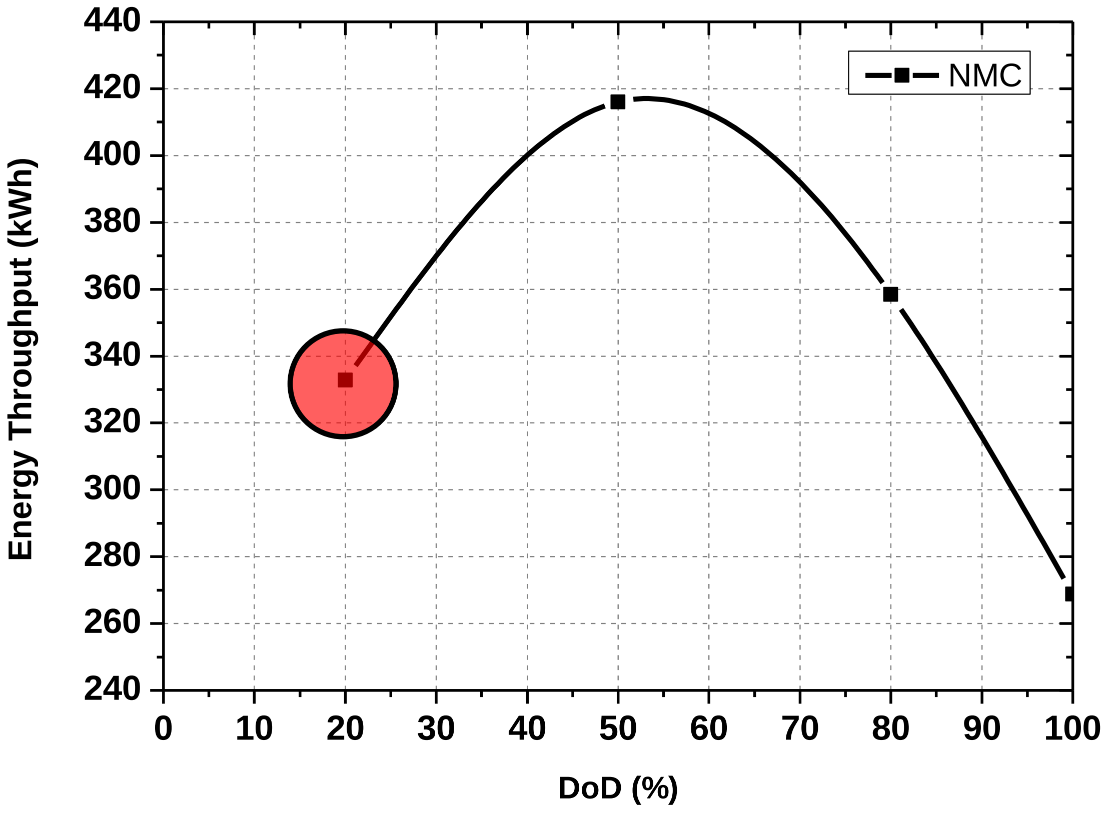
Battery Sizing

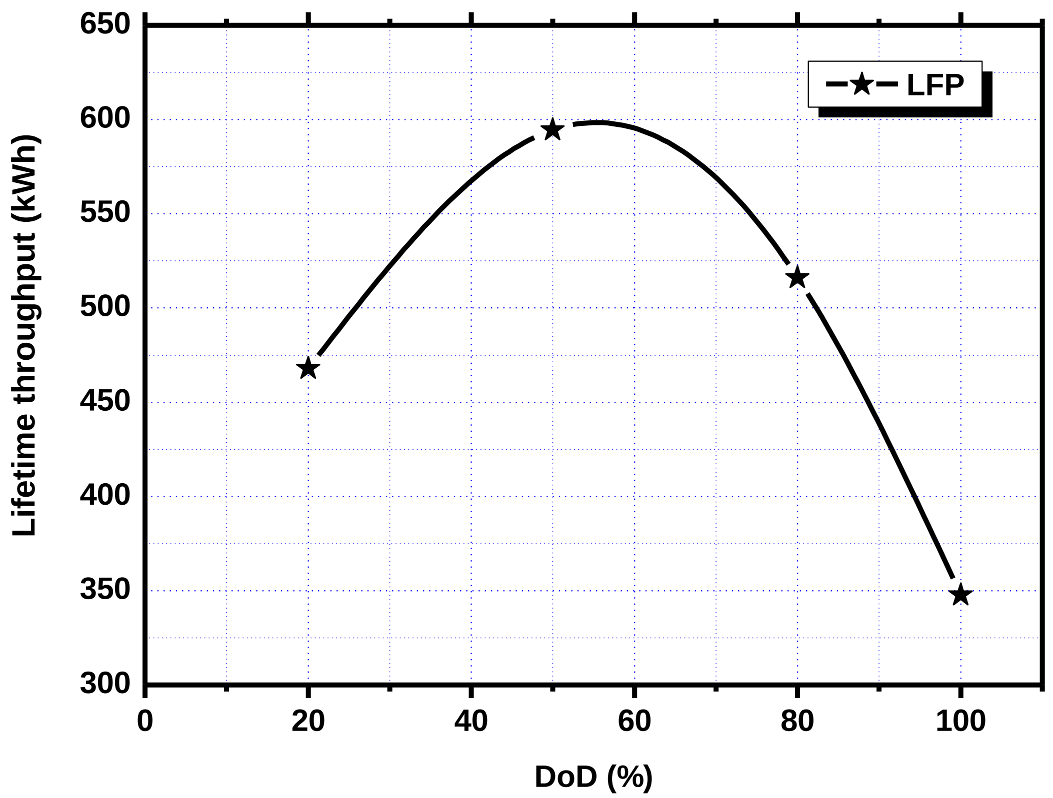
Step 2: Cycle life considerations

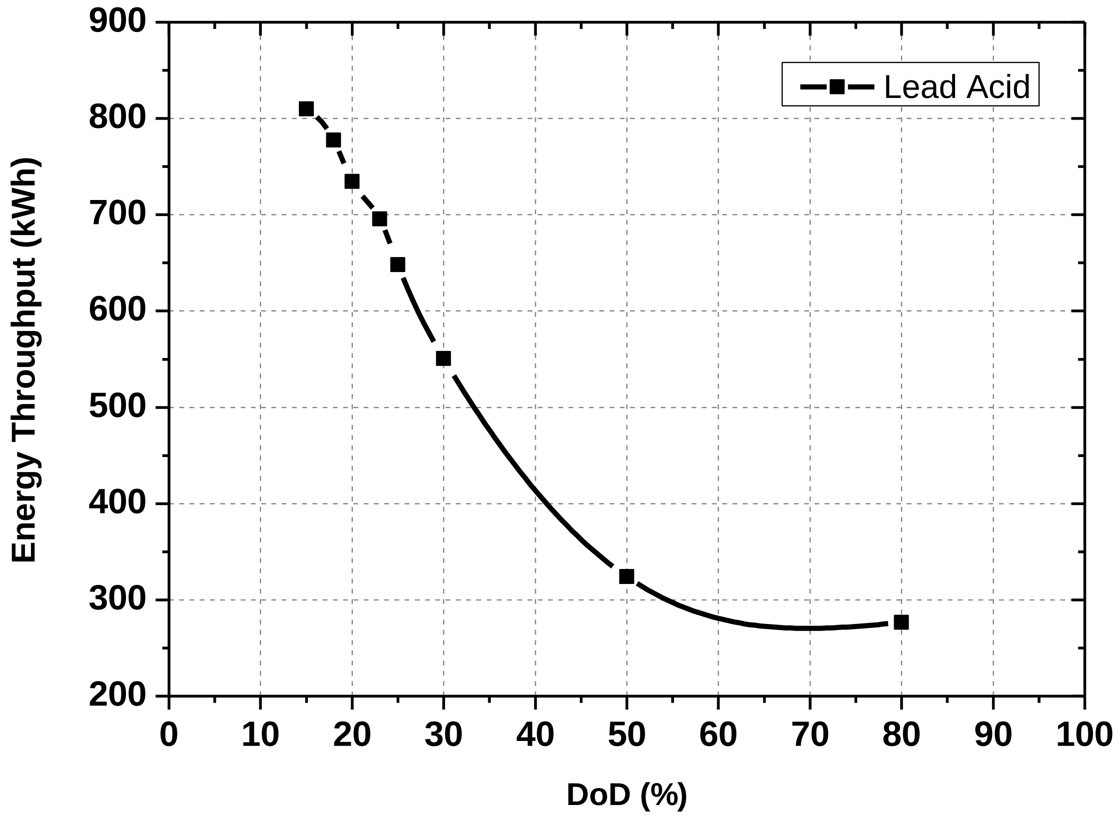
Technology	Capacity	Voltage
NMC	40 Ah (C_5)	3.2 V
LFP	45 Ah (C_5)	3.2 V
Lead-acid	180 Ah (C_5)	12 V

The energy throughput will be…. $C * V * DoD(\%) * Cycles$

Let check the first point for NMC…. $40 * 3.2 * 0.2 * 13000 = 332800$ Wh = 332.8 kWh







