# *Introduction to techno-economics of PEM fuel cells and li-on battery technologies for mobility purposes*

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# PEM Fuel Cell technology

# Fuel cell principles

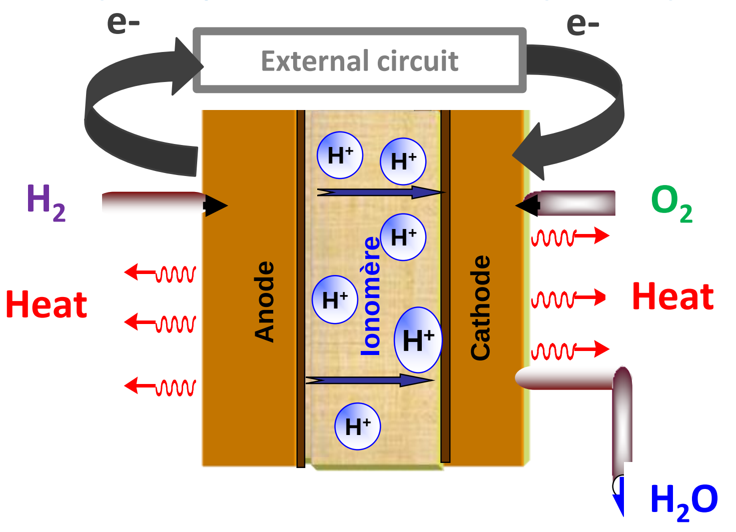
**Fuel Cell converts the chemical energy contained in a fuel into electrical energy.**

- As all electrochemical devices, a **Fuel cell is composed by two electrodes (anode and cathode) separated by an electrolyte**.
- **Between the two electrodes, ions pass through the electrolyte** (ionic conductor and electronic insulator).
- **Fuel cell** is an **open electrochemical generator (batteries = closed systems)**
    - Energy (storage) and power (FC size) are totally dissociated contrary to batteries
    - Suitable for stationary, transportation and mobile applications

***Example of PEM Fuel Cell principle***

**Anode is fed with the fuel**
**Hydrogen Oxidation Reaction (HOR)**

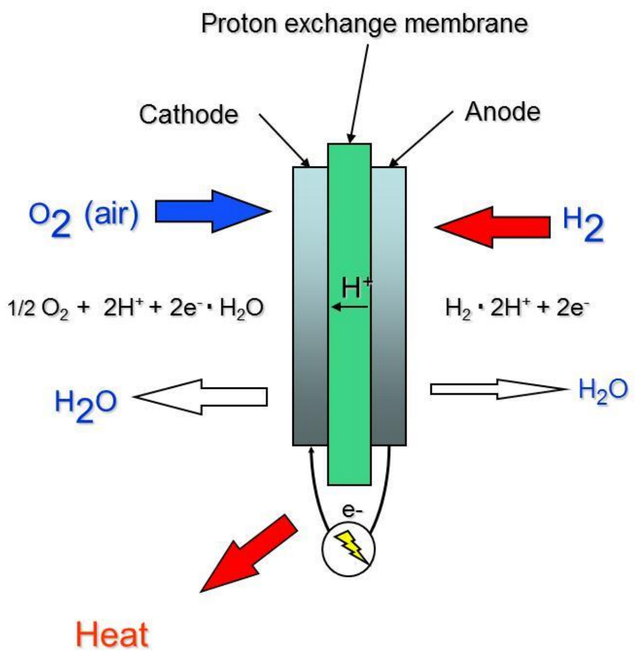
$H_2 \rightarrow 2H^+ + 2e^-$




**Cathode is fed with the comburant**
**Oxygen Reduction Reaction (ORR)**

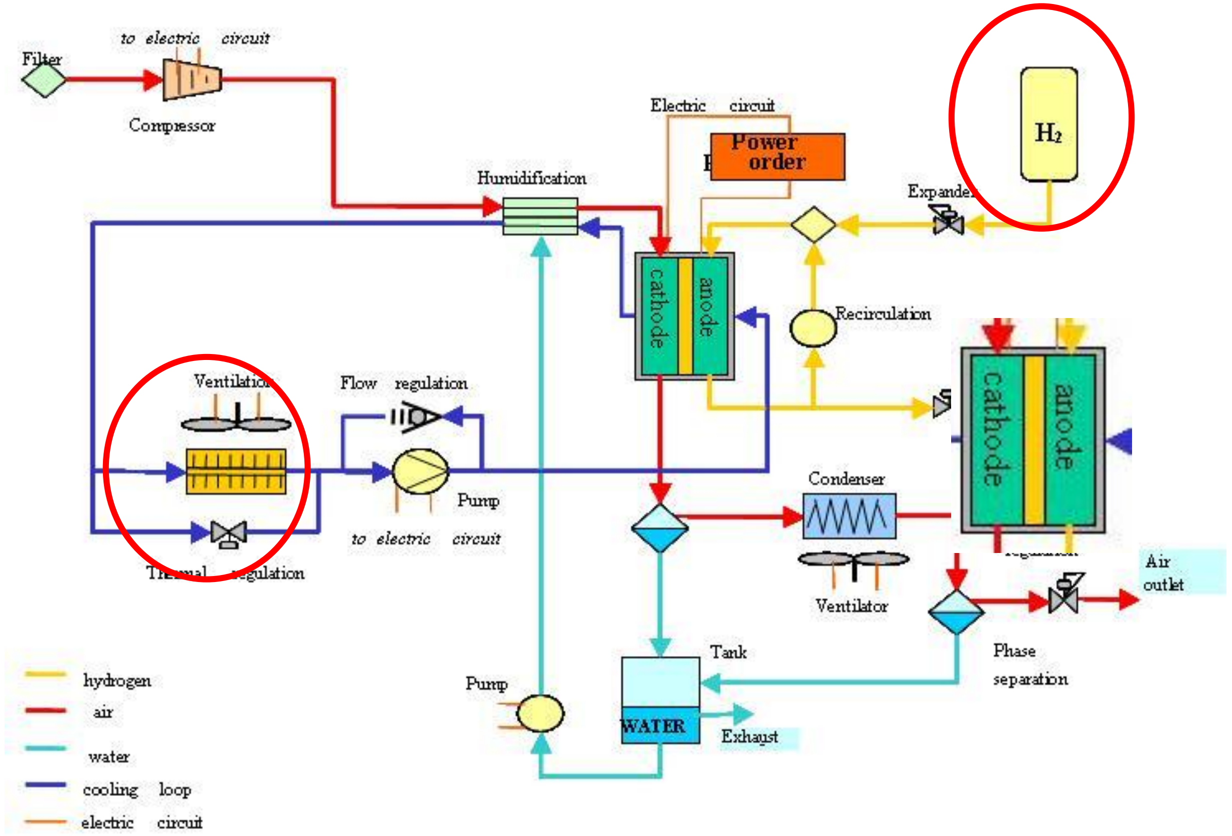
$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightarrow H_2O$

| | **PEMFC : Proton Exchange Membrane Fuel Cell** |
|---|---|
| **Electrolyte** | Membrane perfluoro-sulfonée<br>(PFSA) |
| **Electrode** | Platine sur particules de carbone (0,3 mg/cm²) |
| **Inter-connecteur** | Carbone ou métallique |
| **Operating température** | Ambient – 80°C |
| **Charge carrier** | $H^+$ |
| **Fuel** | $H_2$ |
| **Poison** | CO, $H_2S$ |
| **Ordre de grandeur** | 1W/cm² densité de puissance<br>100 kW stack 30 g de platine |




