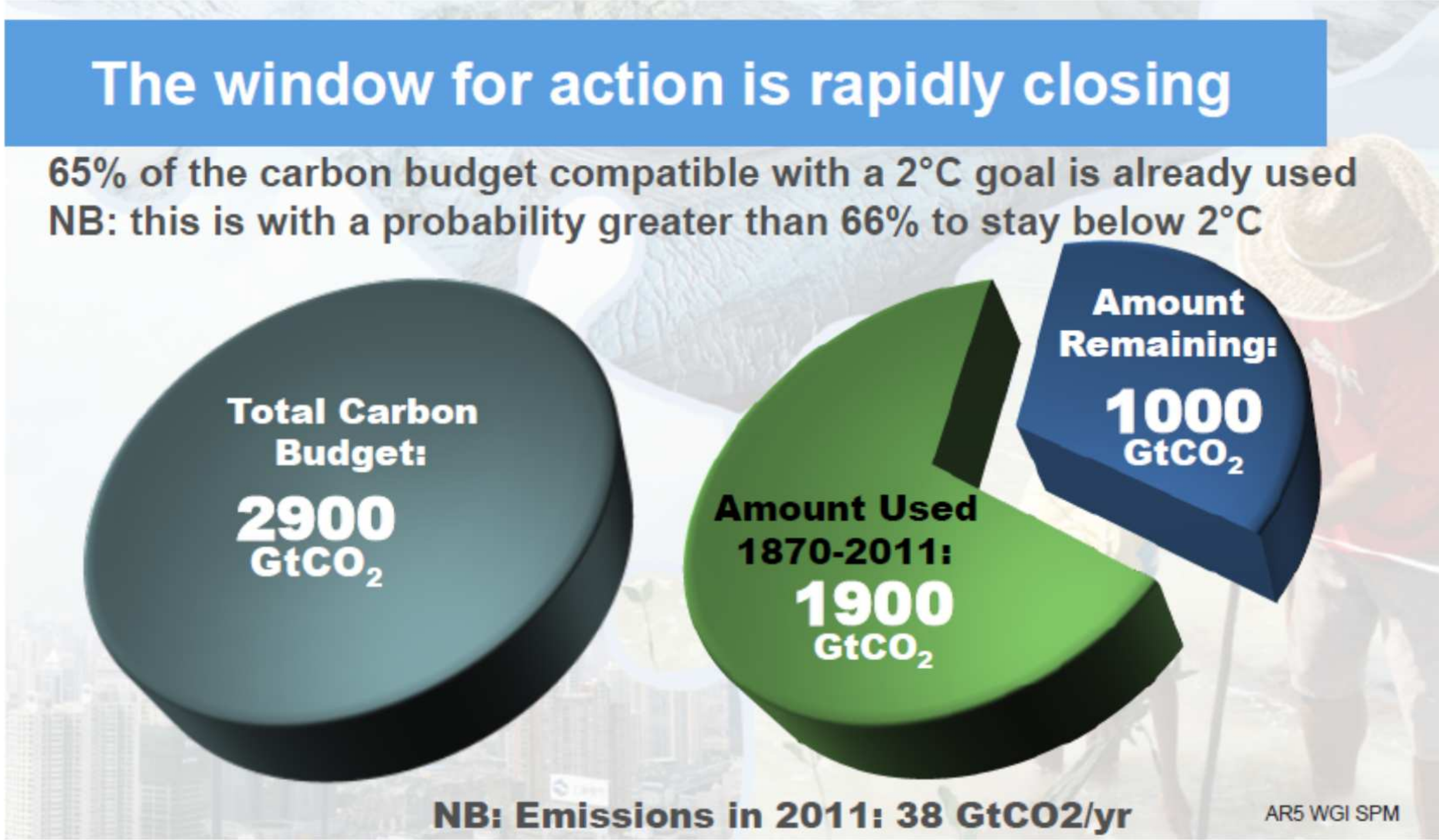
BATTERIES : ENERGY AND MATTER ISSUES FOR RENEWABLES AND ELECTRIC MOBILITY

Fabien Perdu

1. **Context**
2. **Batteries : the size of the problem**
3. **Battery essential parameters**
4. **Material availability**
5. **Impact of battery production**
6. **From battery production to EROI**
7. **Some comparisons**
8. **Conclusion**
9. **Battery ID cards**

