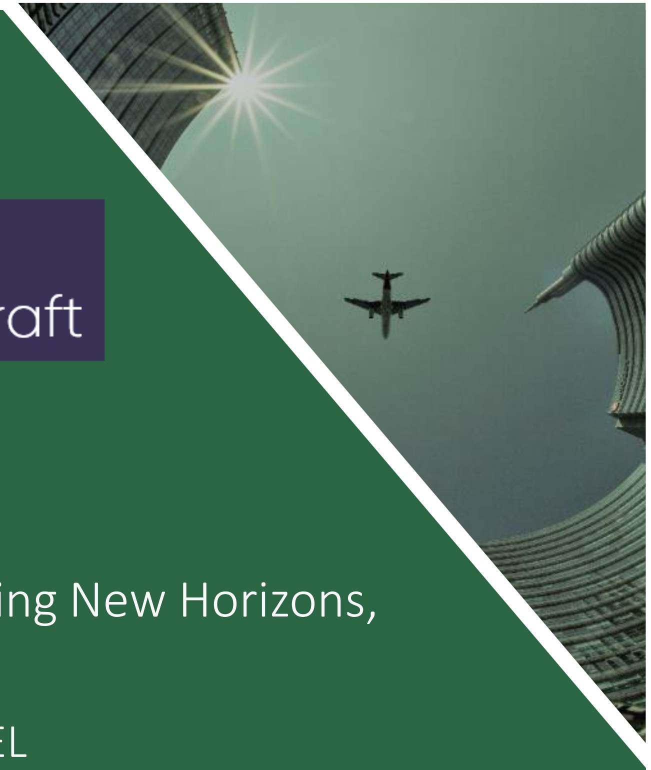
FUTure PRopulsion and INTegration
towards a hybrid-electric 50-seat regional aircraft



An optimal battery sizing algorithm for future aircraft systems studies

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CEA

FUTPRINT50

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European Commission

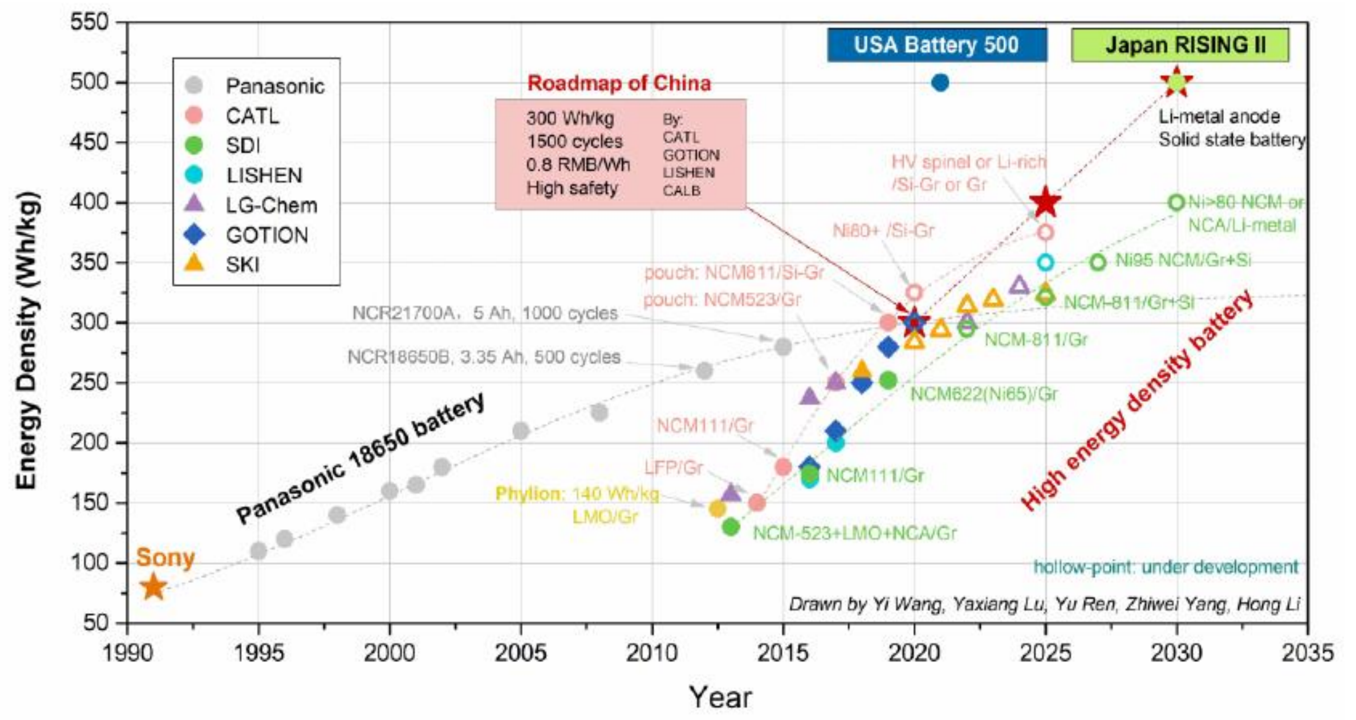
FutPrInt50

Batteries basics

A **battery** is a device that converts **chemical energy** directly to **electrical energy.**

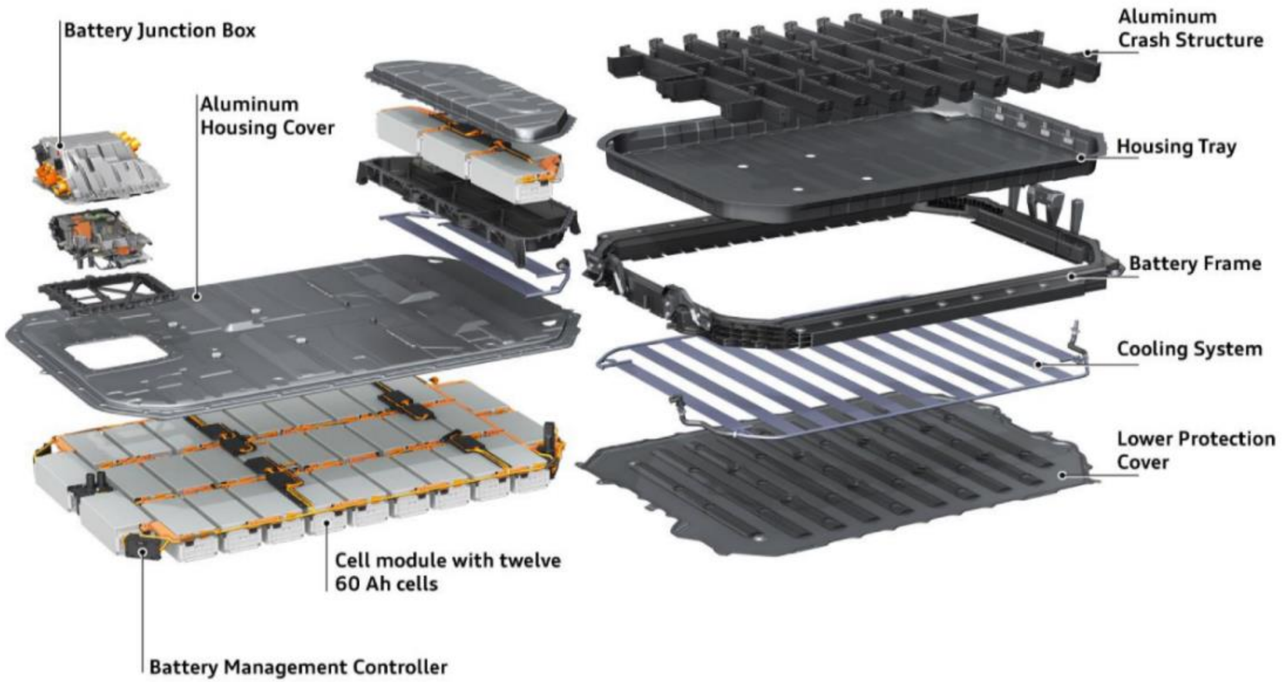
Key figures:

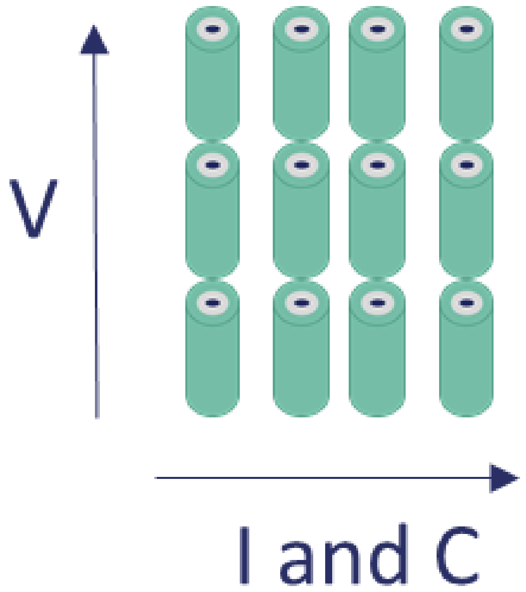
- **Capacity** [Ah]: quantity of electricity stored: 1 Ah = 3600 A.s = 3600 C
- Charge/discharge rate (**C-rate**) [1/h]
  xC is a rate that allows a battery to be charged/discharged in x hours under a constant current
- **Mass**, **volume**, **temperature range**, **aging**…
- **Power density** [W/kg] [W/L] (specific power)
- **Energy density** [Wh/kg] [Wh/L] (specific energy)



