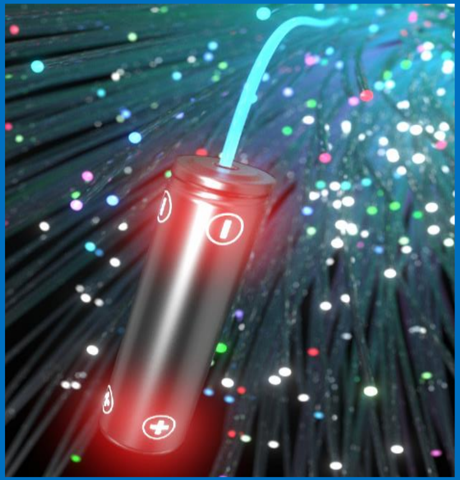
INSTITUTE FOR SUSTAINABLE AVIATION

Video seminar

January 21st , 2025

2 PM



“Batteries: indispensable but perfectible allies of tomorrow’s world”

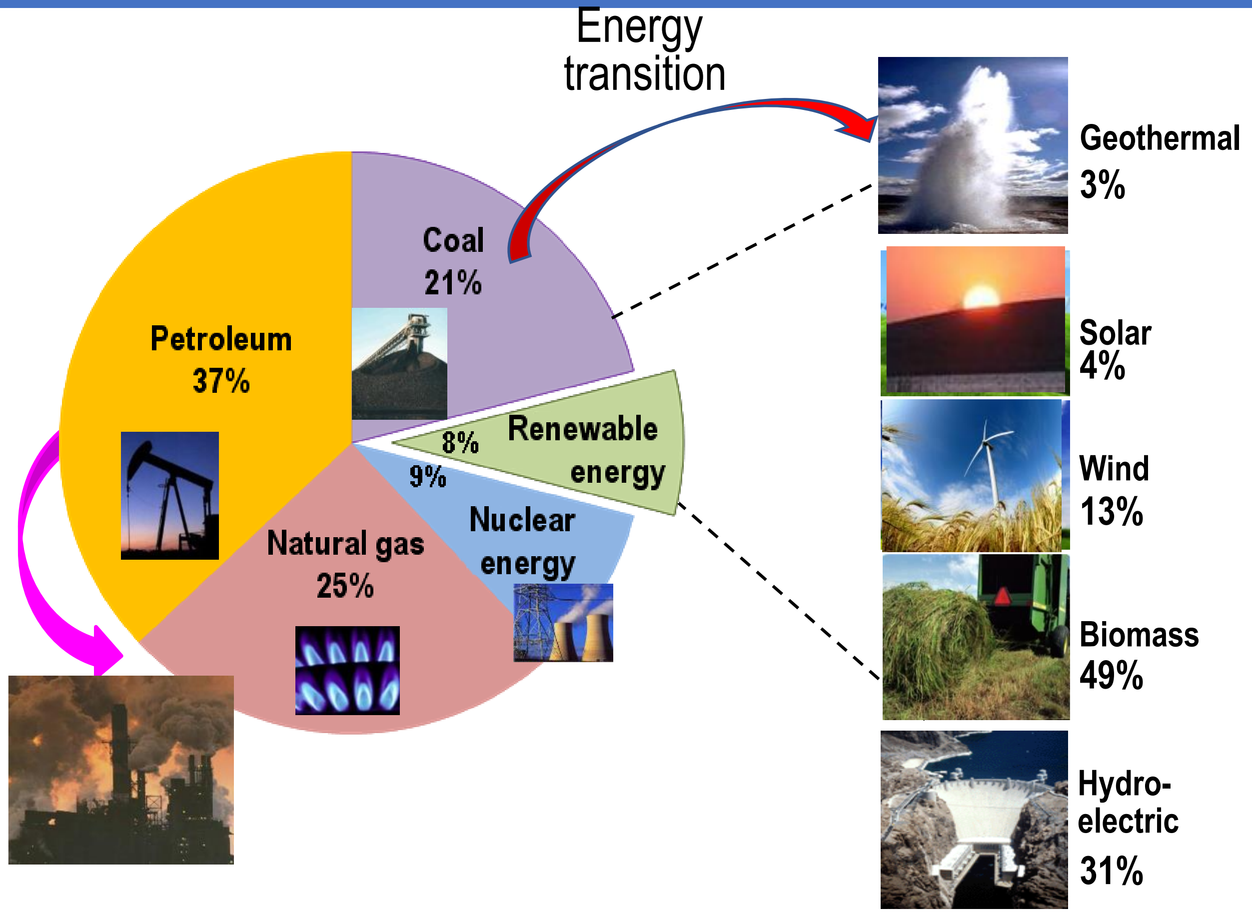
Jean-Marie Tarascon

COLLÈGE DE FRANCE 1530

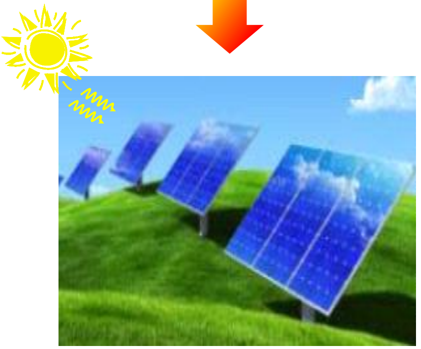
FONDATION INTERNATIONALE BALZAN 1956

ENERGIE RS2E

Batteries within the context of the energy transition to lower CO_2 footprint



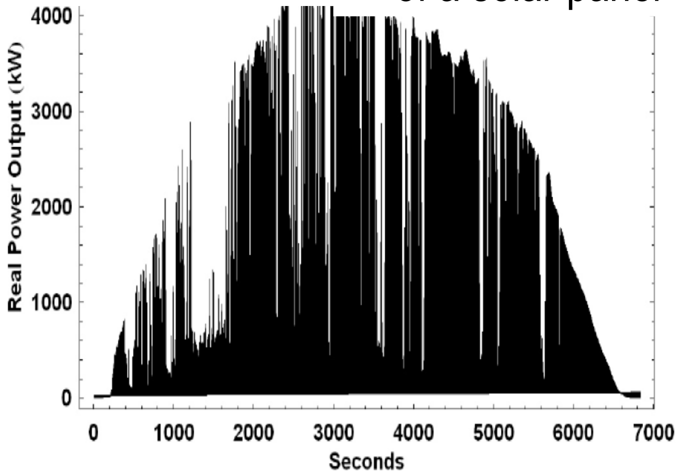
The sun sent to our planet 10000 times the energy it needs



(20 % cost Efficiency)

Cost: 3US cents kWh

Peak power variation of a solar panel

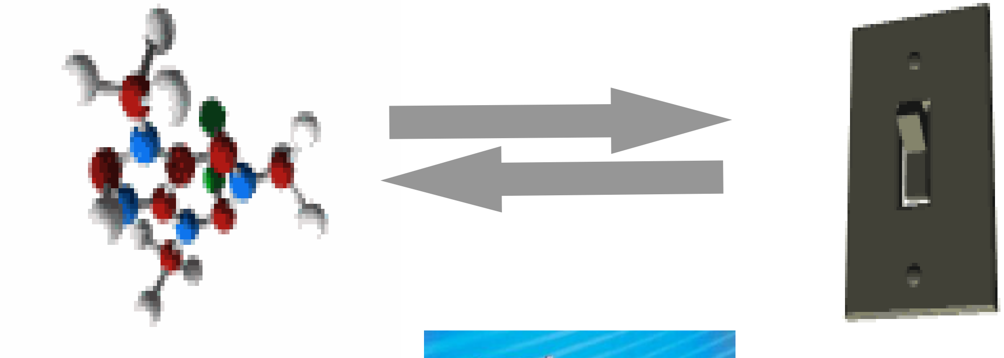


Storage ← How to smooth these fluctuations ← Large variations

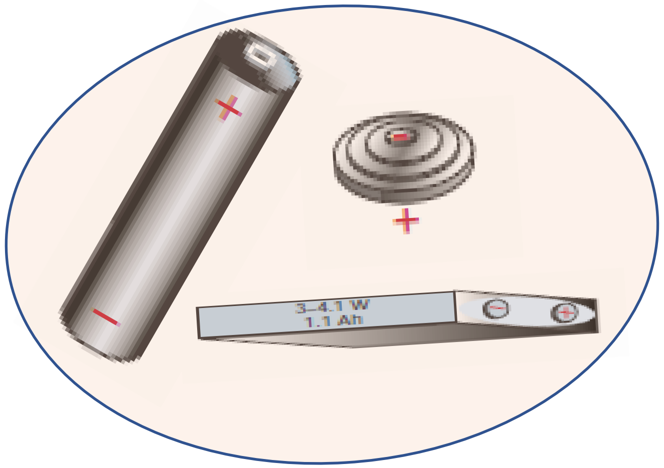
Electrochemical storage

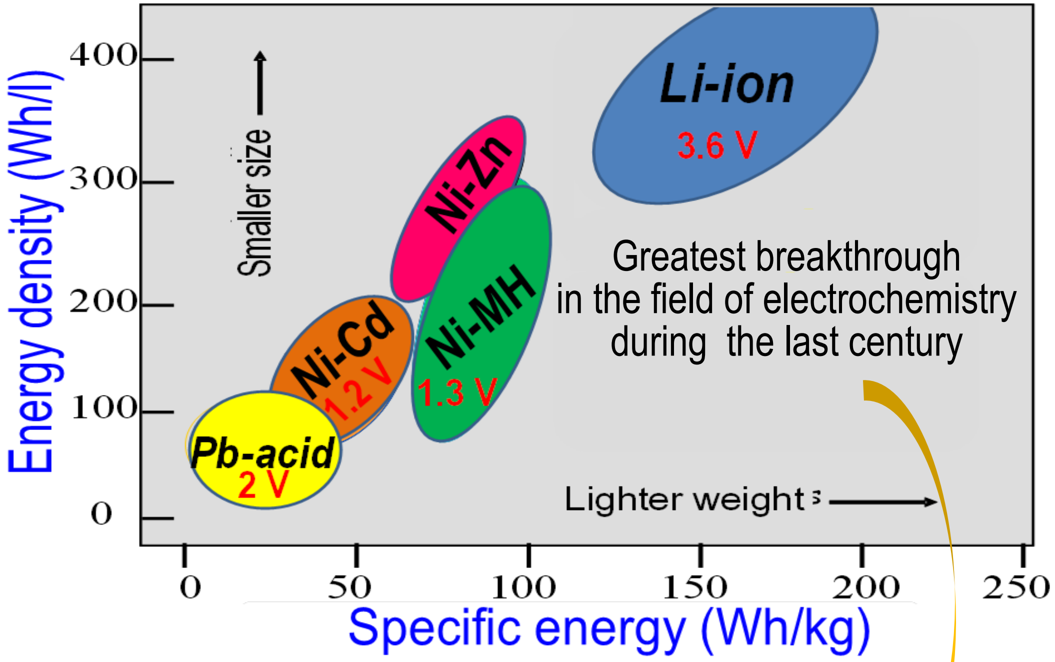
Chemical energy

Electrical energy



Batteries





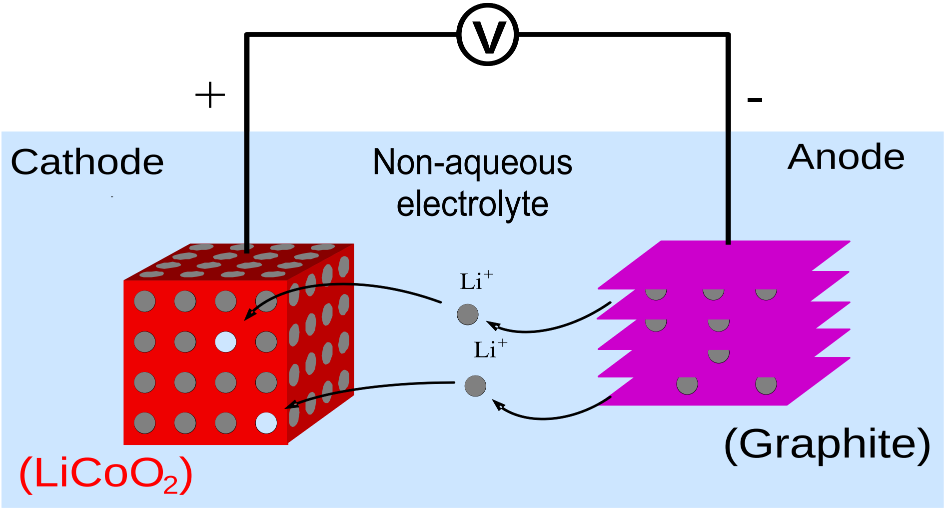
NOBEL 2019

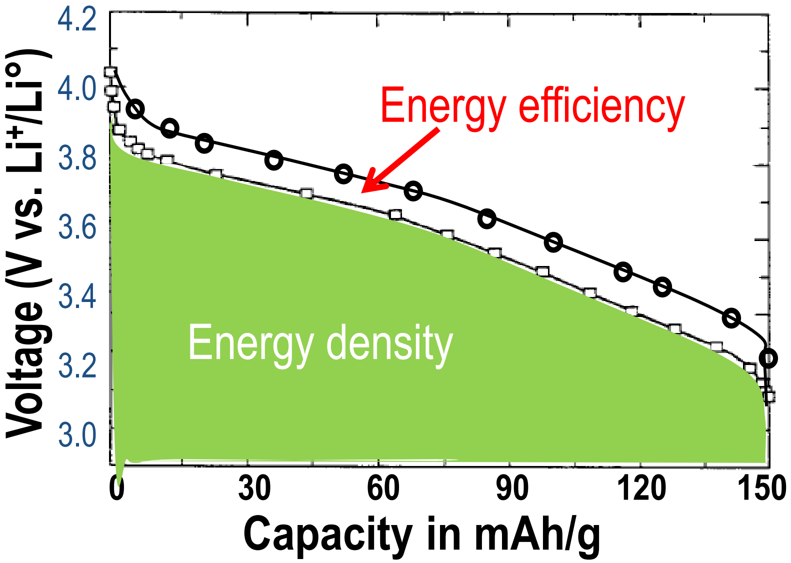
John B Goodenough

Stam Whittingham

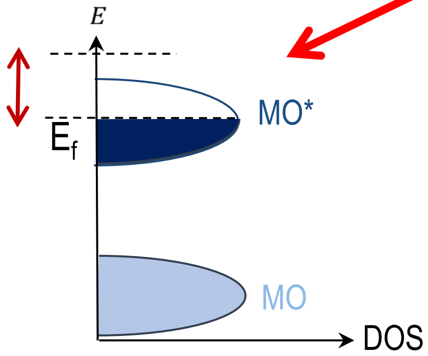
Akira Yoshino

Rechargeable Li-ion batteries: Schematics and principles





Energy density (Wh/kg) = Voltage V (volts) x Capacity (Ah/kg)



Band structure of the material

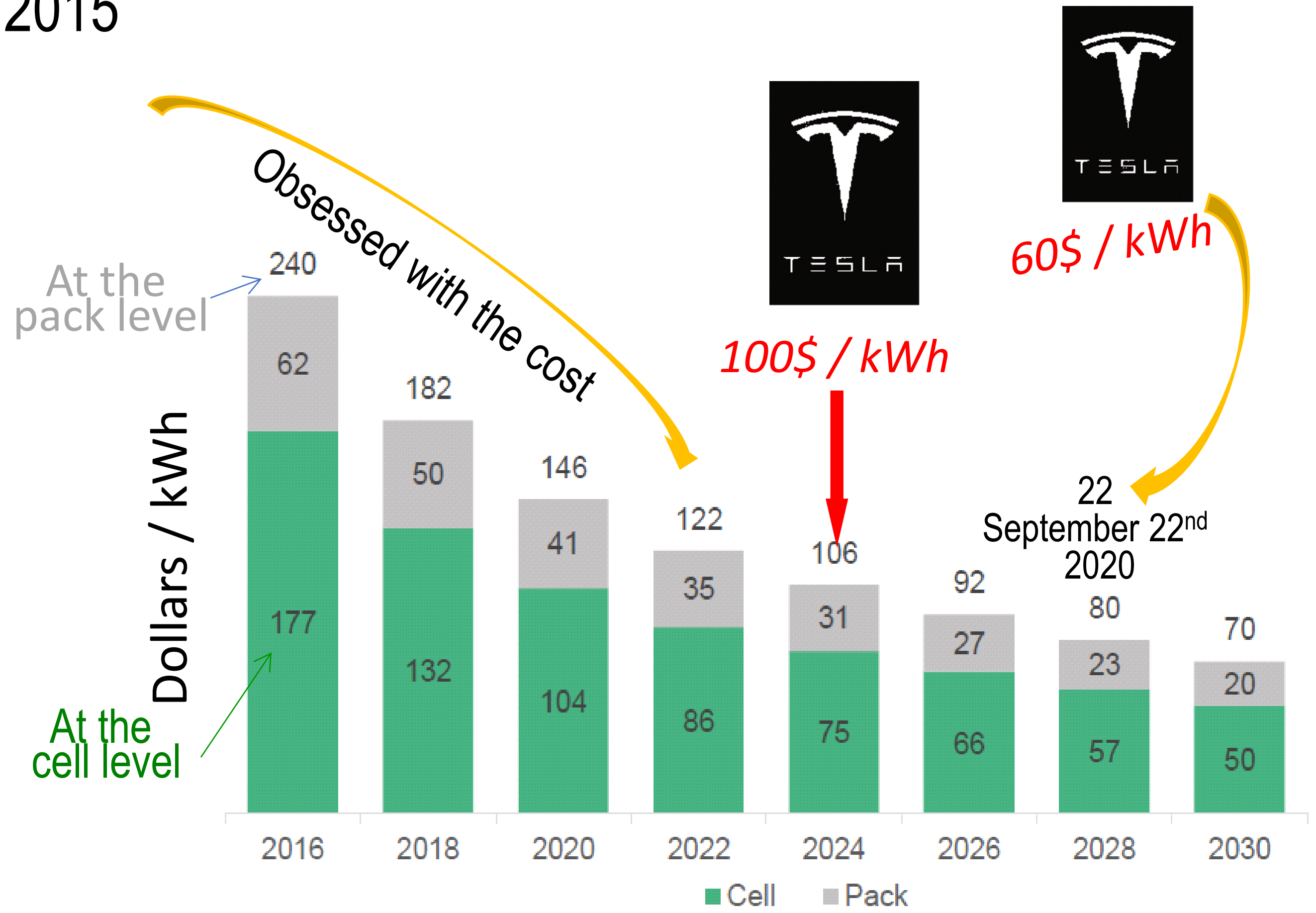
Nb of e- /mol

Capacity (Ah/kg) = 26,8 * $\frac{x}{M}$

Molar mass (kg)

Another key player in Li-ion development

Announcement by E. Musk in April 2015

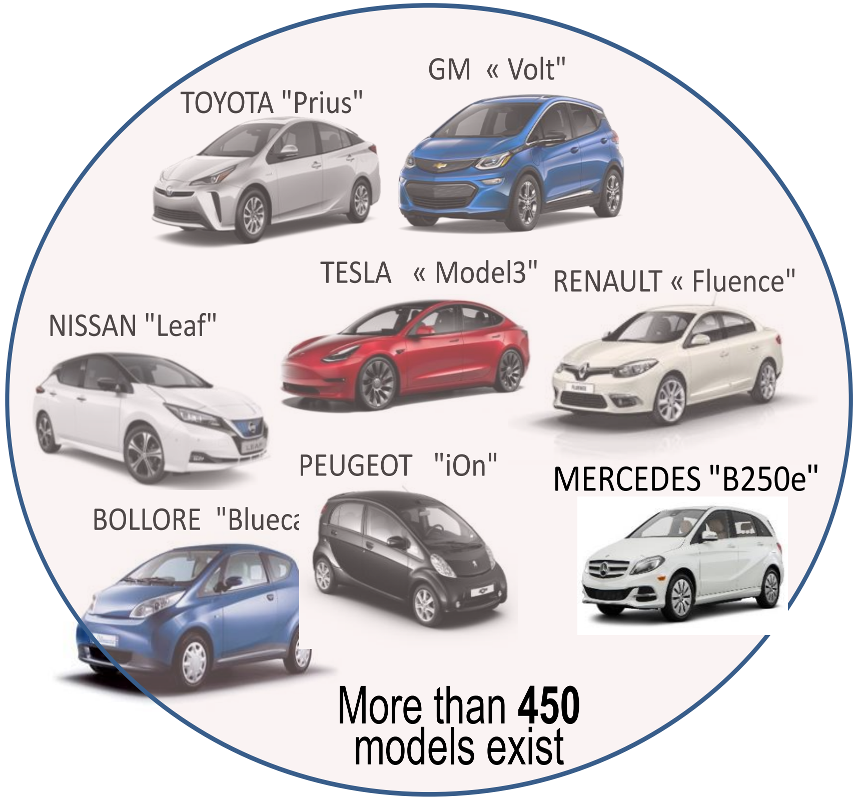


Source: Bloomberg New Energy Finance Scenario 5: Tesla Gigafactory NCA/graphite-Si

Tsunami in the world of battery manufacturers and users

The world of battery has become a dynamic environment

BOOM of the electric vehicle (EV)

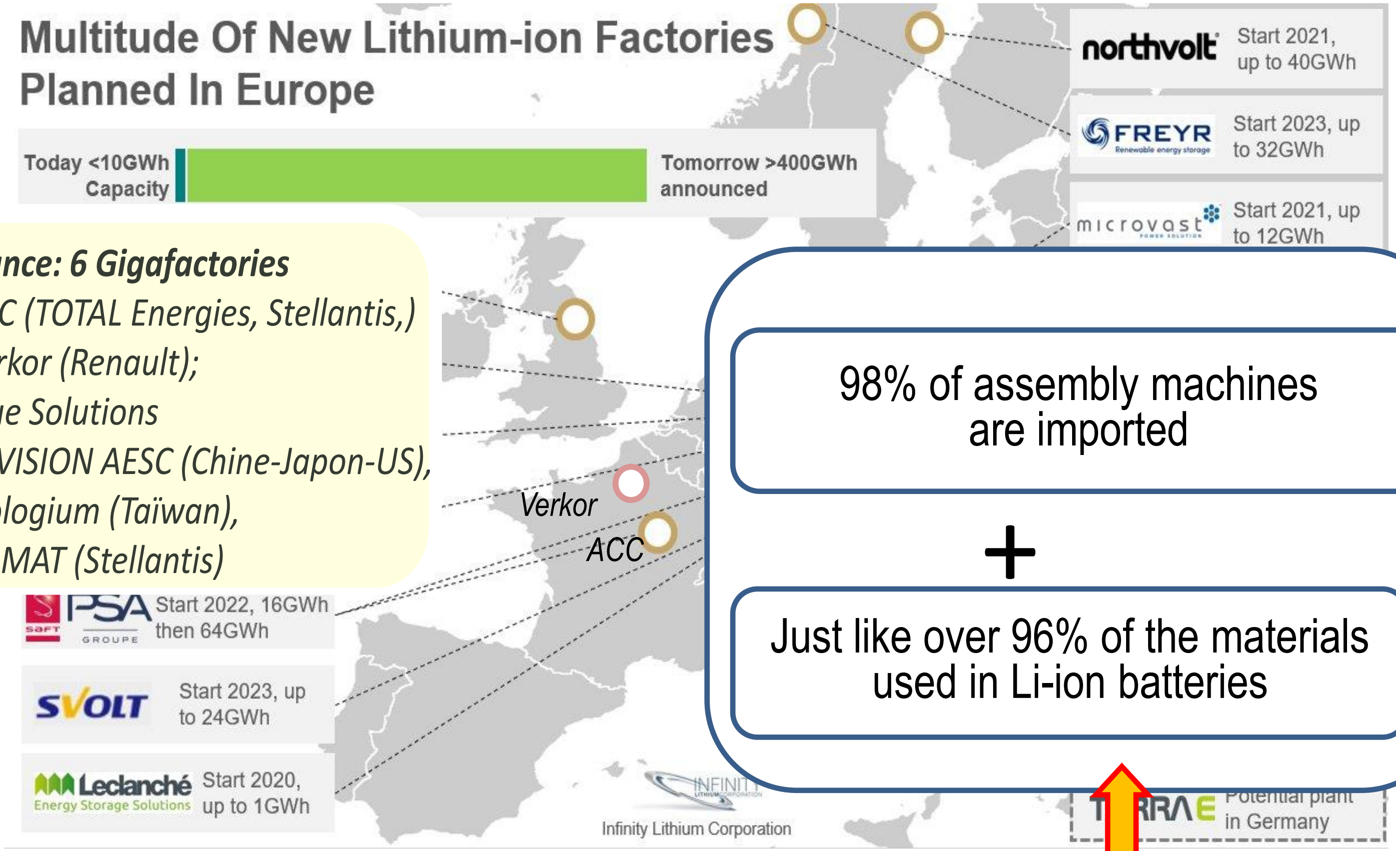


- EV sales

150 millions en 2040

Spectacular expansion of annual battery production?