*Toyota Mirai – PEMFC 114 kW*

# Un système pile fonctionne avec un système



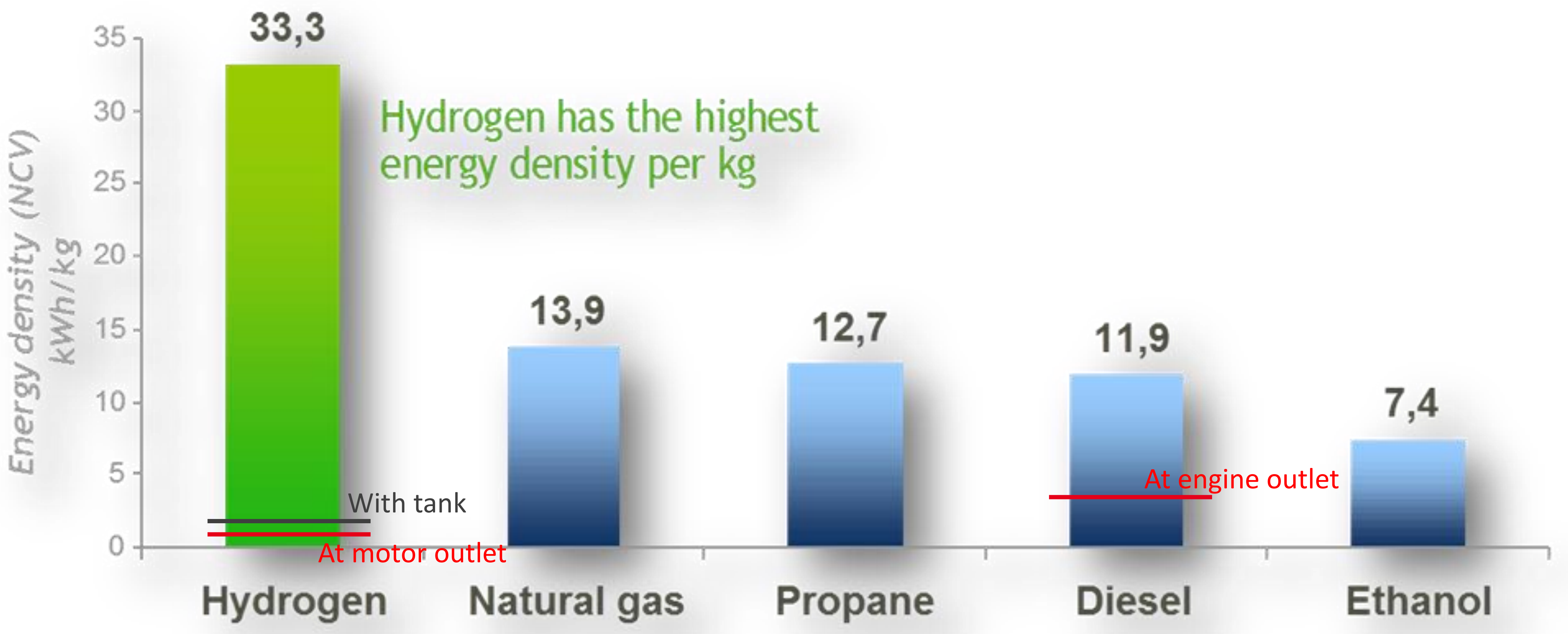

The system assures

- The right gas pressures
- The right water content
- Heat evacuation (40% more than ICE)
- Best voltage/current levels
- H2 storage

A fuel cell never works alone
(hybridation with batteries)

# Hydrogen as energy vector

- 1 kg hydrogen ~ 100 km drive ~ 25 litres at 700 bars

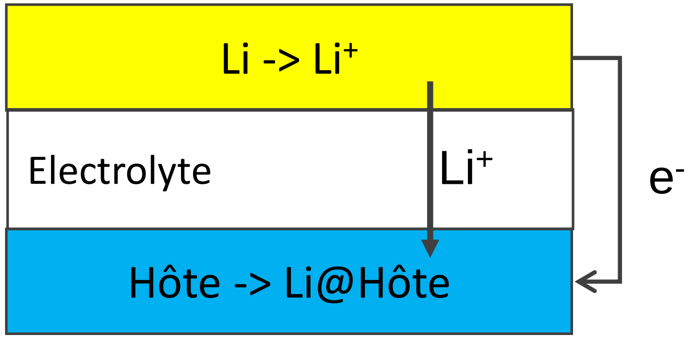


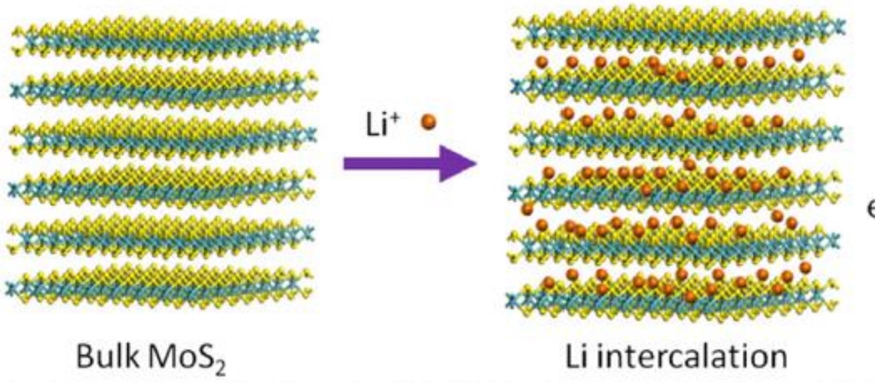
# Li-ion Battery technology

# Li-ion batteries

- Metallic lithium batteries :
  Wittingham, 1976
  Hôte = $MoS_2$ ou $TiS_2$

- **Developed by Moli Energy in the 1980s**
  Up to 100Wh/kg
  (>3 times better than lead-acid)