Batteries basics

Pack → modules → cells

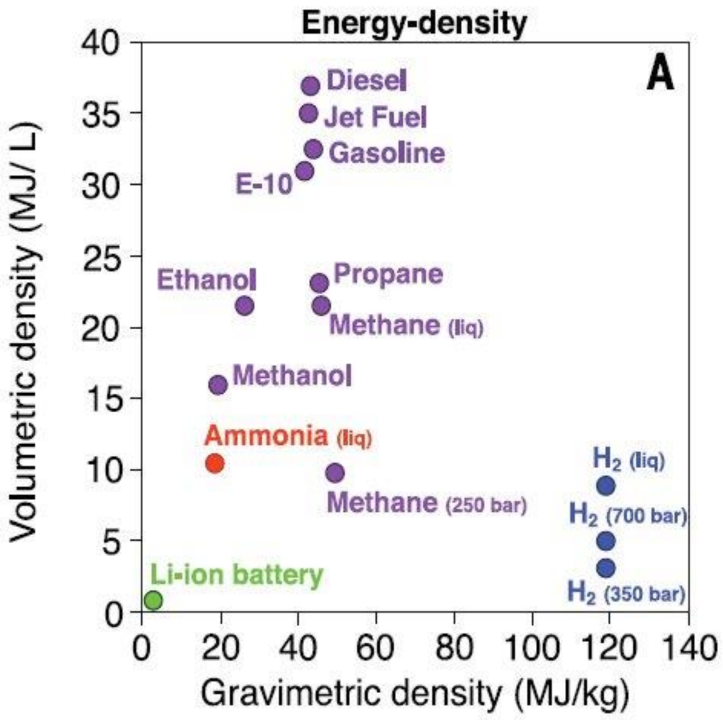




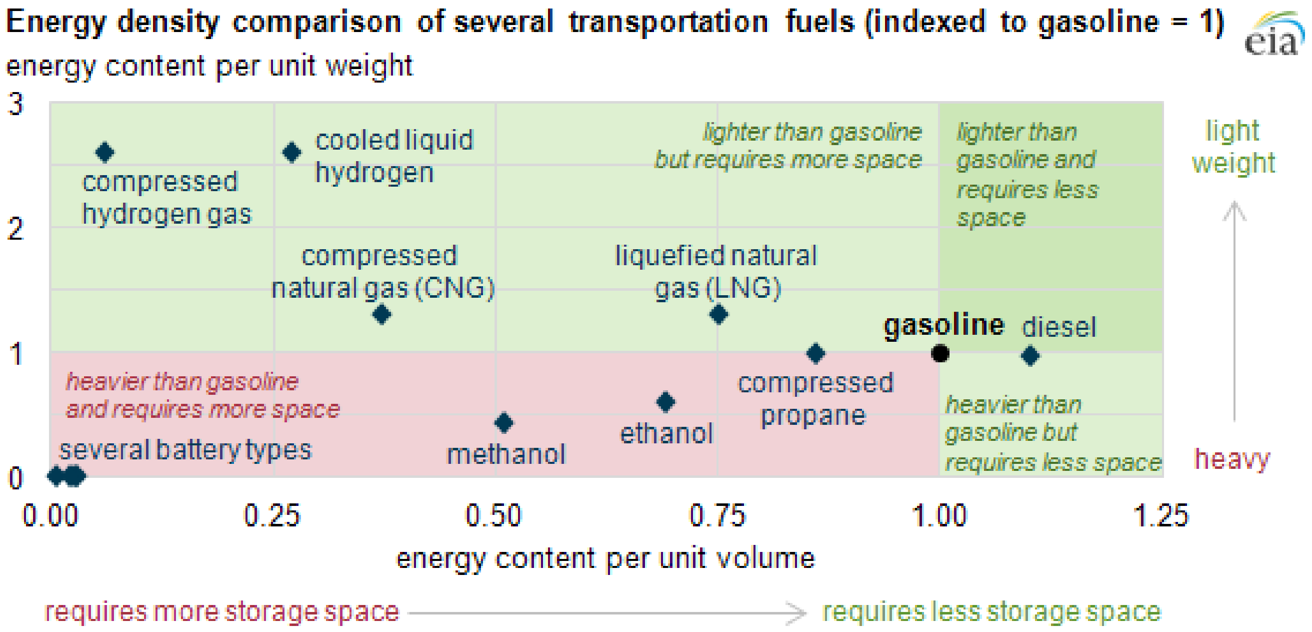
$E = V*C$

$P = V*I$

Why don't we have electric aircrafts yet ?



DOI: 10.1126/science.aas9793



https://www.eia.gov/todayinenergy/detail.php?id=9991

H_2	33 kWh/kg
Jet fuel	12 kWh/kg
LiB cell	0.3 kWh/kg –> pack 0.15 kWh/kg

FutPrInt50

Why don’t we have electric aircrafts yet ?

Safety !!

Two competitive challenges for flying batteries

In order to fly batteries, we must (**objectives**):

- Decrease mass
- Increase safety
- (Without forgetting **aging** and **TCO**…)

Optimization

Three key architectures (**constraints and decision variables**):

- **Mechanical** architecture
- **Electrical** architecture
- **Thermal** architecture

One optimization…

Fixed data

- Expected lifetime (year)
- Sizing profiles (electro-thermal)
  - $P_{elec\_(W)} = f(t\_{(s)})$
  - $T_{amb\_(°C)} = f(t\_{(s)})$
- Sizing profiles (ageing):
  - $P_{elec\_over\_24h\_(W)} = f(t\_{(s)})$
  - $T_{amb\_over\_24h\_(°C)} = f(t\_{(s)})$
- Pack voltage limits :
  - Udc min
  - Udc max
- Module max volume, mass, voltage
- Safety constraints (no thermal runaway propagation, DO311, degassing or not, failure rates requirement)
- Cold source (Q, Tinput_coolant)

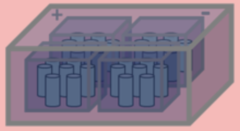
Pack optimization method

Decision variables*

- Cell :
  - type/chemistry/grammage and electrode area
  - or reference
- Cooling-heating techno
- Distance and material between cells, module geometry
- Module casing shape and material
- N modules in series / N modules in parallel
- N cells in series / N cells in parallel
- 'Architecture' for electrics (fuses…)
- 'Architecture' for safety (?)

Iterative simulations

BATTERY PACK MODEL



(*) each decision variable is:
- restricted
- discrete, continuous or from database

Optimal decision variables

Cell, thermal management technology, etc.

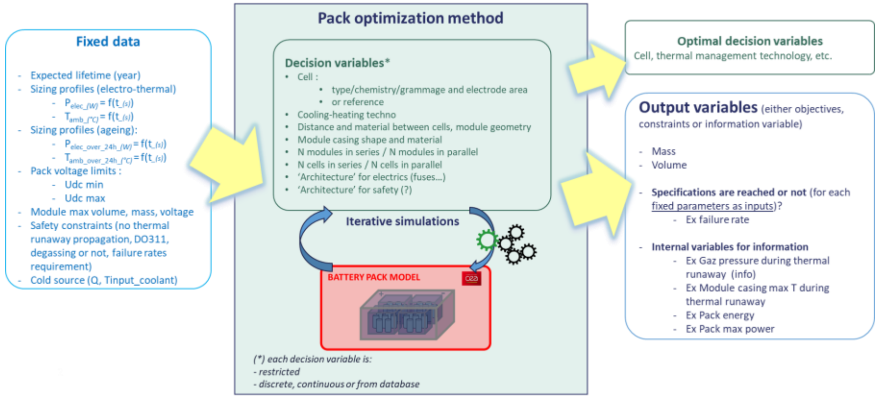
Output variables (either objectives, constraints or information variable)

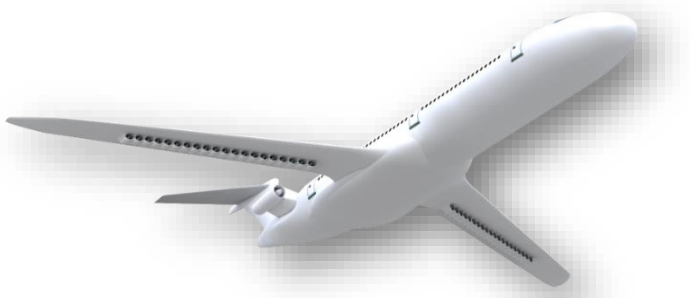
- Mass
- Volume

- **Specifications are reached or not** (for each fixed parameters as inputs)?
  - Ex failure rate

- **Internal variables for information**
  - Ex Gaz pressure during thermal runaway (info)
  - Ex Module casing max T during thermal runaway
  - Ex Pack energy
  - Ex Pack max power