Gigafactories grow like wildfire



In France: 6 Gigafactories

- *ACC (TOTAL Energies, Stellantis,)*
- *Verkor (Renault);*
- *Blue Solutions*
- *ENVISION AESC (Chine-Japon-US),*
- *Prologium (Taïwan),*
- *TIAMAT (Stellantis)*

98% of assembly machines are imported

+

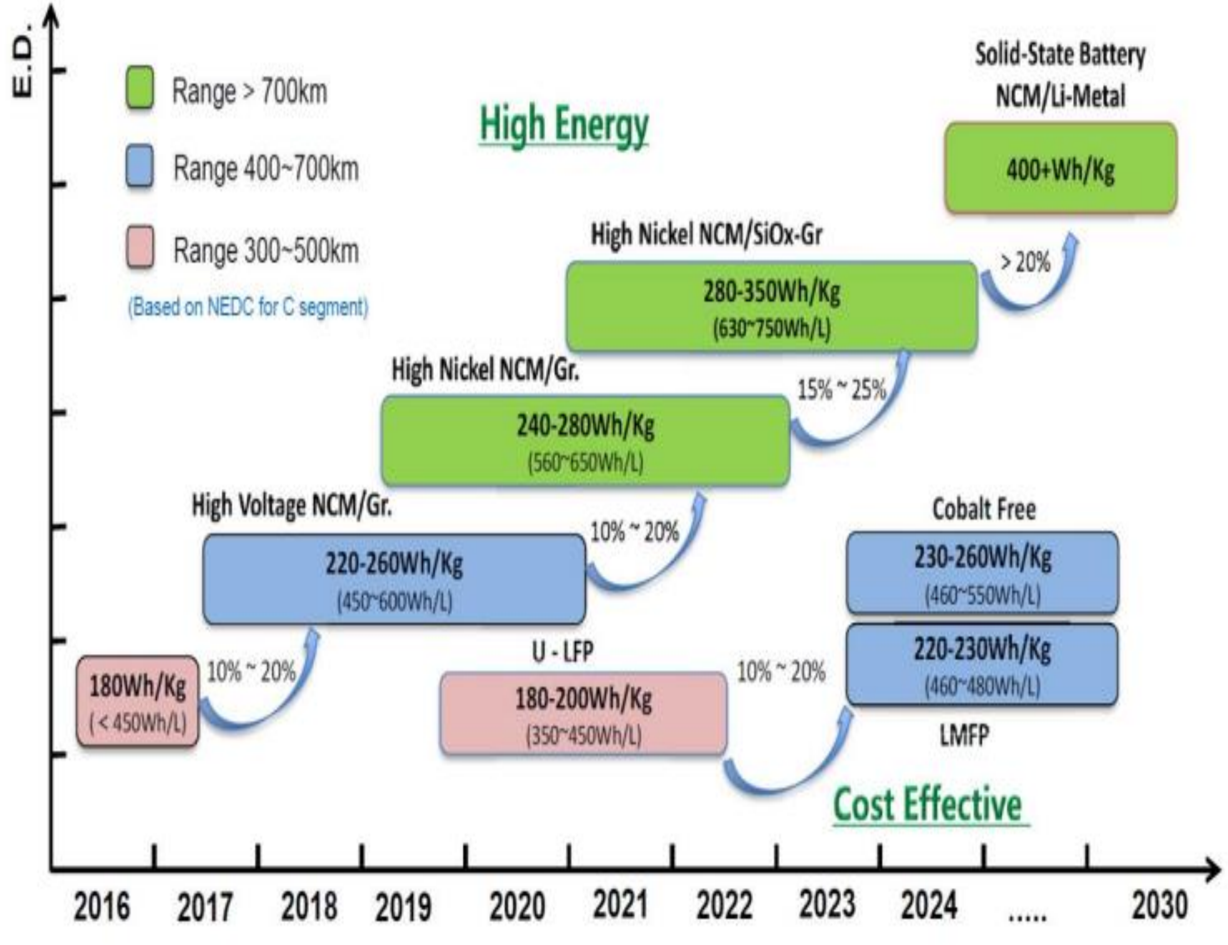
Just like over 96% of the materials used in Li-ion batteries

2020 450 GWh → **2025** 1500 GWh → **2030** 3000 GWh

Europe hopes for 19% of battery production by 2029 compared to 1% today.

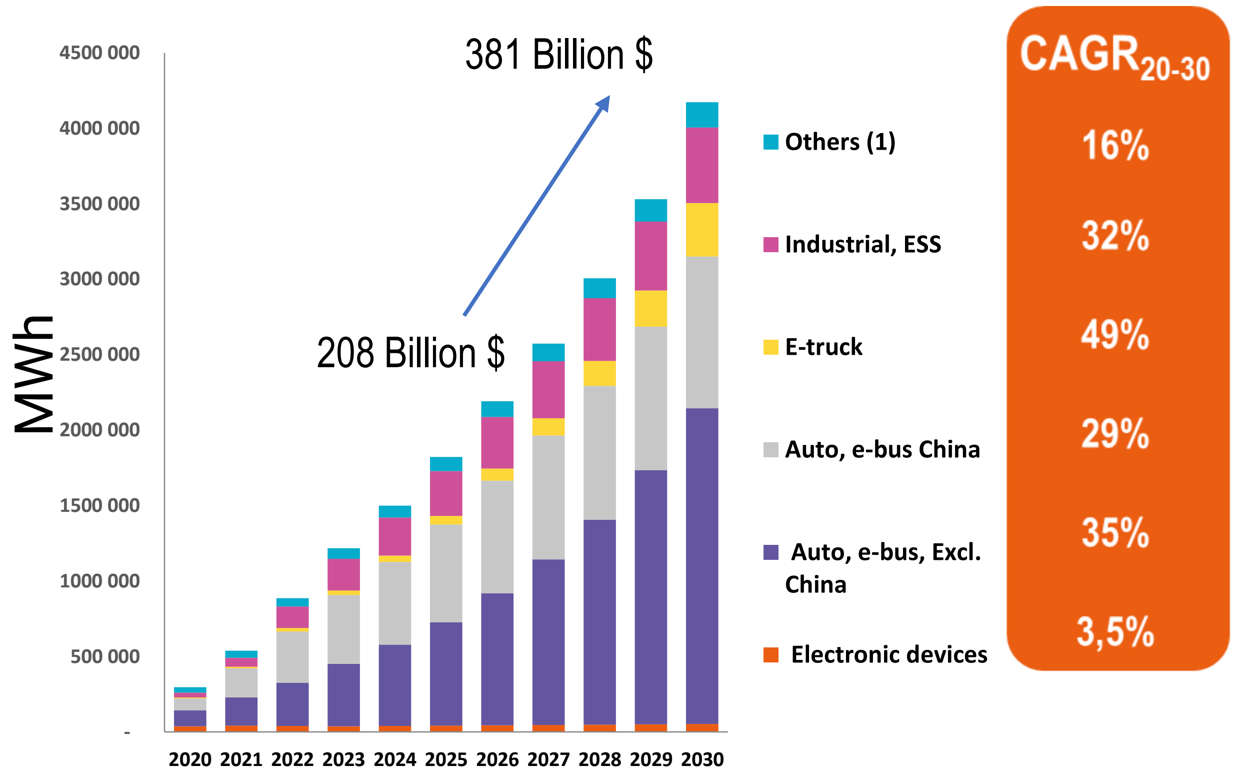
Batteries: a world of constant scientific emulation driven by business

Li-ion: sustained performance improvements



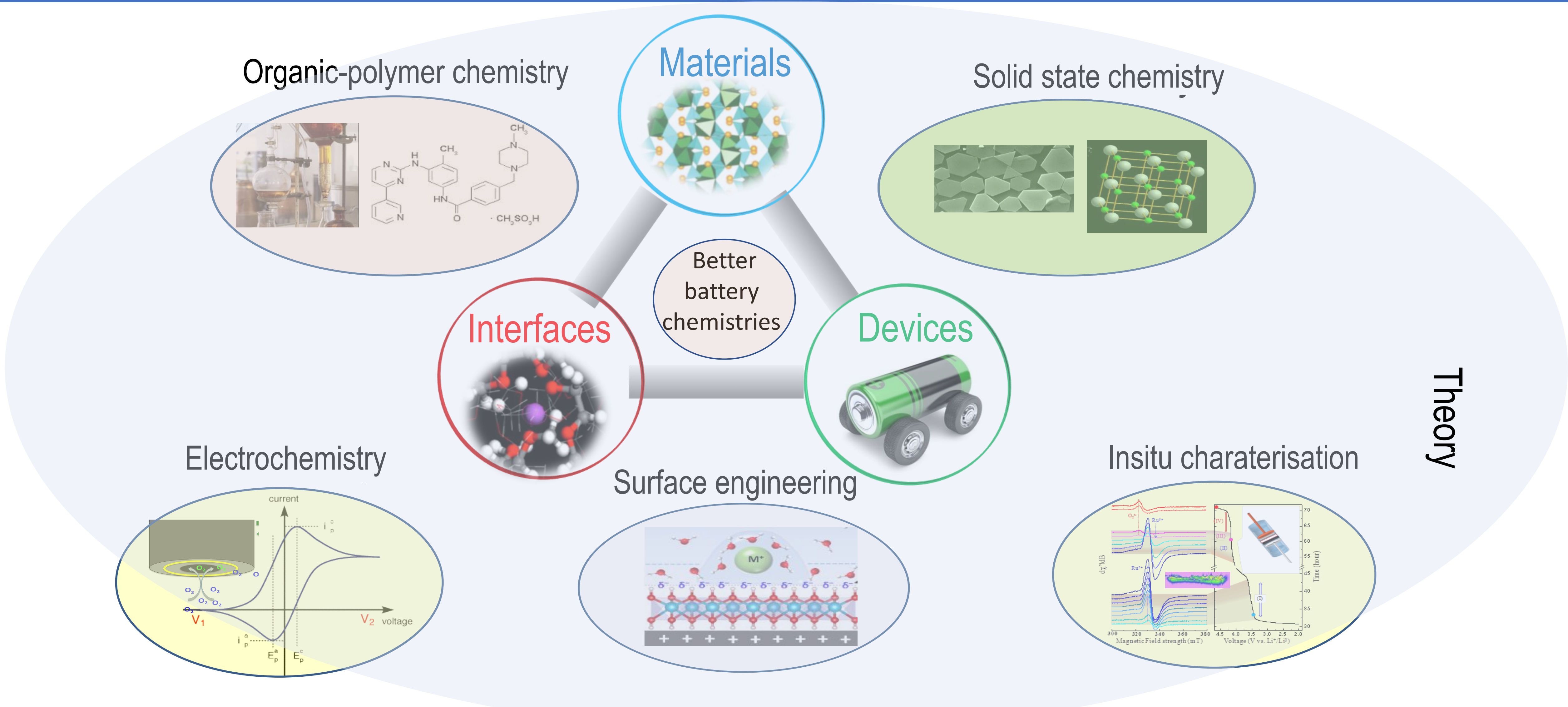
An appealing growing market

The lithium-ion battery market will grow from ≈+1 200 GWh in 2023 to ≈4 200 GWh in 2030



How to keep this momentum ?

The need to pursue a multidisciplinary scientific approach



But what more is needed?

No synergy, no innovation, no real batteries

Scientific knowledge

Why?

The power
of prediction

SYNERGY

Technological knowledge

How?

The power to turn
theory into reality

Importance of a constant ping-pong game between fundamental and technical knowledge

Outline

*- **S**cience and innovation involved towards better batteries -*

- **Autonomy and battery charging ?**

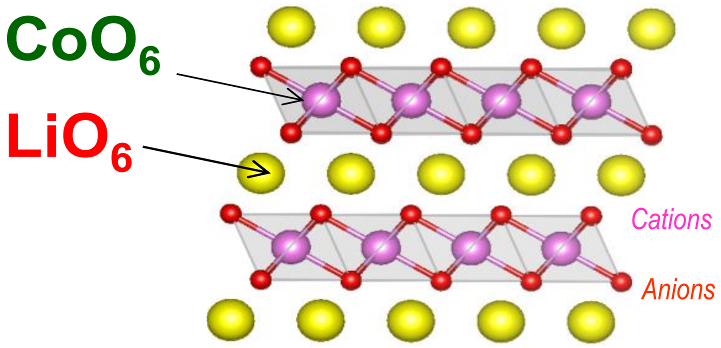
- **Eco-compatibility of batteries ?**

- **Durability and reliability of batteries ?**


- **Abundance of materials– recycling ?**

Layered oxides and their evolution through the years

- *$LiCoO_2$ (1991)*



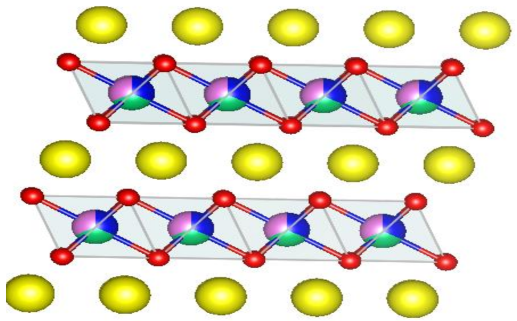
(150 mAh/g)

Replacement of Co by Ni and Mn

Li[NiMnCo]O_2

NMC phases

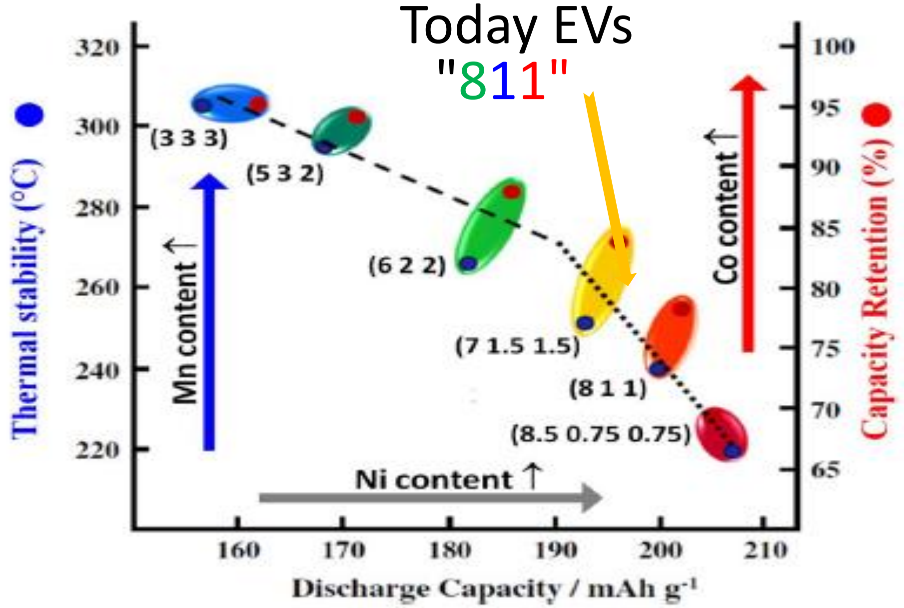
- *Layered oxides (2008)*



(180 mAh/g)

Cobalt mining: An ethical issue

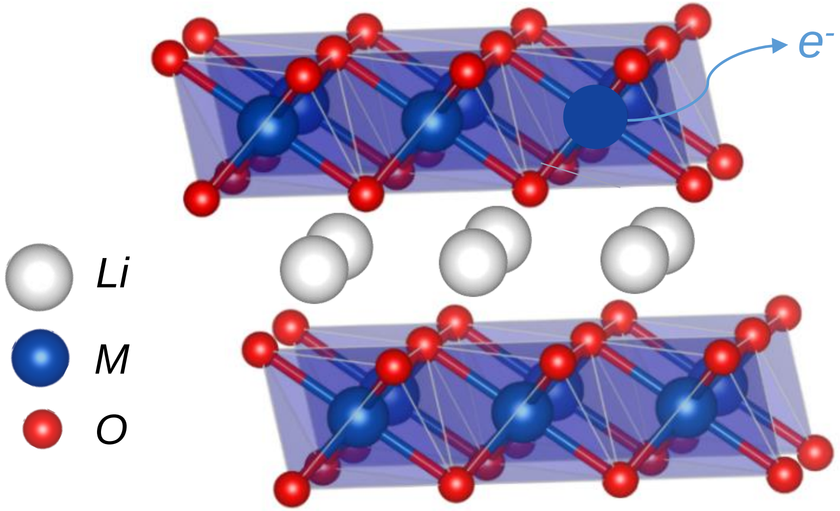
Today EVs "811"



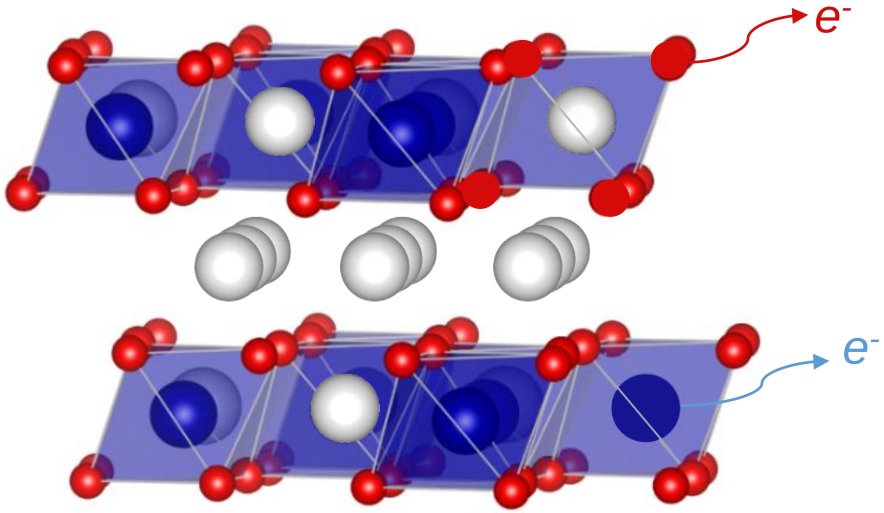
Ni-rich layered oxides are the most widely used cahode materials today

The anionic redox $(O_2)^{n-}$ paradigm in layered oxides

Cationic redox: the only belief since 1991

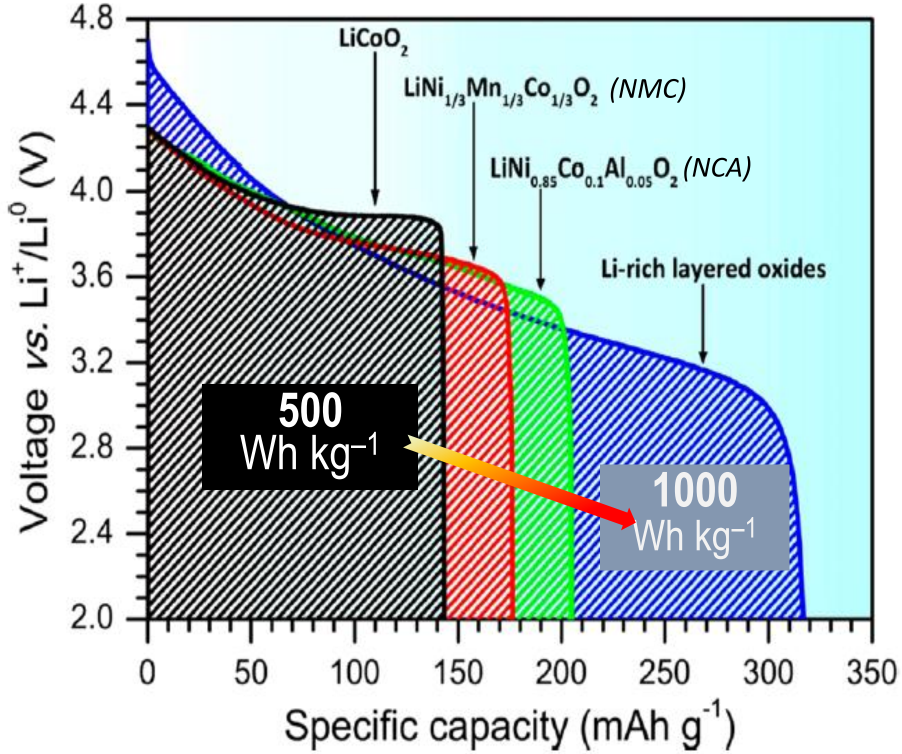


Since 2013, not any longer true: anionic redox



Classical NMCs
(cationic)

Li-rich layered oxides
(cationic + anionic)