Battery Sizing

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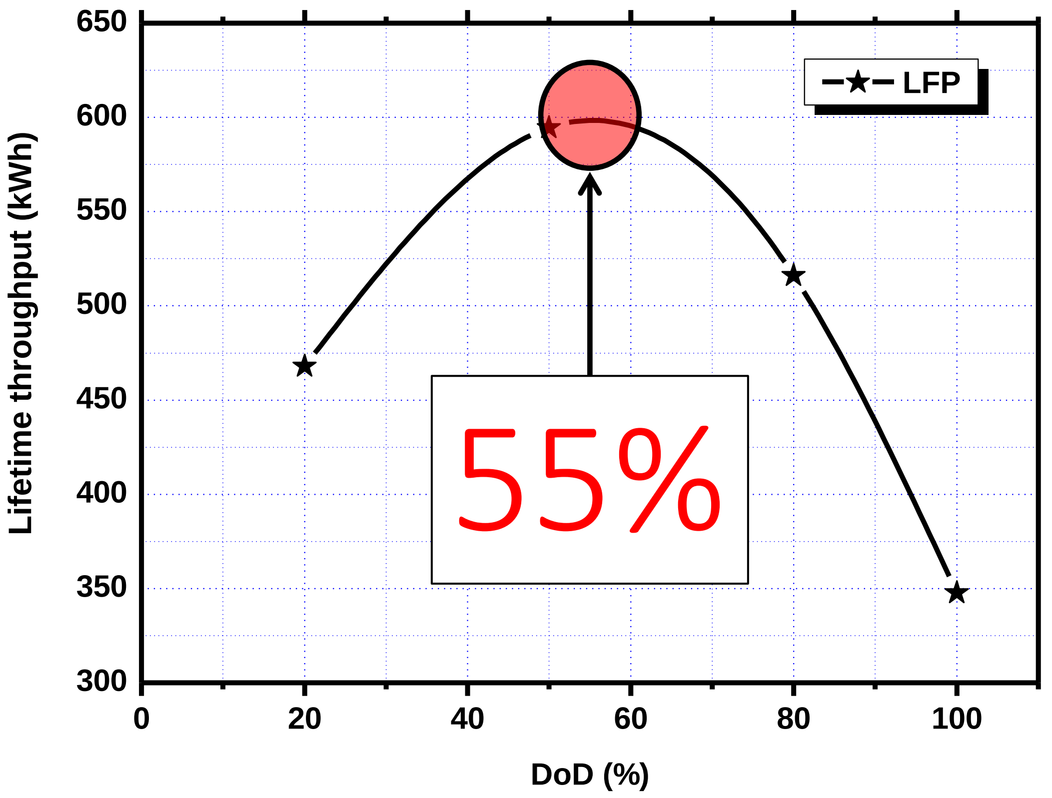
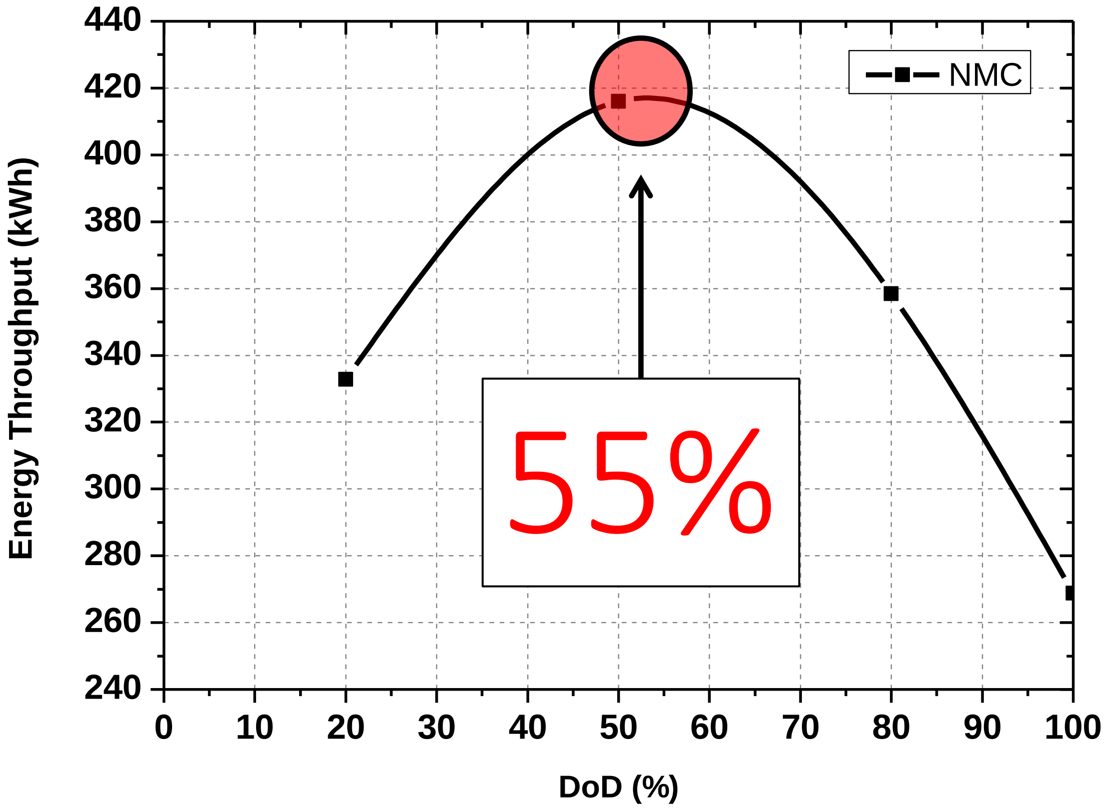
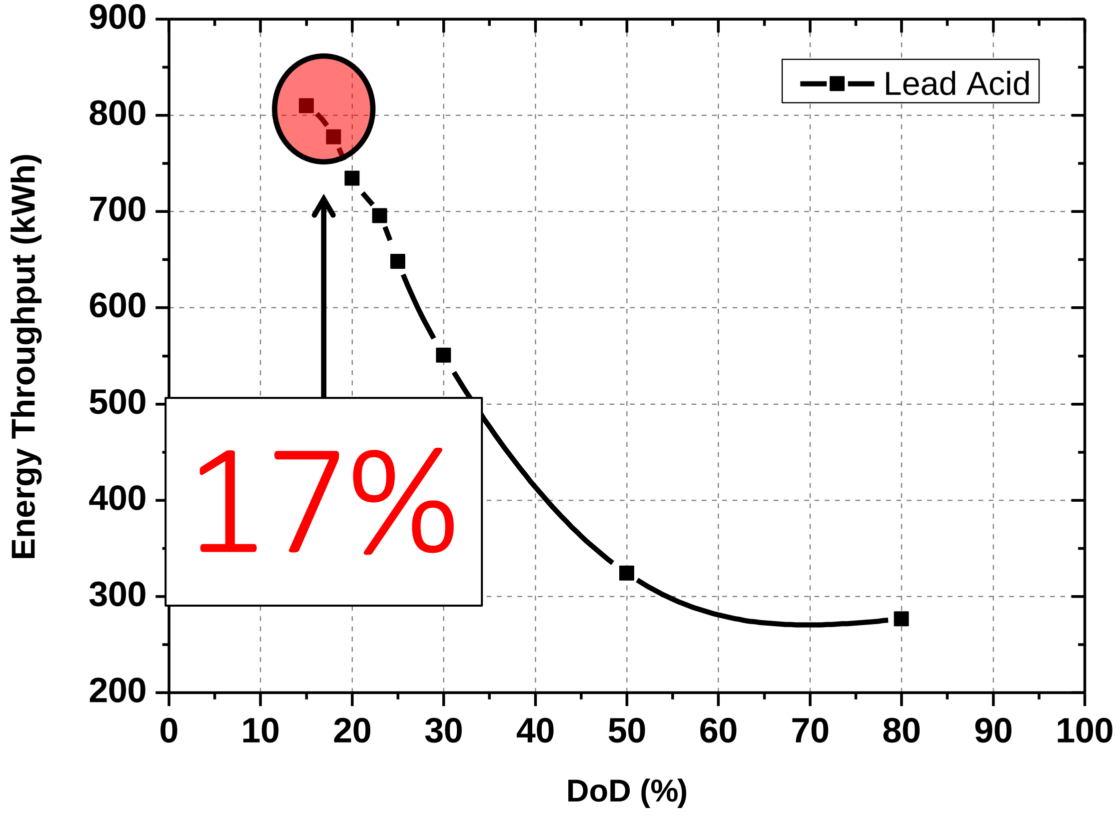
Step 2: Cycle life considerations

Then…..the optimal DoD will be…

Technology	Capacity	Voltage
NMC	40 Ah (C_5)	3.2 V
LFP	45 Ah (C_5)	3.2 V
Lead-acid	180 Ah (C_5)	12 V







Now we can size the battery we need and determine the lifetime!

Battery Sizing

Step 2: Cycle life considerations

Technology	Capacity	Voltage
NMC	40 Ah (C_5)	3.2 V
LFP	45 Ah (C_5)	3.2 V
Lead-acid	180 Ah (C_5)	12 V

Let calculate the NMC size for 3000 Wh…

NMC cells = 3000 Wh / (3.2 V $*$ 40 Ah $*$ 0.55) = 42.6 cells $\Rightarrow$ 43 cells

NMC DC Battery Voltage = 43 Cells $*$ 3.2 V/Cell = 137.6 V

NMC Cycles (for 55% DoD) see the data sheet (Figure)! = 6200 cycles

NMC cycling lifetime = 6200 days (1 cycle/day) = 17 years

Technology	Capacity	Voltage	DoD	Cells (serial)	Voltage	Cycles	Lifetime*
NMC	40 Ah (C_5)	3.2 V	55%	43	137.6 V	6200	17 years
LFP	45 Ah (C_5)	3.2 V	55%	38	121.6 V	8000	22 years
Lead-acid	180 Ah (C_5)	12 V	17%	9	108.0 V	2500	6.9 years

* There are two main mechanisms determining the battery life time: Floating Cycling

Battery Sizing

Step 2: Cycle life considerations

Lithium ion battery data sheets (about calendar life and cycling life)

Parameter	NMC	LFP
FLOAT LIFETIME (years)	**20**	**20**
LIFETIME THROUGHPUT of cell (kWh)	415 @ 50 %DOD @ 25ºC	590 @ 50 %DOD @ 25ºC
MINIMUM SoC (%) recommended	20 % DOD 80 SoC	20 % DOD 80% SoC
ROUND TRIP EFFICIENCY (%)	97.5	97.2

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Step 2: Cycle life considerations

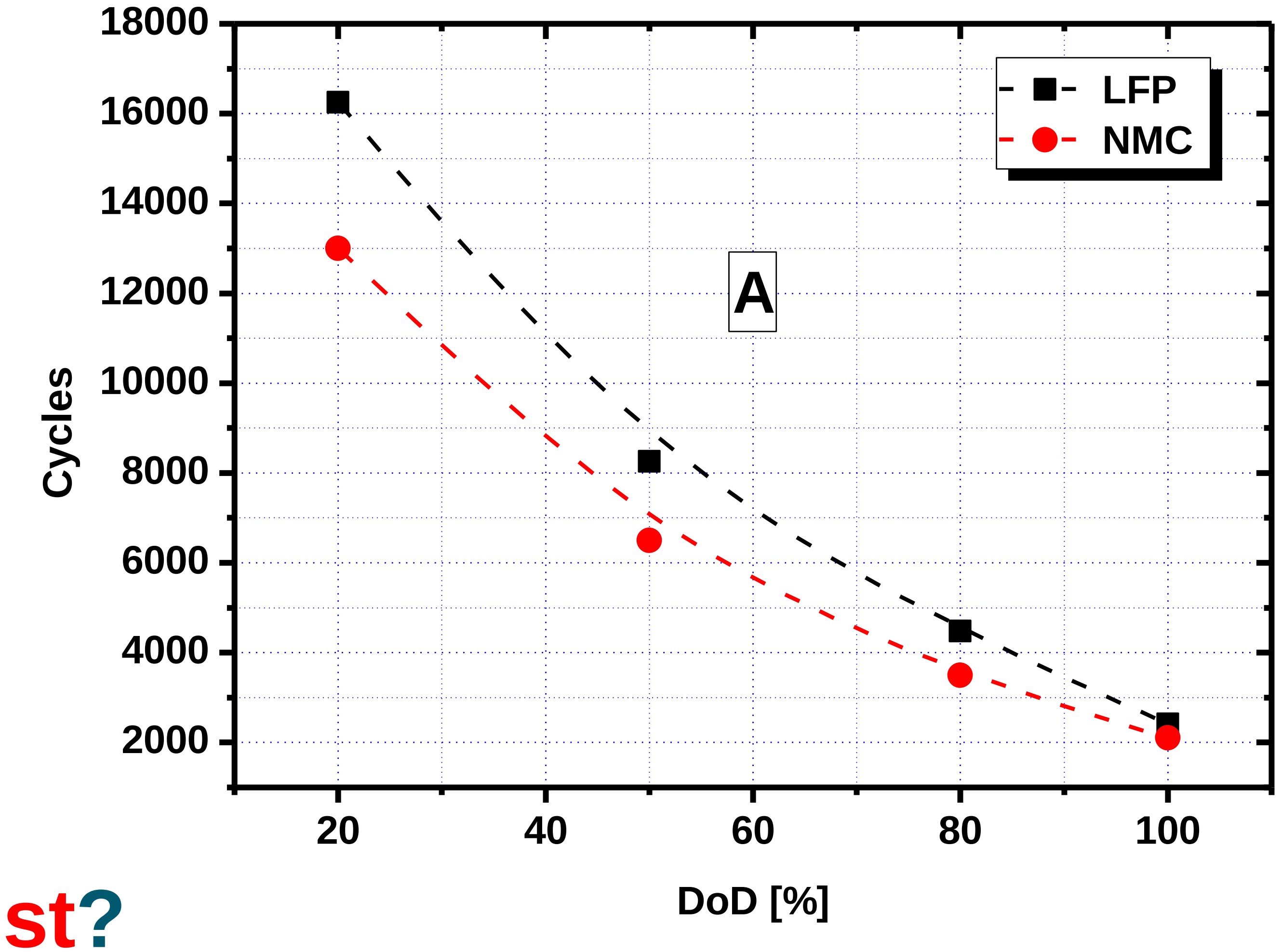
Technology	Capacity	Voltage	DoD	Cells (serial)	Voltage	Cycles	Lifetime
NMC	40 Ah (C_5)	3.2 V	55%	43	134 V	6200	17 years
LFP	45 Ah (C_5)	3.2 V	**58%**	**36**	**115,2 V**	**7300**	**20 years**
Lead-acid	180 Ah (C_5)	12 V	17%	9	108 V	2500	6.9 years

If the lithium ion battery floating lifetime is 20 years… it will not last 22 years in cycling…

…then you can use more than 55% of this battery capacity to fit the maximum float time of 20 years…

….doing the calculation in the reverse direction

20 years = 7300 cycles ≈ 58% DoD



OK…but how to evaluate which solution is the best?