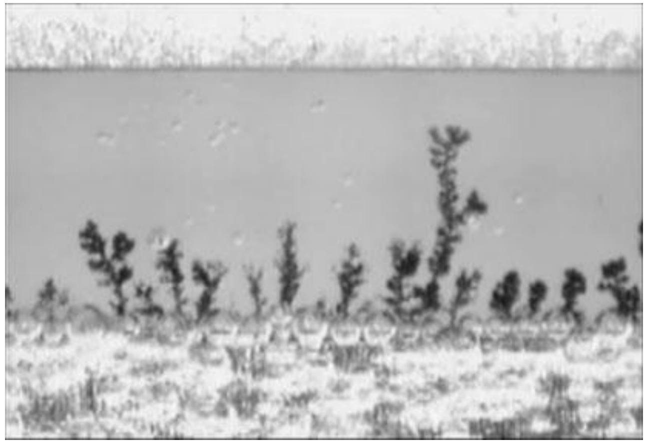


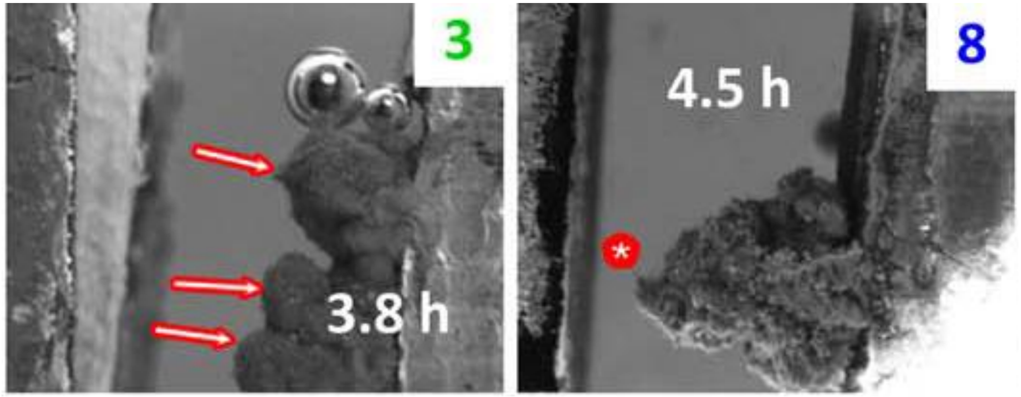




J. Electrochem. Soc. **2017**volume 164, issue 1, **A5019-A5025**

## Dendrites problem

- Redeposition of metallic lithium during recharge

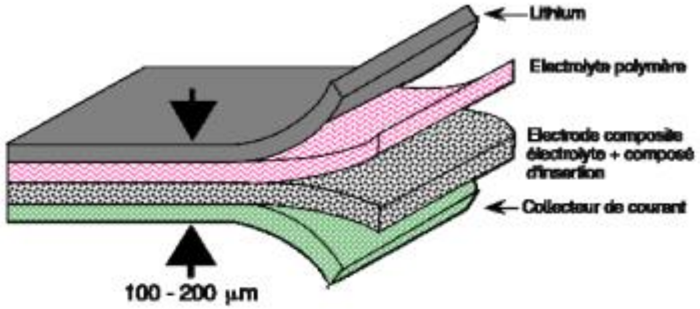





- Risk of short circuit : explosions, portable phones fires (already!)
- Stopped in 1989.

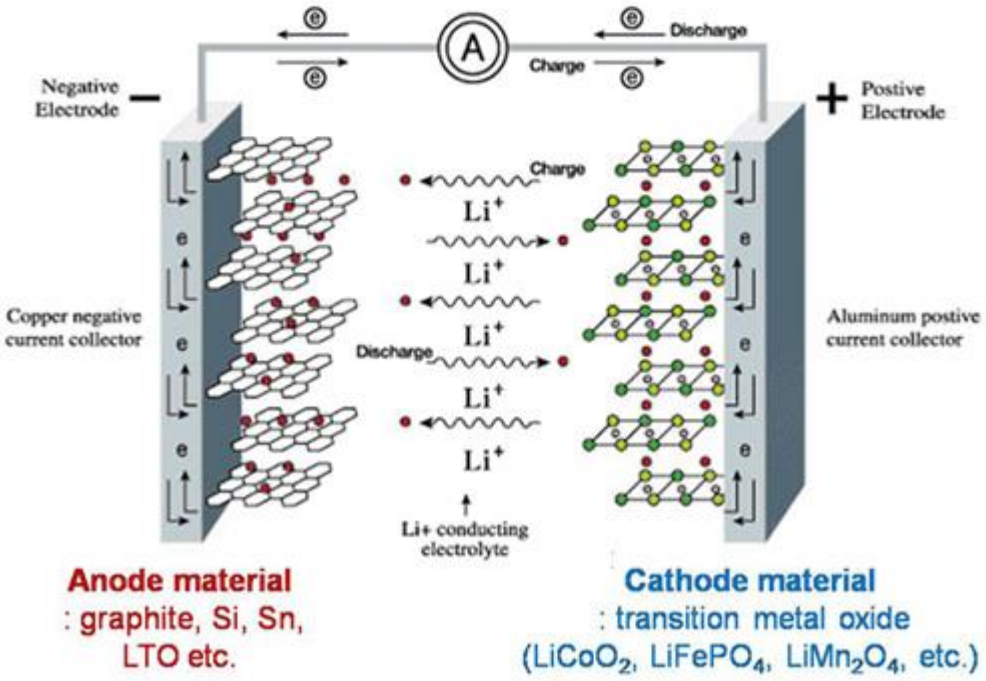
**Solution 1.**
**Keep metllic lithium behind a solid barrier (Solid-State Battery)**

- Ex. Blue Car – Autolib
  Difficult to find a material with good conduction even at ambiant temperature
  ~80°C for Blue Car




**Solution 2.**
**Store lithium in non metallic form**
**= Li-ion or ‘rocking-chair battery’**

Goodenough (1980), commercialized by Sony in 1991
Most often graphite (now with a bit of silicon) at negative electrode