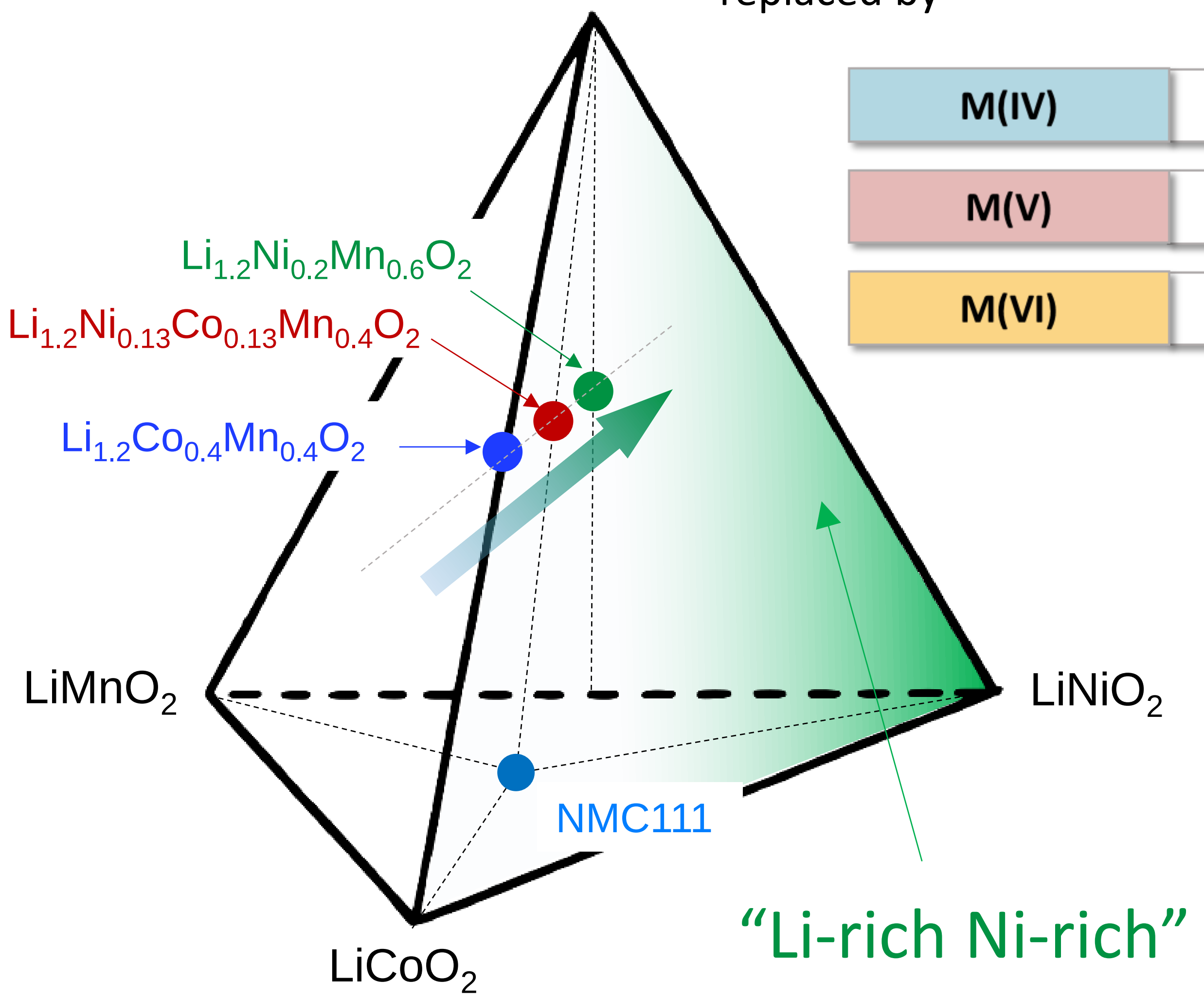


A number of technological hurdles still have to be overcome…

Designing model materials for better understanding

Balancing cationic and anionic redox contribution: further exploring the composition space

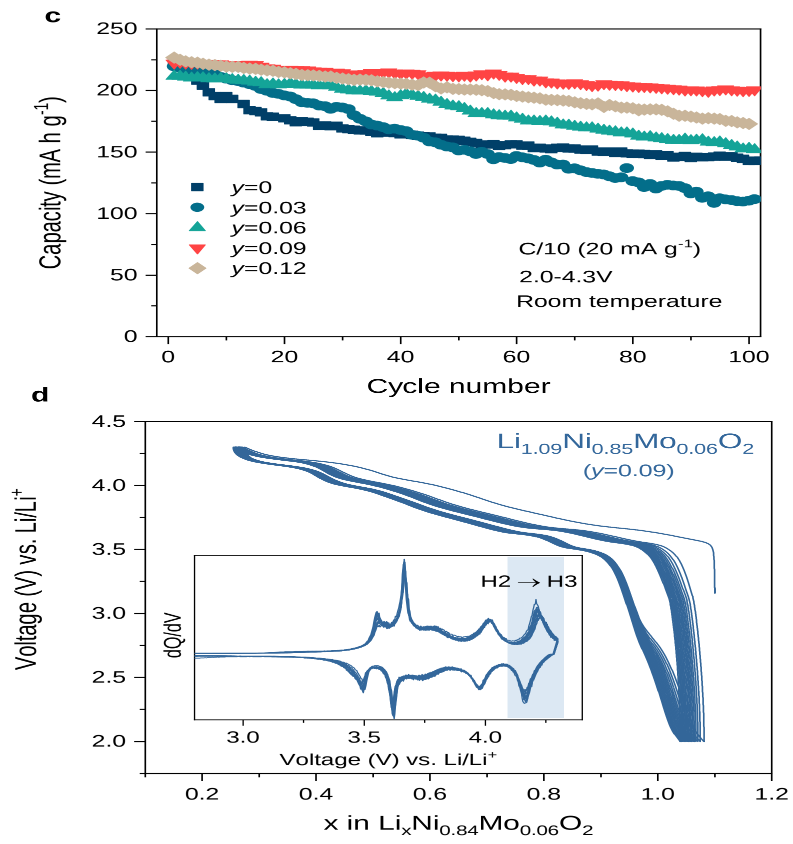
Li_2MnO_3 —Can be replaced by→ Li_2TiO_3, Li_3NbO_4, Li_4MoO_5…



M(IV)	$Li_{1+y}Ni_{(2-3y)/2}M^{4+}{}_{2y}O_2$
M(V)	$Li_{1+y}Ni_{(1-2y)}M^{5+}{}_{y}O_2$
M(VI)	$Li_{1+y}Ni_{(3-5y)/3}M^{6+}{}_{y2/3}O_2$

Proof of concept

$Li_{1+y}Ni_{(3-5y)/3}Mo_{2y/3}O_2$

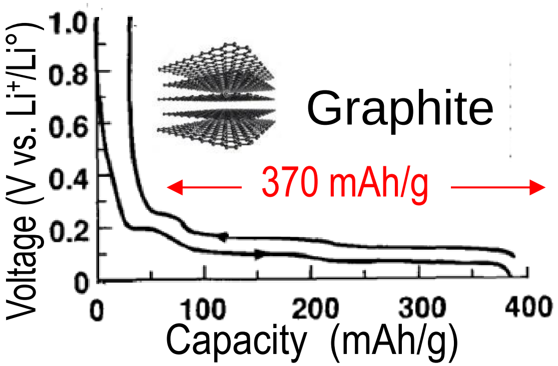


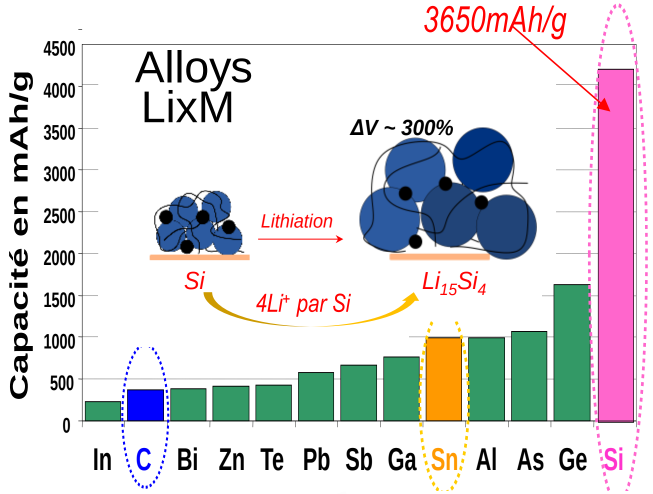
“Li-rich Ni-rich”

Li-rich Ni-rich: a new playground for high capacity and highly stable electrodes

Increasing energy density: recent advances

Carbon electrodes loaded with Si

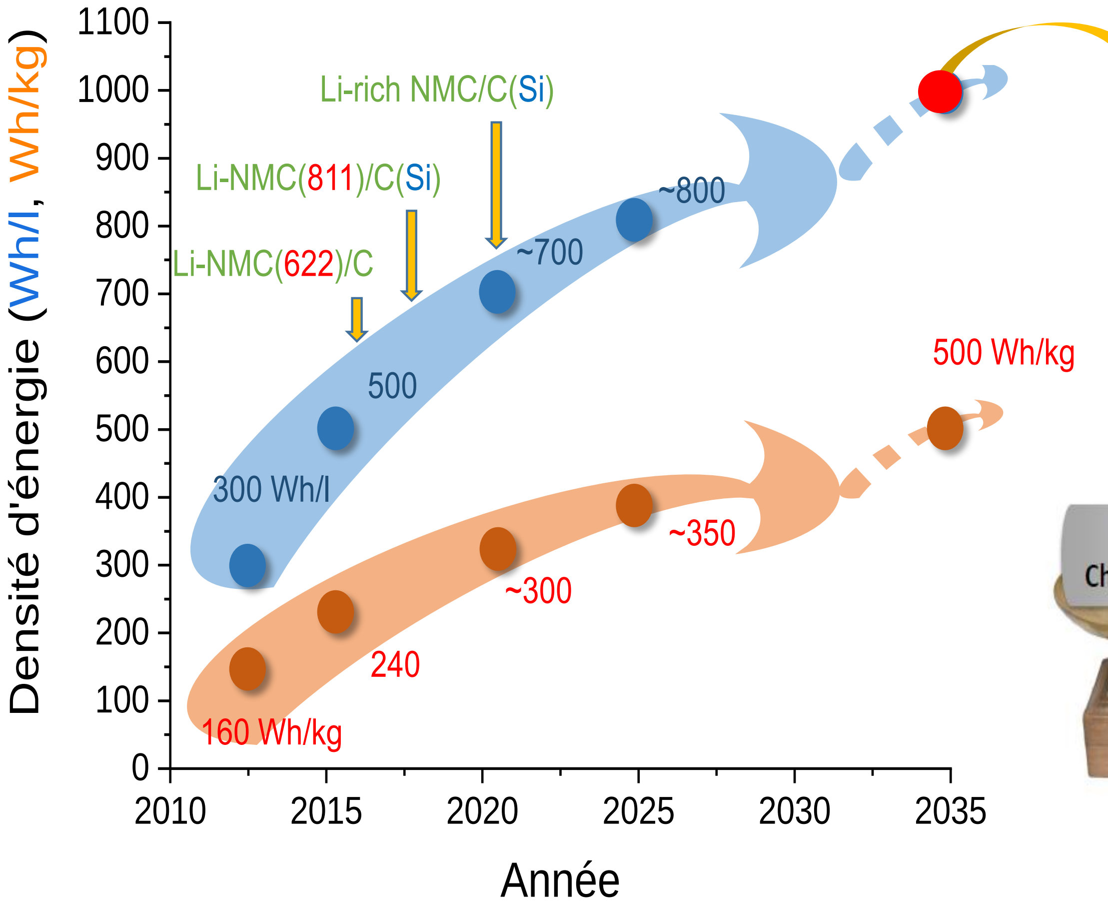




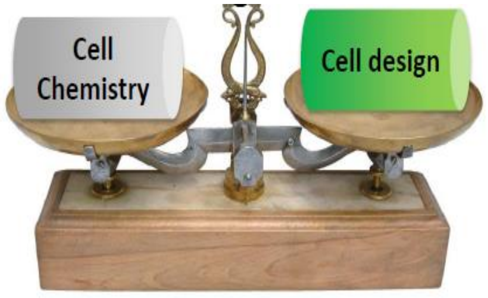
Composites C + 10%Si

Panasonic and many others

Li-ion technology: What can we expect ?



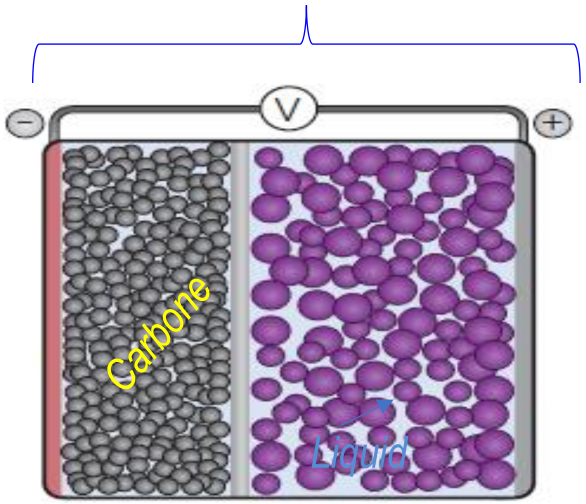
How to reach 800 Wh/l and go beyond?



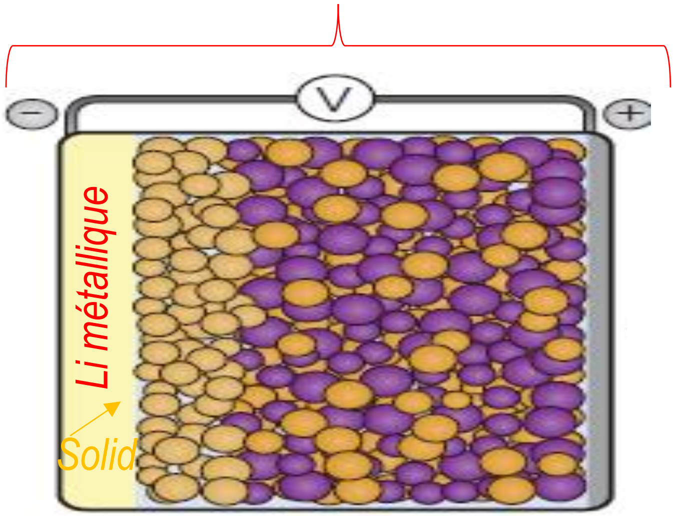
Solid State batteries

All-solid state batteries: the biggest excitement of today in the field

Li-ion liquid batteries



Li-metal solid state batteries



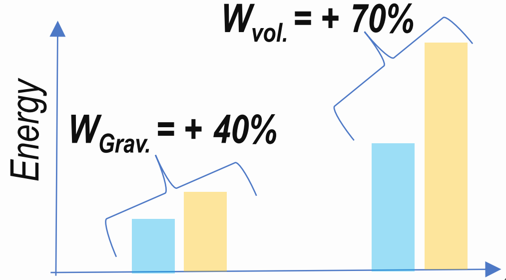
Sécurity

Solid electrolyte
Rather than liquid

Enhanced security

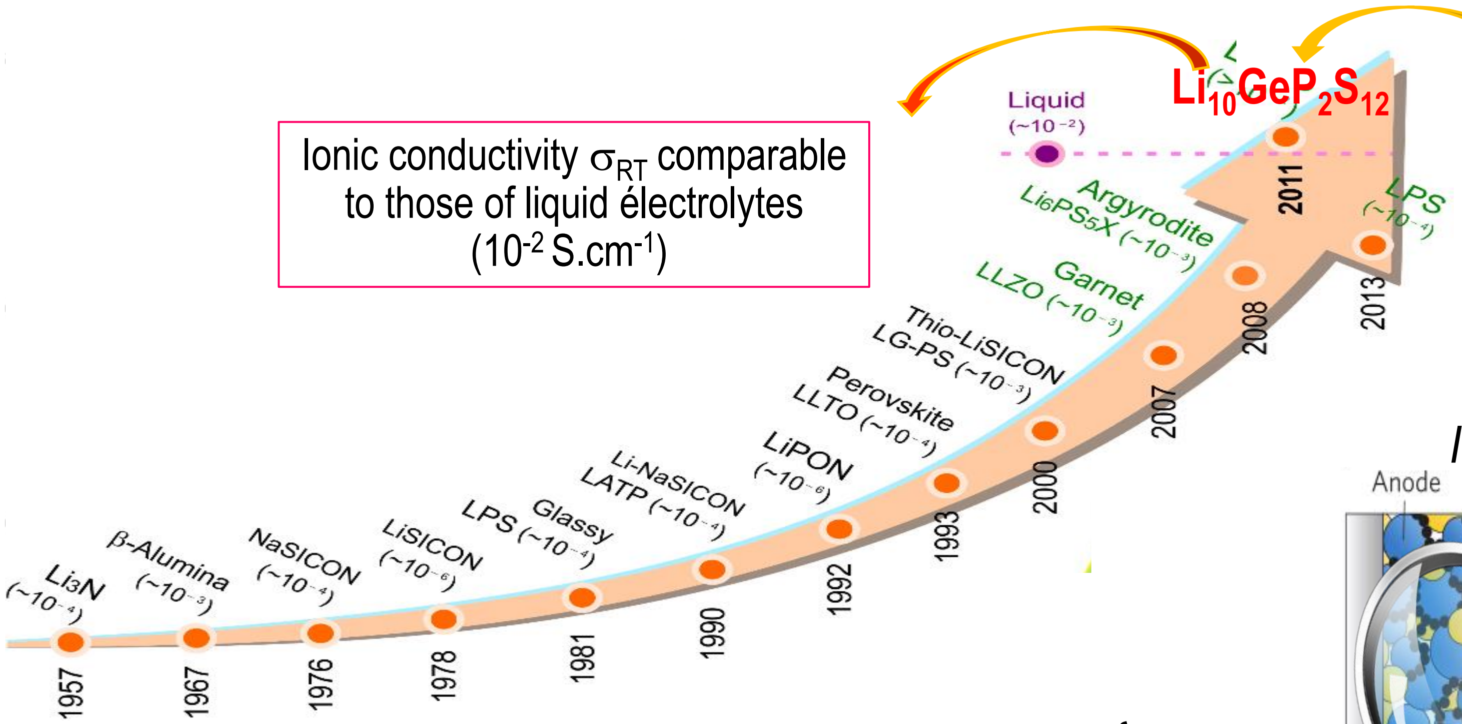
Energy density

Replacing Carbon
by Li metal



Energy density gains** (Wh/kg) or (Wh/l) **only if the Li interface is mastered ..

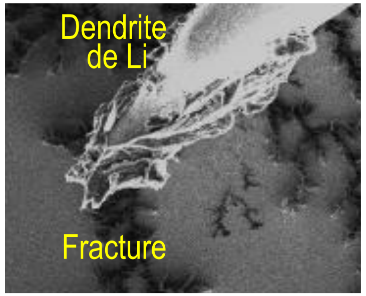
Significant progress in inorganic compounds with high ionic conductivity



$Li_{10}GeP_2S_{12}$

Japanese group (2011)

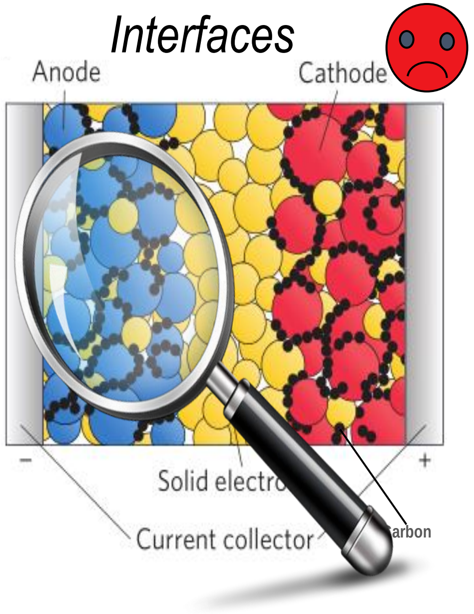
Ionic conductivity σ_{RT} comparable to those of liquid électrolytes (10^{-2} S.cm^{-1})



Résistance of grain boundaries

Growth of Li dendrides

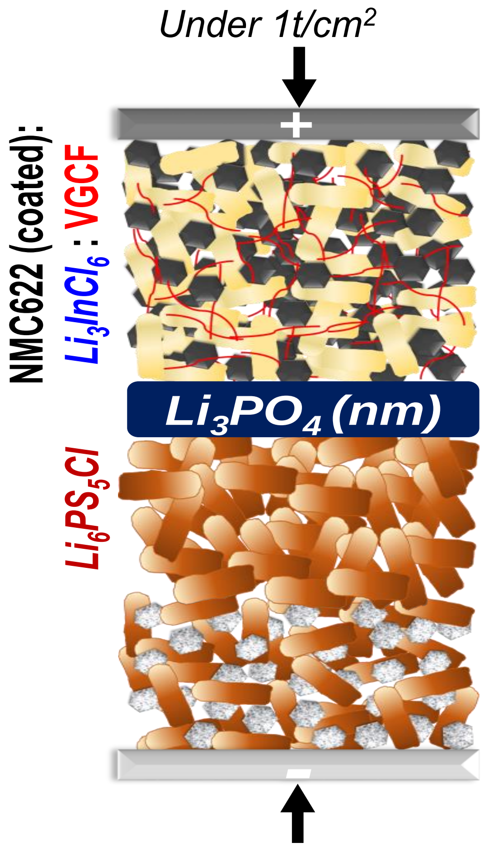
Interfaces

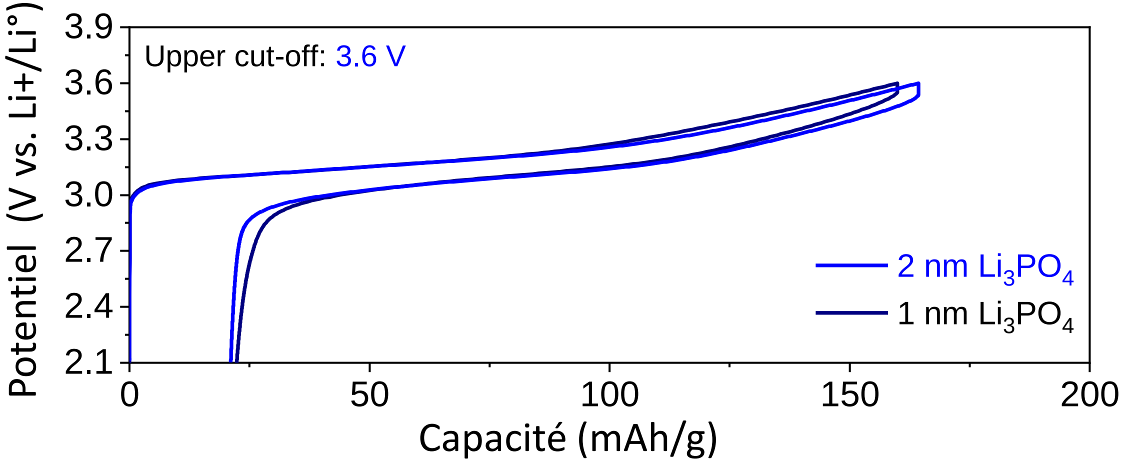


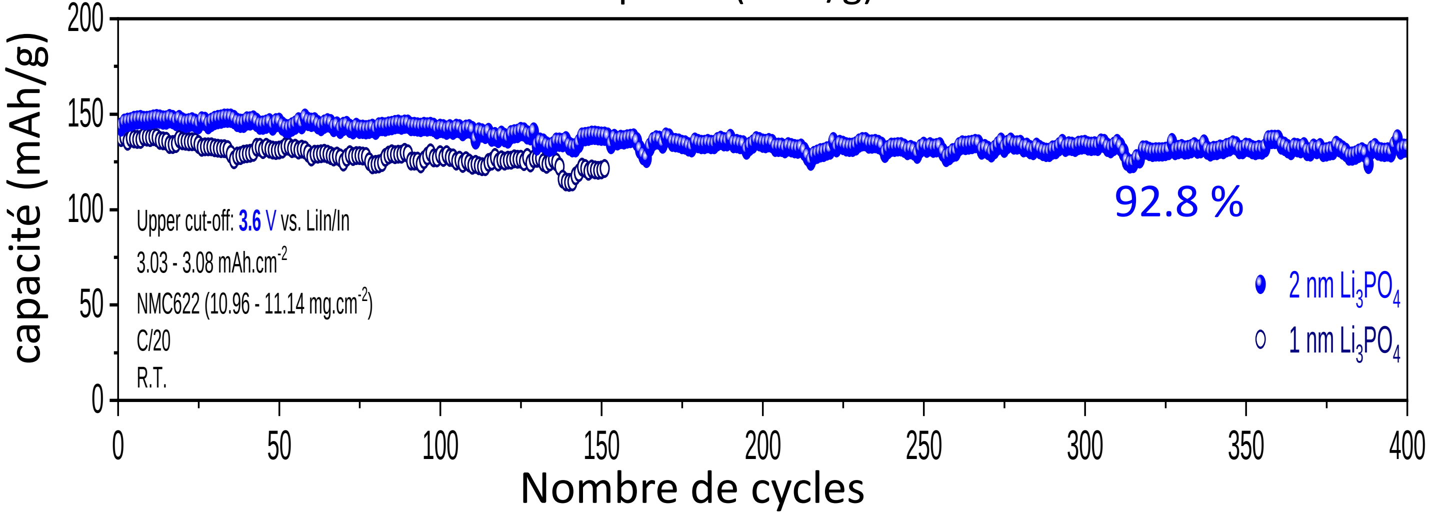
The Li electrode has not yet been mastered: we are now moving towards hybrid systems