One optimization integrated into a global and complex aircraft architectures optimization

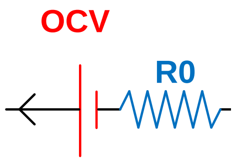




Aircraft architectures optimization tools

Battery sizing : current situation in aircraft design studies

Simple battery models give approximated results



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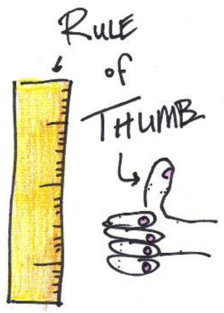


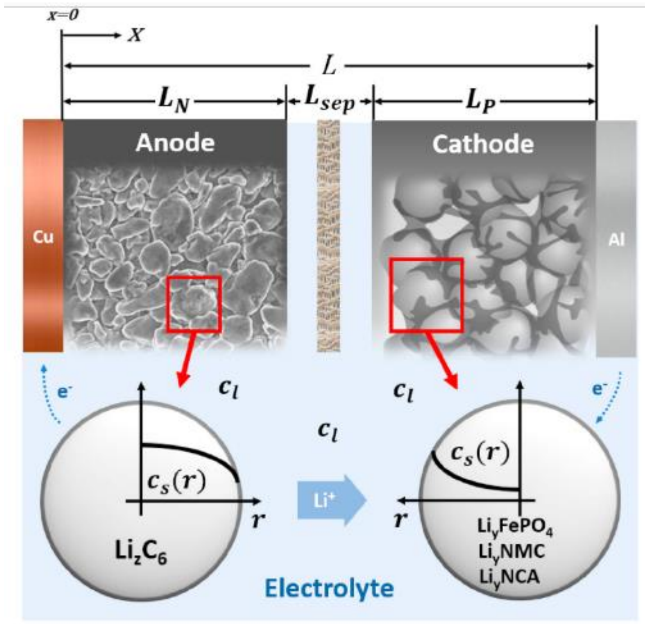
Only electrical performances sizing with **expert rules** for :

- Aging
- Casing mass

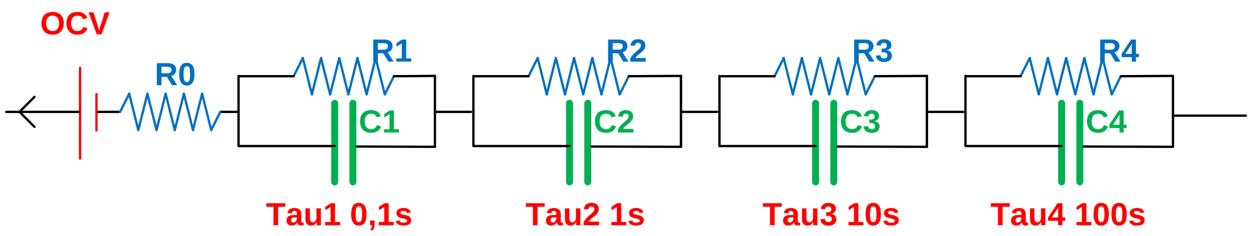
No retroaction of safety on battery sizing

We need **more accurate** battery models

Advanced battery models : electrochemical performances and aging



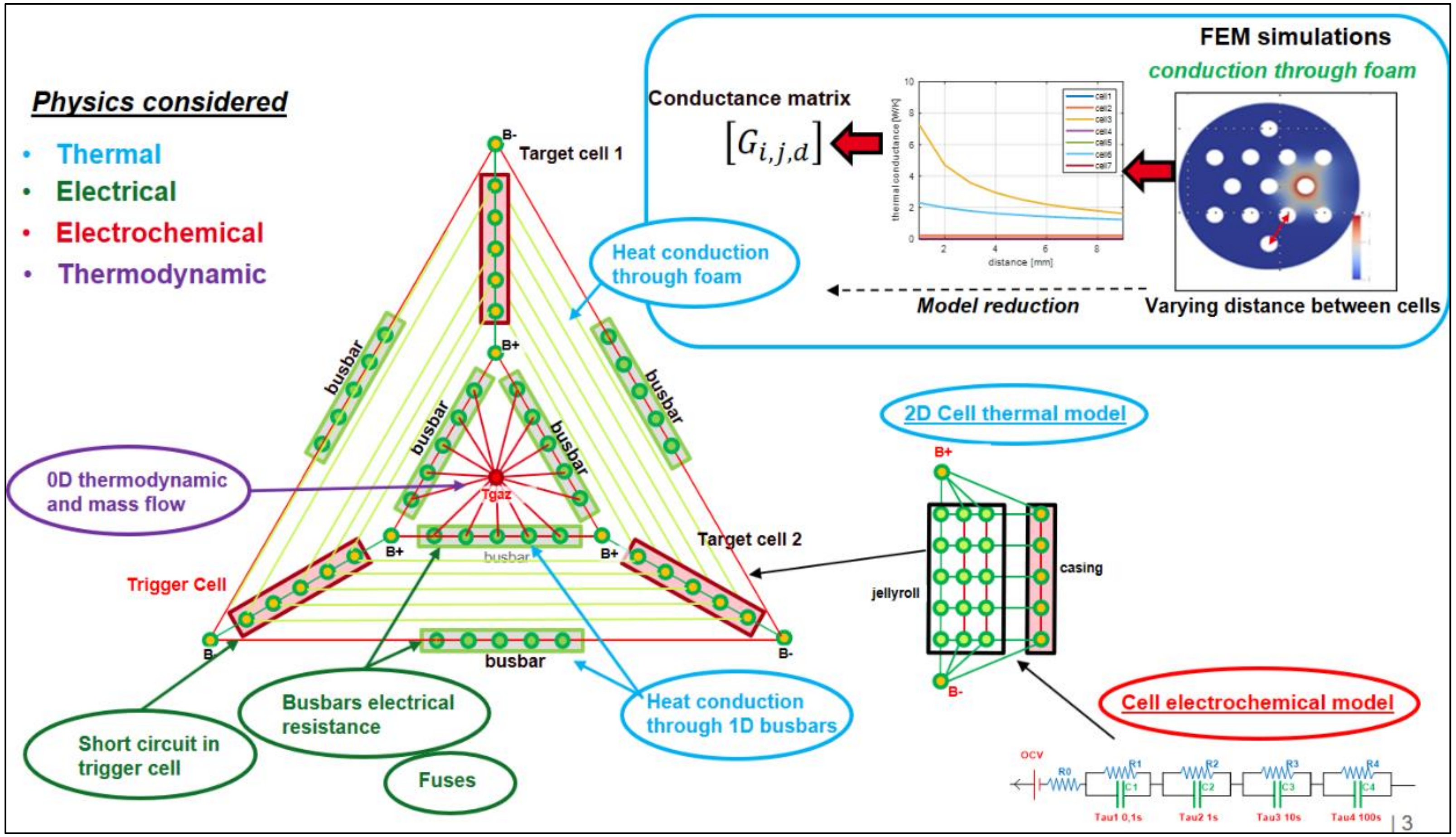
Doyle-Fuller-Newman model (DFN)

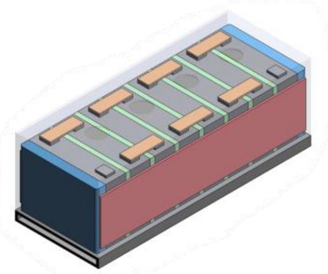


Electrical equivalent circuit model (EEC)

U = f(current, temperature, SoC, SoH)

Advanced battery models : safety

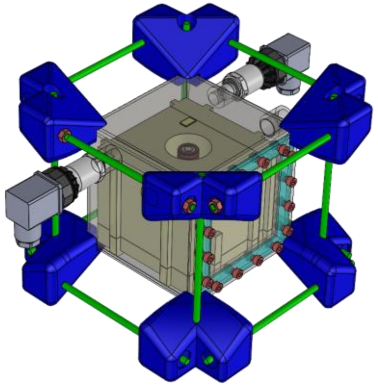




Module
- Max pressure
- Max temperature

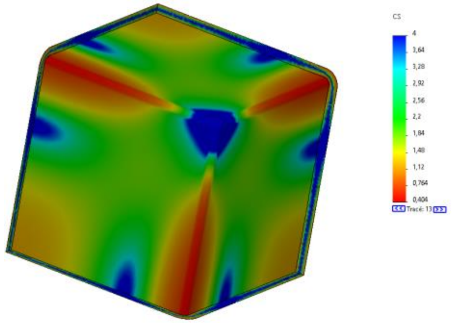
Advanced battery models: module casing mechanical model