## What is a good battery ?

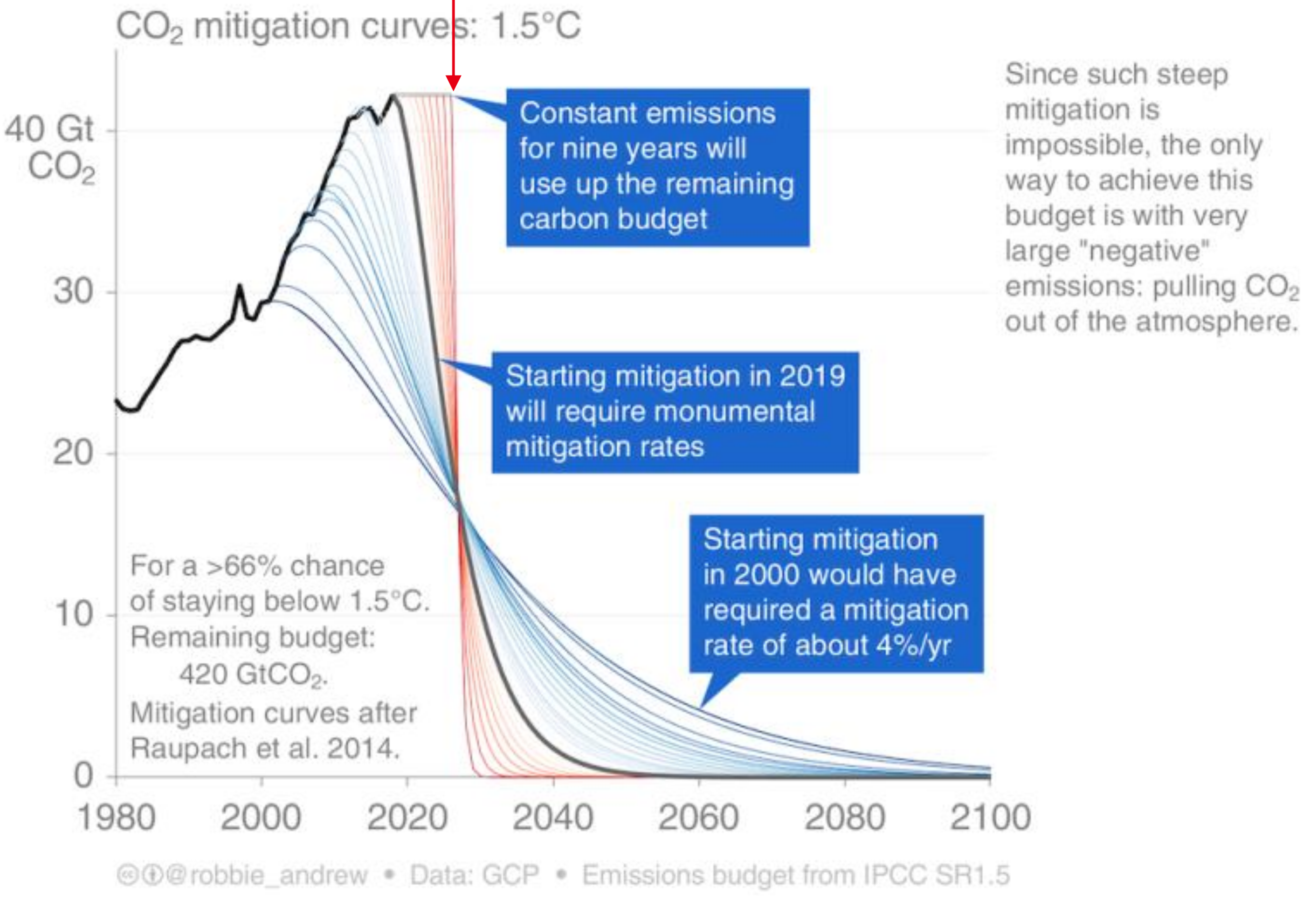
- Performances
  - Energy and power density
  - Round Trip efficiency
  - Lifetime (cycles & calendar)
- Operating conditions
  - Temperatures, …
- Deployment potential
  - Availability of materials
- Cost and externalities
  - Cost
  - Security
  - $CO_2$, resource use,…

We always have to perform trade-offs between these criteria

# Transport decarbonation

# CO2 BUDGET

Budget carbone pour 1.5°C épuisé en **2028**



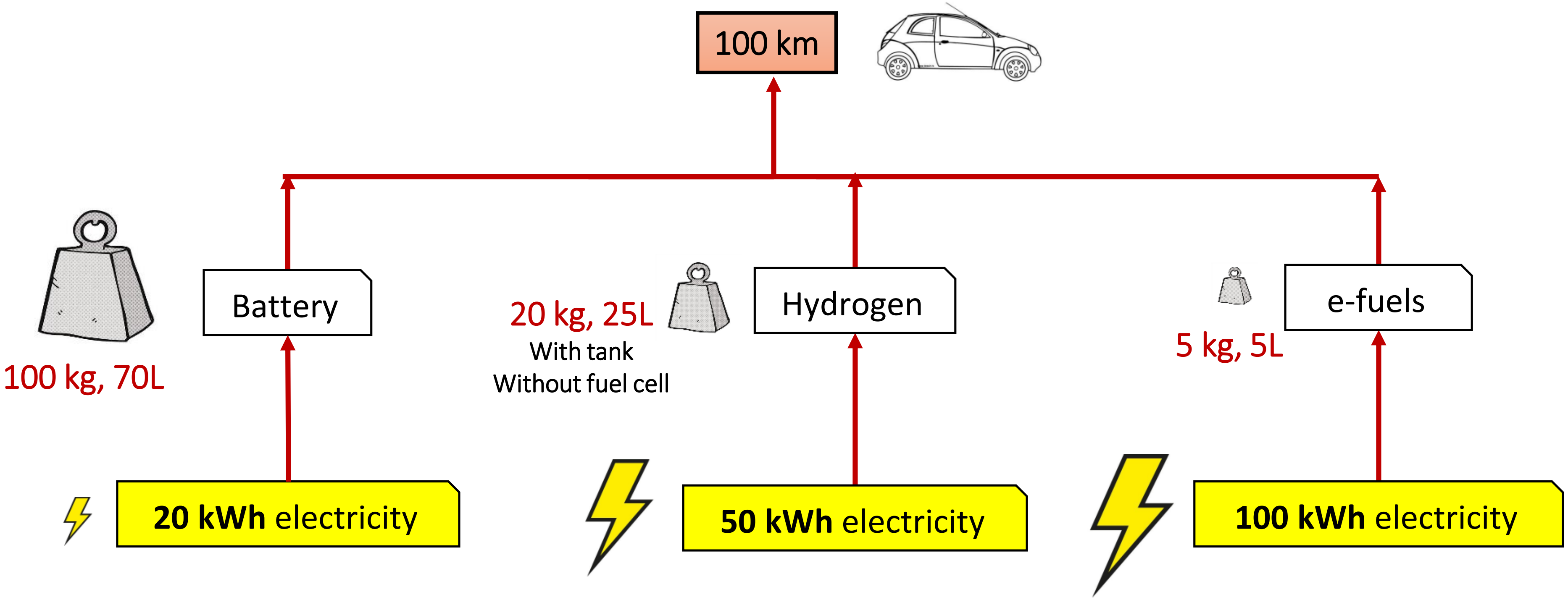
# REDUCING THE DEMAND

- Reduce distances
- Reduce the number of vehicles
  - Public transport
  - Pay for use rather than possession
  - Mass reduction
  - Soft mobility
  - Smaller vehicles and smaller batteries
- Vehicle load factor
  - Carpooling
  - Flexible delivery delays
- Slower speed and less power

conso /30
batterie /100

Thèse Aurélien Bigo : http://www.chair-energy-prosperity.org/wp-content/uploads/2019/01/These-Aurelien-Bigo.pdf