Innovations: surface chemistry and solid electrolytes

Addition of Li3PO4 interface





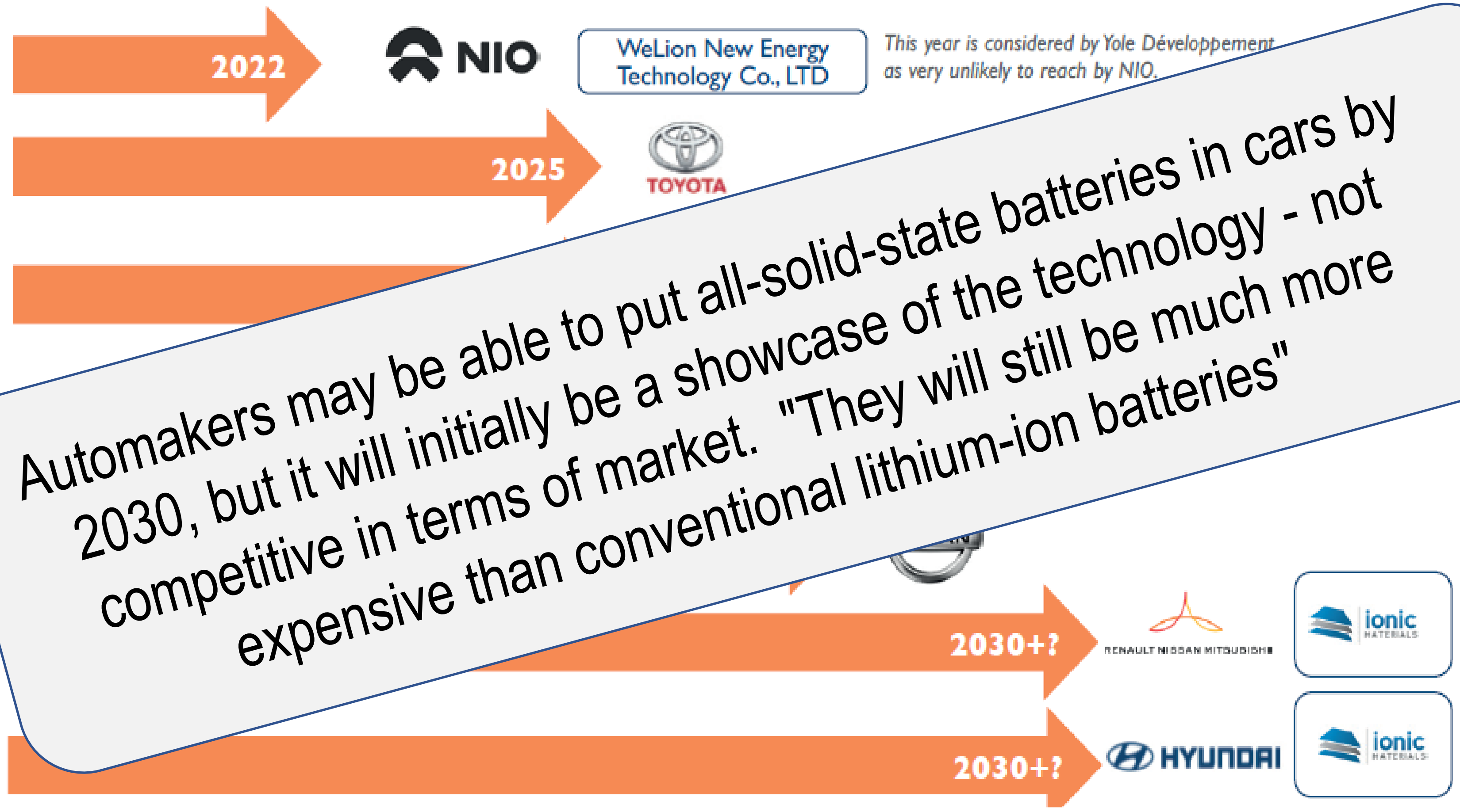


Quite spectacular results, but the transformation at industrial level has not yet been achieved, because of remaining chemical and engineering issues

T. Koç et al. ACS Energy letters, 7 (2022).+ Patent filed WO-8316-02à227

B. Hennequart et et al. Patent filed 03756- 002023-86e

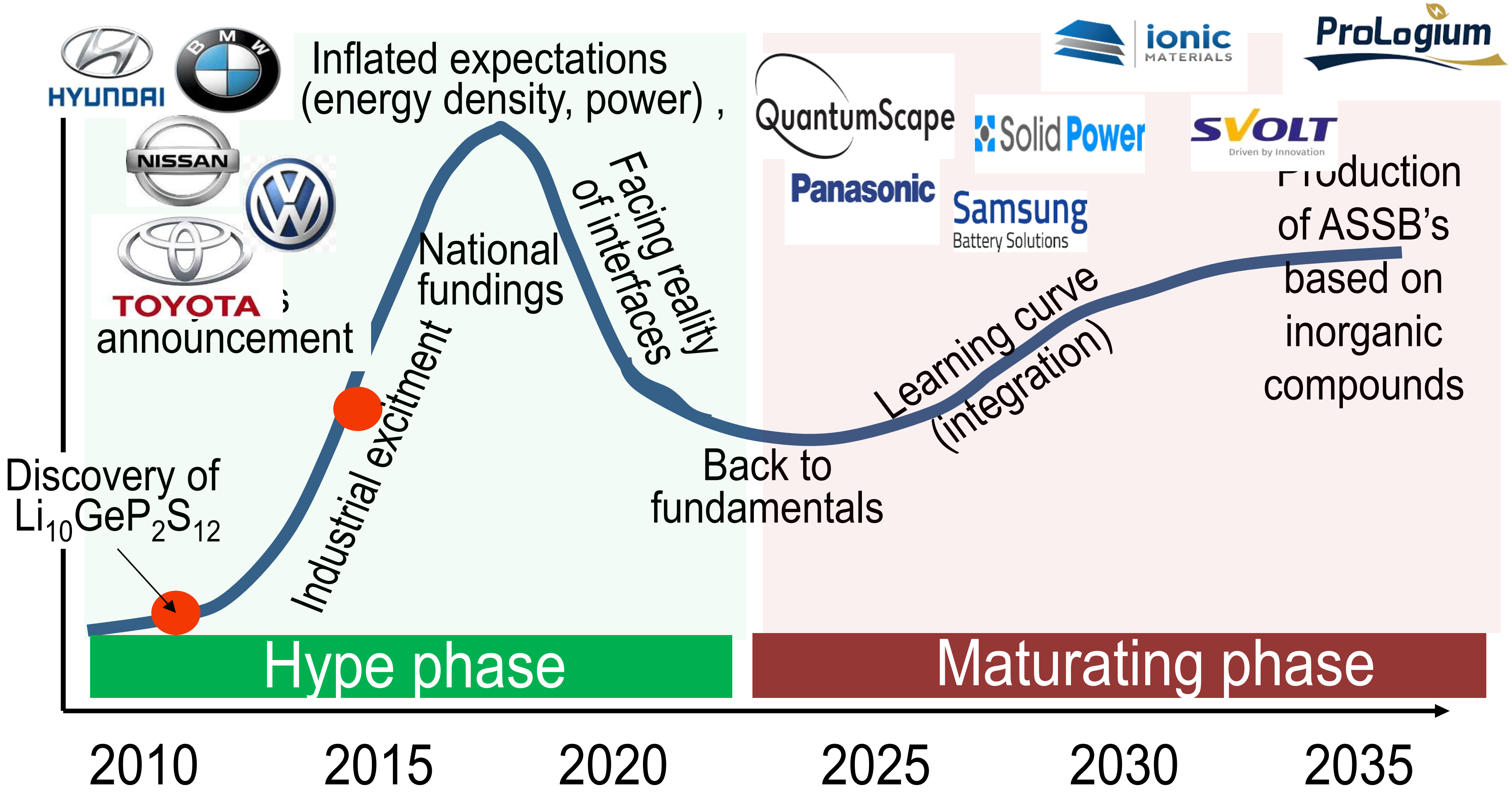
Manufacturers position themselves through partnerships, hoping to capitalize on the right start-up



Automakers may be able to put all-solid-state batteries in cars by 2030, but it will initially be a showcase of the technology - not competitive in terms of market. "They will still be much more expensive than conventional lithium-ion batteries"

Not a university laboratory, not a battery manufacturer, and not a car manufacturer in the world that does not work on the solid state...

The all-solid battery: between idealism and pragmatism



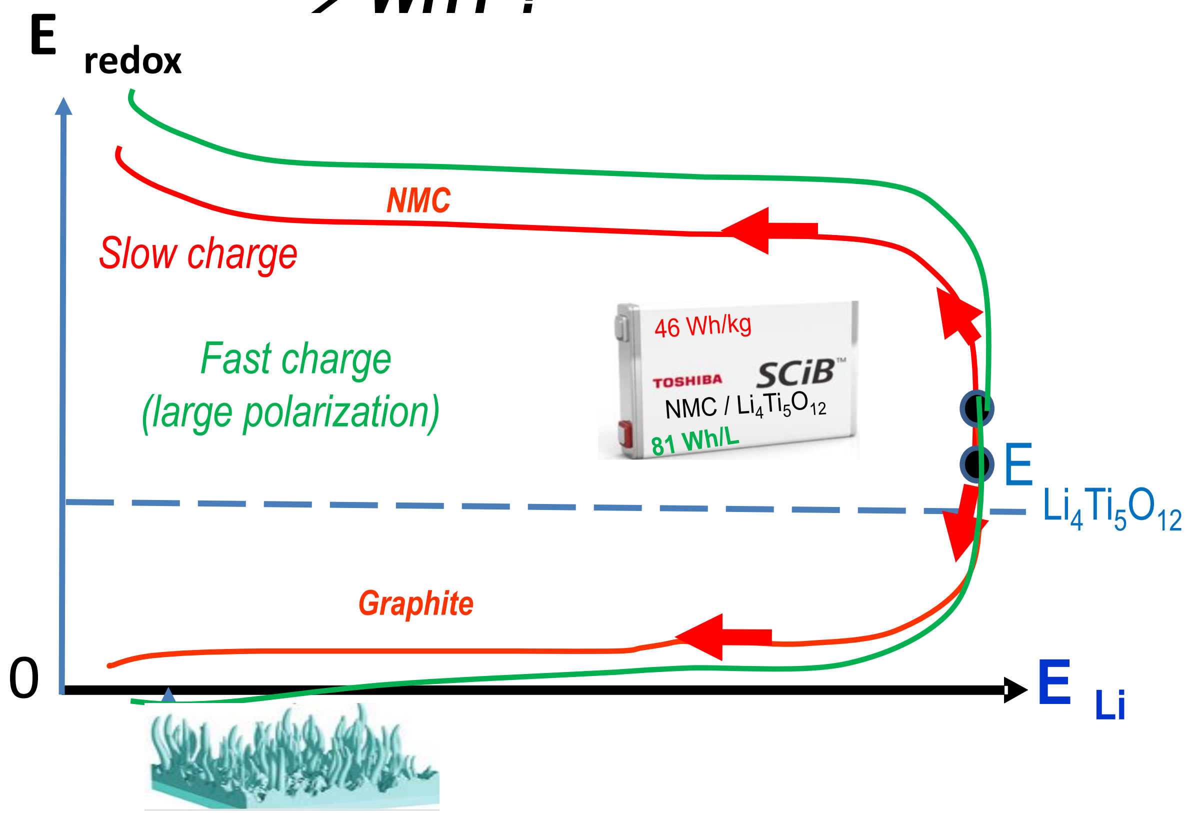
Maturation time uncertain, despite worldwide enthusiasm, consortia formation, colossal investments and constant announcements that remain vague

Another challenge: Fast charging ?

Minimize charging time

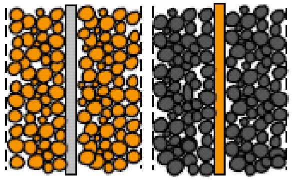
↳ *Fast charging more difficult than fast discharging due to Li deposition problems*

→ *WHY ?*

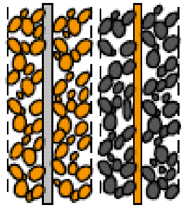


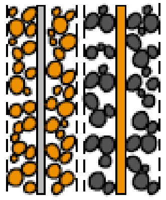
A few approaches to enhance power performances

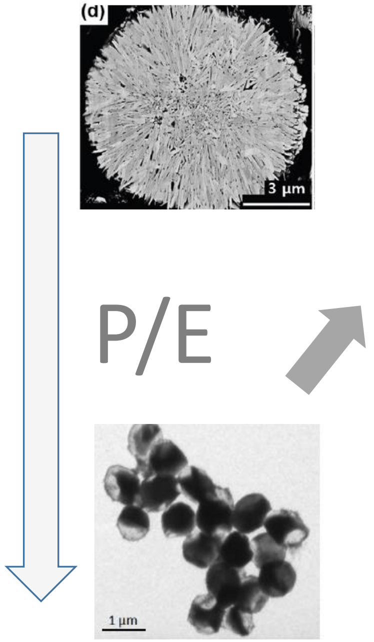
Acting at the cell level



Reduce Distance to be covered by Li+ ions by reducing thickness of the electrodes

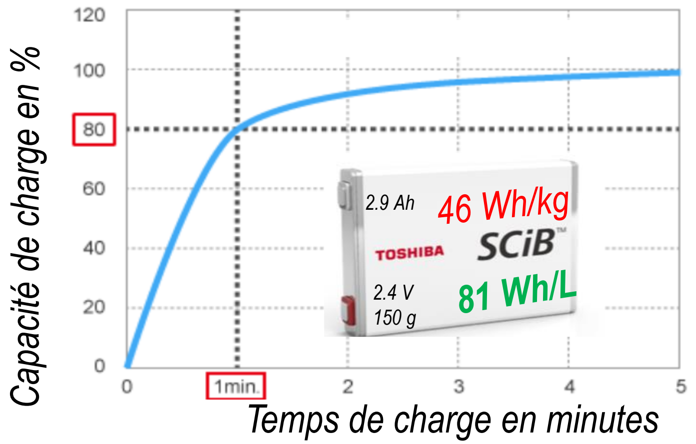


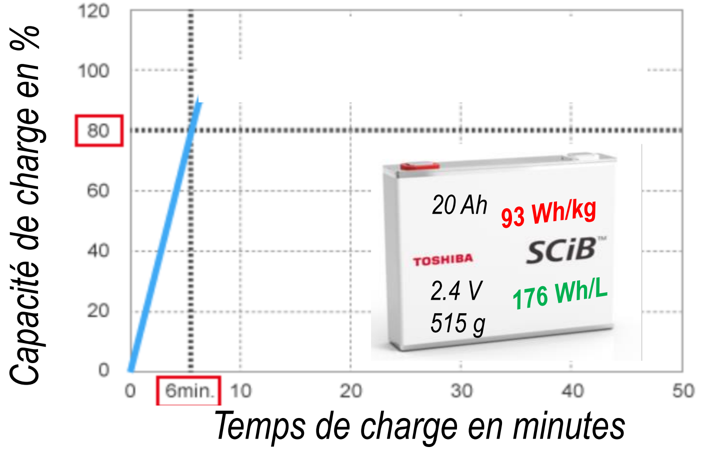




► Increase power at the expense of autonomy

Performances upon charging



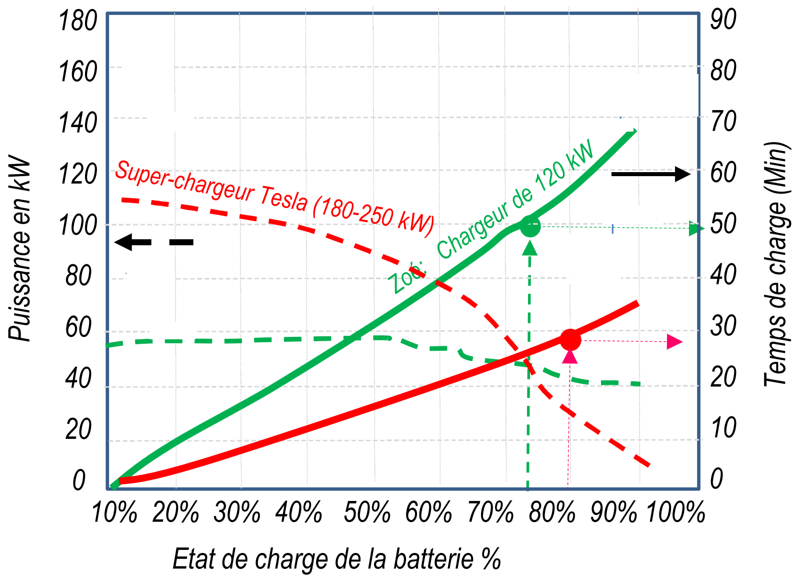


Battery Size will influence charging speeds due to the amount of energy generated...

State of the art in EV recharging to date

Charging tests for the Zoé ZE50
52 kWh battery at 400V
(Autonomy in normal use 350 kms)

Charging test for a Tesla model V3
74 kWhbattery at 400V
(Autonomy in use 490 kms)



- *Charge 15 -> 80% takes nearly 45-50 min*
- *Charge 15 -> 80% takes nearly 25 min*

Full recharge in 5 minutes ➔ **" colossal amounts of energy to be transferred** ➔ **"Physics says NO "**

1500 A at 400V

Supraconductor wires (-195°C)

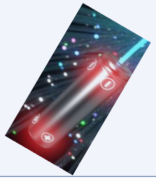
Fast charging in less than 10 minutes is a false dream

Science and innovation involved towards better batteries …

- Autonomy and battery recharge?

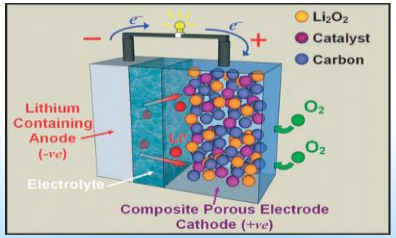
- **Eco-compatibility of batteries ?**

- Durability and reliability of batteries ?

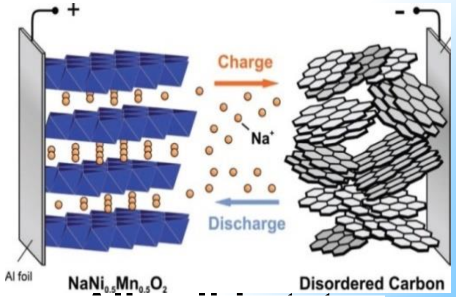


- Abundance of materials– recycling ?

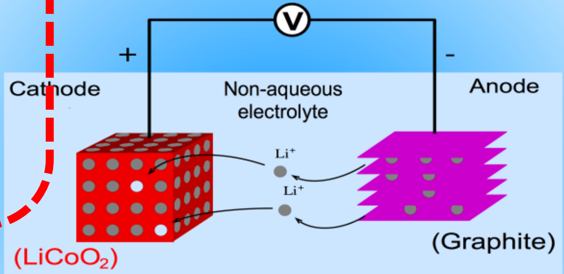
Towards greener and more eco-friendly batteries ....



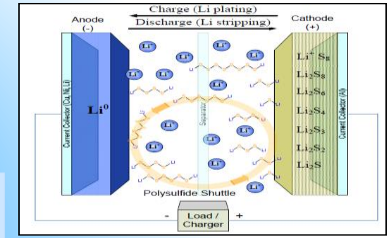
Li/air batteries



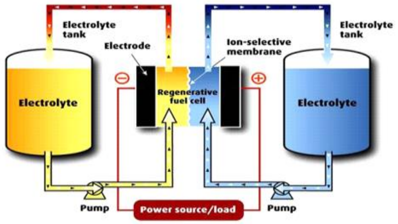
Na-ion batteries



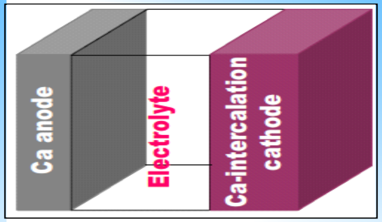
Li-ion batteries



Li/S batteries



Redox flow batteries

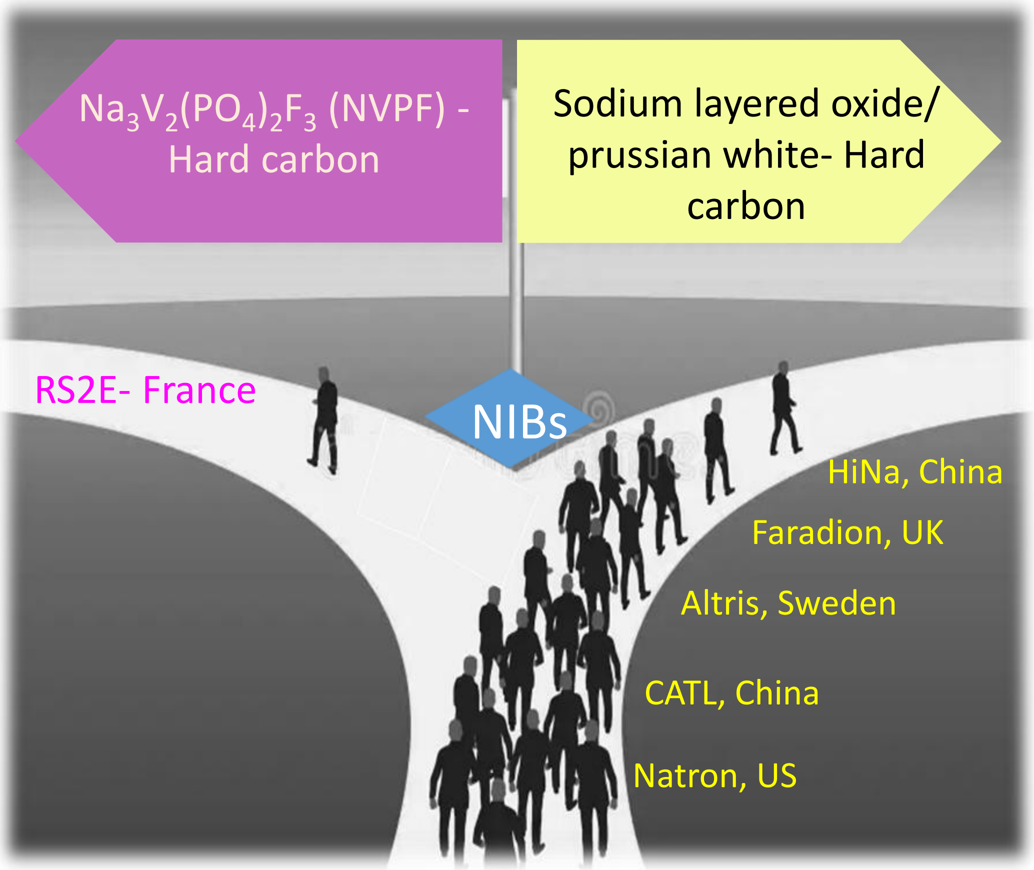


Multivalent cation (Mg^{2+}, Ca^{2+}) batteries

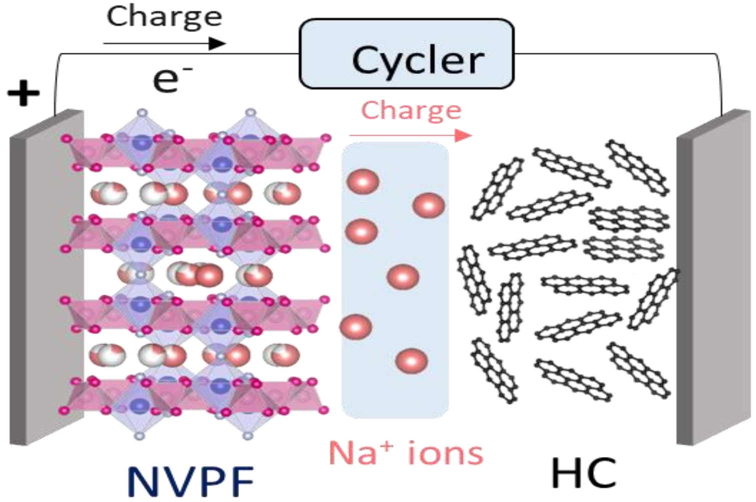
None of them has reached a sufficient state of maturation...