Battery Sizing

Step 3: Cost issues

Now about the cost issues…

Technology	Nominal Capacity	Nominal Voltage	Number of Cells*	Cost per cell	Total battery cost	Cost per year
NMC	40 Ah (C_5)	3.2 V	43	U$ 318.00	U$ 13,674.00	U$ 804.4
LFP	45 Ah (C_5)	3.2 V	36	U$ 270.00	U$ 9,720.00	U$ 486.0
Lead-acid	180 Ah (C_5)	12 V	9	U$ 196.00	U$ 1,764.00	U$ 255.6

* Be sure to include all equipment needed to operate the batteries (with it cost per year!!!), here were used only the battery costs!

Battery Sizing

Comments about some hidden questions

1. What happens if discharge time is different from 5 h used in our example (as it was done after cycling life correction)?

Nothing happens…because the effect of this change is included in the cycling life vs DoD dependence.

2. What happens if you change the discharge current used?

Then you need to use the capacity corresponding to the current used!!!! (This effect will be different for different battery technologies. This effect is big for lead acid batteries (Peukert´s Law), and very small for lithium ion batteries)

Battery Sizing

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Comments about some hidden questions

3. what if you don´t have a constant load (current)?

The best thing to do is minimize the error.

To do that calculate the average current drawn and use this value in your calculation.

For example, consider a repetitive cycle where each cycle is 1 hour. It consists of 1 second 20 A followed by 59 minutes and 59 seconds with 0,1 A.

Then, the average current = $20*1/3600 + 0.1(3599)/3600 = 0.1044$ A average current

Ther capacity will we close to the capacity calculated with this current.

In fact, the capacity at this rate of discharge is very difficult to predict where you have small periods of high currents (like in EV´s)...sometimes you will need to test yourself...

Battery Sizing

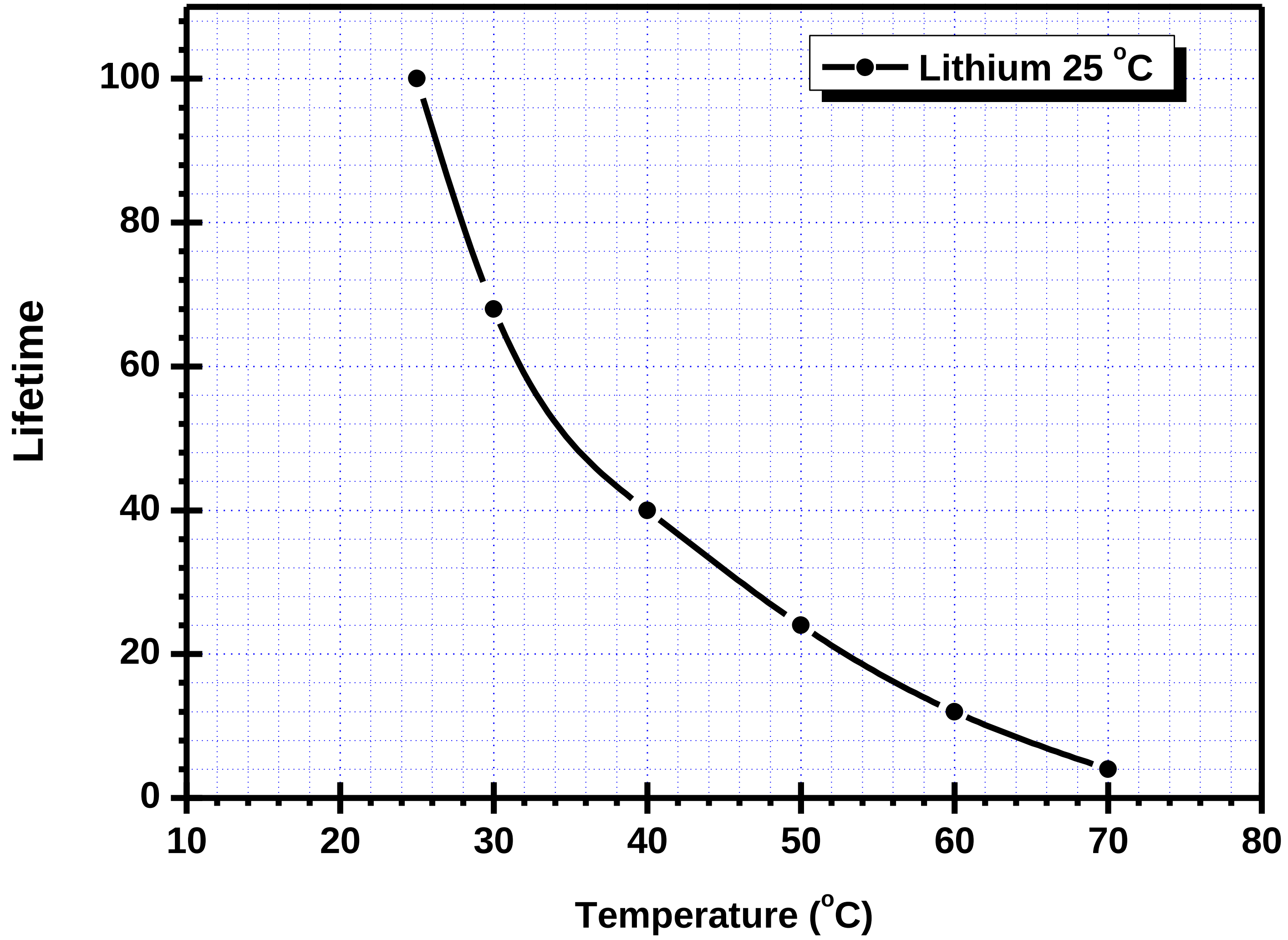
Comments about some hidden questions

4. what about battery operation temperature?

It must be considered as a correction factor to the lifetime calculated.

Look at the lifetime vs temperature dependence.

Then the battery cost per year will be different !!!!



Technology	Capacity	Voltage	DoD	Cells (serial)	Voltage	Cycles (25 °C)	Lifetime (25 °C)	Cycles (40 °C)	Lifetime (40 °C)
NMC	40 Ah (C_5)	3.2 V	55%	43	137.6 V	~~6200~~	~~17 years~~	2480	6.8 years
LFP	45 Ah (C_5)	3.2 V	55%	38	121.6 V	~~8000~~	~~22 years~~	3200	8.8 years
Lead-acid	180 Ah (C_5)	12 V	17%	9	108.0 V	~~2500~~	~~6.9 years~~	2250 (90%)	6.2 years

Battery Sizing

Comments about some hidden questions

5. What if battery operation temperature is not constant?

This is typical in photovoltaic applications (temperature changes during a day).

The best thing to do, to minimize errors, is calculate a weighted average value.

For example: if a battery lifetime at 40 ºC is 1 year and at 25 ºC is 10 years and you use it 2 hours a day at 40 ºC and 22 hours a day at 25 ºC, then your battery will lose (2/8760) of it lifetime at 40 ºC and 22/87600 of it lifetime at 25 ºC. When the sum of these values achieve 100% your battery will be died.

For more complicated operation temperature duties, this calculation will be more complicated. In our example we don’t considered the transient period between temperatures.

Battery Sizing

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Comments about some hidden questions

6. what about the load voltage level?

You must fit it! (in our example if the amount of cells are not enough you will need to add more cells and lower the current! or if the amount of cells extrapolate the voltage you will need to use another serial/parallel configuration)

You can use a voltage transformer if available (considerate it efficiency to determine the battery load)

7. what about battery efficiency?

In our calculation it is not important because we don´t worried about how to charge the batteries….but if your batteries will be charged by photovoltaic panels, it will be important for panel sizing… The answer depend on the application!!! (Smart Grid!, VE´s)

Battery Sizing

Comments about some hidden questions

8. what about the Power?

In our example we calculated an energy demand application without a power restriction.

If you need power, your battery must be able to provide the current needed… then you need first at all to choose it to provide this current and then follow the example.

9. All data used to size batteries predict the battery lifetime as the time to achieve 80% of it initial capacity value (due to degradation).

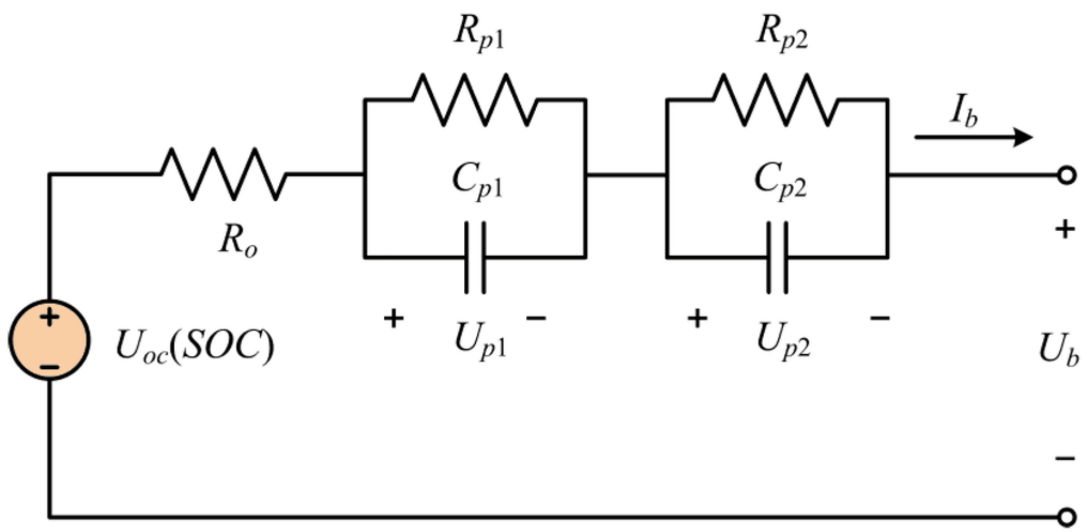
10. In a long term battery application never forget about the maintenance cost (it must be added to the battery cost)

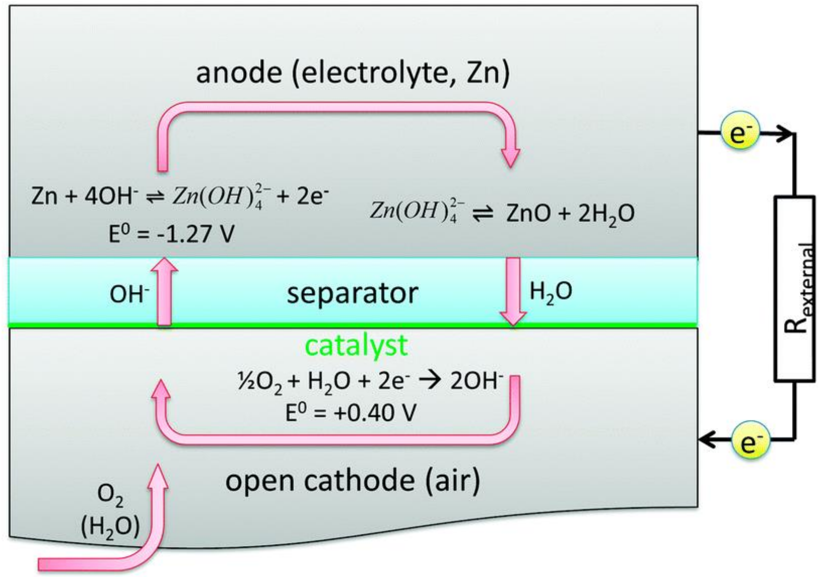
Battery Simulations

Battery models have become an indispensable tool for the design of battery-powered systems.