CONTEXT 1: COP21



The window for action is rapidly closing

65% of the carbon budget compatible with a 2°C goal is already used
NB: this is with a probability greater than 66% to stay below 2°C

Total Carbon Budget: **2900** $GtCO_2$

Amount Used 1870-2011: **1900** $GtCO_2$

Amount Remaining: **1000** $GtCO_2$

NB: Emissions in 2011: 38 GtCO2/yr

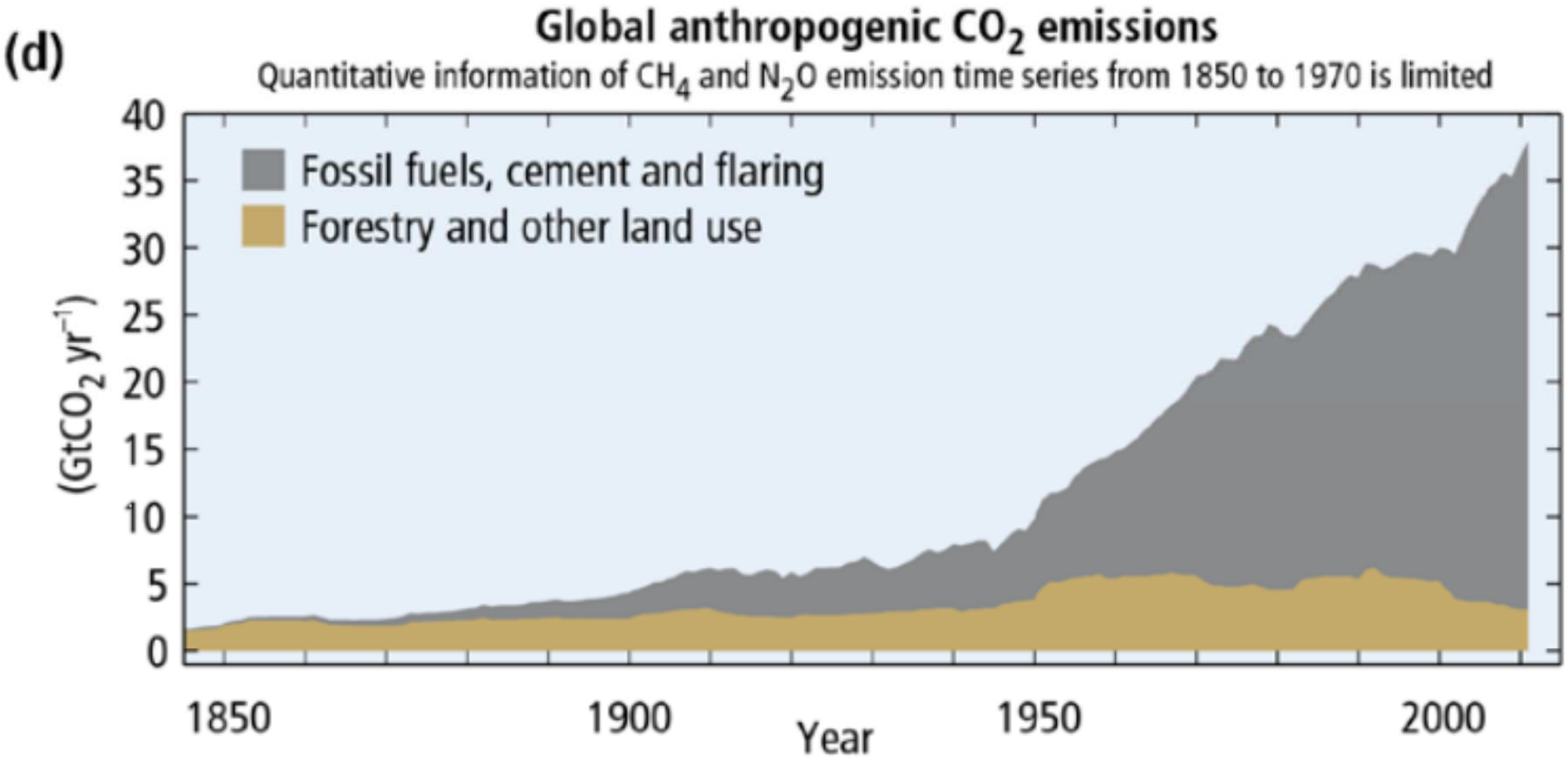
AR5 WGI SPM

JP van Ypersele
Former IPCC vice-chair

Reserves are far above the threshold
(2734Gt in proved reserves, Heedea & Oreskesa 2016).
At current rate the budget will be spent before 2040.