Model design

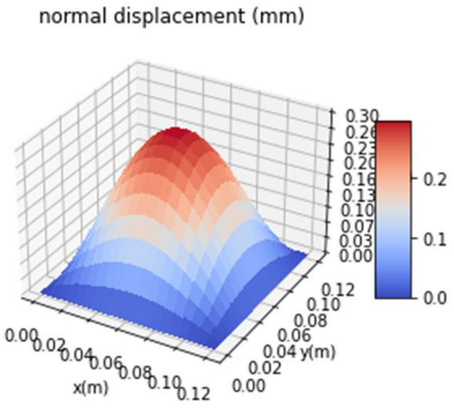


Exp. model

FEA model

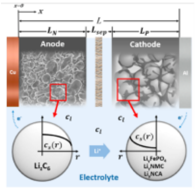


Analytical model



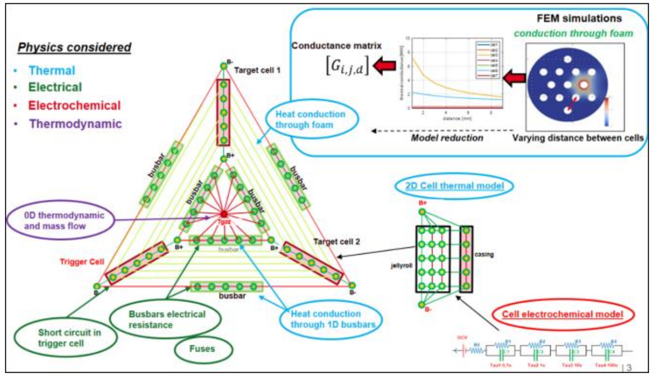
Casing mass and volume

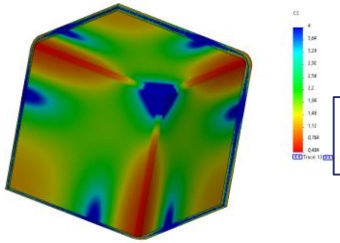
Reality check



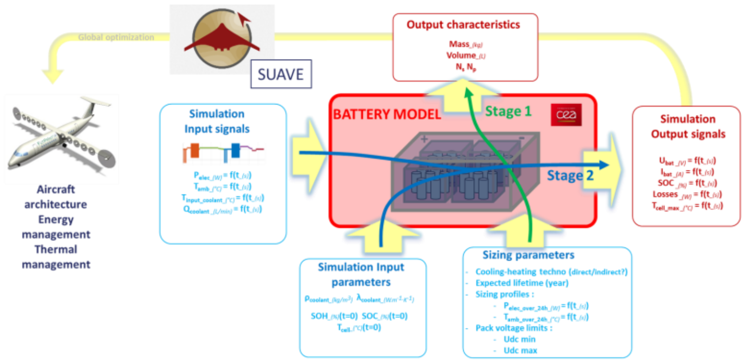
Doyle-Fuller-Newman model

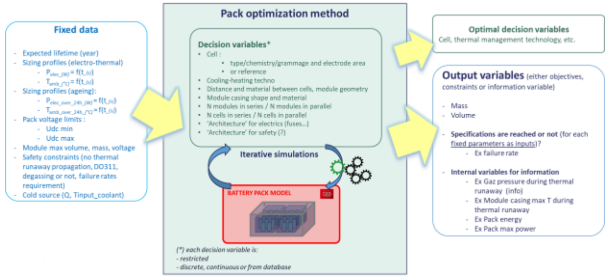
Electrical equivalent circuit model



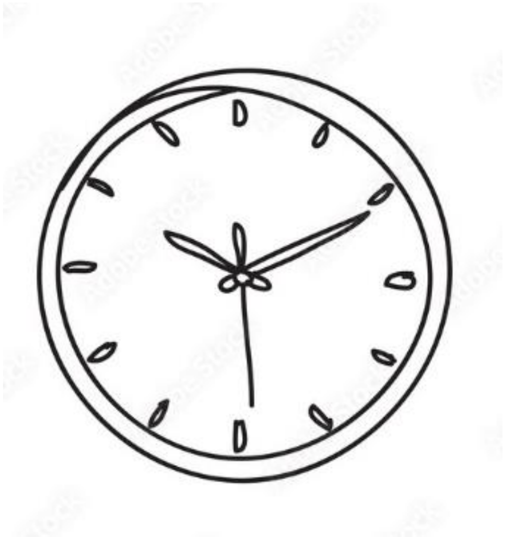


Complex models





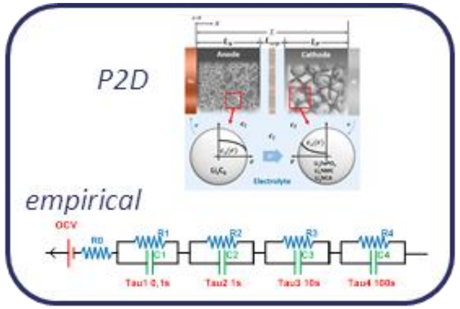
Multi levels optimizations



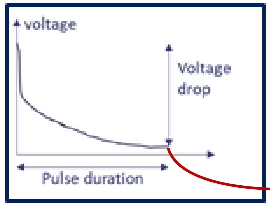
Long computation time

Surrogate models and two steps sizing algorithm

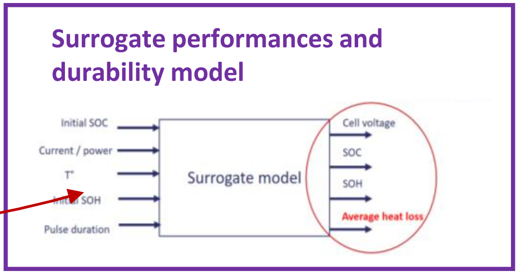
MODELS

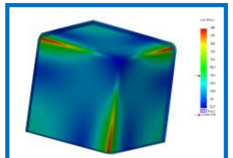


Electrochemical performance / ageing



parametric temporal simulations

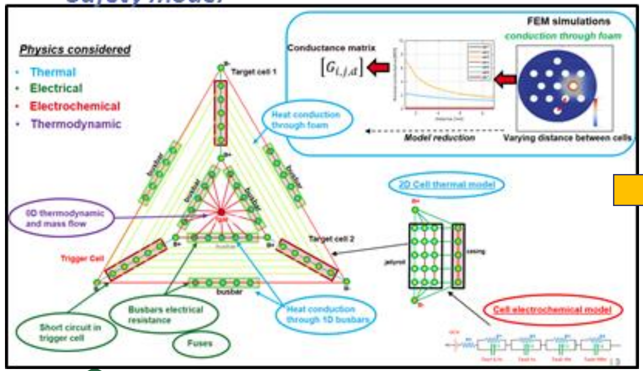


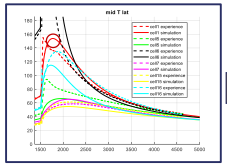


Module casing mechanical model

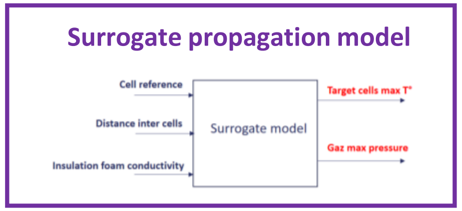
Analytical module casing mechanical model

Safety model



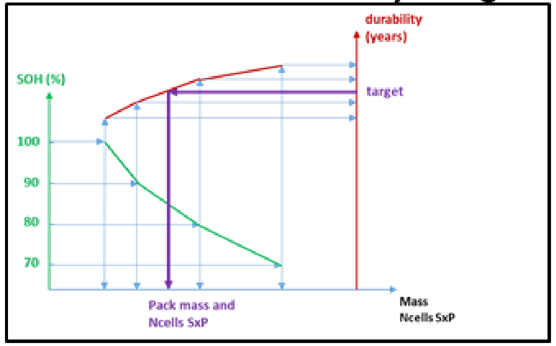


Parametric temporal simulations



SIZING ALGORITHMS

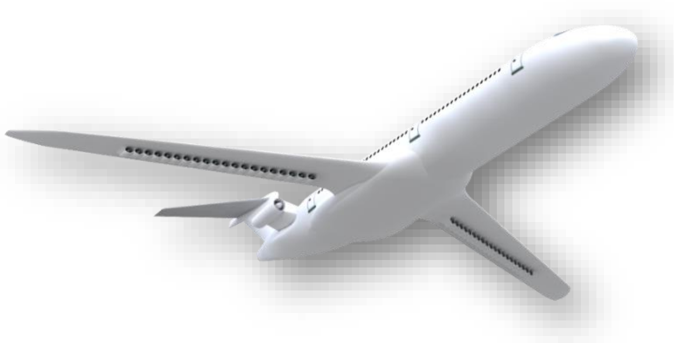
1) Performance and durability sizing



Performances vs aging

Finale optimization
→ mass vs safety

Development of a mechanical model based on experimental tests

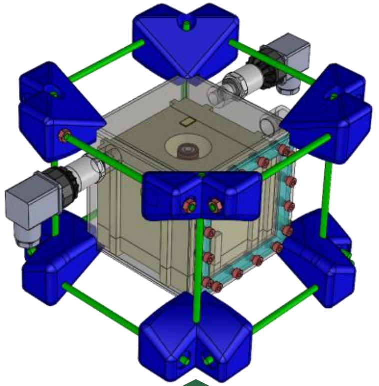


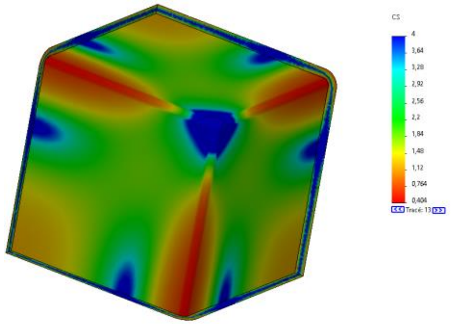
Objectives :