Their uses include battery characterization, state-of-charge (SOC) and state-of-health (SOH) estimation, algorithm development, system-level optimization, and real-time simulation for battery management system design.

There are two main ways to simulate: Equivalent Circuits models or Physical-Chemical models





Battery Simulations

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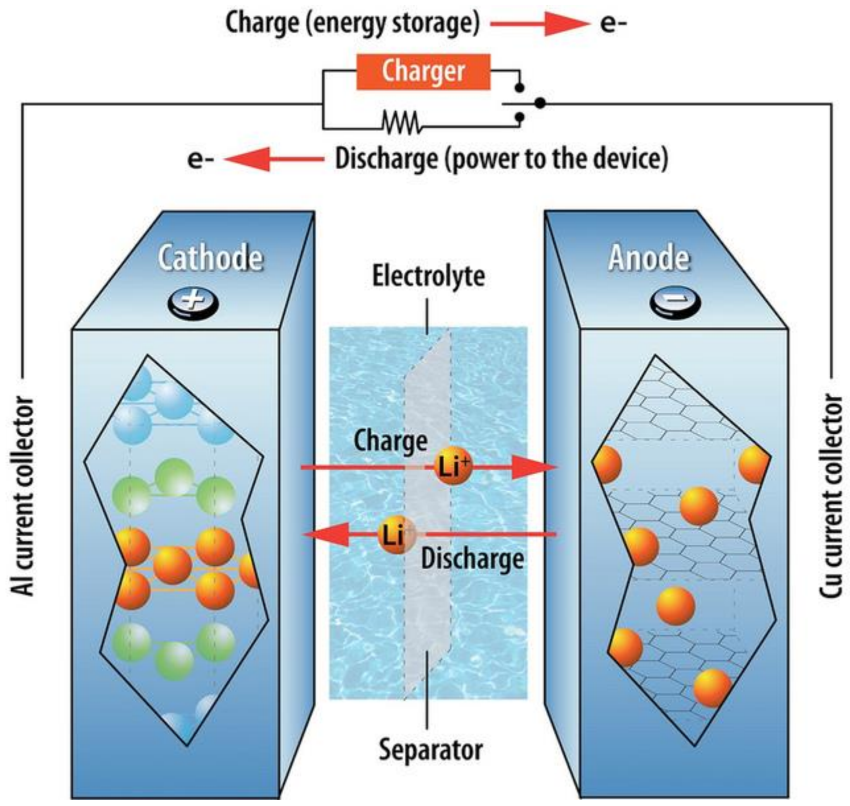
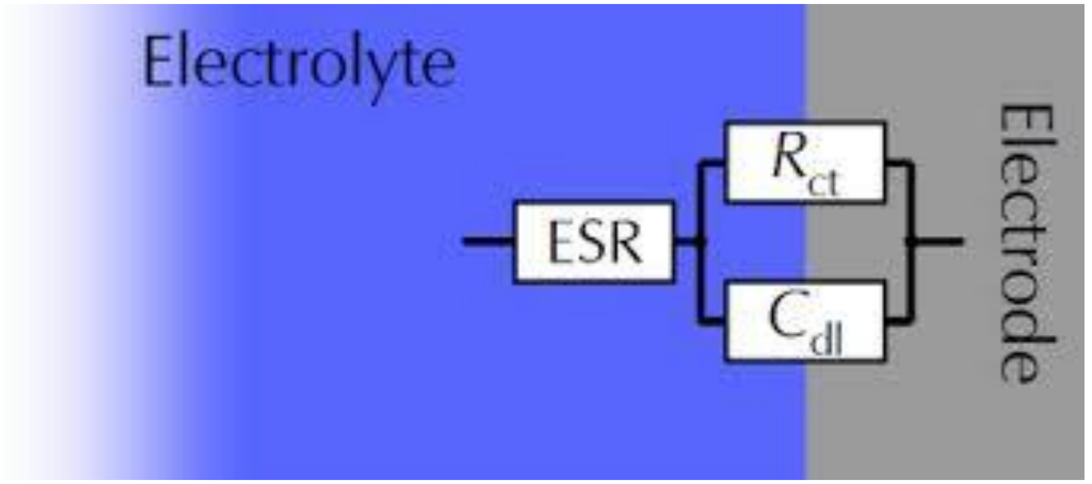
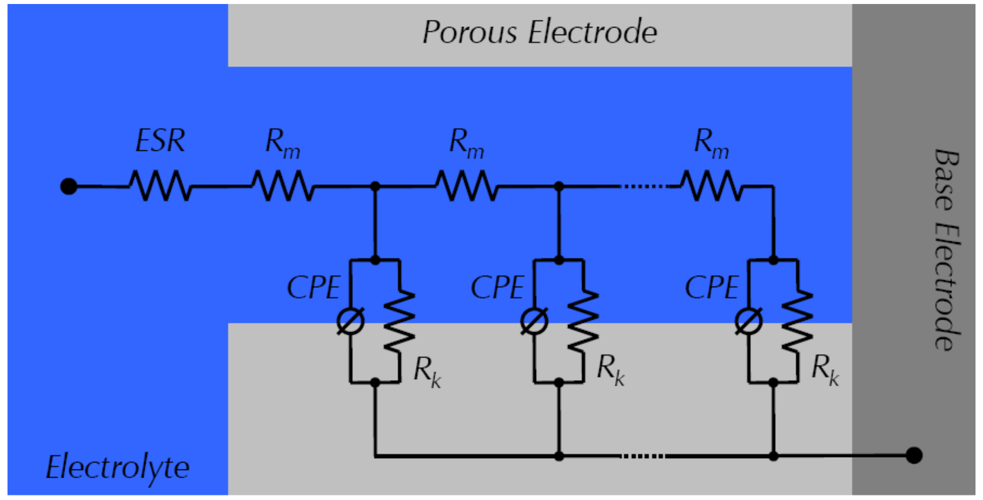
1. Equivalent circuits (Simulink, Zview2 and others)

Battery models based on equivalent circuits are preferred for system-level development and controls applications due to their relative simplicity.

Engineers use equivalent circuits to model the thermo-electric behavior of batteries, parameterizing their nonlinear elements with correlation techniques that combine models and experimental measurements via optimization.



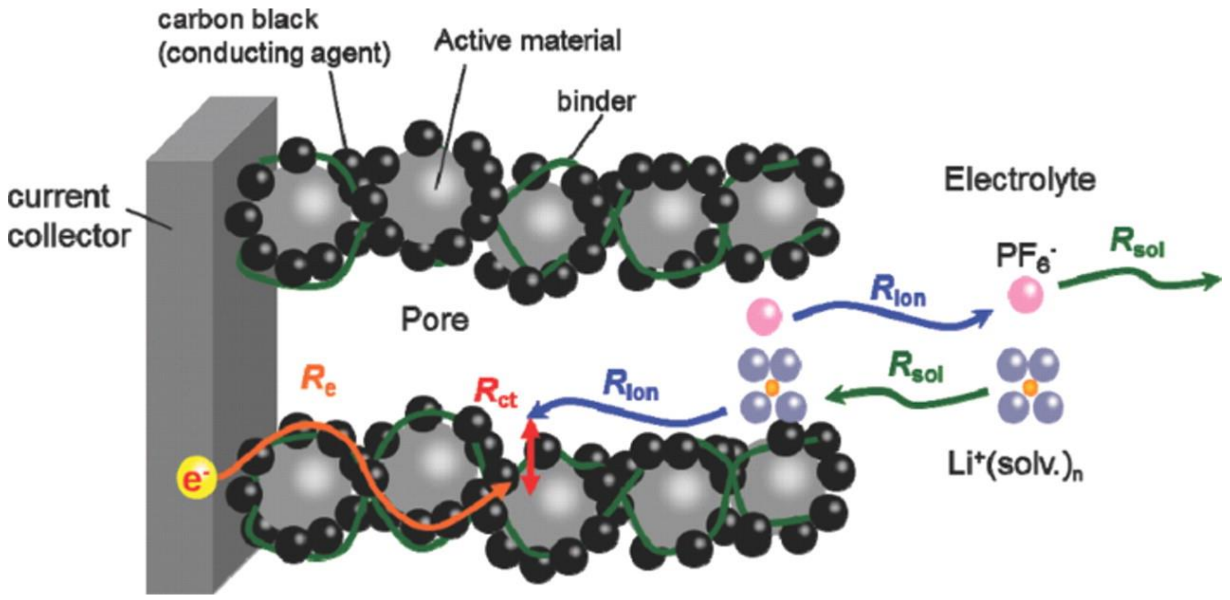


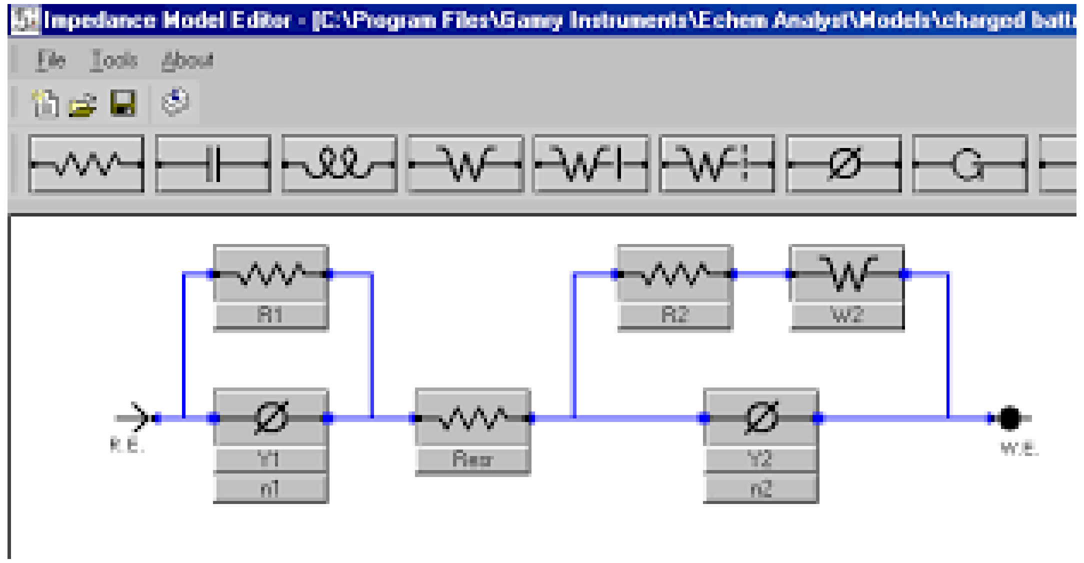


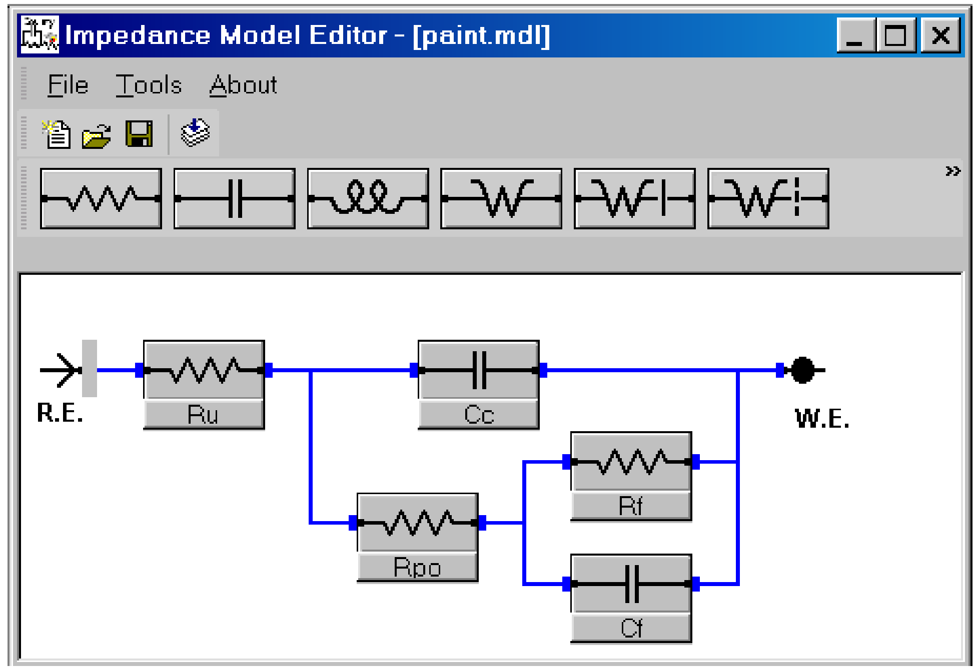
Battery Simulations

1. Equivalent circuits

The **first step** in the development of an accurate battery model is to **build** and parameterize an **equivalent circuit** that reflects the battery’s nonlinear behavior and dependencies on temperature, SOC, SOH, and current.
These dependencies are **unique to each battery’s chemistry** and need to be determined using measurements performed on battery cells of **exactly the same type** as those for which the application is being designed.