# AUTONOMY VS EFFICIENCY

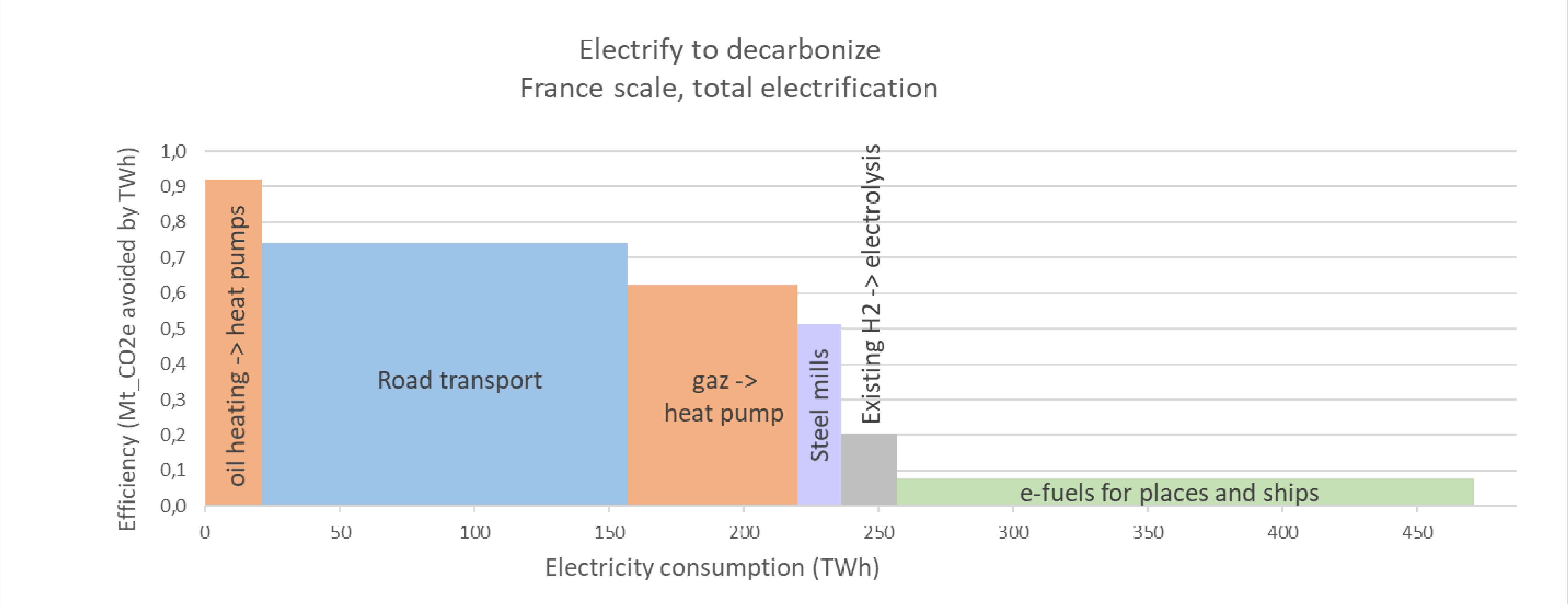



Tradeoff between autonomy and efficiency
e.g. : if heavy transport in H2 : 160 TWh/an -> 215 TWh/an

**H2 and e-fuels should be used where direct electrification is not possible**

Calculs : F. Perdu 2021

# ELECTRIFY TO DECARBORNIZE




Current French electricity consumption = 480 TWh

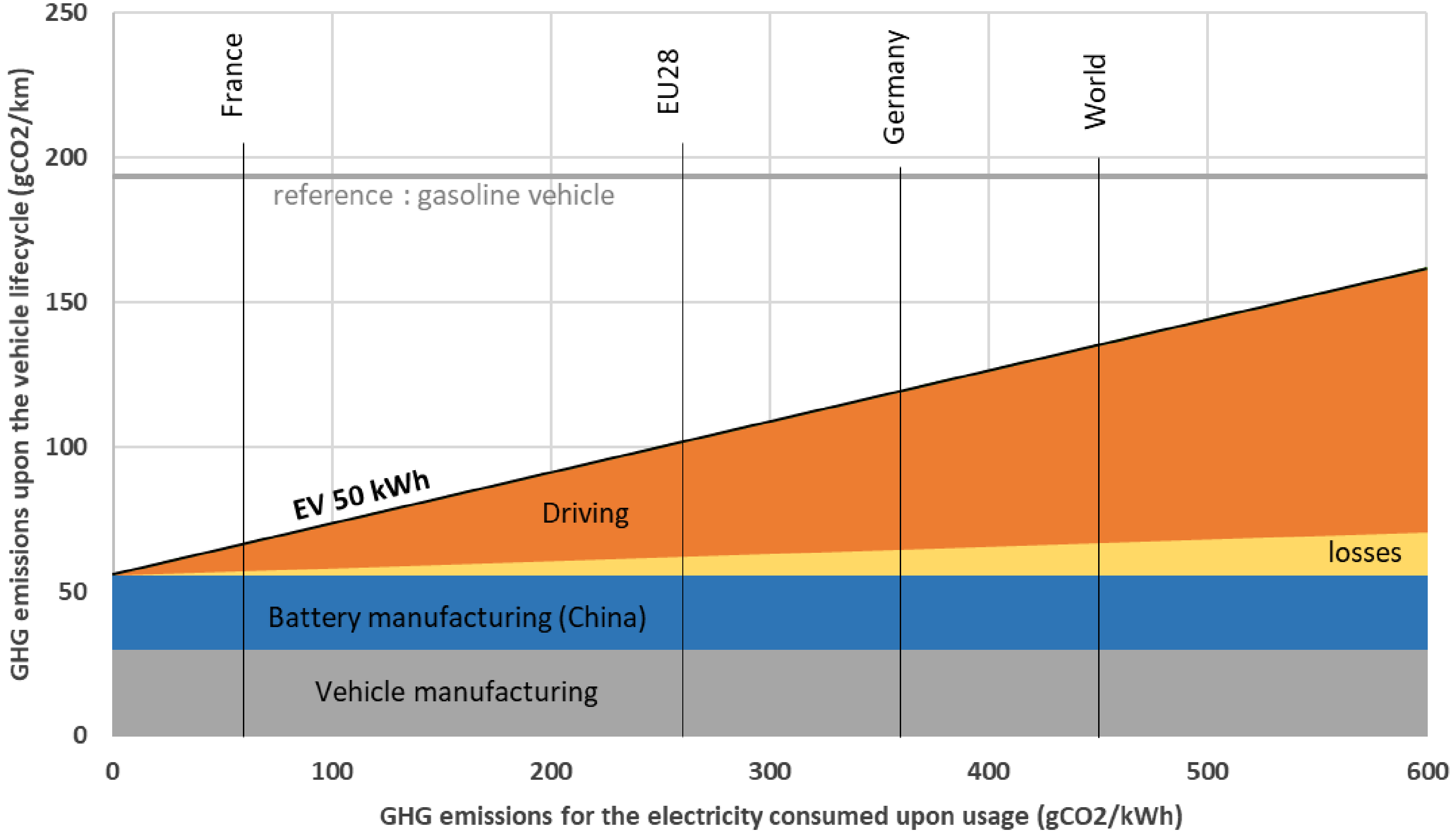
# ■ Li-ion Battery LCA

# Objective

Minimize the ratio

$$\frac{\text{Environmental impacts}}{\text{Service provided}}$$

# BATTERIES – GLOBAL WARMING POTENTIAL




**~3 times less GWP over the lifetime <u>in France</u>**

Batteries as more interesting when
- Electricity is low carbon
- The vehicle is heavily used
- The battery is small