Na-ion a battery alternative driven by sustainability

Back to 2012: Decision to move into NIB development, but with what chemistry?



$Na_3V_2(PO_4)_2F_3$ (NVPF) | Hard carbon



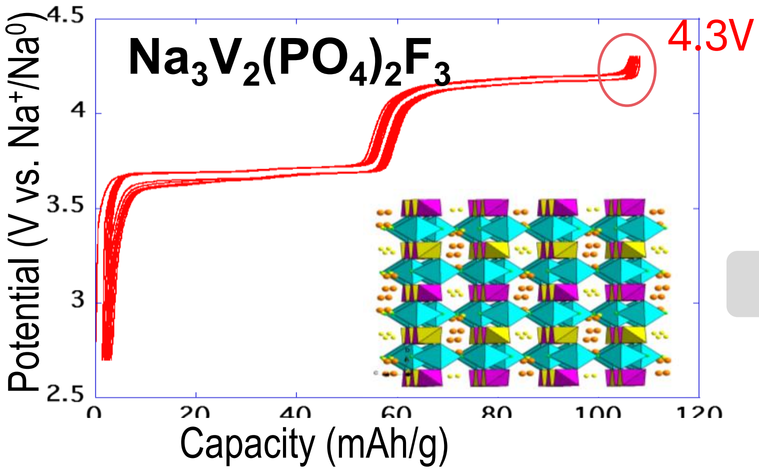
Structural and air-moisture stability

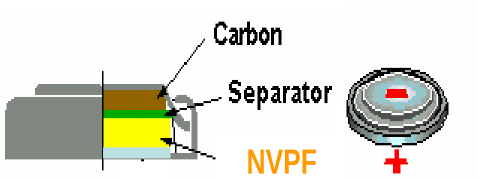
High Na^+ diffusion

Development requires innovations in materials and electrolytes as well in mastering interfaces .

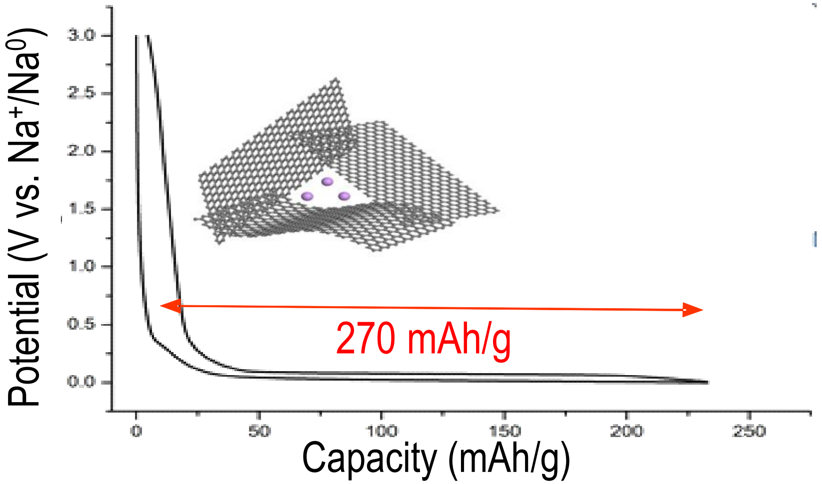
A. Ponrouch et al Energy Environ. Sci., 2013,6, 2361-2369

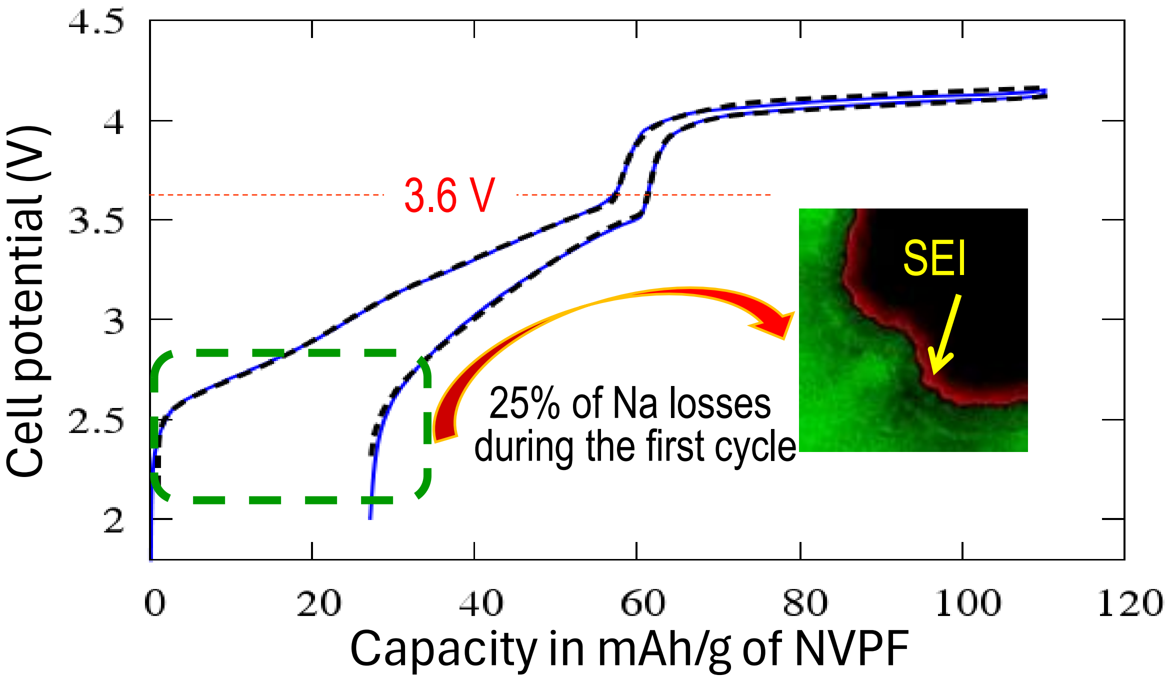
The $Na_3V_2(PO_4)_2F_3$/C system: from sodium half-cells to full Na-ion cells





$Na_3V_2(PO4)_2F_3$ / 1M $NaPF_6$ in EC-DMC/C





Need of an extra Na source

Oversodiated materials ?

$Na_3V_2(PO_4)_2F_3$ + Na

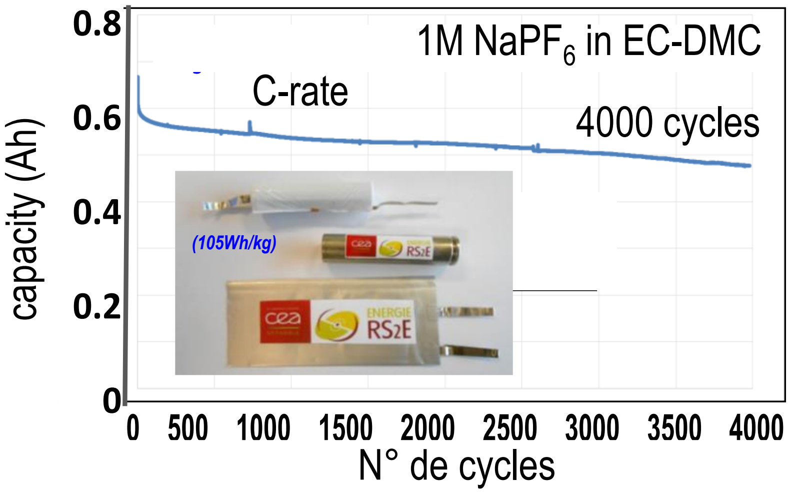
Composites

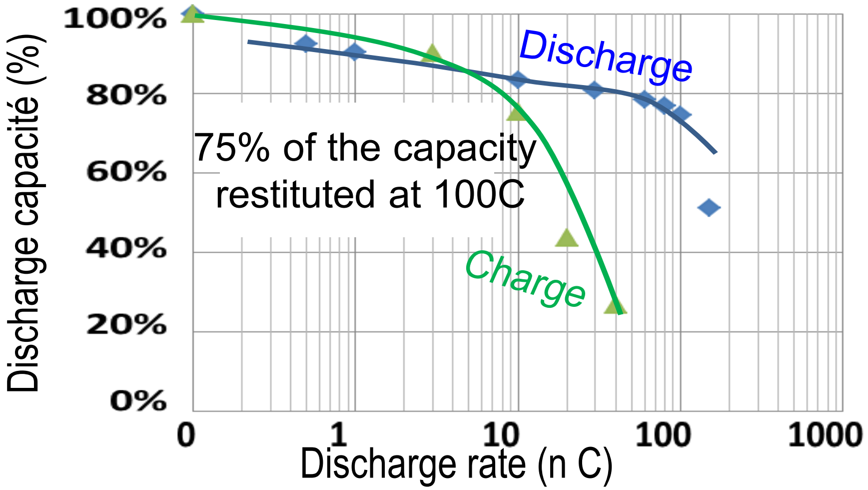
$Na_{3+x}V_2(PO_4)_2F_3$

A. Ponrouch et al Energy Environ. Sci., 2013,6, 2361-2369
B. Zhang et al. Nature communications (2016)
G. Yun, S. Mariyappan, R. David and J.M. Tarascon, WO2019207043A1

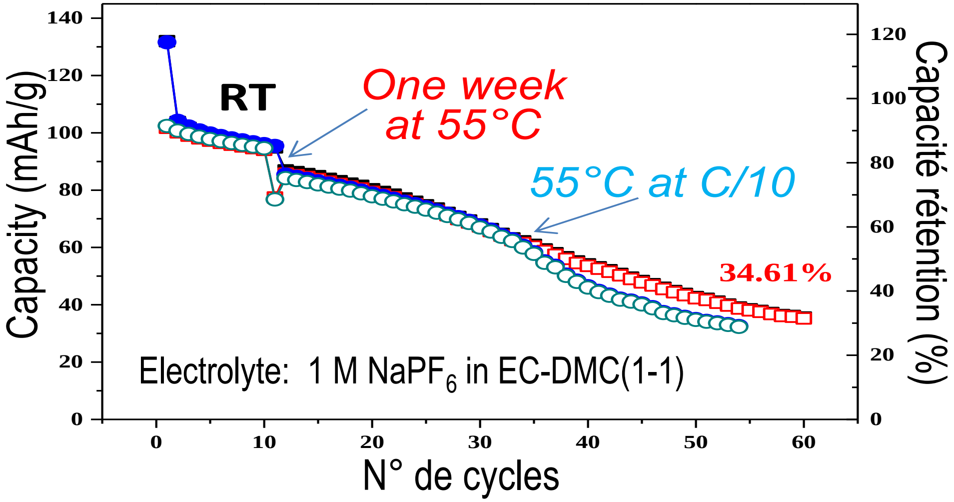
The $Na_3V_2(PO_4)_2F_3$/C technology : the first 18650 prototype

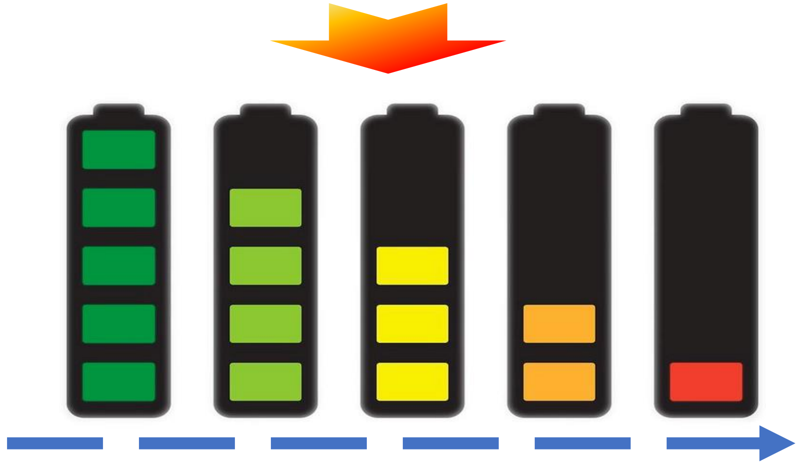
Performances at 25°C





Performances at 55°C



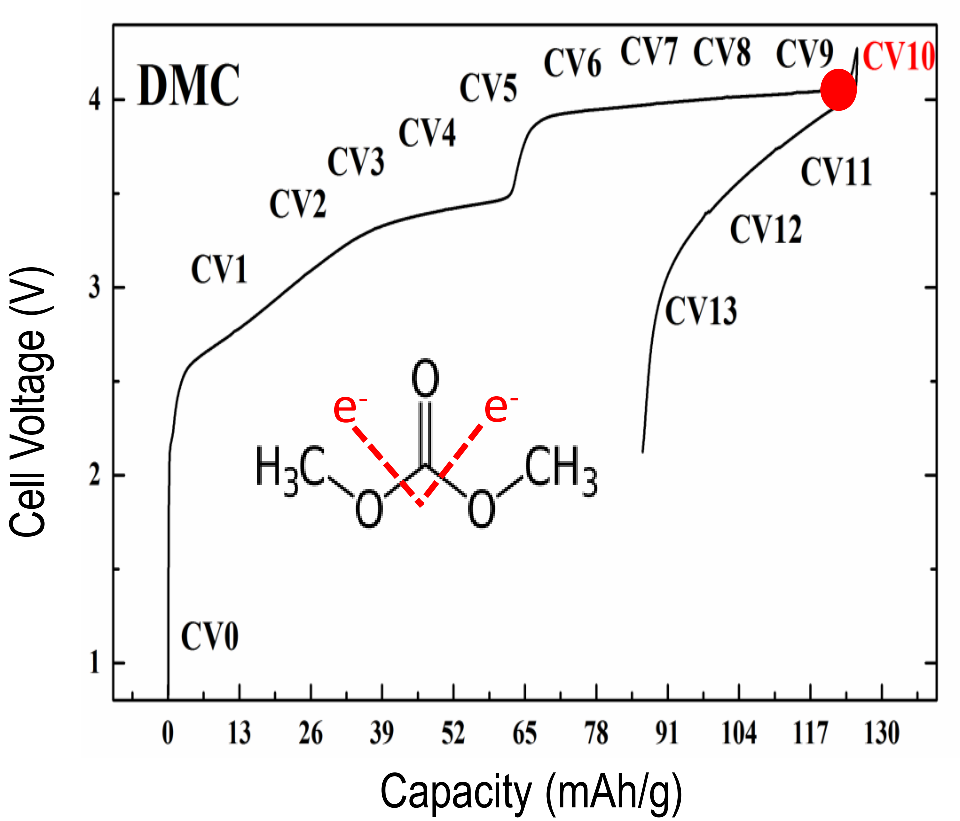


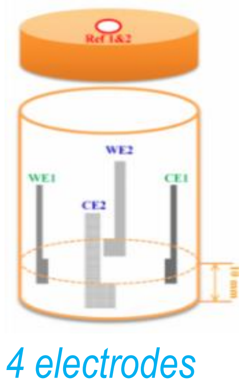
Cell on rest at 100% SOC: Huge self-discharge

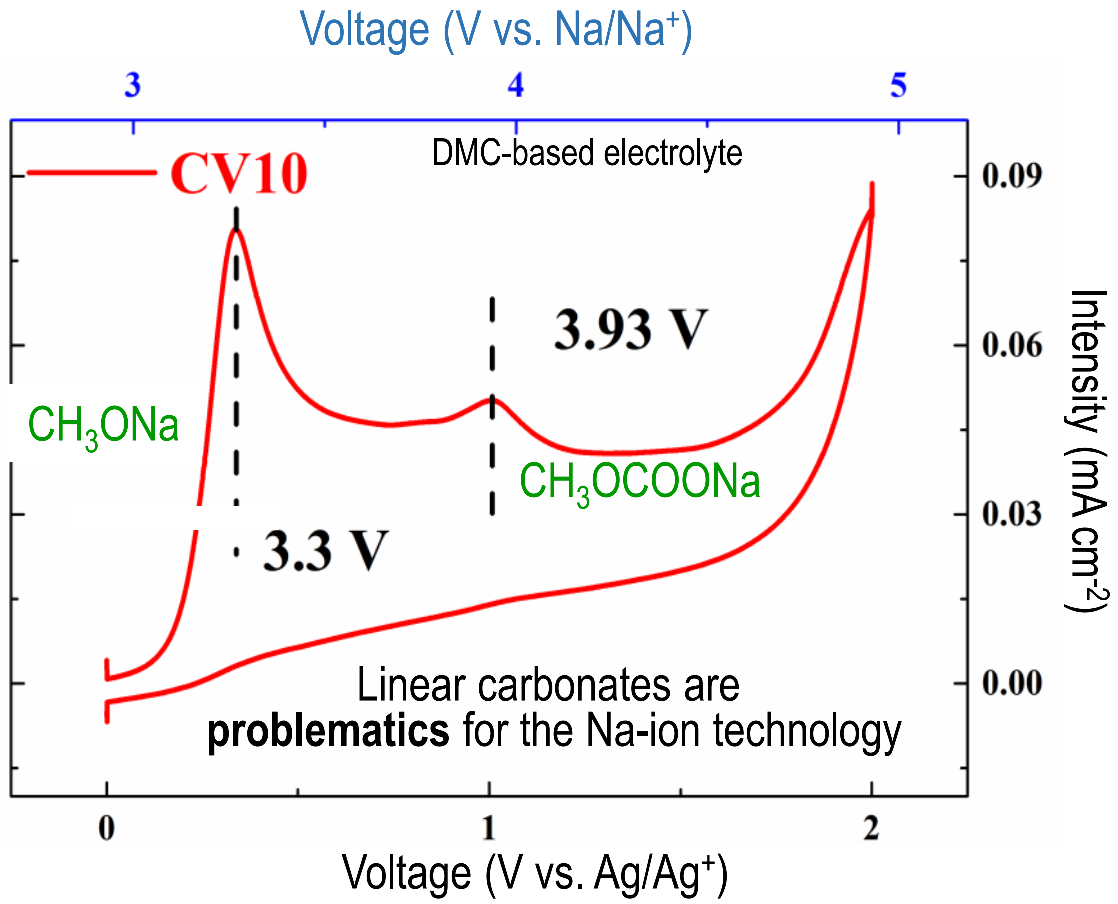
Back to fundamentals to better understand the electrolyte and discover that DMC was the disruptive element.

Searching for the causes of self-discharge

Searching for EC-DMC $LiPF_6$ electroyte stability







We also need to go back to a survey of various electrolytes and additives

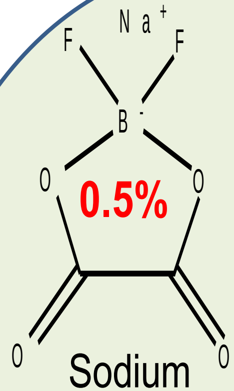
Key steps in the development of electrolyte for the NVPF/C technology

2015 — 2019 — 2023

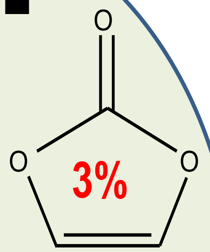
2015

$1NaPF_6$
EC-PC

Wettability issues



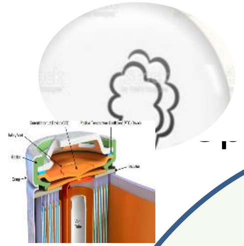
Sodium difluoro(oxalato)borate
(NaODFB)



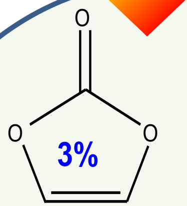
Vinylene carbonate
(VC)

Succinonitrile
(SN)

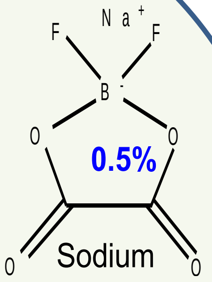
2019



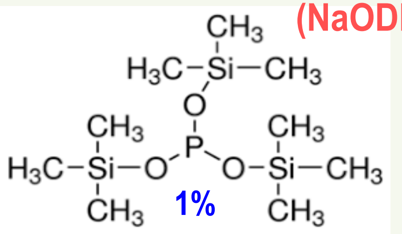
$1NaPF_6$
EC-DMC



Vinylene Carbonate
(VC)



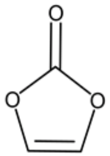
Sodium Difluoro(oxalo)borate
(NaODFB)



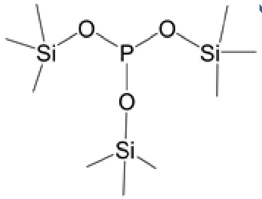
Tris(trimethylsilyl) phosphite
(TMSPi)

2023

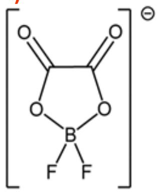
$1NaPF_6$
EC-PC-DMC



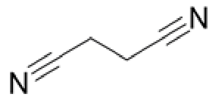
Vinylene carbonate
(VC)



Tris(trimethylsilyl)phosphite
(TMSPi)



Sodium oxalatodifluoro borate
(NaODFB)



Succinonitrile
(SN)

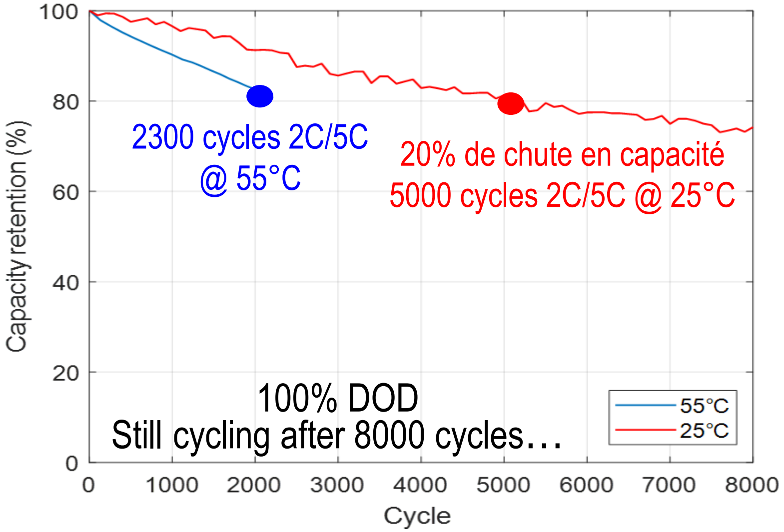
Long time because the choice of additive remains overly an empirical research
(New research tools such as ML or AI have not yet added value)