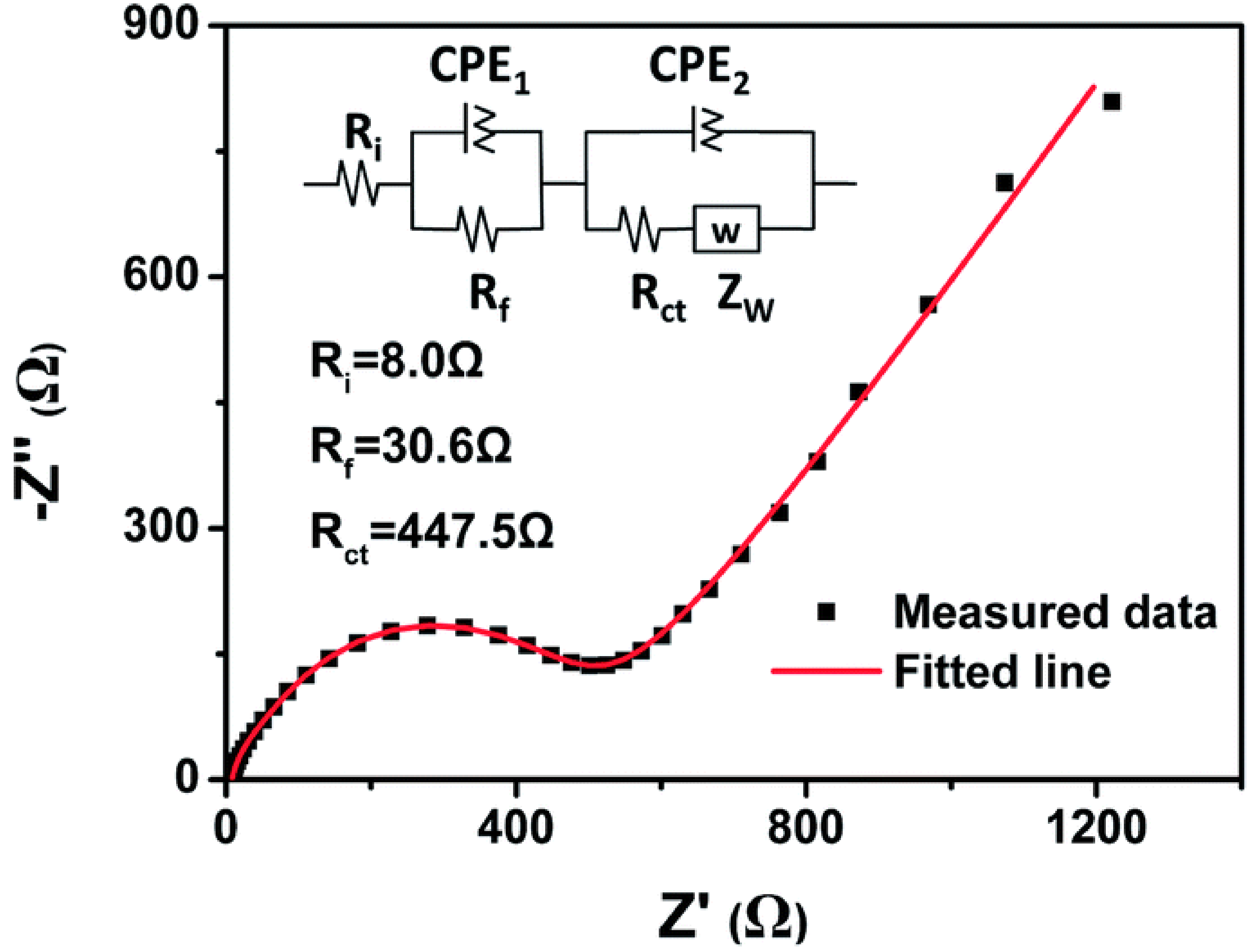


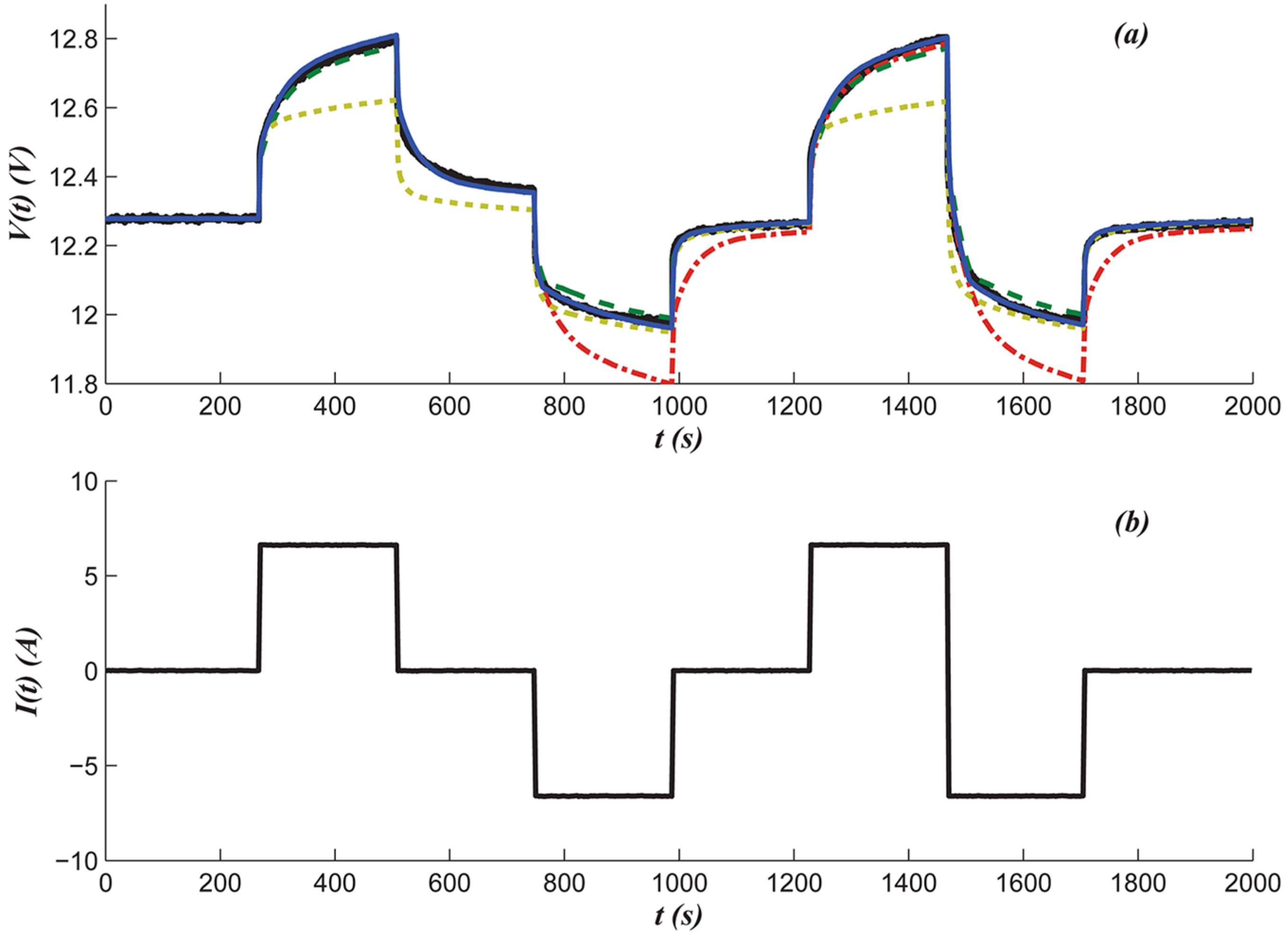


Battery Simulations

1. Equivalent circuits

The result must be a good fitting of battery behavior…





Battery Simulations

1. Equivalent circuits

You can model anything with a minimal knowledge about battery chemistry….but…

…not always is possible to understand the physical meaning of used circuit elements.

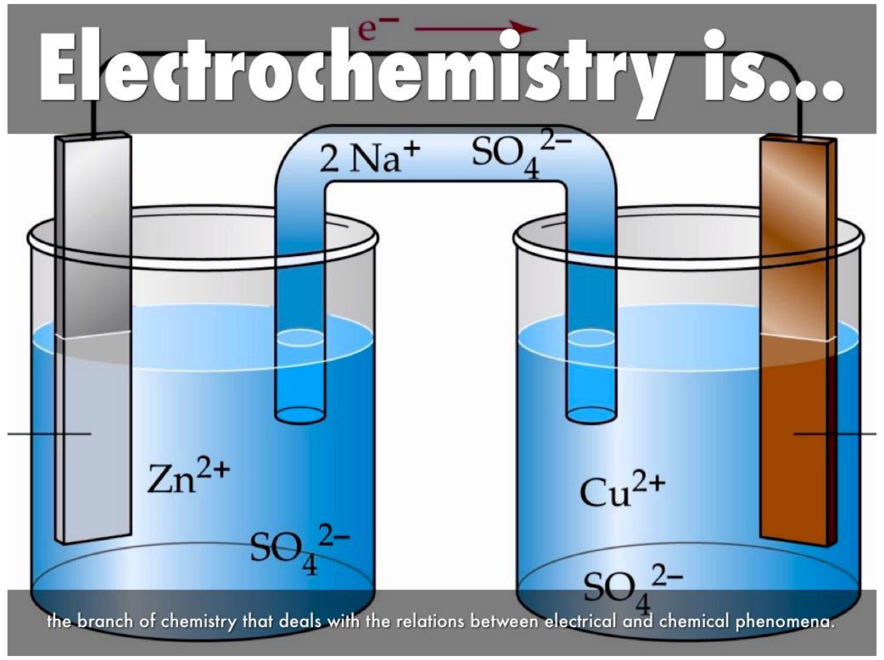
Due to this lack of understanding, some people prefer physical-chemical models…more realistic and more complicated….