# How to decrease carbon footprint ?

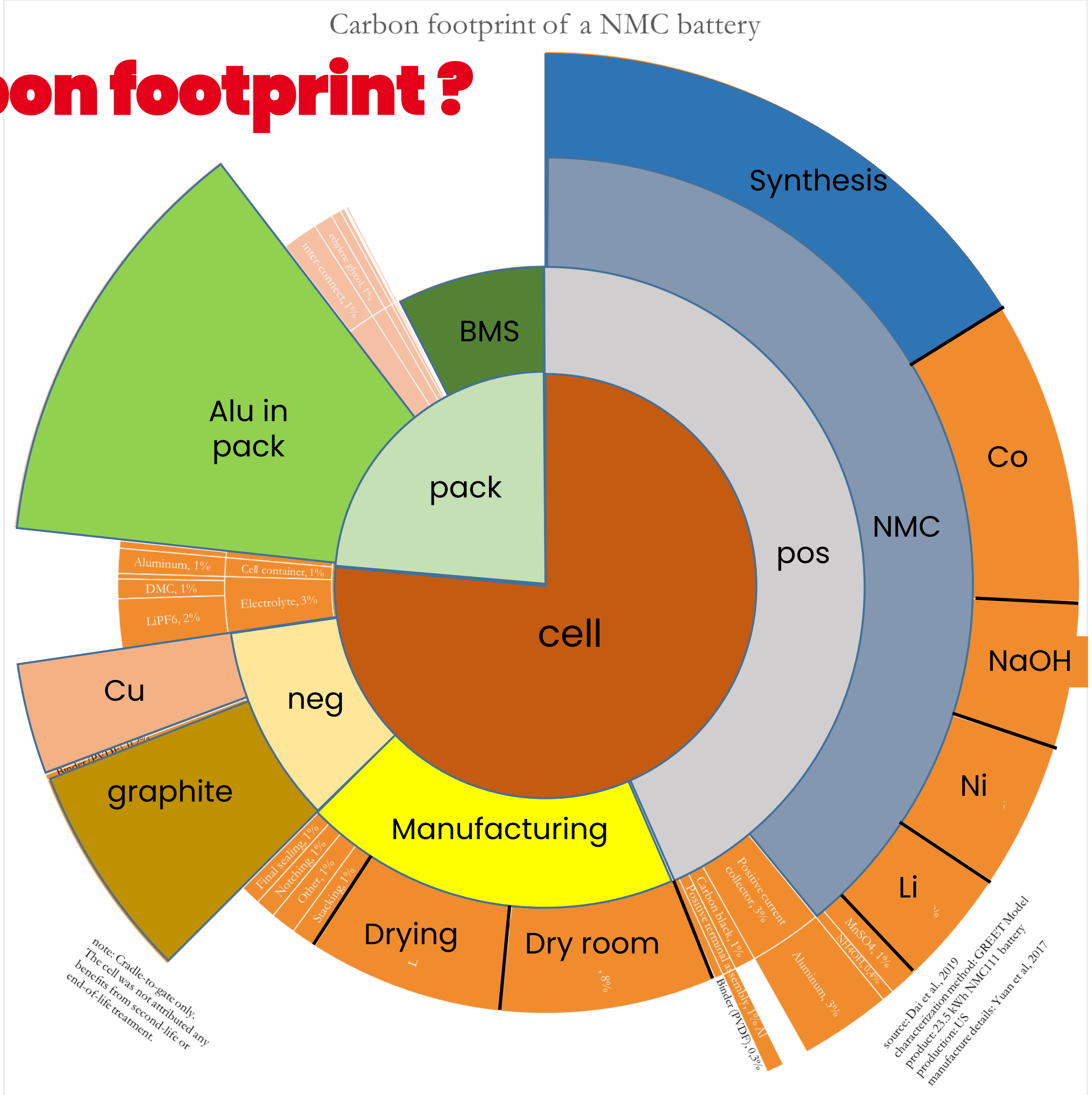
**R&D**

- New materials
- Synthesis using less energy
- Process without solvents

**Industry**

- Upscale processes (done)
- Low carbon electricity for
  - Gigafactory
  - Material synthesis
  - Aliminum
- Choose low carbon material providers

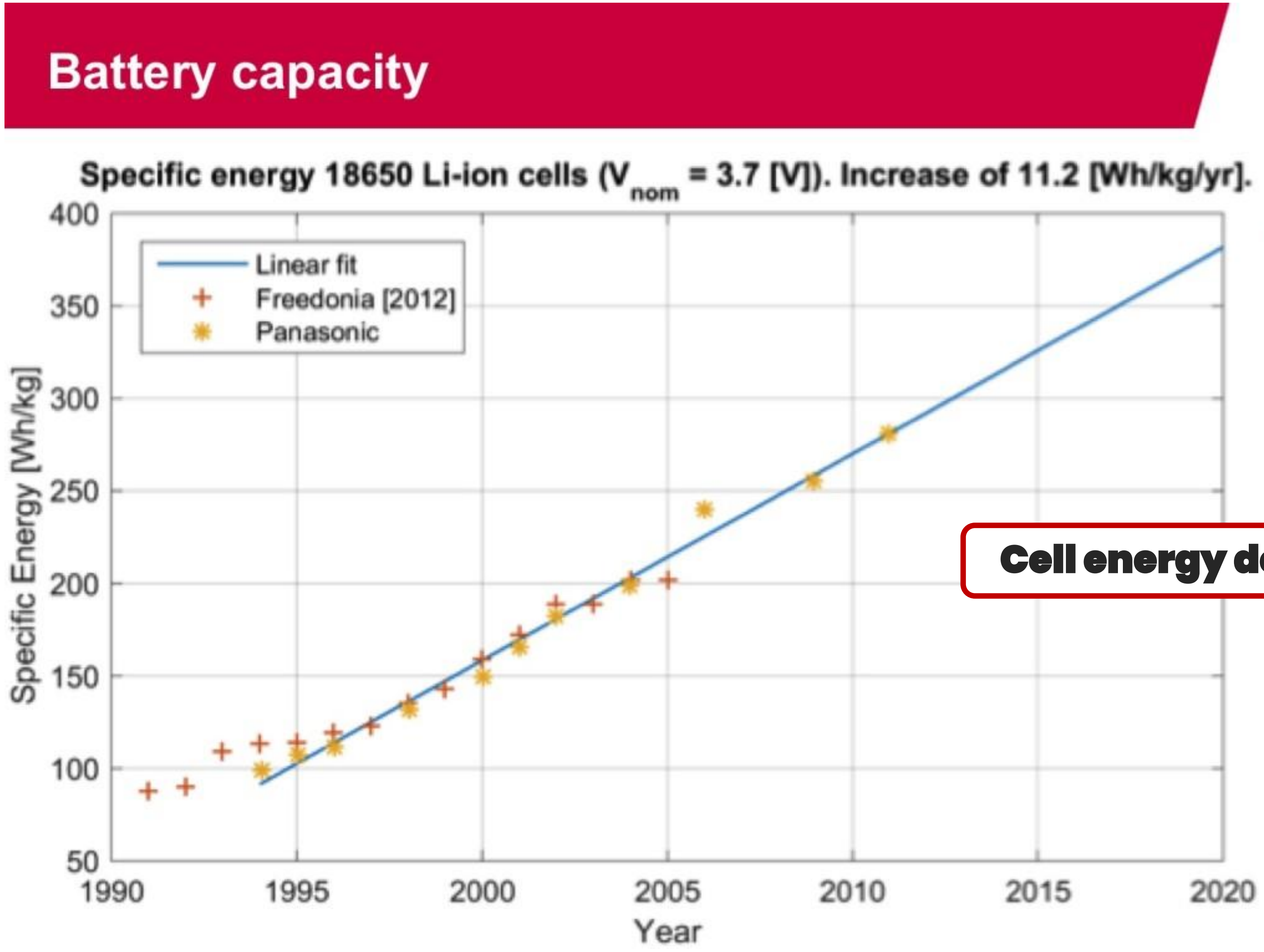
**Objective /2 or /3**




Inspiré d'un travail du DTNM pou Hydra (F. Blondin et E. Monnier)

cea

# BATTERIES – PROSPECTIVE




Prof Maarten Steinbuch, Director Graduate Program Automotive Systems, Eindhoven University of Technology