CONTEXT 1: COP21

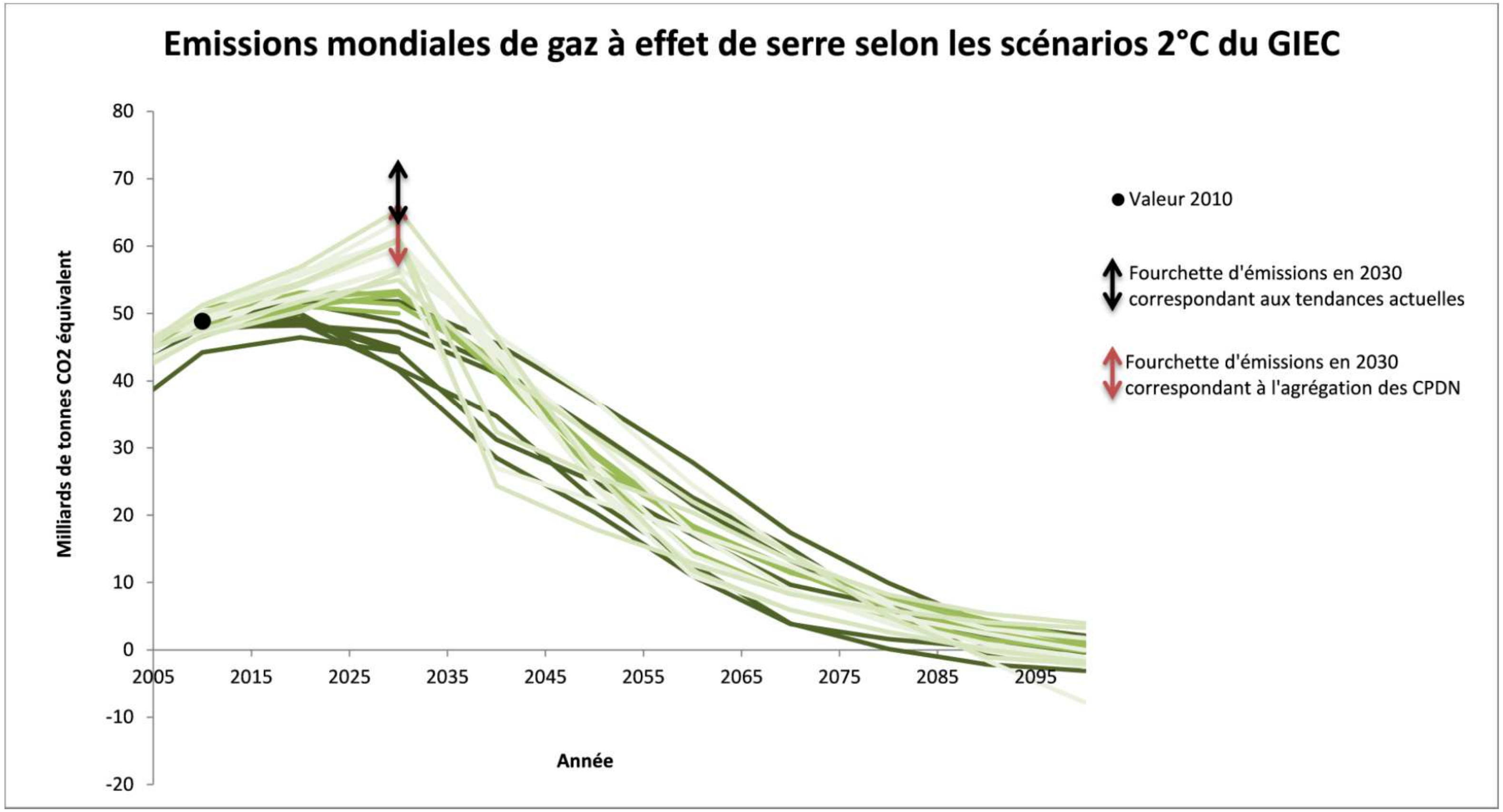
Fossile fuels are the main contributors



Source : IPCC, AR5, 2014

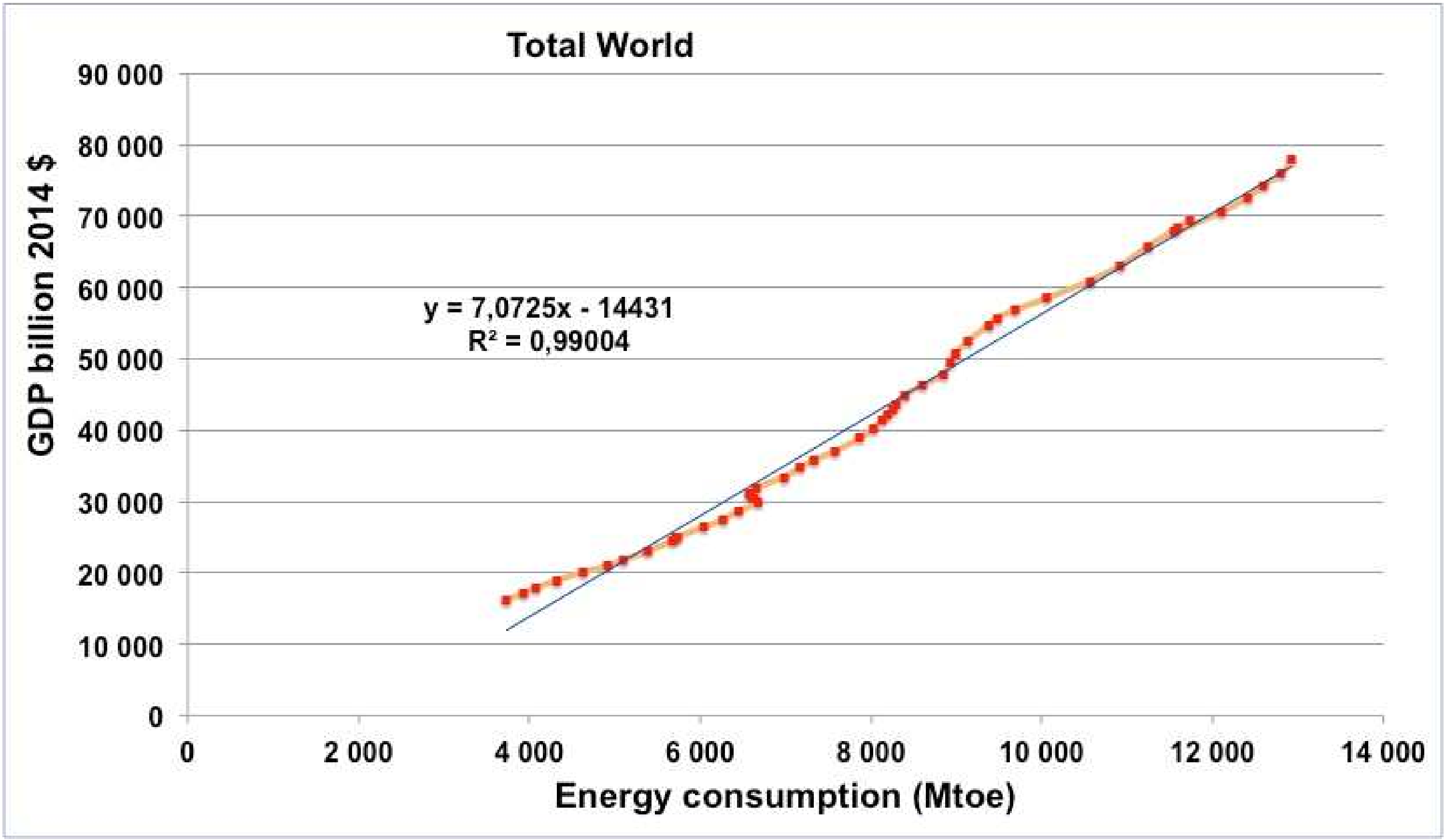
CONTEXT 1: COP21

Emission pathways compatible with 2℃ show a strong and fast decrease



Source : IPCC, AR5, SPM, 2014 ; GICN, 2015,
Courtesy of O. Boucher and H. Benveniste