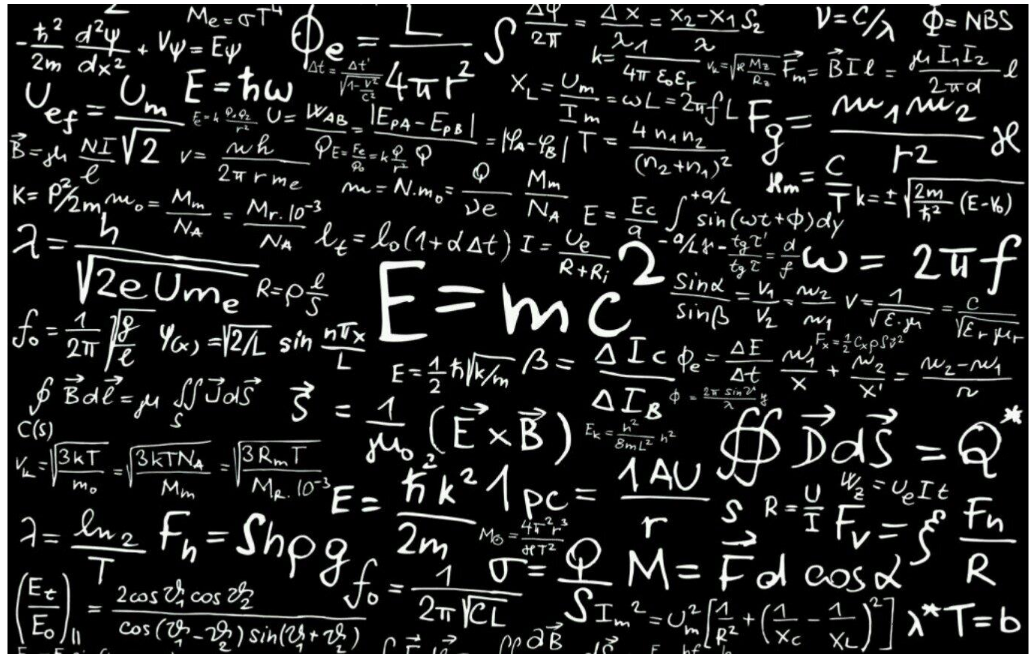
Battery Simulations

2. Physical-chemical models (Comsol Multiphysics and others)

Physical-chemical models use electrochemical equations to solve the current and voltage behavior problems (in an always changing system) and its consequences (structure modifications, SoC, SoH, degradation and others).

To develop these models it is necessary a deep knowledge of battery electrochemistry (mainly thermodynamics, kinetics and transport) and mathematics (specially knowledge about how to resolve coupled differential equations). Let see an example using Comsol Multiphysics Software

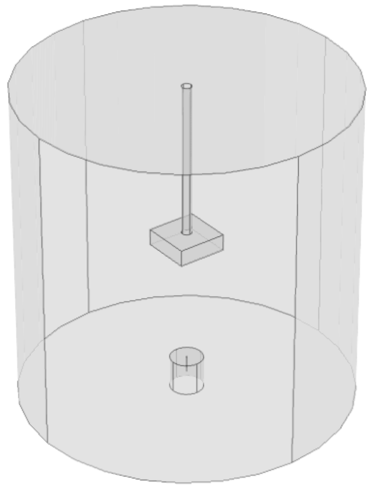




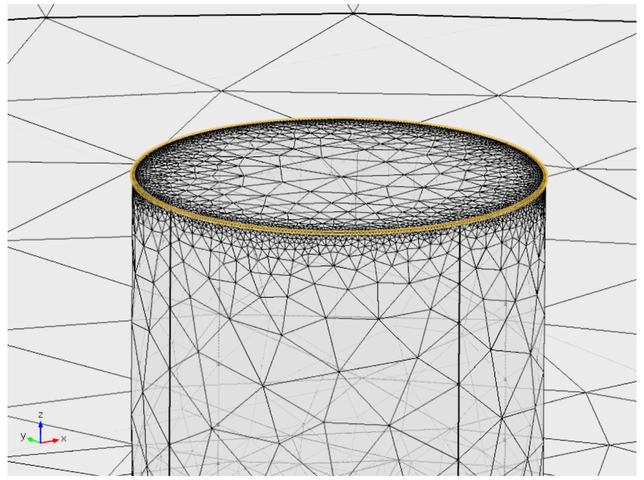
Battery Simulations

2. Physical-chemical models

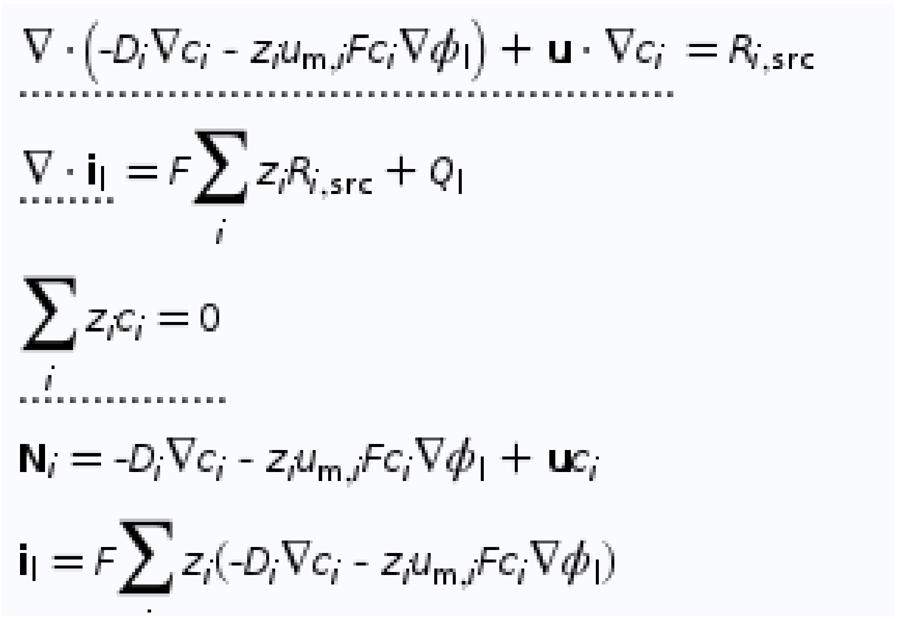
Geometry



Mesh



Equations



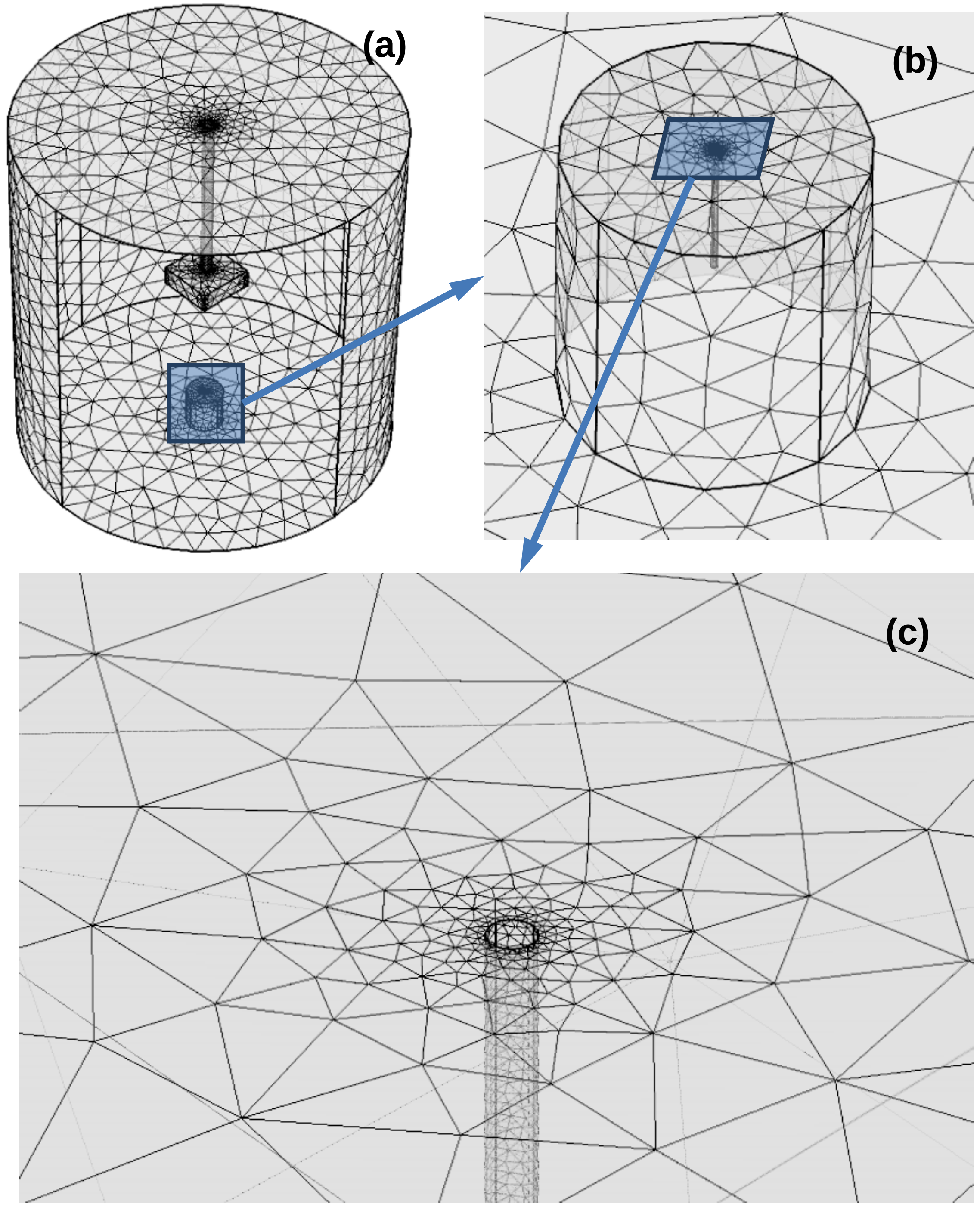
$$\nabla \cdot \left(-D_i \nabla c_i - z_i u_{\mathrm{m},i} F c_i \nabla \phi_l\right) + \mathbf{u} \cdot \nabla c_i = R_{i,\mathrm{src}}$$

$$\nabla \cdot \mathbf{i}_l = F \sum_i z_i R_{i,\mathrm{src}} + Q_l$$

$$\sum_i z_i c_i = 0$$

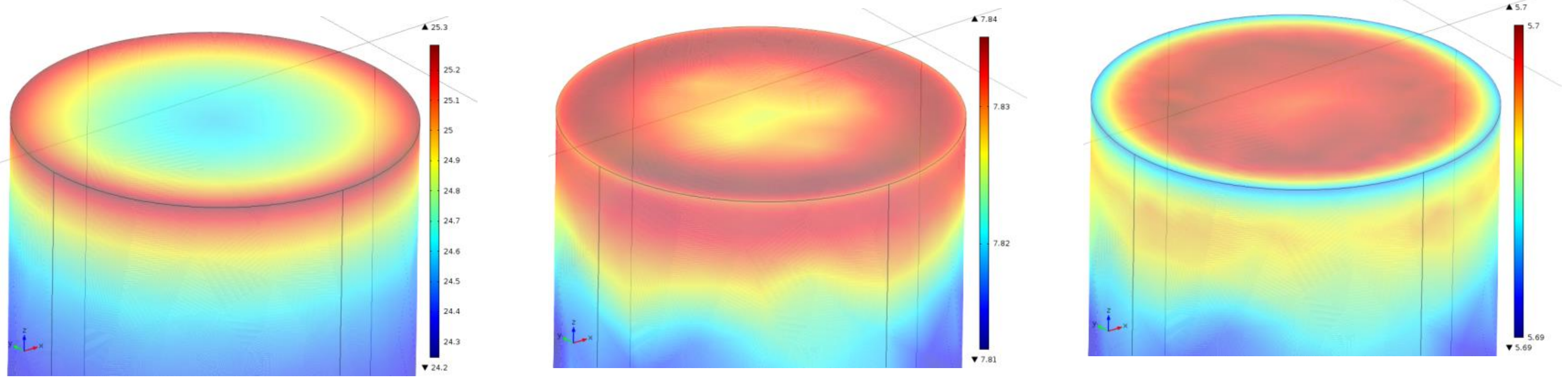
$$\mathbf{N}_i = -D_i \nabla c_i - z_i u_{\mathrm{m},i} F c_i \nabla \phi_l + \mathbf{u} c_i$$

$$\mathbf{i}_l = F \sum_i z_i \left(-D_i \nabla c_i - z_i u_{\mathrm{m},i} F c_i \nabla \phi_l\right)$$



Results

Open Comsol Multiphysics



Battery Simulations

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2. Physical-chemical models

You can model anything with enough knowledge about physics, chemistry and mathematics.