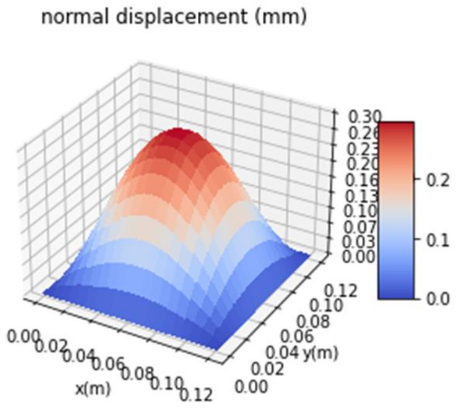
- Mechanical model validation of a battery casing under thermal runway pressure
- Sizing validation from the Finite Elements Analysis (FEA) simulation to the analytic model

Methodology

Model design → **Exp. model** → **FEA model** → **Analytical model**



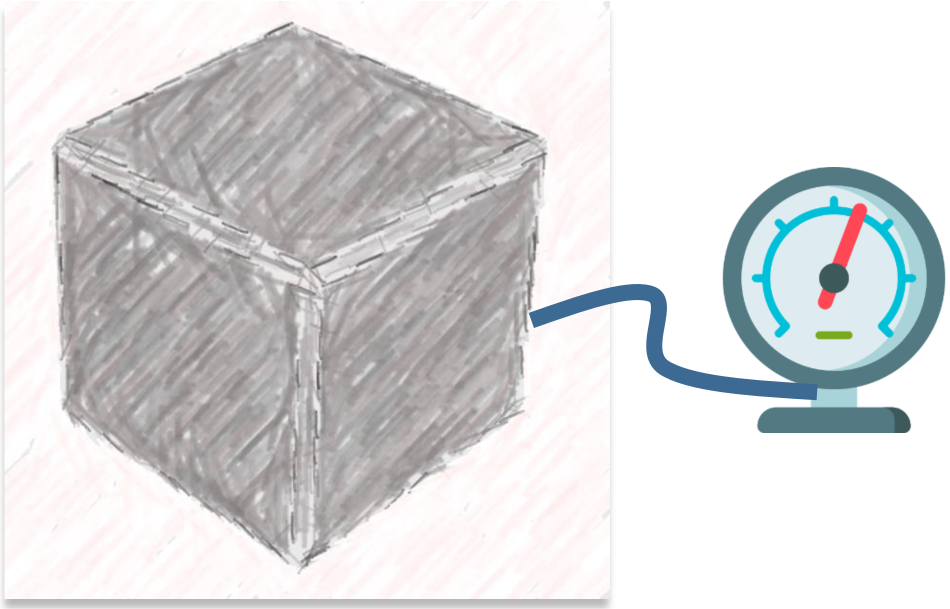




Development of an experimental module

Requirements from CEA feedback:

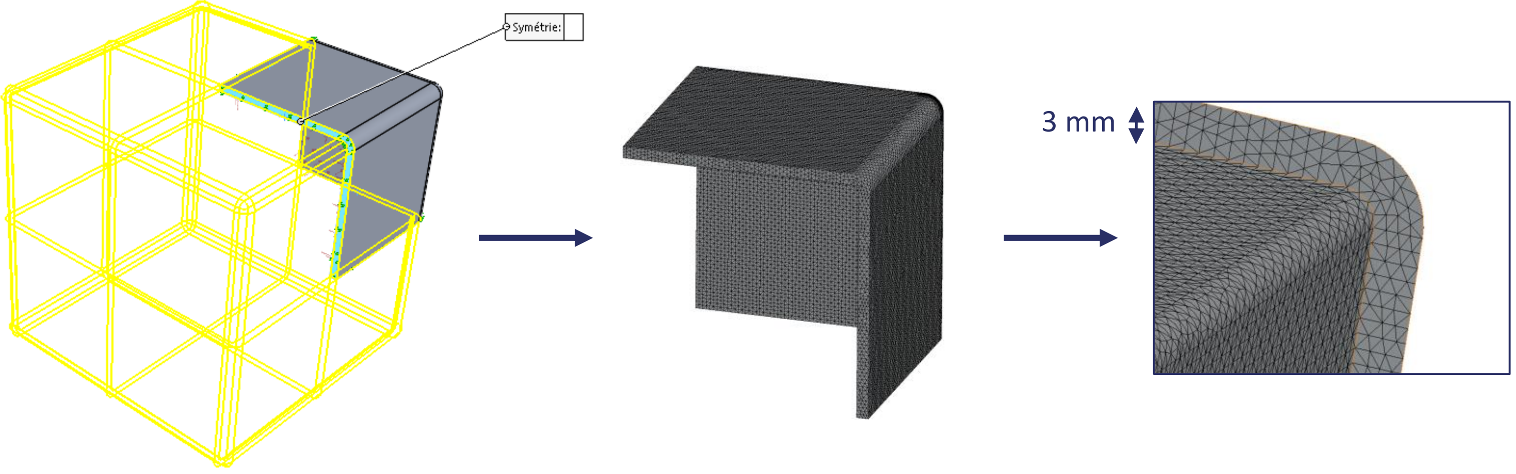
- 3 bar max
- About 1 to 2 liters max
- Cube geometry (127 mm x 127 mm x 127 mm)
- 2 vents
- 1 cell in thermal runway
- 30% free space inside
- Free face displacement
- Several sensors (TC, Strain gauges, pressure)
- Rapid camera

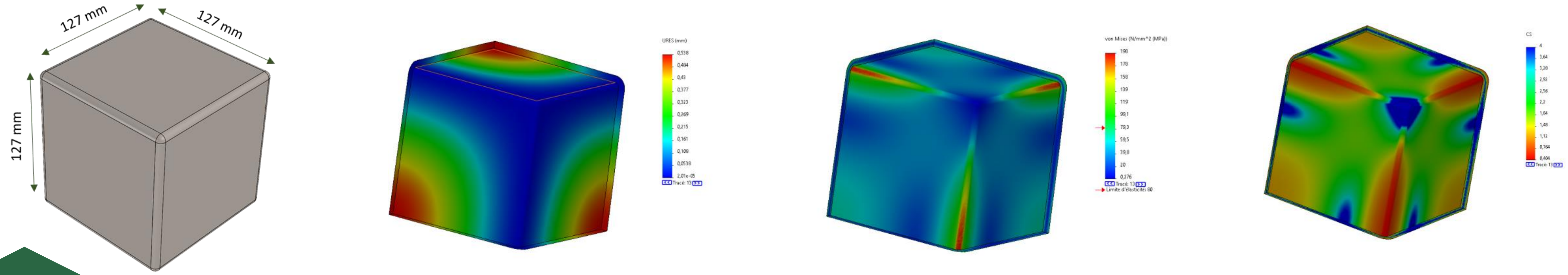


Experimental module design

Square cube model

1. Mesh detail for the 1/8 of the square cube
   - 3 nodes minimum in the thickness
   - Analytic solution not available for the complete casing
2. FEA simulation
   - Experimental designs and trade off mass
   - Metal sheet of **3 mm thick**
   - Material : **AL 5454 H111**