H. Hijazi, S. Mariyappan and J.-M. Tarascon (Patent WO2022200343A1)

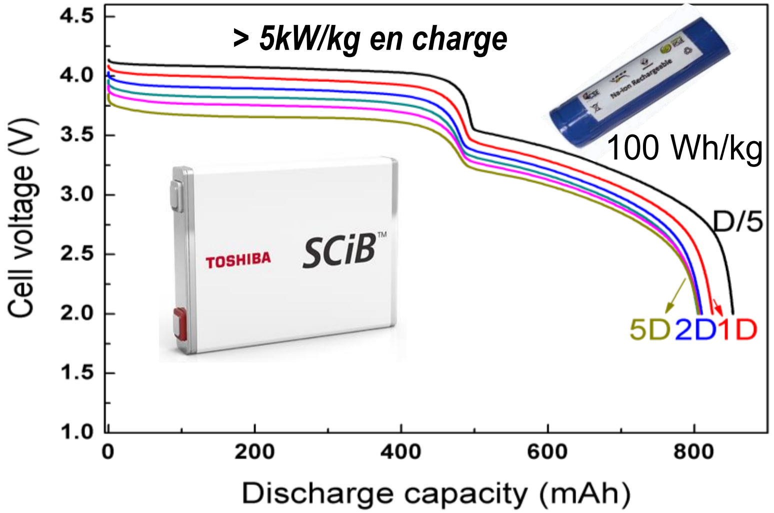
G Yan, J-M. Tarascon, (Patent WO2019072986A1)

Na-ion: 10 years of research to master its chemistry

Cycling performances



Power performances

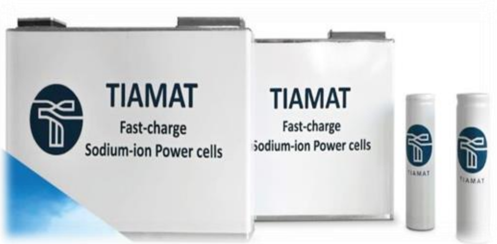


➢ ***A French start-up: TIAMAT (2018)***

Na-ion: a quick recap

2012 — Concept + development

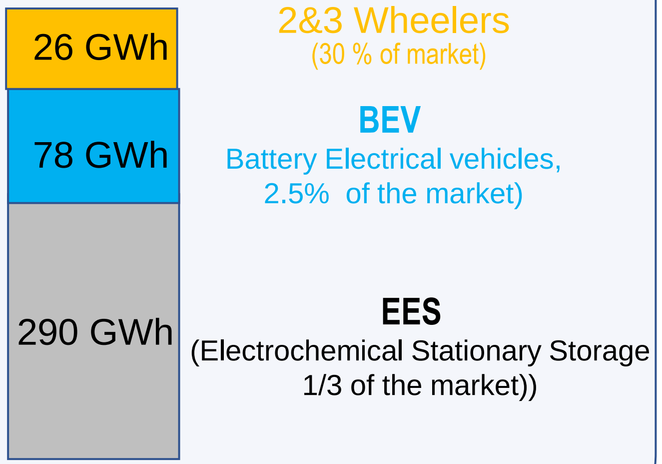
2018 — Creation of TIAMAT



2023 — Commercialisation

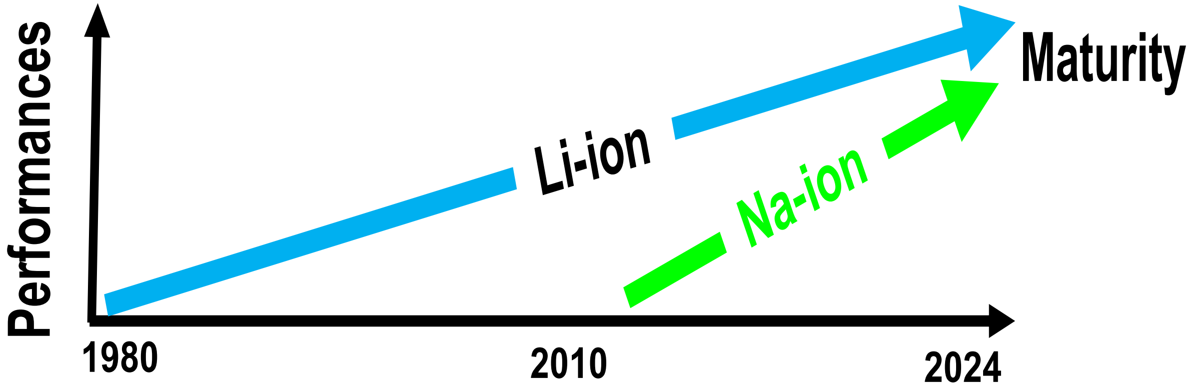
2025

➢ Battery market and projections for Na-ion in GWh for 2030



Total: 394 GWh (8% of market)

➢ **Faster development**



"The huge knowledge gained from the LiBs made the road for the NiBs commercialisation shorter"

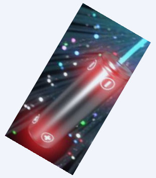
"Faster developpment accelerated by the launching of a new battery diagnostic area dealing with optical sensing"

Science and innovation involved towards better batteries …

- Autonomy and battery recharge?

- Eco-compatibility of batteries ?

- **Durability and reliability of batteries ?**



- Abundance of materials– recycling ?

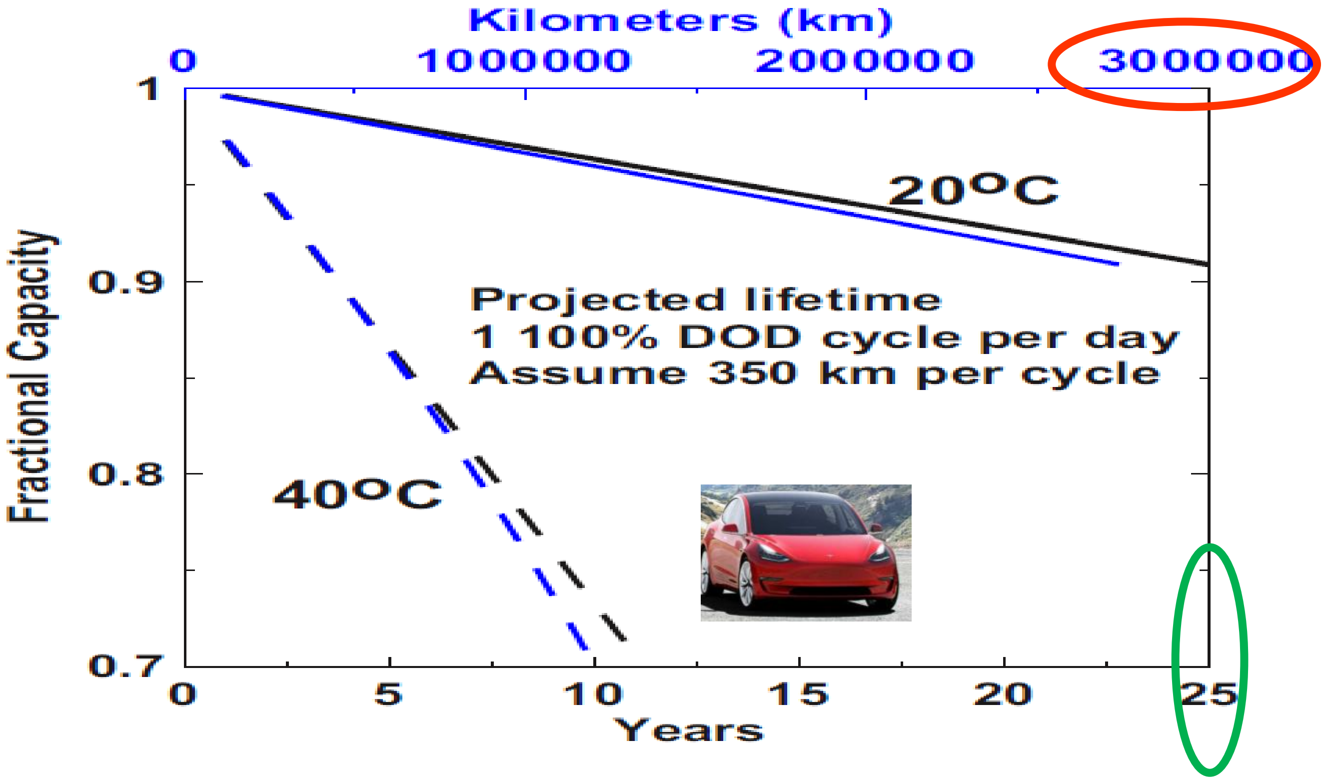
The Li-ion technology: A brief status in terms of durability

September2019

A Wide Range of Testing Results on an Excellent Lithium-Ion Cell Chemistry to be used as Benchmarks for New Battery Technologies

Jessie E. Harlow,[1,2] Xiaowei Ma,[1,2] Jing Li,[1,2] Eric Logan,[1,2] Yulong Liu,[1,2] Ning Zhang,[1,2] Lin Ma,[1,2] Stephen L. Glazier,[1,2] Marc M. E. Cormier,[1,2] Matthew Genovese,[1,2,*] Samuel Buteau,[1,2] Andrew Cameron,[1,2] Jamie E. Stark,[1,2] and J. R. Dahn[1,2,**,z]

3 years of extensive tests at 55°C on (NMC(532)/Carbon) pouch cells



Advances in the chemistry of these systems have improved their lifespan, but what are the remaining challenges ?

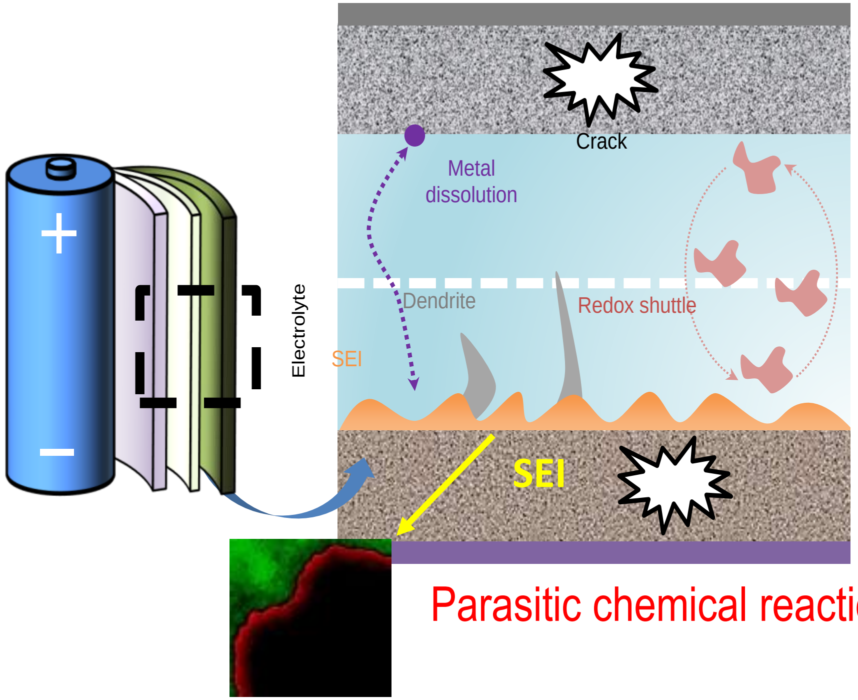
How to increase the lifetime of batteries while improving their performances ?

Monitoring under real conditions of use?

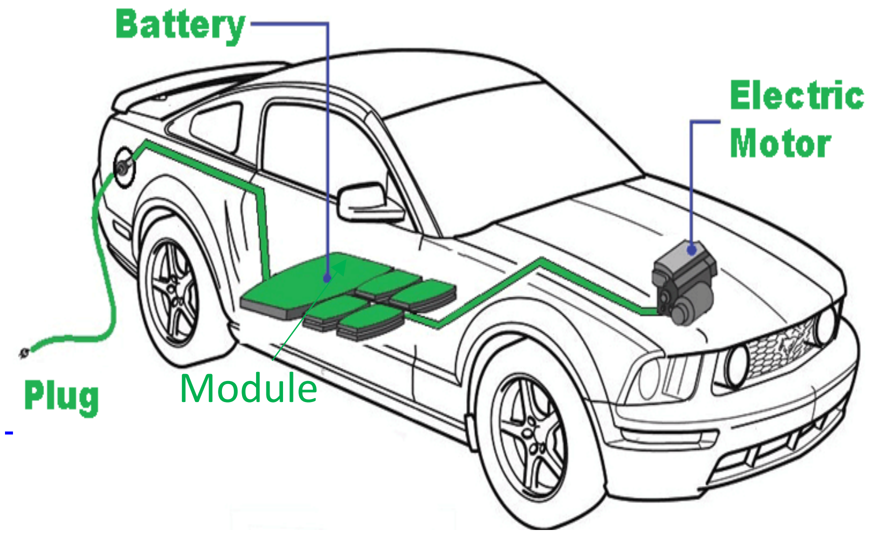
- Lab scale

Level of complexity

- Systems



Parasitic chemical reactions

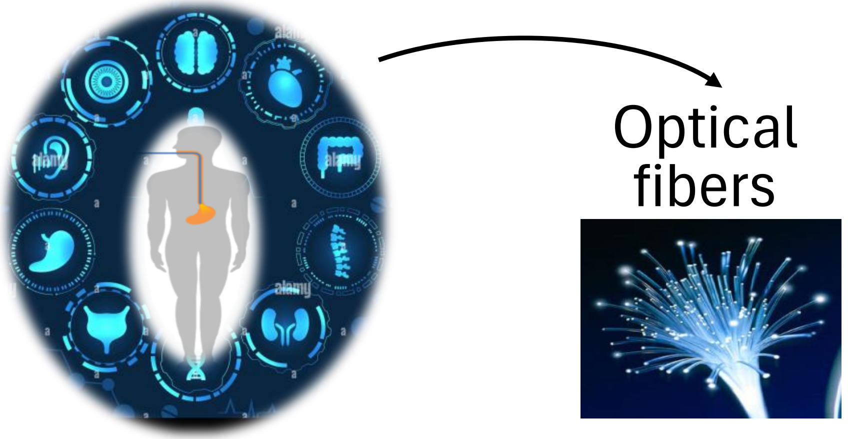


How to detect and anticipate cell failures in integrated systems?

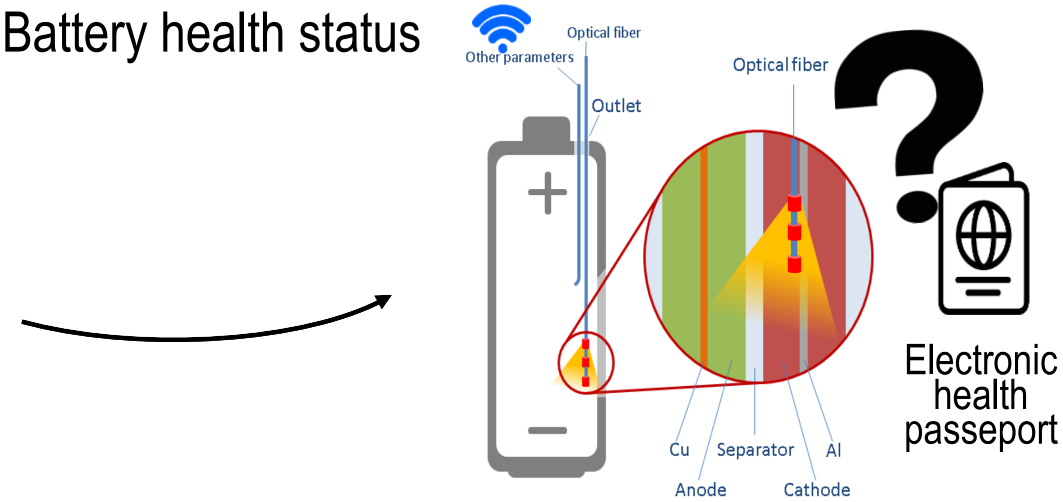
Injecting smartness into batteries to increase their durability

Inspiration from medecine

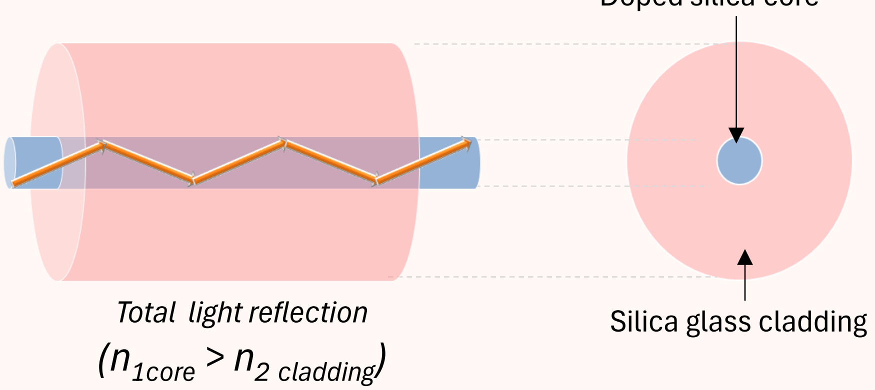
- Bio-medical



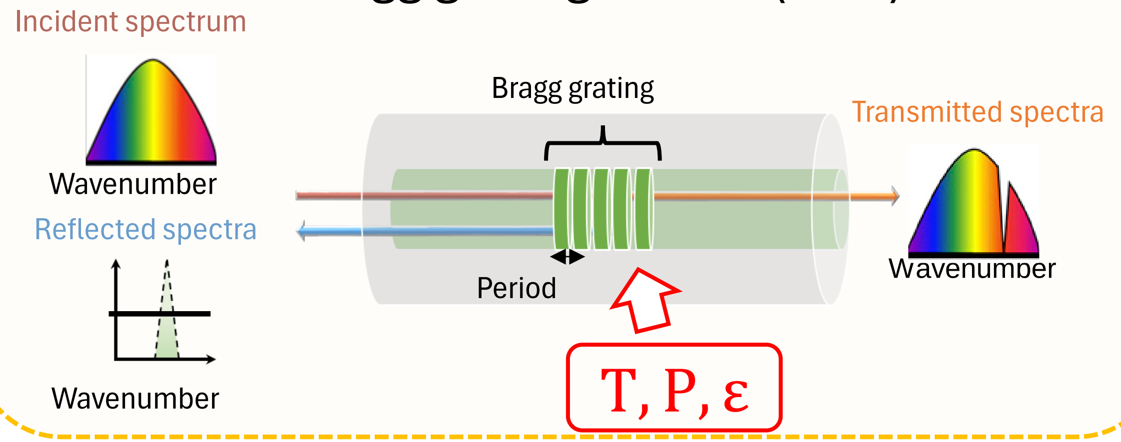
- Battery health status



- Light transport

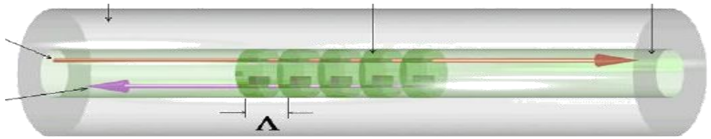


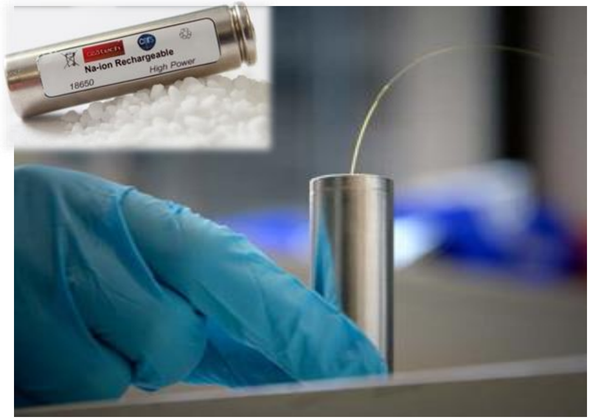
- Bragg grating sensor (FBG)

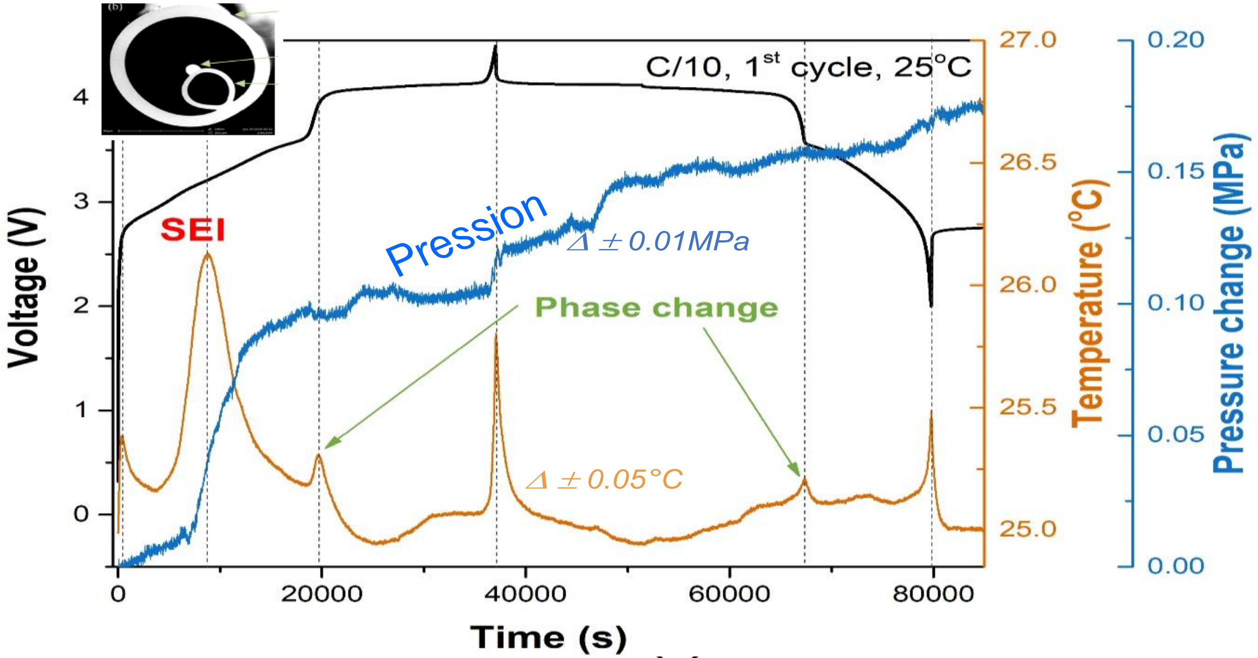


Monitoring the intimate life of batteries using optical sensors

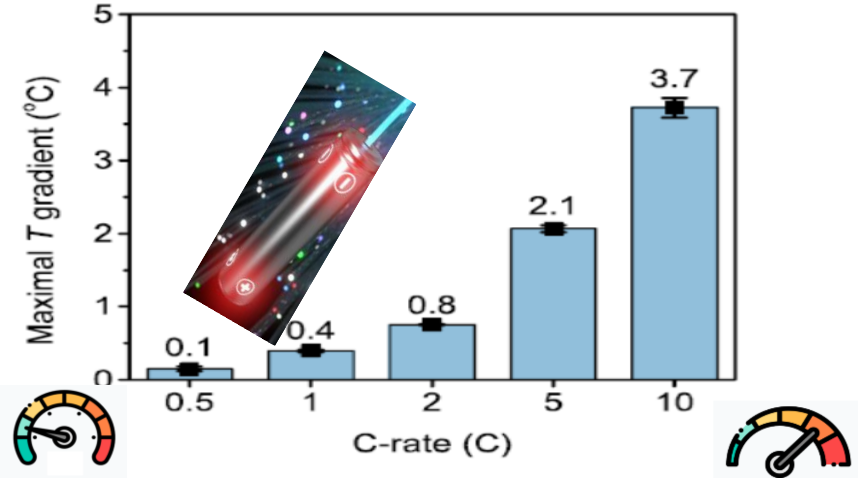
Use of Bragg sensors (FBGs)