You can propose equations and test what happens macroscopically (current, voltage, temperature, phases distributions, concentration gradients….) if microscopically the physics laws are the proposed ones…and compare with experimental results.

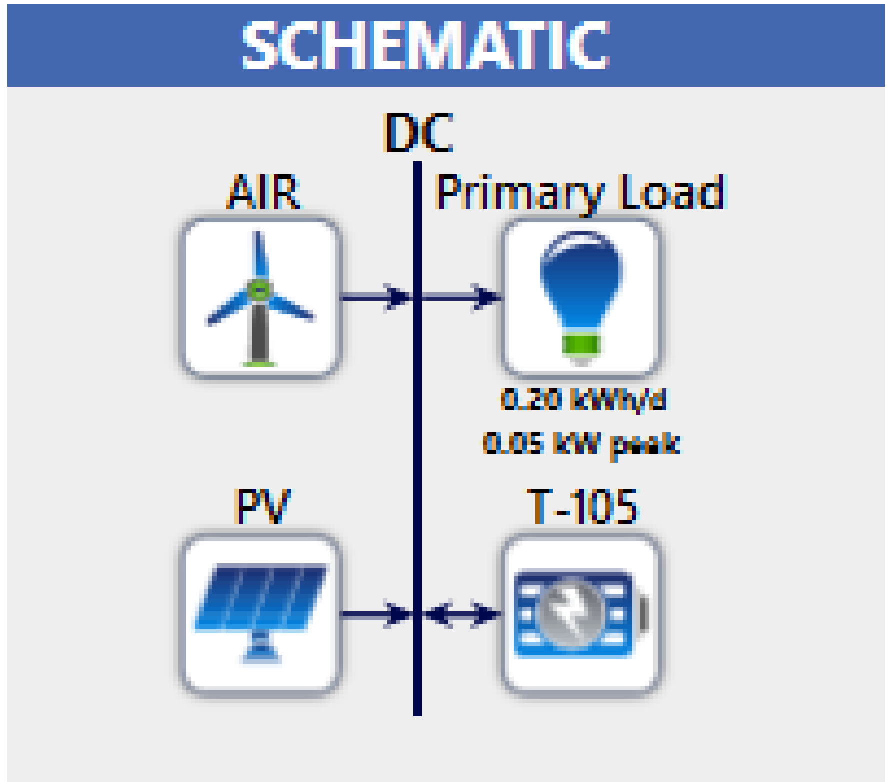
The only link to reality are the equations used and the real experimental results…if they are right may be your model is right for the simplification used (not all physical laws can be included!!!)

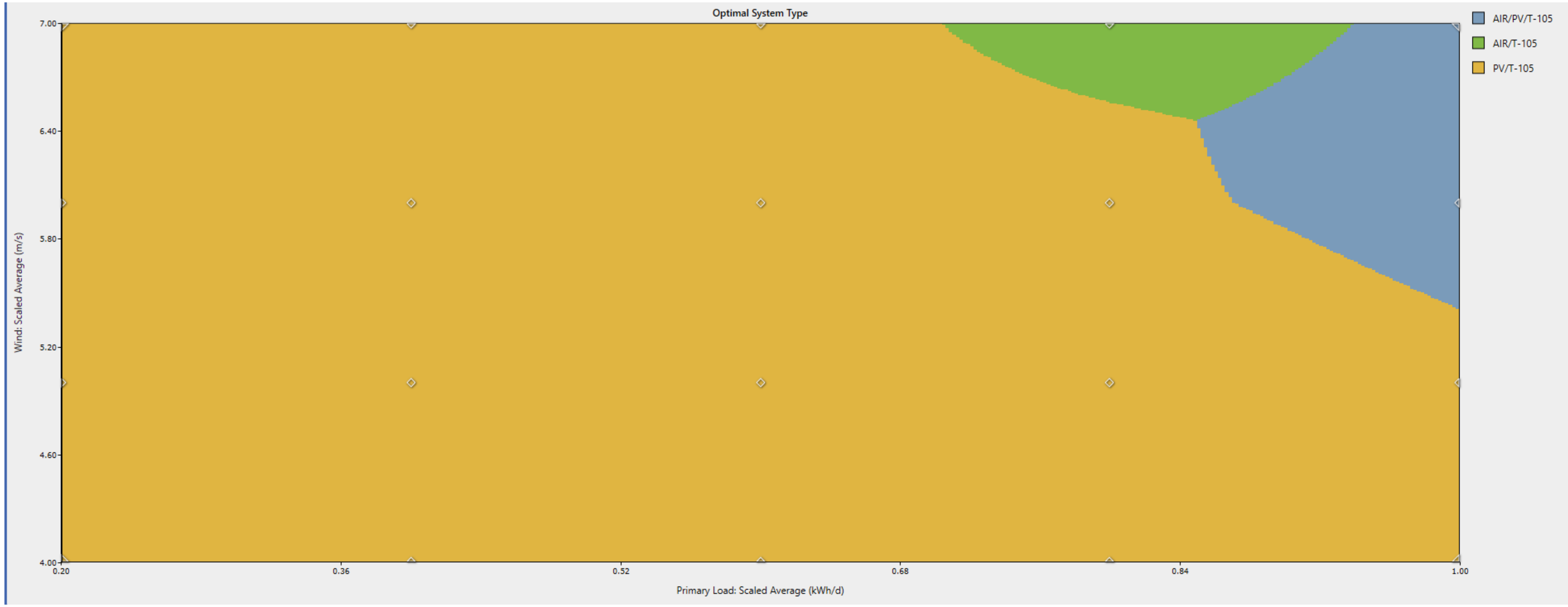
Battery Applications Simulations

Homer Energy software

Use all battery knowledge to simulate and calculate economic issues.

Open Homer software





Battery Applications Simulations

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Considerations about some battery applications

1. for photovoltaic systems

Deep cycling, uncontrolled ambient conditions, low cost, remote areas (small scale systems)

2. for Smart Grid applications

Low maintenance cost, high power, reliable, modular design

3. for EV´s applications

Light, high power, high energy, reliable, long cycling life (Lithium ion DoD~30%)

Battery Testing

Why to test batteries?

Testing is designed to tell us things we want to know about individual cells and batteries. Some typical questions are:

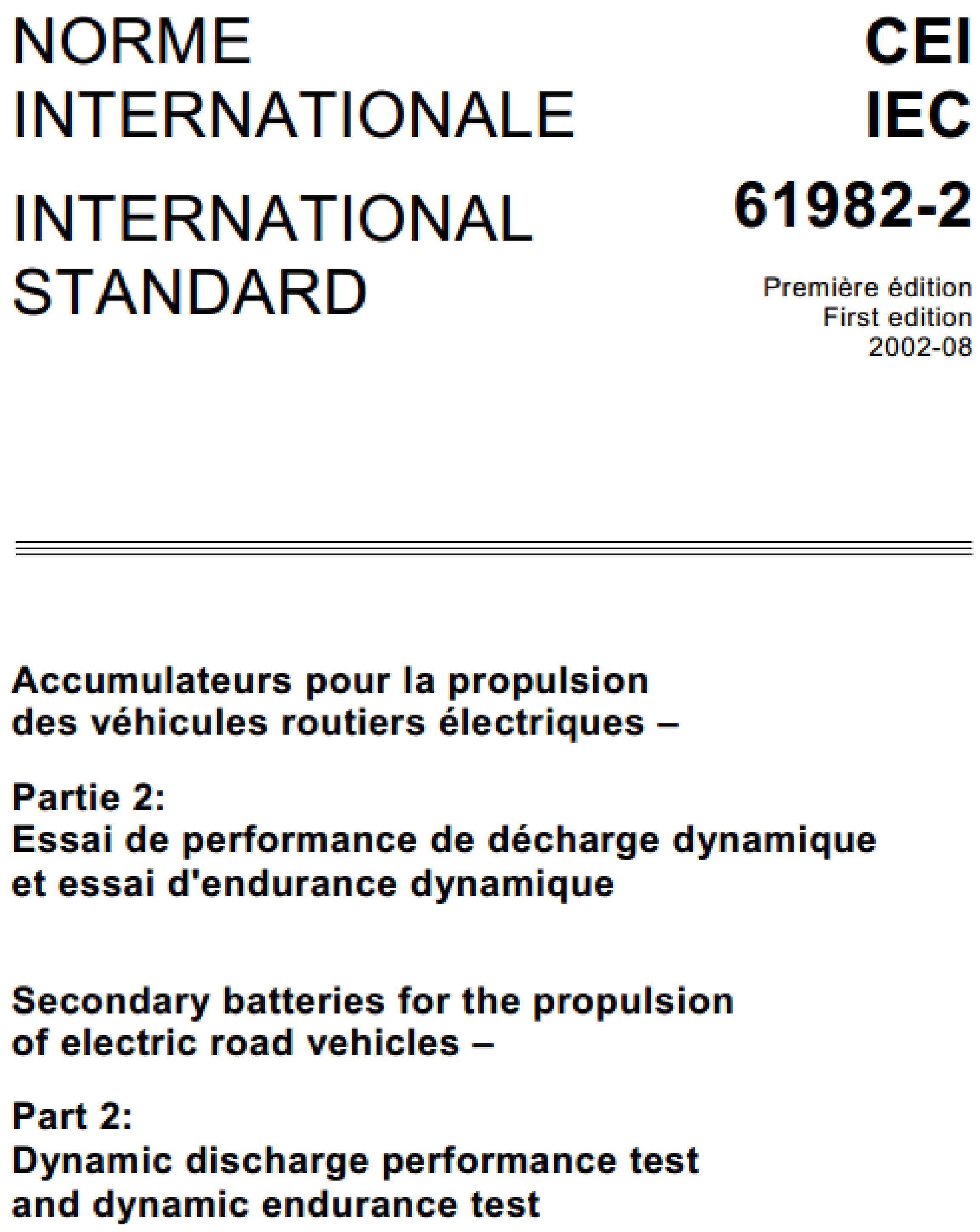
How much charge is left in the battery ? (SoC)
Does it meet the manufacturer's specification ?
Has there been any deterioration in performance since it was new ? (SoH)
How long will it last ?
Do the safety devices all work ?