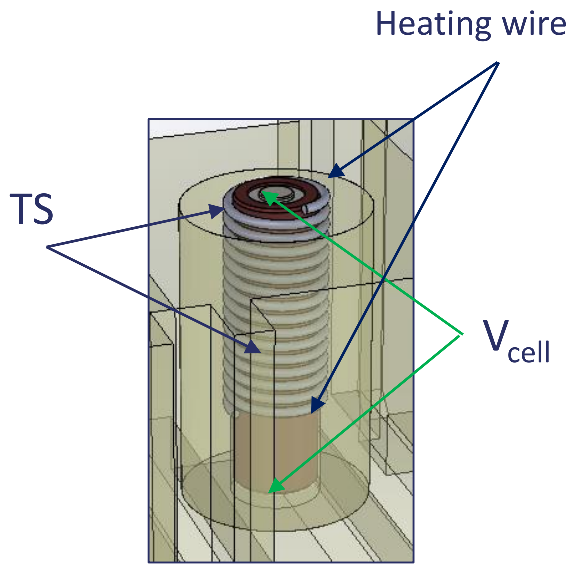


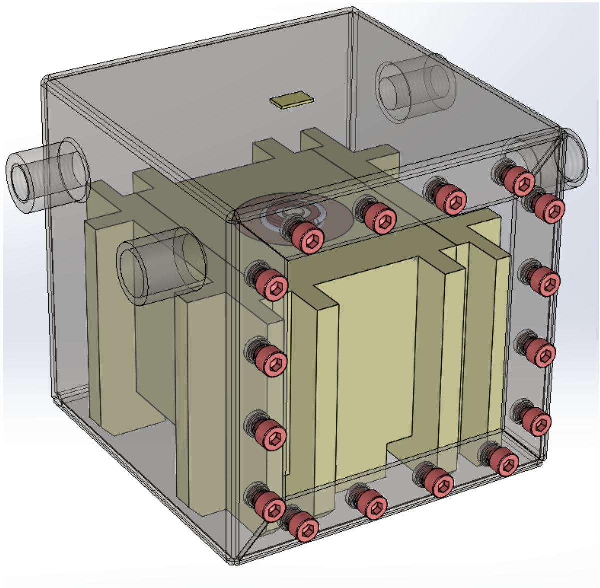


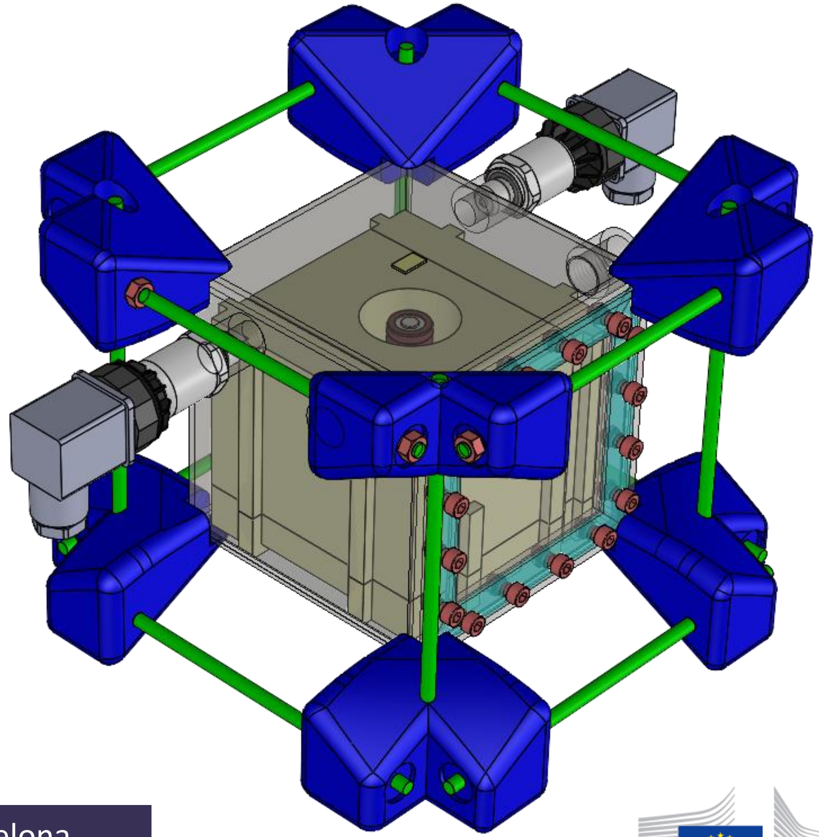
Experimental module design

Casing design for thermal runway

- Tests with thermal runway of one cell
- Temperature sensor (TS), cell voltage measurement (V_{cell}) and heating wire



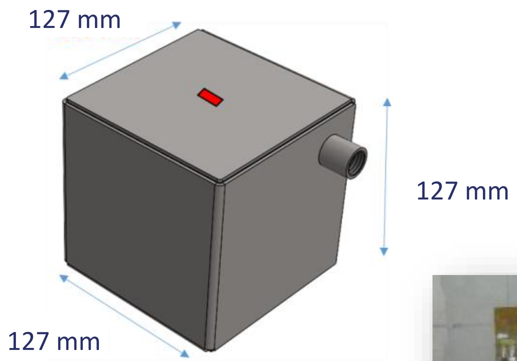


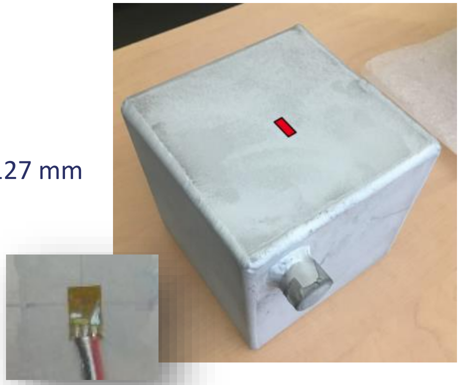


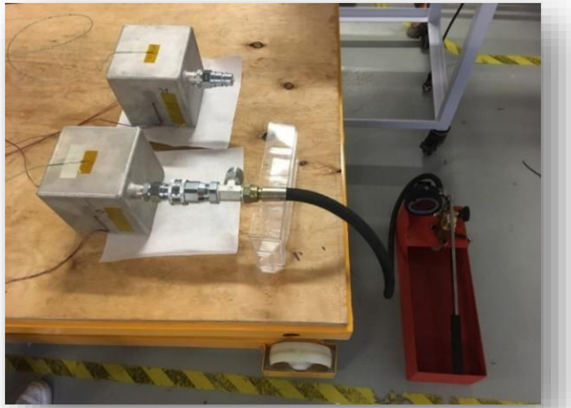
Experimental module design

Test plan

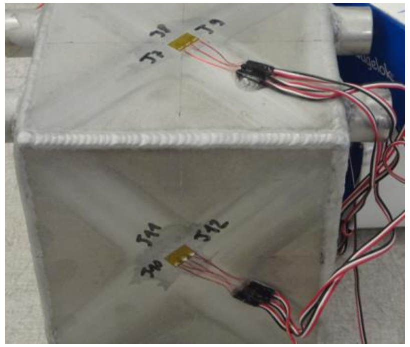
- 1× test under pressure with water
  - 1 x test up to plastic deformation (waterproof casing)
  - 1 x test elastic limit (Final casing)

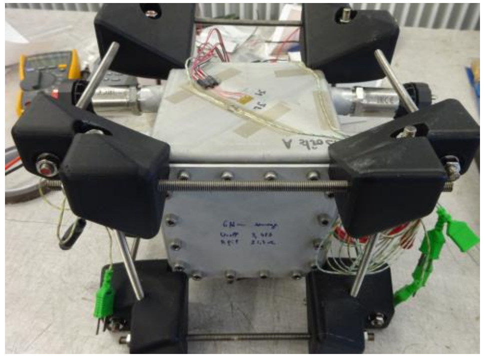






- 2× tests with thermal runway of the cell inside
  - x1 additional test with parameters variations and reproducibility