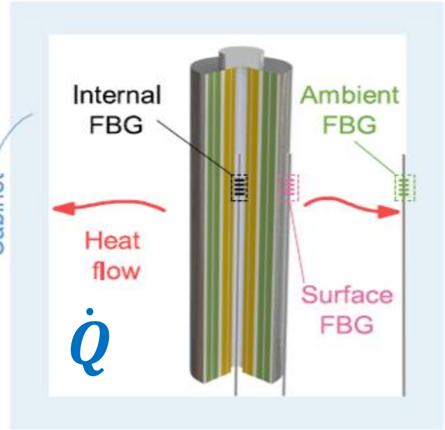




- Cell temperature imaging

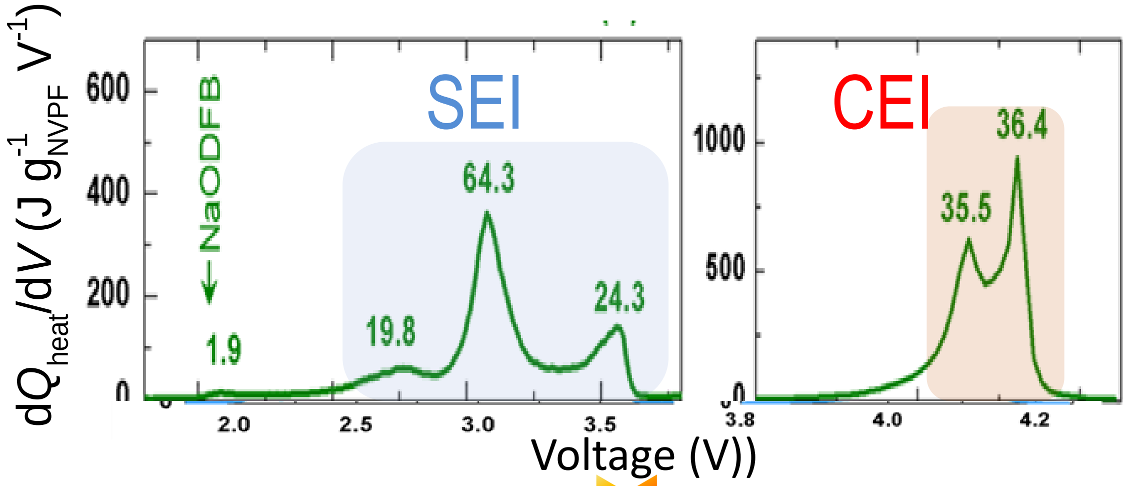


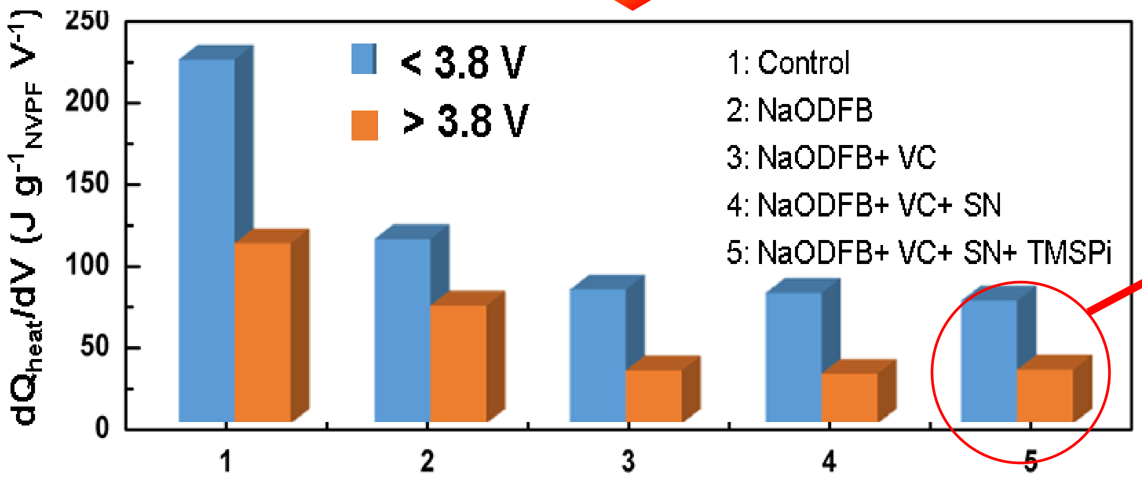
- Optical calorimetry



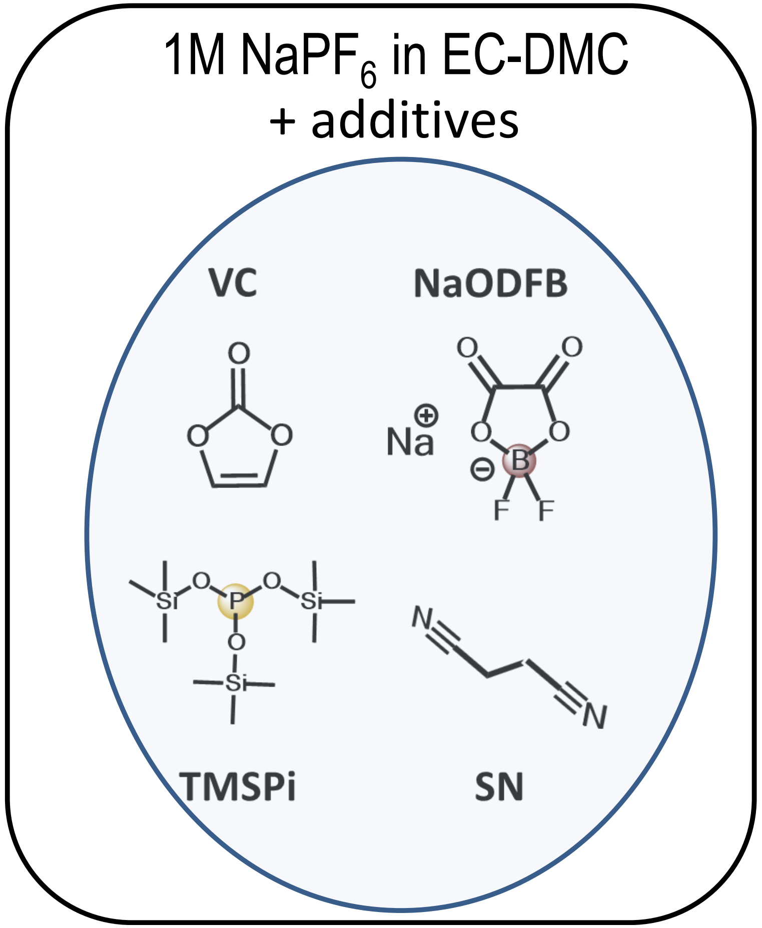
FBGs as a way to identify proper electrolyte additives

- Additives for Na-ion $Na_3V_2(PO_4)_2F_3$/Cells

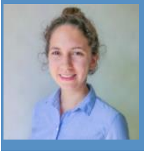




Optimum electrolyte formulation

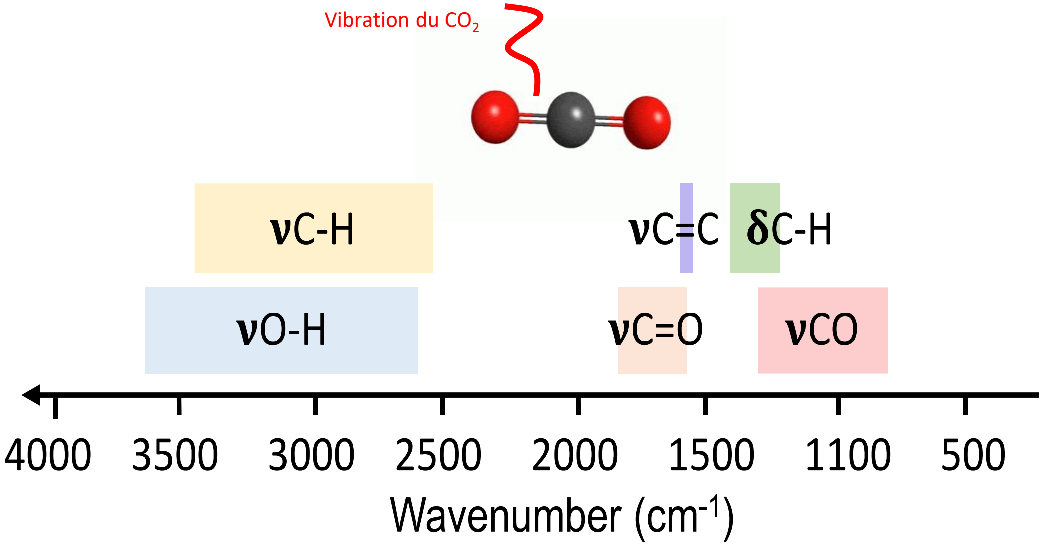


FBGs enable to assess the heat associated to the formation of both SEI and CEI: What about the chemical species ?



How do you find out the nature of chemical species?

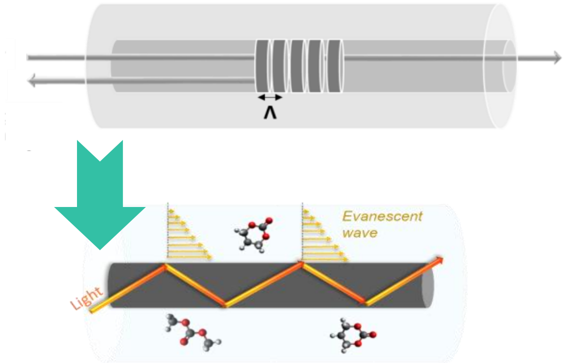
Infrared spectroscopy help to identify electrolytes and interfaces...



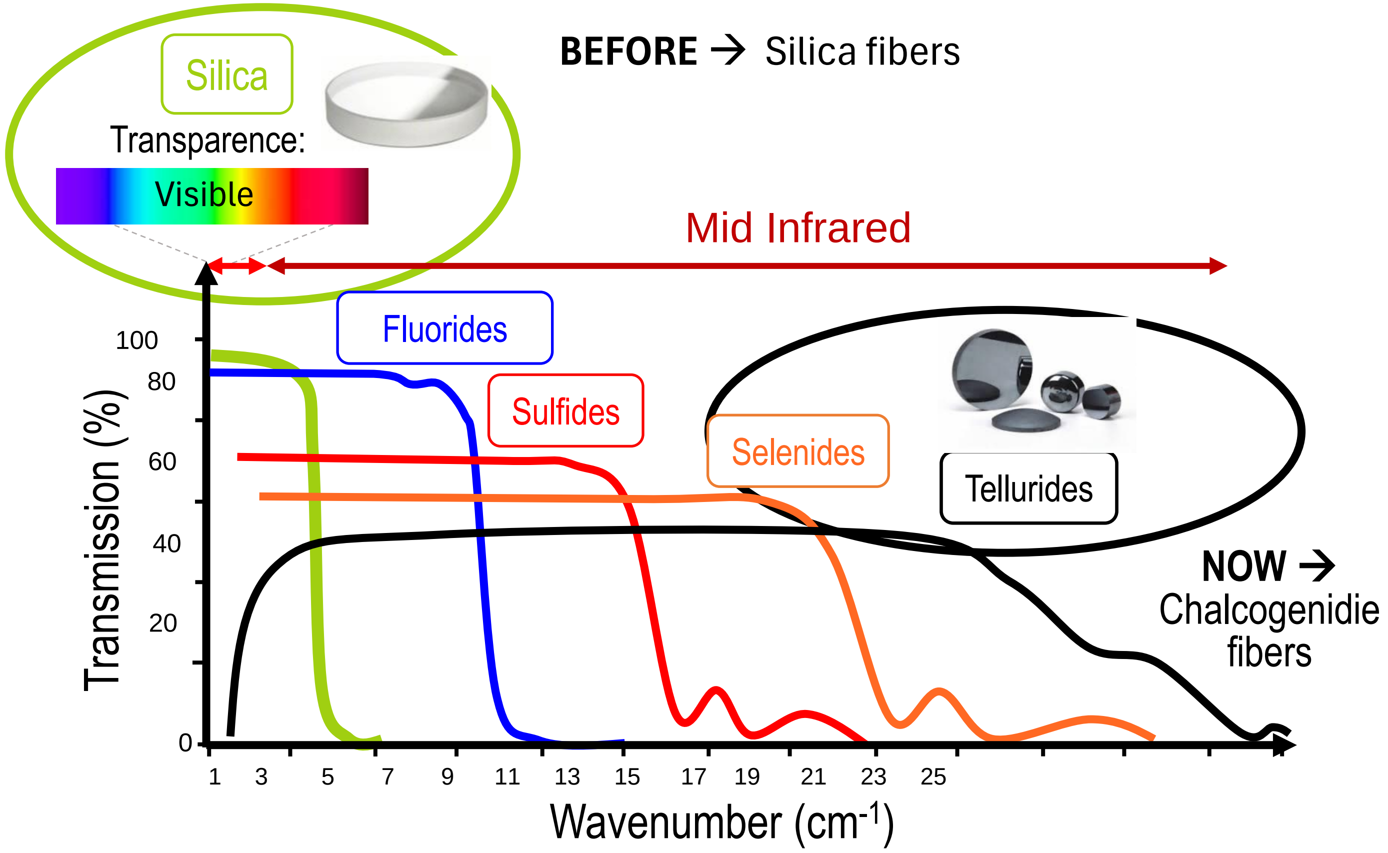
IR via optical fiber ?

Core Optical fiber

Raw Optical fiber

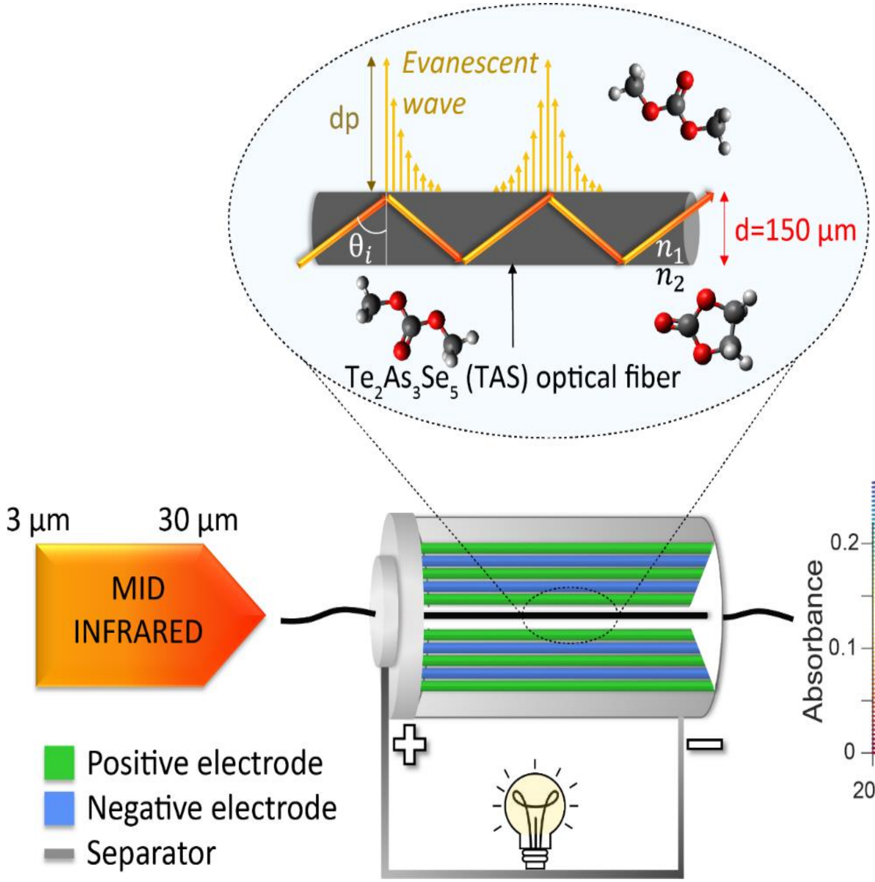


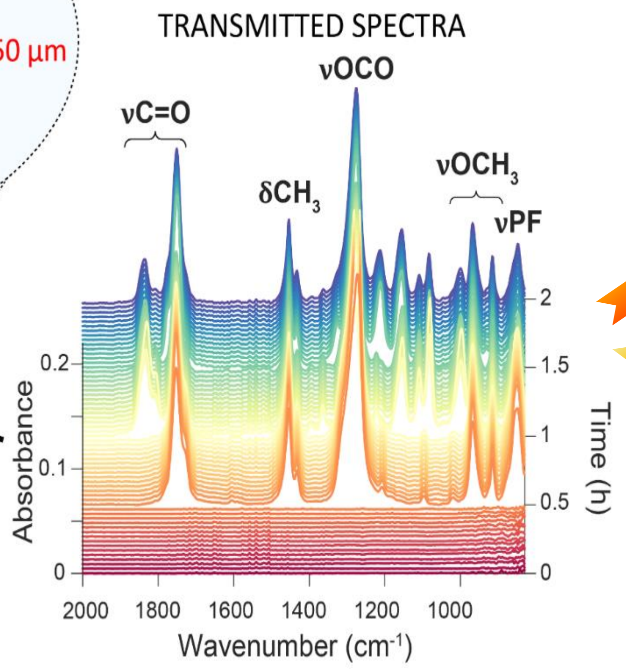
How to inject infrared light into batteries?



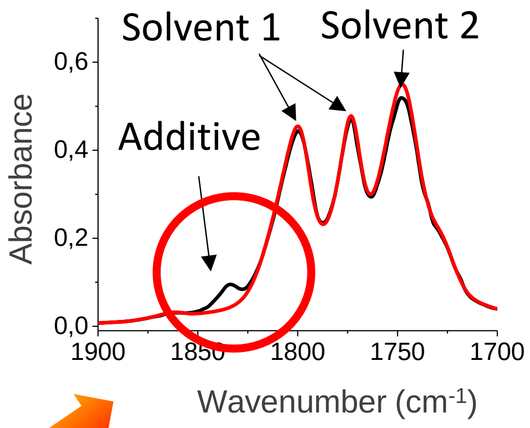
Characterization of commercial cells by evanescent-wave infrared spectroscopy

How does it works?

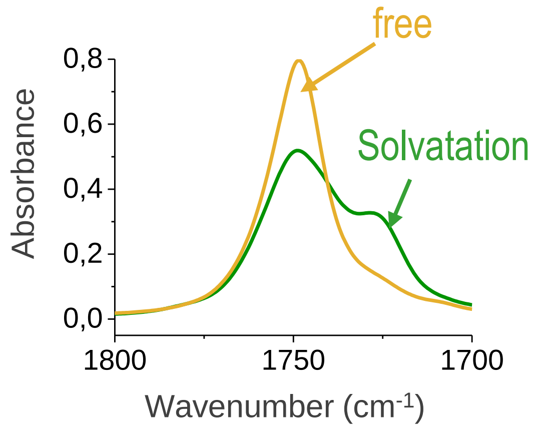




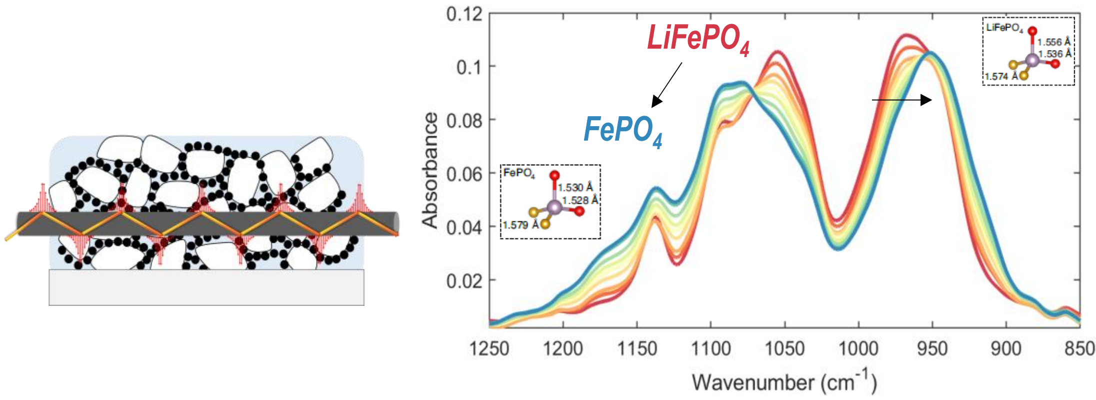
➢ Decomposition of additives



➢ Solvatation



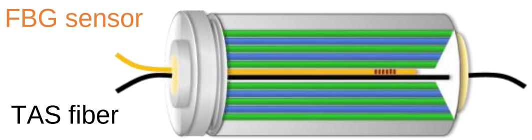
➢ Redox processes in cathodes ($LiFePO_4$)



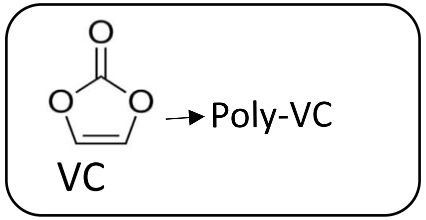
C. Gervillié-Mouravieff et al. Nat. Energy **7**, 1157–1169 (2022)

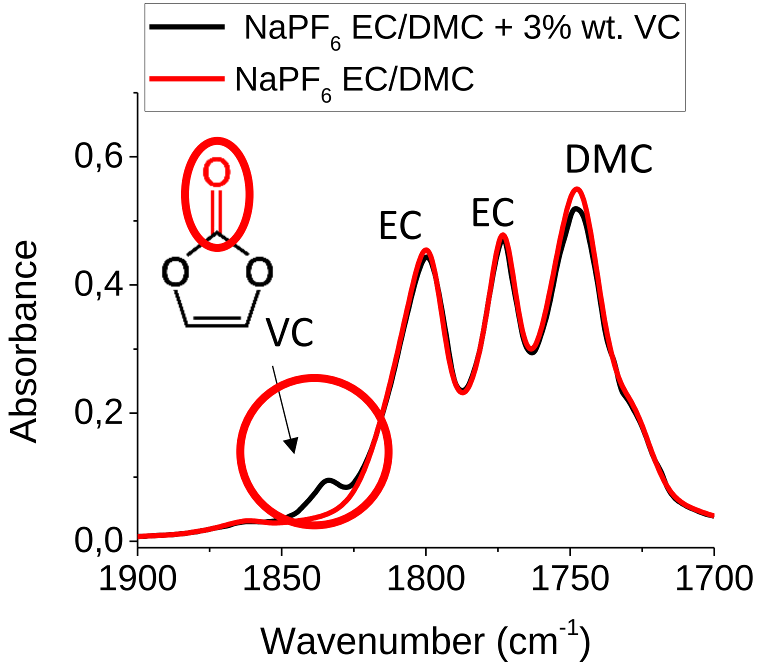
Patent: C. Gervillié-Mouravieff et al., n° EP4124849A1 (2023)