The answers are not always straightforward

There exist many standards (when producers and users agree about how to test)

Battery Testing

Let see and example: IEC 61982 about batteries for EV´s



NORME
INTERNATIONALE

INTERNATIONAL
STANDARD

CEI
IEC
61982-2

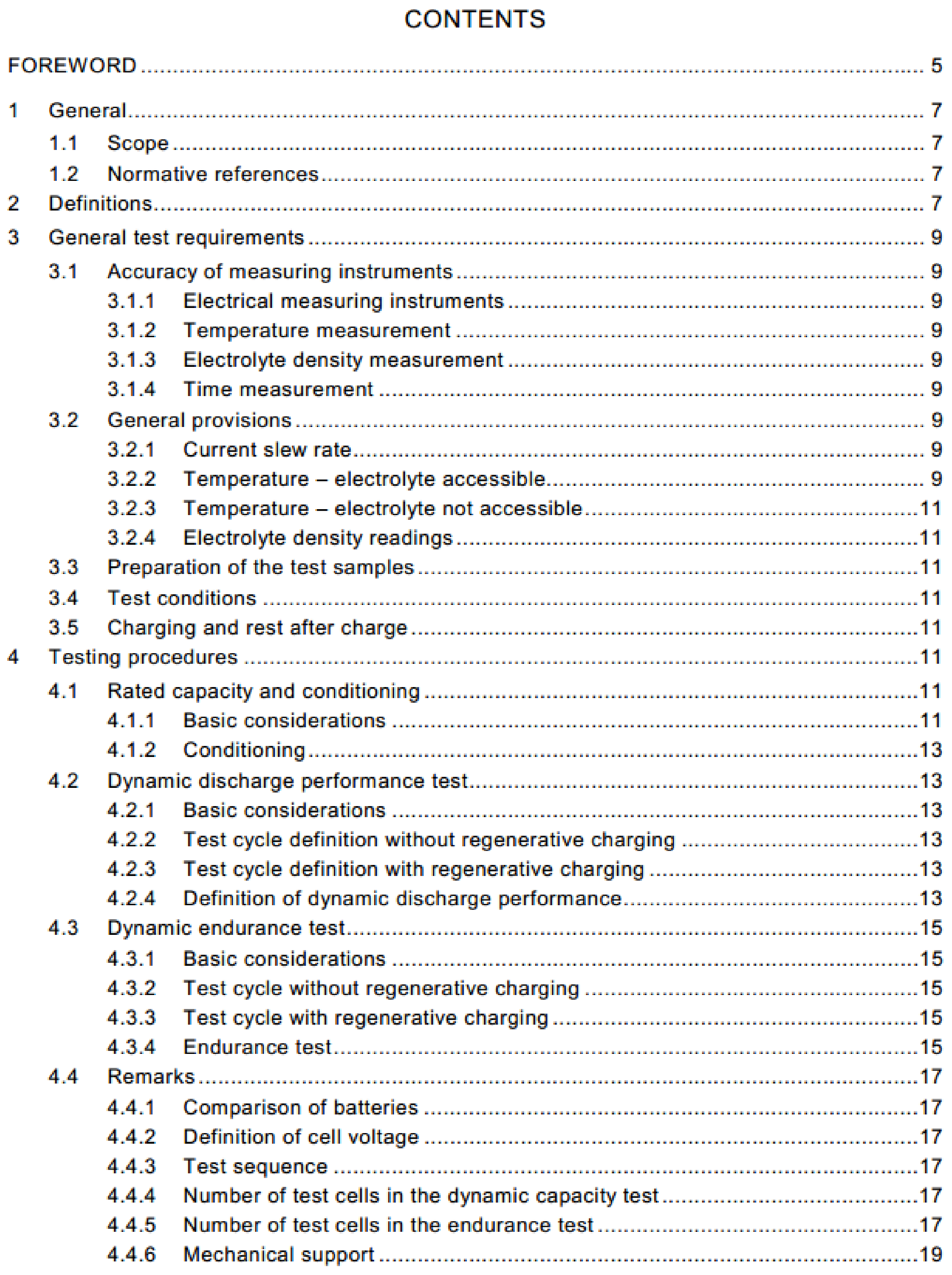
Première édition
First edition
2002-08

Accumulateurs pour la propulsion des véhicules routiers électriques –

Partie 2:
Essai de performance de décharge dynamique et essai d'endurance dynamique

Secondary batteries for the propulsion of electric road vehicles –

Part 2:
Dynamic discharge performance test and dynamic endurance test



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Battery Testing

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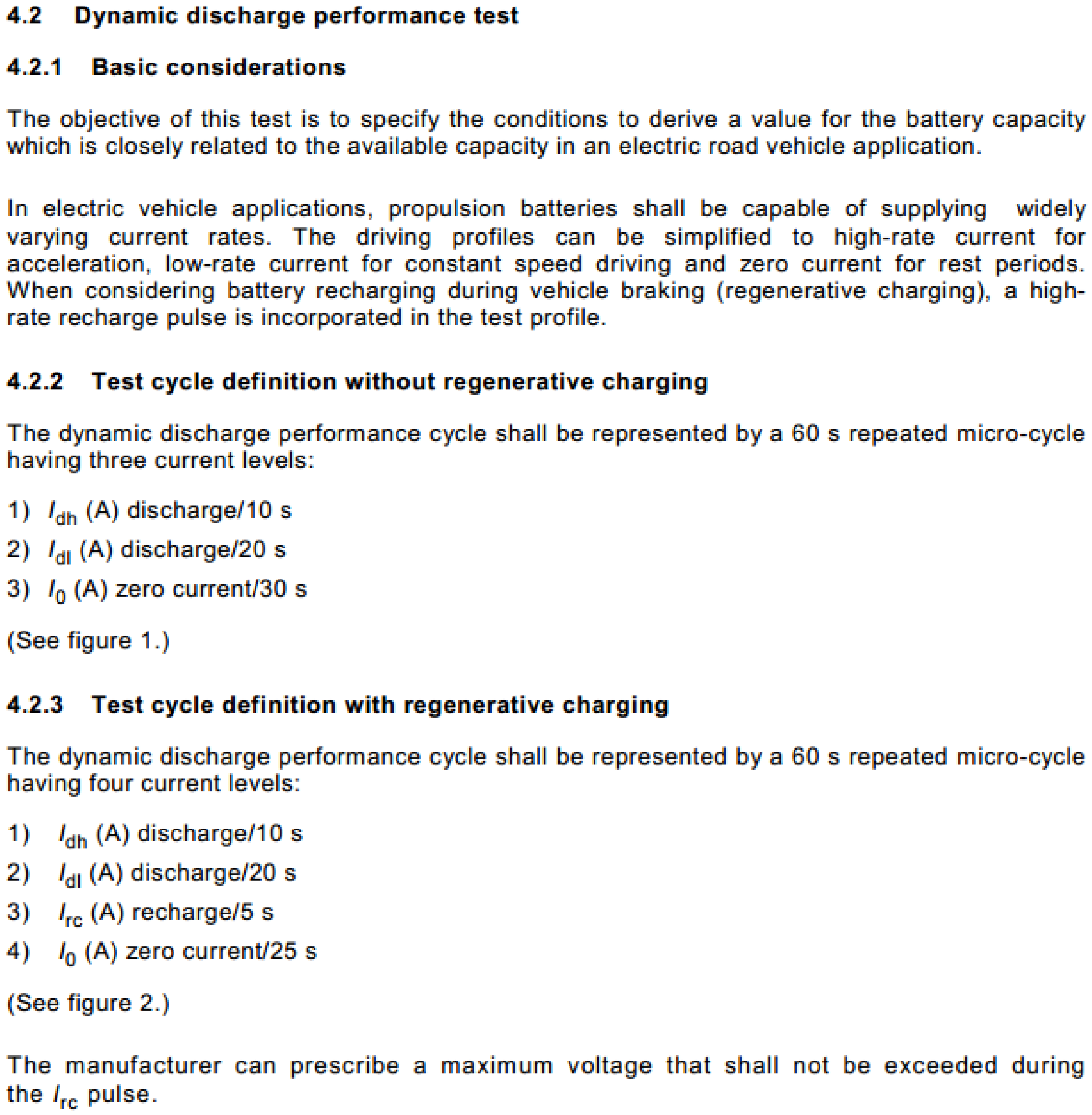
Dynamic discharge performance…..



4.2 Dynamic discharge performance test

4.2.1 Basic considerations

The objective of this test is to specify the conditions to derive a value for the battery capacity which is closely related to the available capacity in an electric road vehicle application.

In electric vehicle applications, propulsion batteries shall be capable of supplying widely varying current rates. The driving profiles can be simplified to high-rate current for acceleration, low-rate current for constant speed driving and zero current for rest periods. When considering battery recharging during vehicle braking (regenerative charging), a high-rate recharge pulse is incorporated in the test profile.

4.2.2 Test cycle definition without regenerative charging

The dynamic discharge performance cycle shall be represented by a 60 s repeated micro-cycle having three current levels:

1) I_{dh} (A) discharge/10 s
2) I_{dl} (A) discharge/20 s
3) I_0 (A) zero current/30 s

(See figure 1.)

4.2.3 Test cycle definition with regenerative charging

The dynamic discharge performance cycle shall be represented by a 60 s repeated micro-cycle having four current levels:

1) I_{dh} (A) discharge/10 s
2) I_{dl} (A) discharge/20 s
3) I_{rc} (A) recharge/5 s
4) I_0 (A) zero current/25 s

(See figure 2.)

The manufacturer can prescribe a maximum voltage that shall not be exceeded during the I_{rc} pulse.

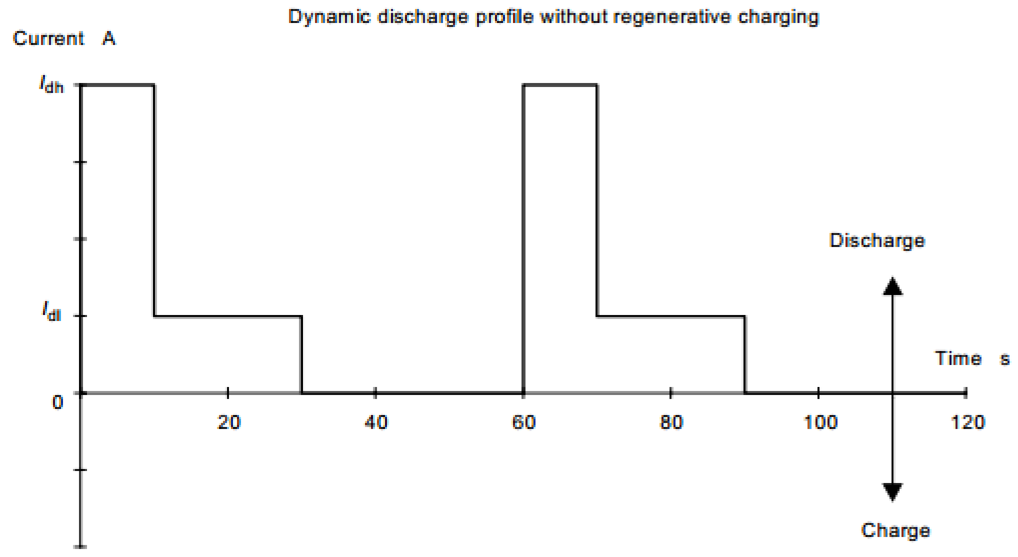


Figure 1 – Test profile without regenerative charging

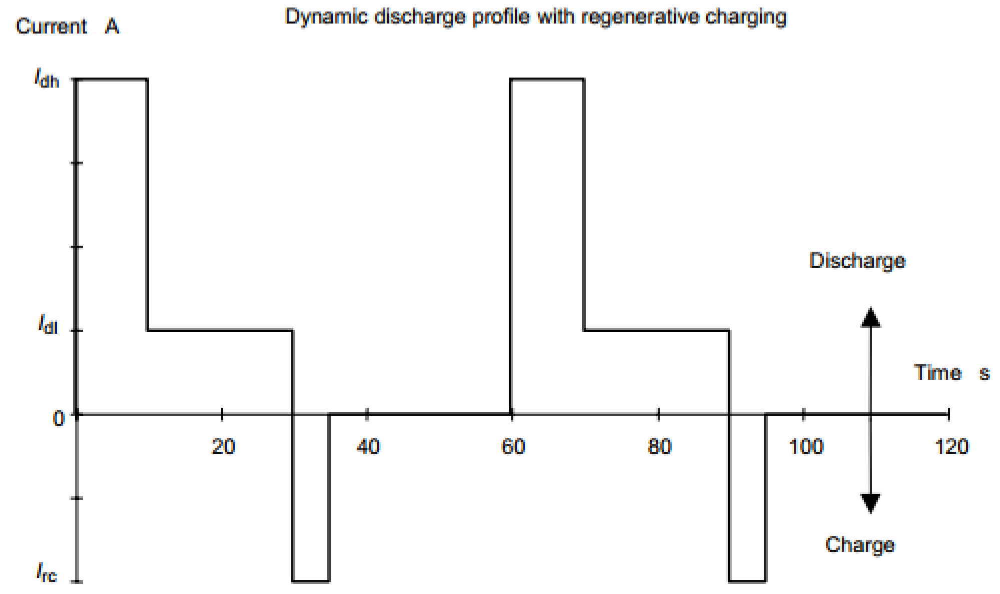


Figure 2 – Test profile with regenerative charging

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THANK YOU