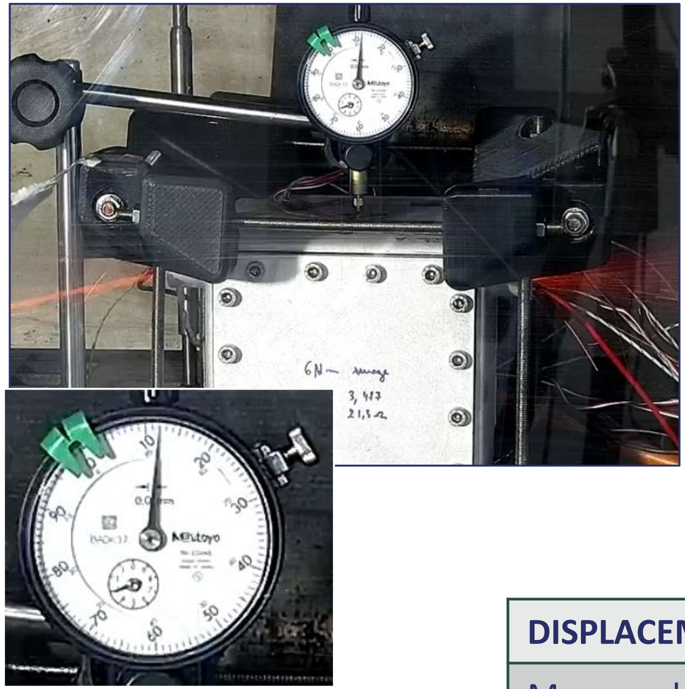




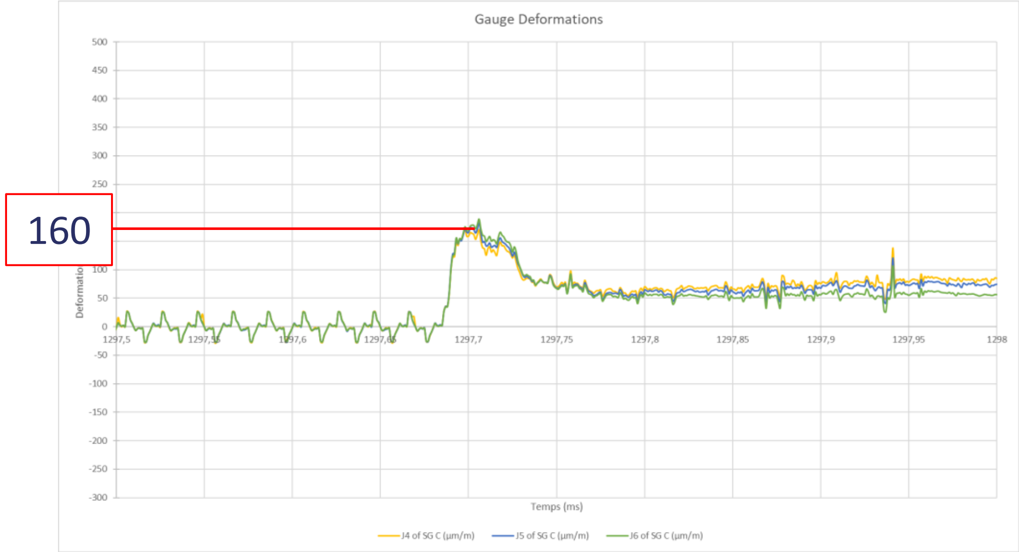
FEA model of the battery casing

Results of the safety test

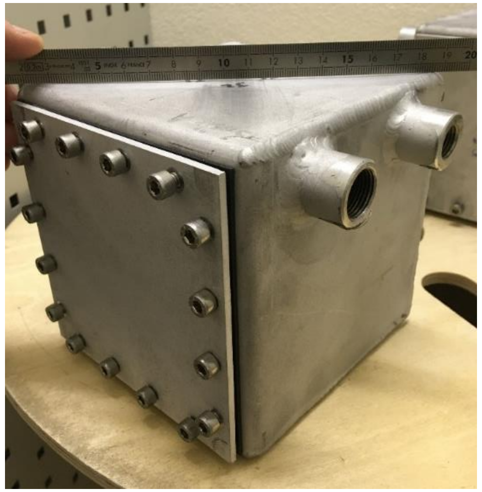
@0.6 bar



Displacement$_{maxi}$ = $120\ \mu m$



Check of the elastic deformation
Plan surface after test



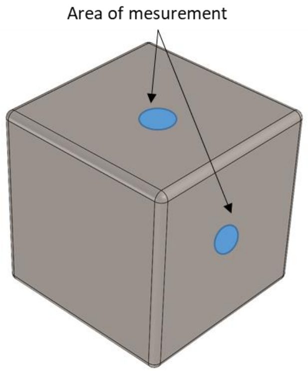
DISPLACEMENT	
Measured (Dial indicator) :	120 µm

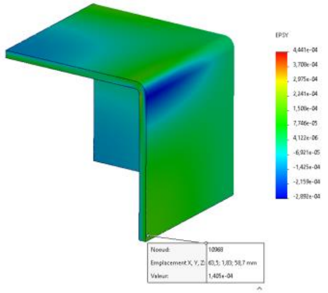
DEFORMATION	
Measured (Gauges) :	160 µm/m

Finite Elements Analysis (FEA) model of the battery casing

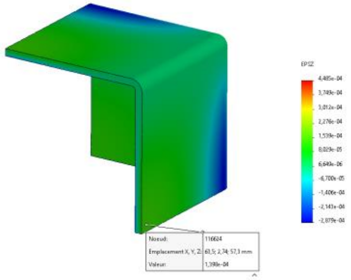
FEA Cubic model

@0.6 bar (from experimental tests)

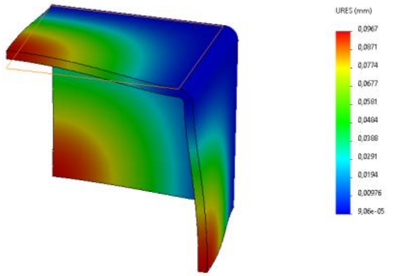




$\varepsilon_{yy\ max} = 140\ \mu m/m$



$\varepsilon_{xx\ max} = 140\ \mu m/m$



$\text{Displacement}_{maxi} = 97\ \mu m$

DISPLACEMENT	
FEA model	97 µm
Measured (Dial indicator) :	120 µm
Error	**20%**

DEFORMATION	
FEA model	140 µm/m
Measured (Gauges) :	160 µm/m
Error	**14%**

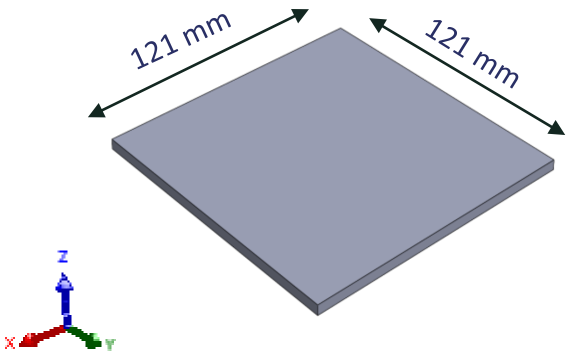
Analytical vs FEA model of the battery casing

Square plate model

@0.6 bar

GOULD hypothesis (1994) vs **FEA** Analysis

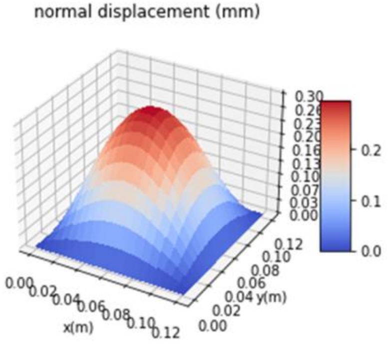
- Plane stress and deformation: $\varepsilon_{zz} = \sigma_{zz} = 0$
- Linear elastic constitutive law
- Constante pressure