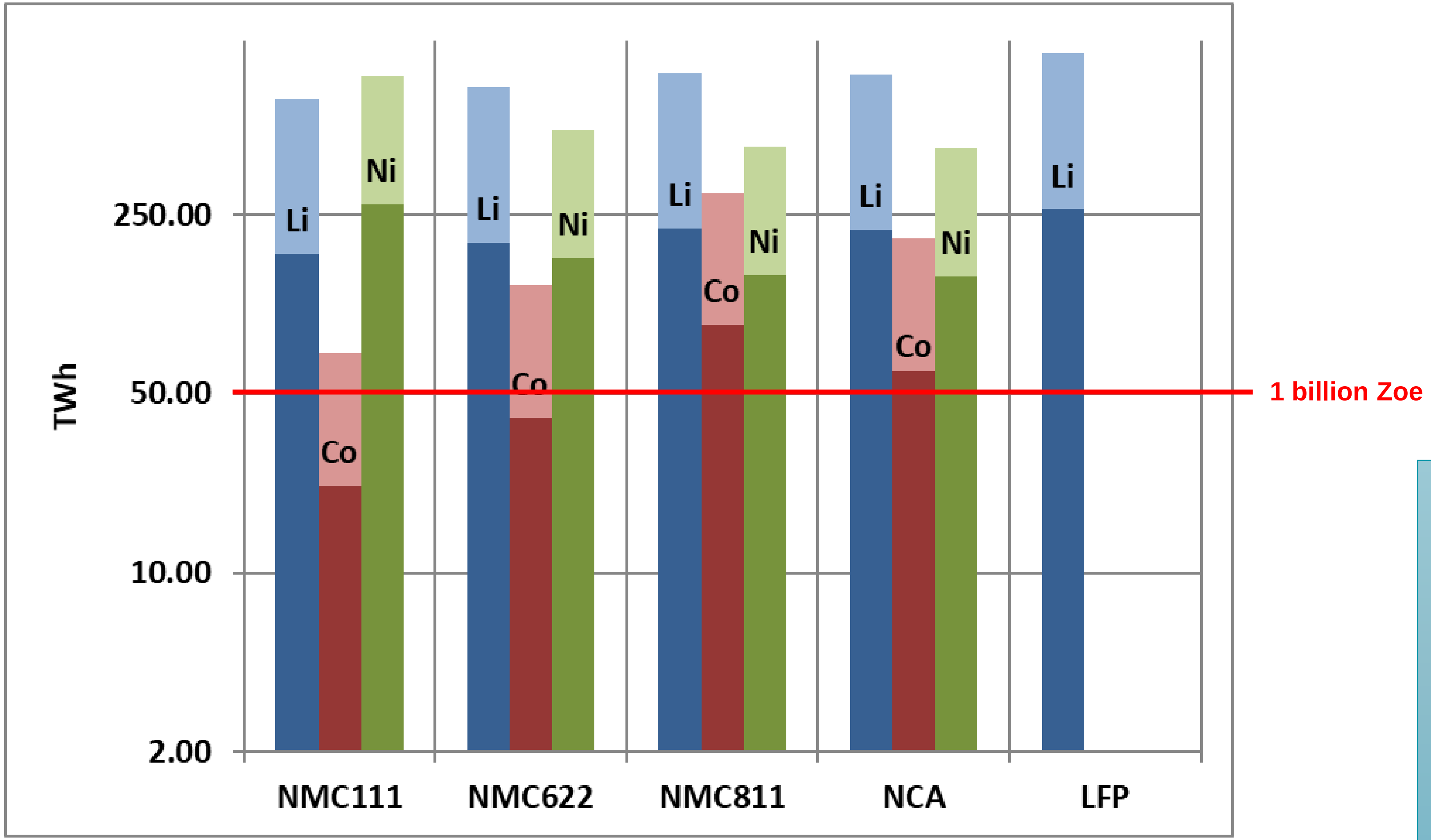
★ 2024

**Cell energy density no longer improves**

Other improvements :

- Lifetime
- Cost
- Pack density

# BATTERY MATERIALS : A STOCK PROBLEM



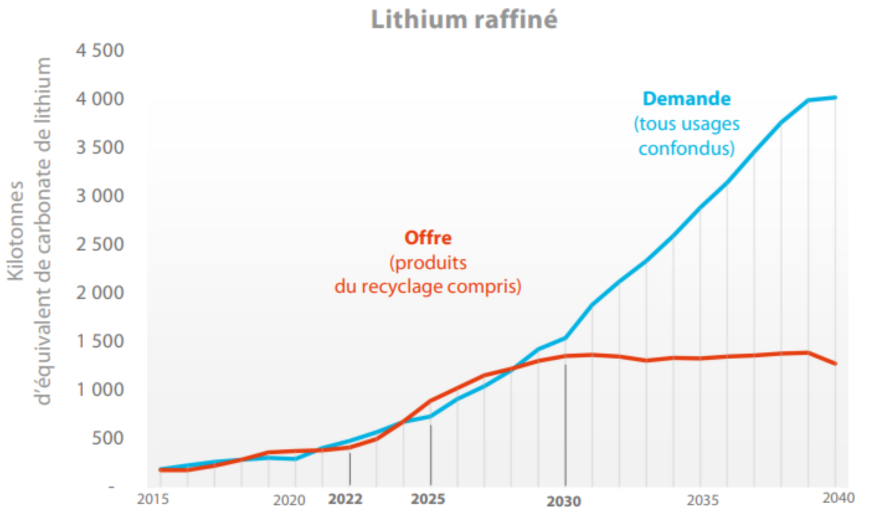

CEA, F. Perdu & A. Marie, using USGS 2022 reserves (dark colors) and resources (light colors)