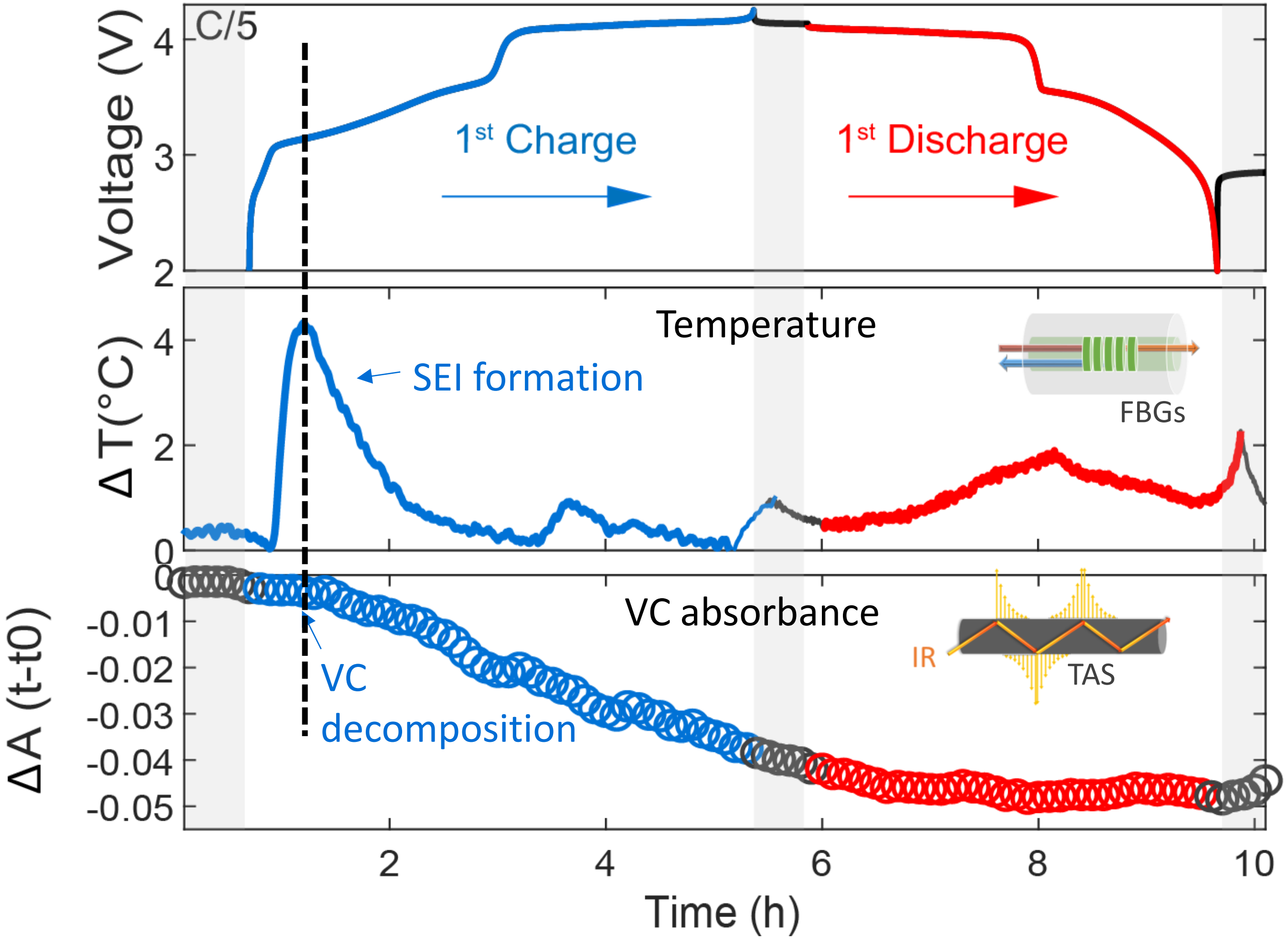
Operando tracking of Li-driven reduction of VC in commercial Na-ion cells



$NaPF_6$ EC/DMC + 3 wt% VC

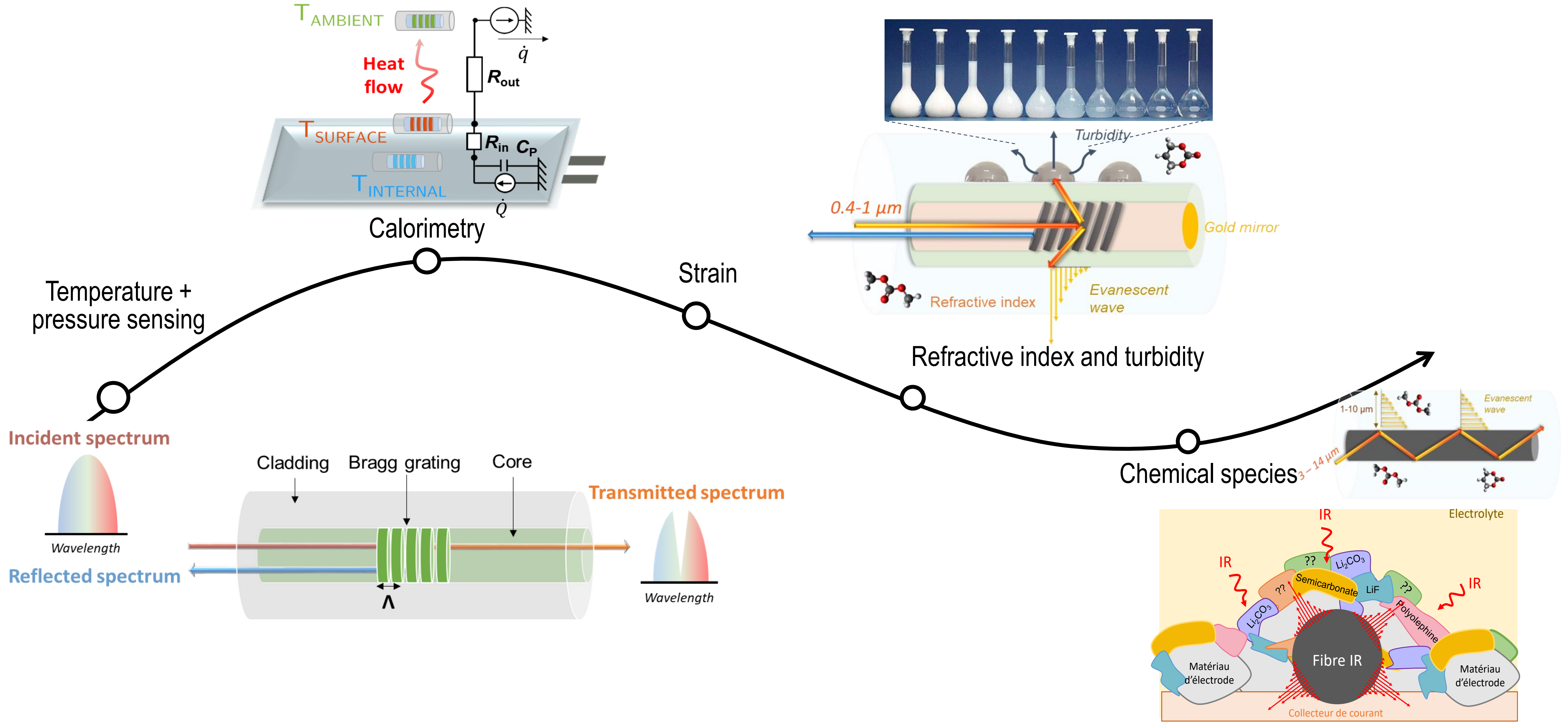






Reduction of VC at the carbon negative electrode at 3.15 V in Na-ion cell to form a long lasting stable SEI

Optical sensing: from physical to chemical observables in Li(Na)-ion cells



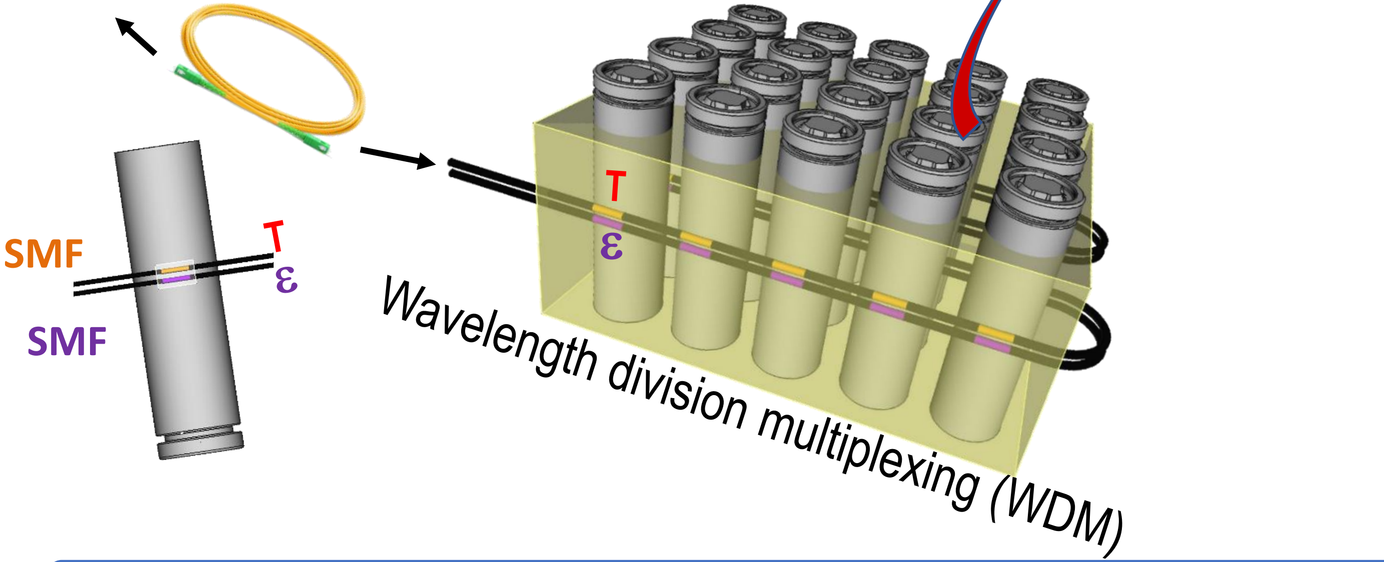
So how practical optical sensing is?

Technological demonstrator for industrial applications

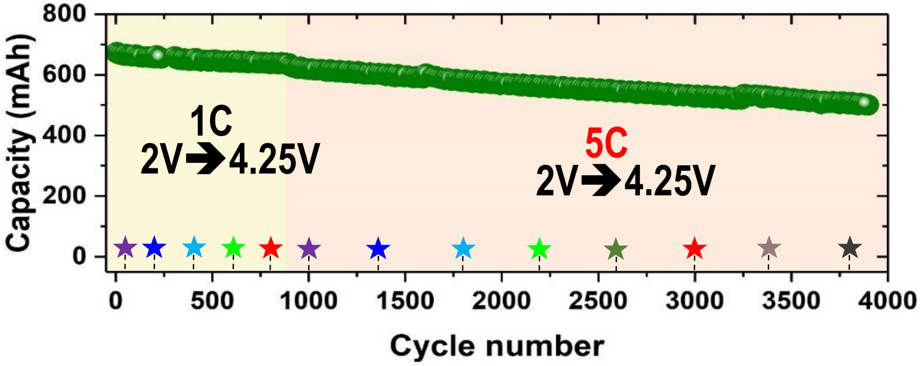
➢ Real time temperature and strain monitoring with wireless data communication

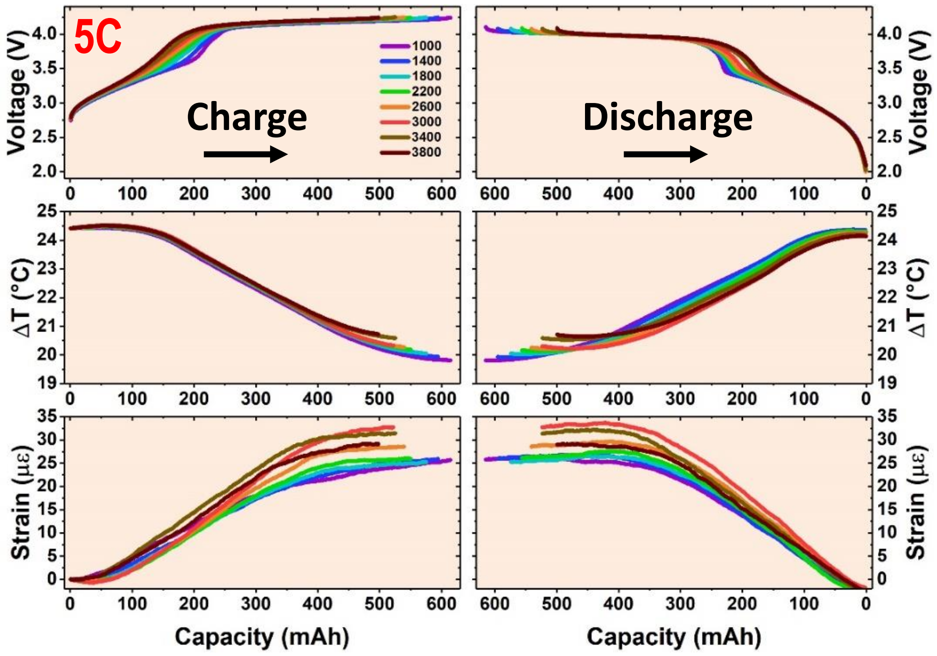
Prof. Hwa-yaw *TAM*

Further reduction
Expected (size & cost)



Na-ion NVPF/C





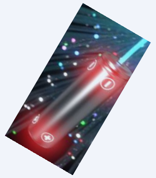
Ongoing project involving a wide range of industrial sectors and international collaborations

Science and innovation involved towards better batteries …

- Autonomy and battery recharge?

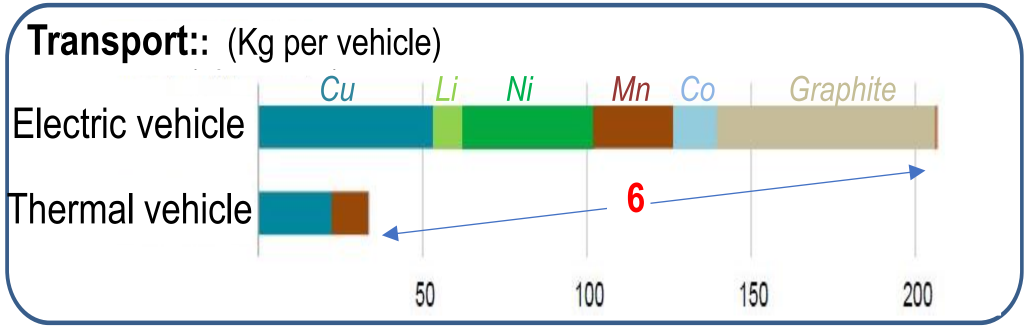
- Eco-compatibility of batteries ?

- Durability and reliability of batteries ?

- **Abundance of materials– recycling ?**

The energy transition: abundance of materials and recycling?



Crucial need to develop an efficient recycling sector …

Future scientific challenge: Simplifying recycling

Recycling recycling processes

2 méthodes

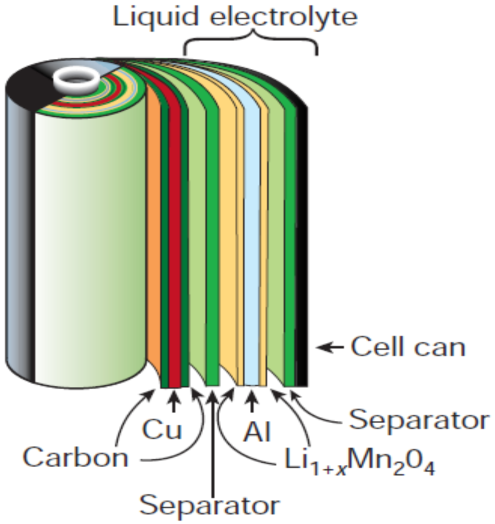
Pyrométallurgie *Hydrométallurgie*

Promote single step recycling processes :

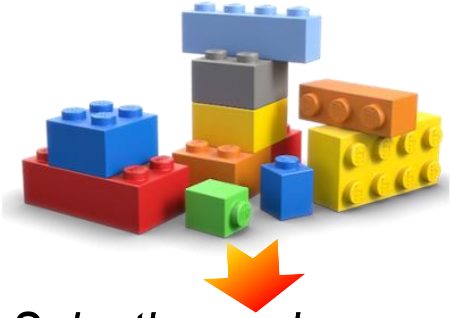
Direct method

(Physical separation and reprocesing)

Rethinking battery configuration



"LEGO" type battery



Selective replacement of battery components

Battery Europe: the new legislative framework

Health and lifespan

July 2025
Obligation to equip the batteries with a diagnostic system

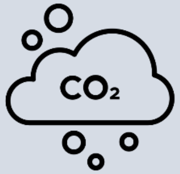
January 2027 :
Implementation of an electronic passport

Carbon footprint

July2024 : Compulsory delaration of the CO_2 foot print

January 2026 :
Display of the performance class linked to CO_2 foot print

July 2027 :
Mandatory compliance with maximum CO_2 footprint thresholds



Recycled materials

July 2027 :
Compulsory display of recycled Ni, Co and Li content

January 2030 :
Mimimum rates of recycled materials to be respected (10%Co, 4% Ni et 4%Li)

January 2035 :
Minimum rates raised to 20, 10 and 12 % of Co, Li, Ni, respectively

General conclusions

The battery world is, and will continue to be, a dynamic environment

In the field of chemistry and engineering

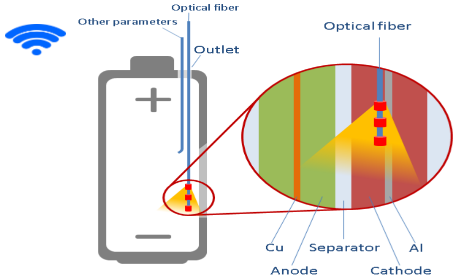
- *New chemistries (solid state, Na-ion…)*

In the industrial field

- *Setting-up gigafactories*

In the field of sustainable development

- *Battery diagnostic – Battery recycling*



Looking ahead

AI

data science

Acknowledgments

erc European Research Council

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THANK FOR YOUR ATTENTION

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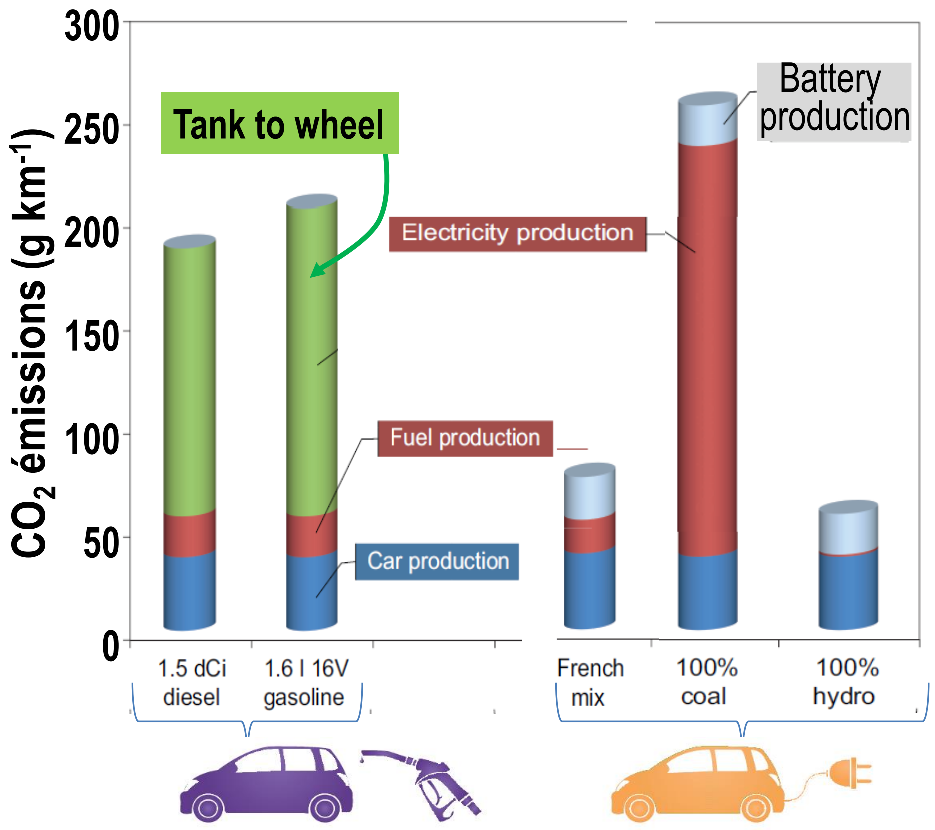
FONDATION INTERNATIONALE BALZAN 1956

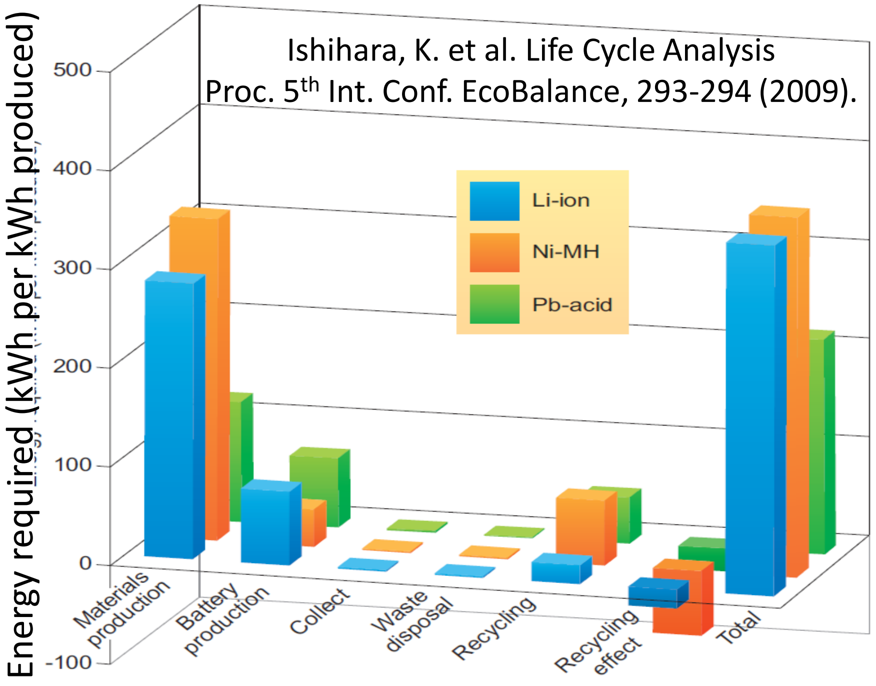
Are electric vehicles the best solution for a low CO2 footprint ?

Importance of primary energy source



Energy from thermal power plans : NO

Life cycle analysis cost



- Assembing of a battery of 1kWh

✓ Energy needed ≈ **327 kWh**
✓ CO_2 rejected ≈ **90 kg**