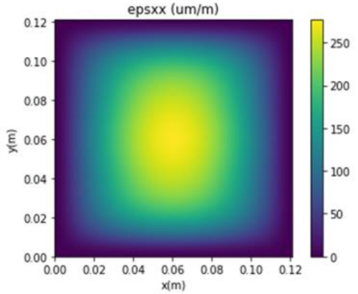
Field of displacement

Field of strain

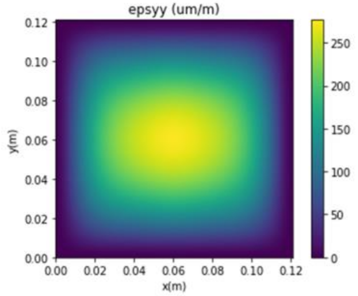
Analytic Analysis



$\Delta_{maxi} = 300\ \mu m$

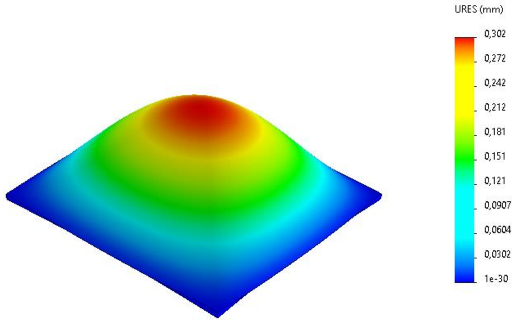


$\varepsilon_{xx\ max} = 276\ \mu m/m$

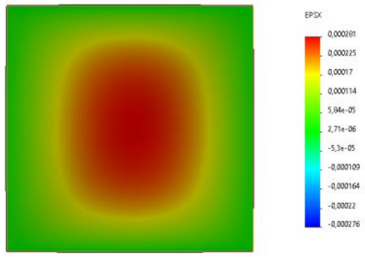


$\varepsilon_{yy\ max} = 276\ \mu m/m$

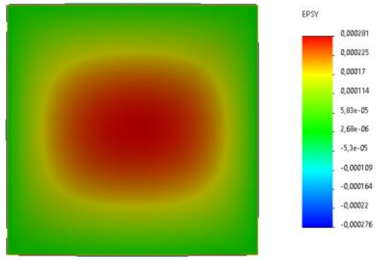
Finite Element Analysis



$\Delta_{maxi} = 302\ \mu m$



$\varepsilon_{xx\ max} = 281\ \mu m/m$



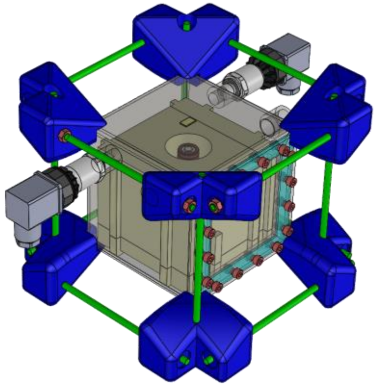
$\varepsilon_{yy\ max} = 281\ \mu m/m$

Error Analytical/FEA = 0,6%

Error Analytical /FEA = 1,8%

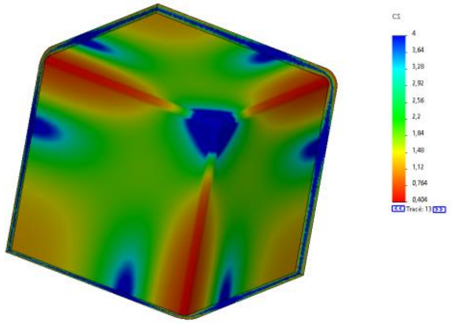
Mechanical model overview

Model design

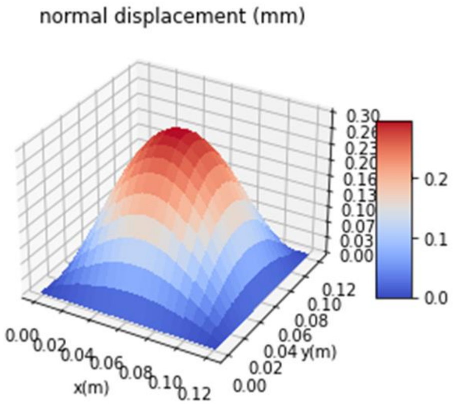


Exp. model

FEA model



Analytical model

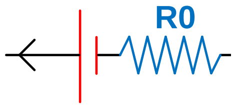


$\varepsilon_{xx\ max}$
$\varepsilon_{yy\ max}$
Δ_{max}

Battery optimization
→ mass vs safety

Results

Before

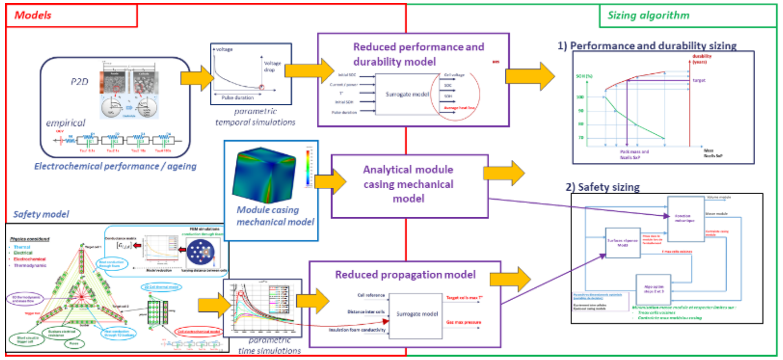


Only electrical performances sizing with expert rules for :
- Aging
- Casing mass estimation

No retroaction on safety

Now

Fast and more accurate algorithm for battery presizing and aircraft design exploration



Key parameters:
- **Electrical performances**
- **Temperature dependency**
- **Aging**
- **Safety**
- **Casing sizing**

THANK YOU!

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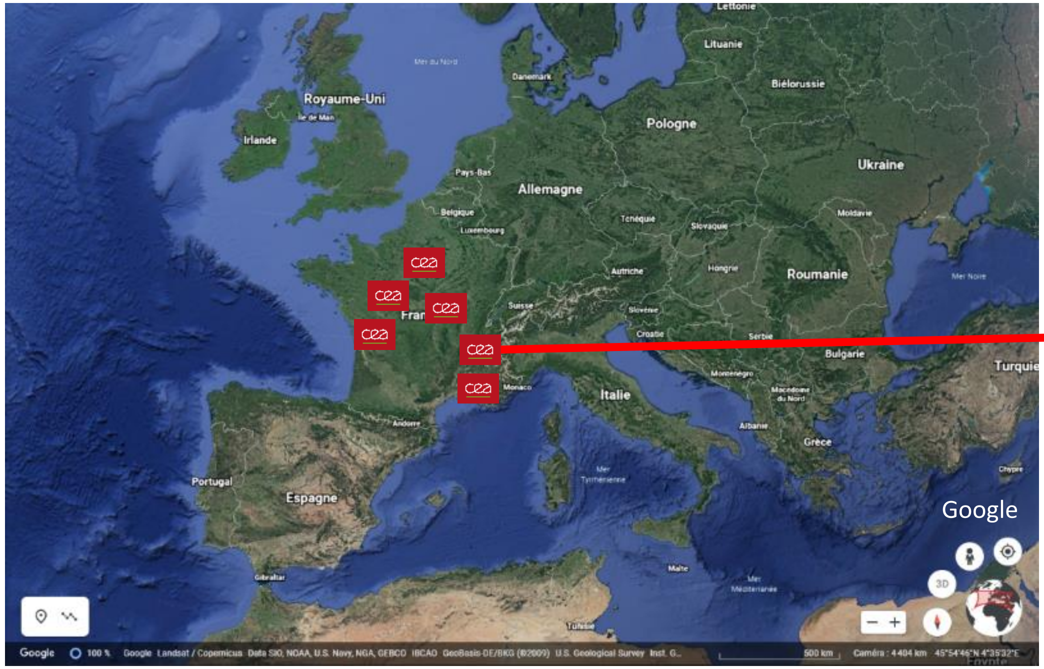
The FUTPRINT50 project

FutPrInt50 is an **EU** funded collaborative research project set out to **identify** and **develop** technologies and configurations that will accelerate the entry-into-service of a commercial **hybrid-electric aircraft** In a class of up to 50 seats by **2035/40**.

FutPrInt50 focuses on **energy storage**, **energy recovery** and the **thermal management** of hybrid systems. In addition to improving existing technologies, it will research and share an **open-source tool** for **designing new hybrid-electric aircraft**, hybrid-electric aircraft designs and reference data sets

The French Alternative Energies and Atomic Energy Commission (CEA)

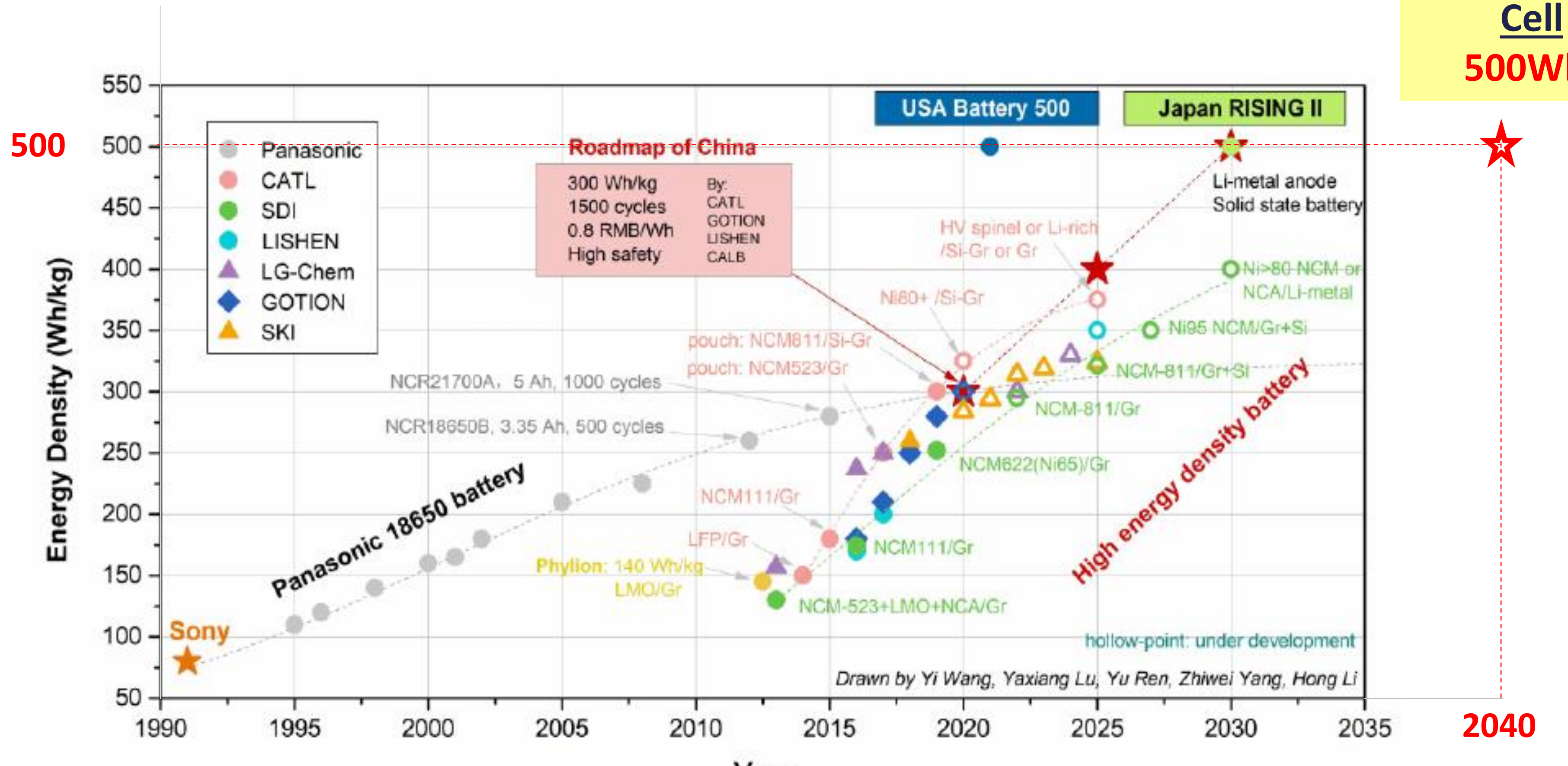


French public research organization with 20 000 employees

Defense and security, low carbon energies (nuclear and renewable energies), technological research for industry, fundamental research in the physical sciences and life sciences.

Energy roadmap

Cell level:
500Wh/kg???



Source [Bat6]

Mash-up of China / USA / Japan / Europe roadmaps