Reduction or substitution of
1. Cobalt
2. Nickel
3. Lithium

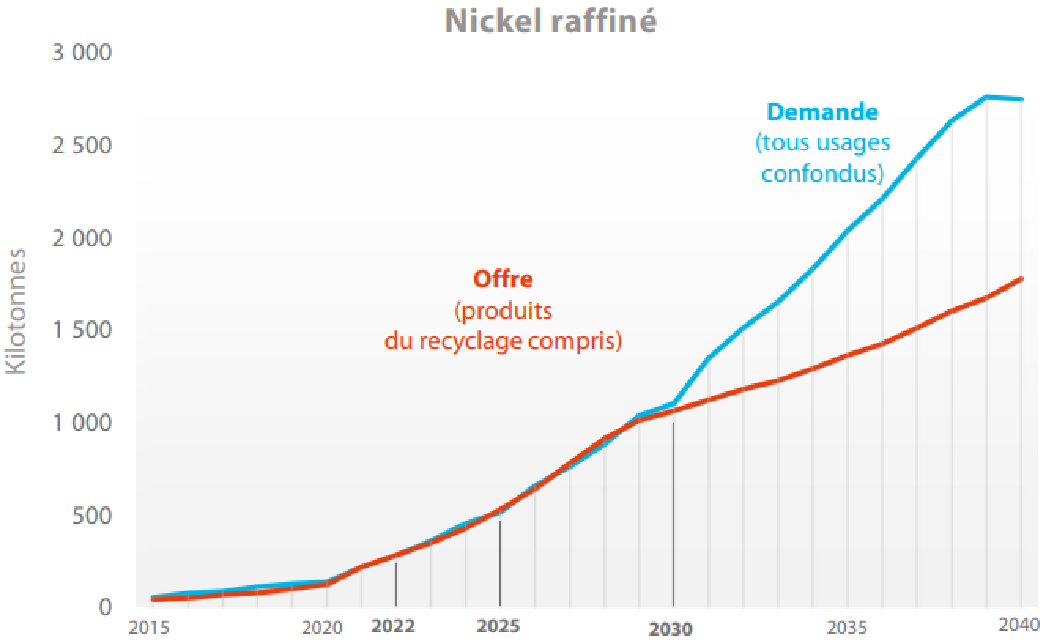
Strong R&D to find alternative chemistries : Na-ion, Li-S…

Keeping in mind
- Energy density
- Lifetime (cal + cycl)

# BATTERY MATERIALS : A FLOW PROBLEM




*Source*: Analyse des difficultés liées aux chaînes d'approvisionnement pour les batteries réalisée par le Centre commun de recherche sur la base d'un scénario de demande moyennement élevée de carbonate de lithium et de nickel raffiné. Afin de tenir compte de l'incertitude inhérente aux prévisions à long terme, des scénarios selon lesquels la demande et l'offre sont élevées ou faibles ont également été pris en considération pour la réalisation de l'analyse complète.




European Court of Auditors, 2023 : **lithium** and **nickel** deficit since 2030.
We need 5 to 20 years to open a mine !

Nickel structural deficit in 2027 (Roskill 2021) or even 2024 (Rystad Energy 2021)

**The mine industry is unable to follow the battery industry (x10 every 10 years). Recycling is only a solution in the long term, when market has stabilized.**

# BATTERIES - SUMMARY

Low life cycle $CO_2$ but concentrated on production phase
Use limitations (autonomy / recharge)
Materials limitations

⇒ Do not oversize the battery, and use it intensively

Perfect on short distances
**Complement to be found for long distances**

- **Long distances ?**

# ELECTRIC ROAD SYSTEM (ERS)

**Bring the electricity to the vehicle while driving**

- **Main roads would be equipped**
- **A small battery for beginning and end of trips**
- **No more fast charge !**

Caténaires (Siemens)

Rails au sol (Alstom, Elonroad, Evias)


Induction (Electreon, IPT, OLEV, Wipower One)

plus mature ← → moins mature

Source : https://www.ecologie.gouv.fr/sites/default/files/GT1%20rapport%20final.pdf

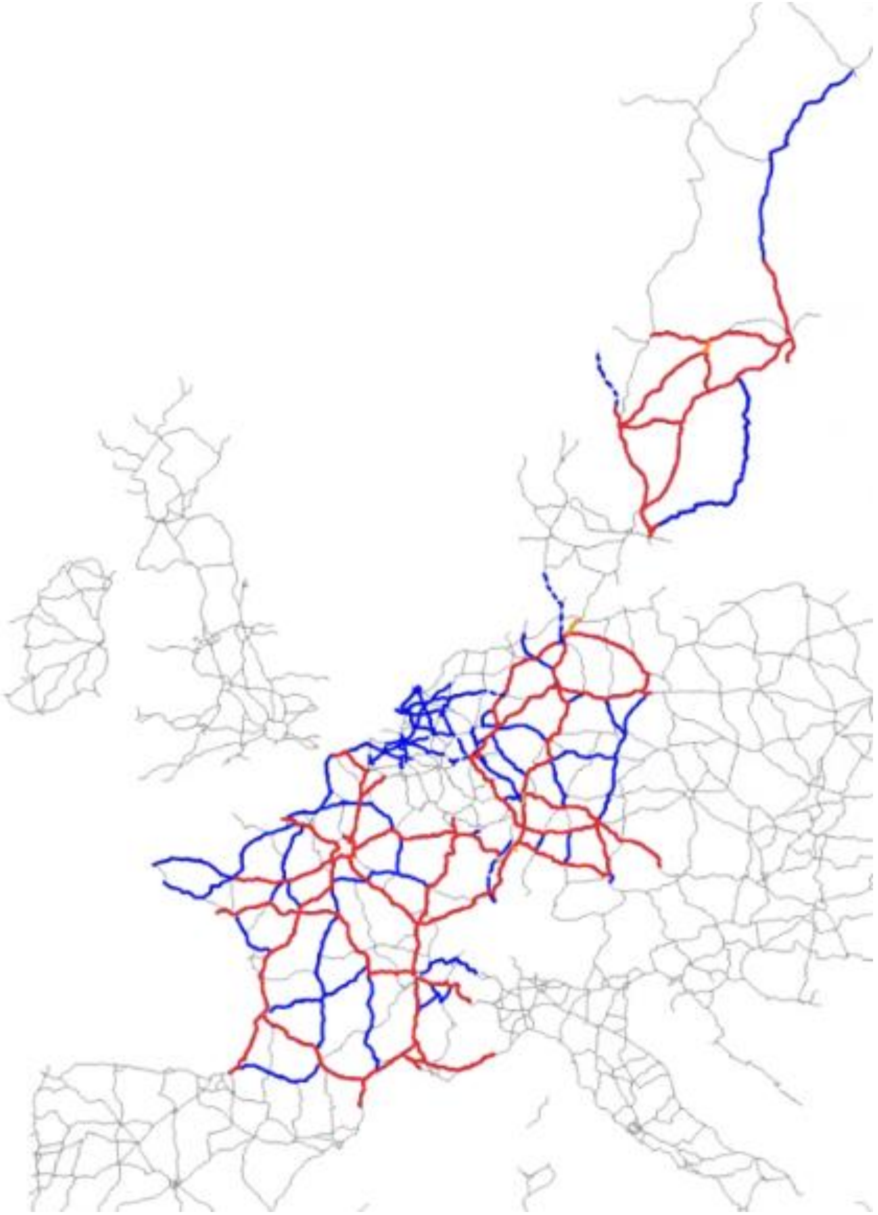
# ROUTE ÉLECTRIQUE

**Several countries are considering the solution**

**3 demo projects launched in France**

**Could allow /3 in global battery size**

**Cost-effective**
**but requires large upfront investment**



Source : https://www.ecologie.gouv.fr/sites/default/files/GT1%20rapport%20final.pdf

# ■ Conclusion

# SUMMARY ON ROAD DECARBONIZATION

No solution is at the same time :

- Really low carbon
- Available soon
- Deployable at large scale

The right combination should be found, including demand reduction

| | CO2 emissions | Available in 10 years ? | Available at large scale ? |
|---|---|---|---|
| Diesel | | | |
| Fossile gas | | | |
| Biofuels and biogas | | | |
| Batteries | | | |
| $H_2$ from electrolysis | | | |
| Electric road | | | |

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