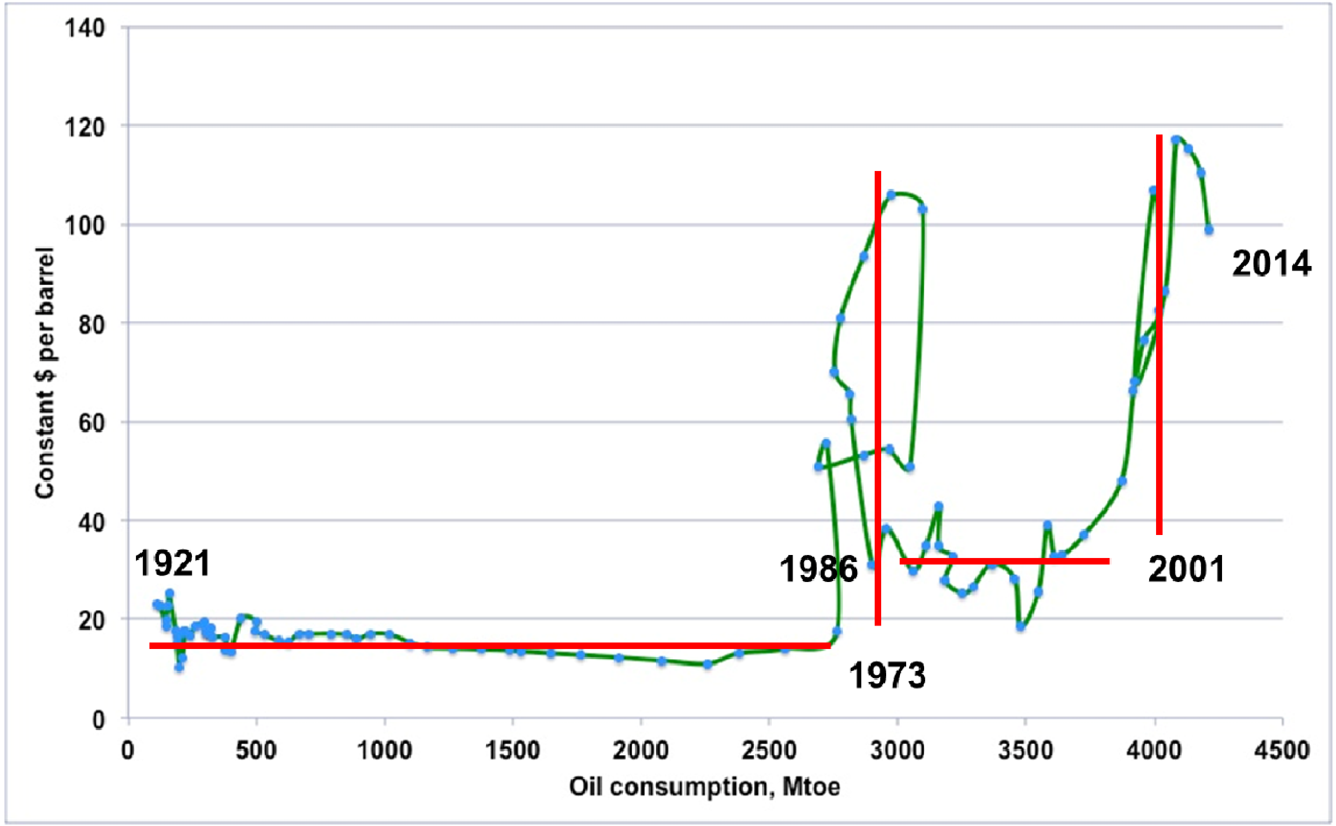
CONTEXT 2: ENERGY IS THE FUEL OF ECONOMY



From 1965 to 2014. JM Jancovici, source World Bank 2014 for the GDP, BP Statistical Review 2014 for energy

Fits much better than « land, labor and capital »

CONTEXT 2: ENERGY IS THE FUEL OF ECONOMY



Jancovici, 2014, on various data (oil prices from BP Stat).

We are dependant on energy :
the demand is insensitive to price

WHICH SUSTAINABLE ENERGY SCENARIO ?

Criteria :

1. **Climate friendly, quickly get rid of fossile fuels**
2. **No other environmental consequences**
3. **Can be deployed quickly and at the right order of magnitude**
4. **Can be maintained ’a certain time’ (100 years?)**

Analysis must include all that is needed to maintain the mix :

upstream : material industry, transportation,…

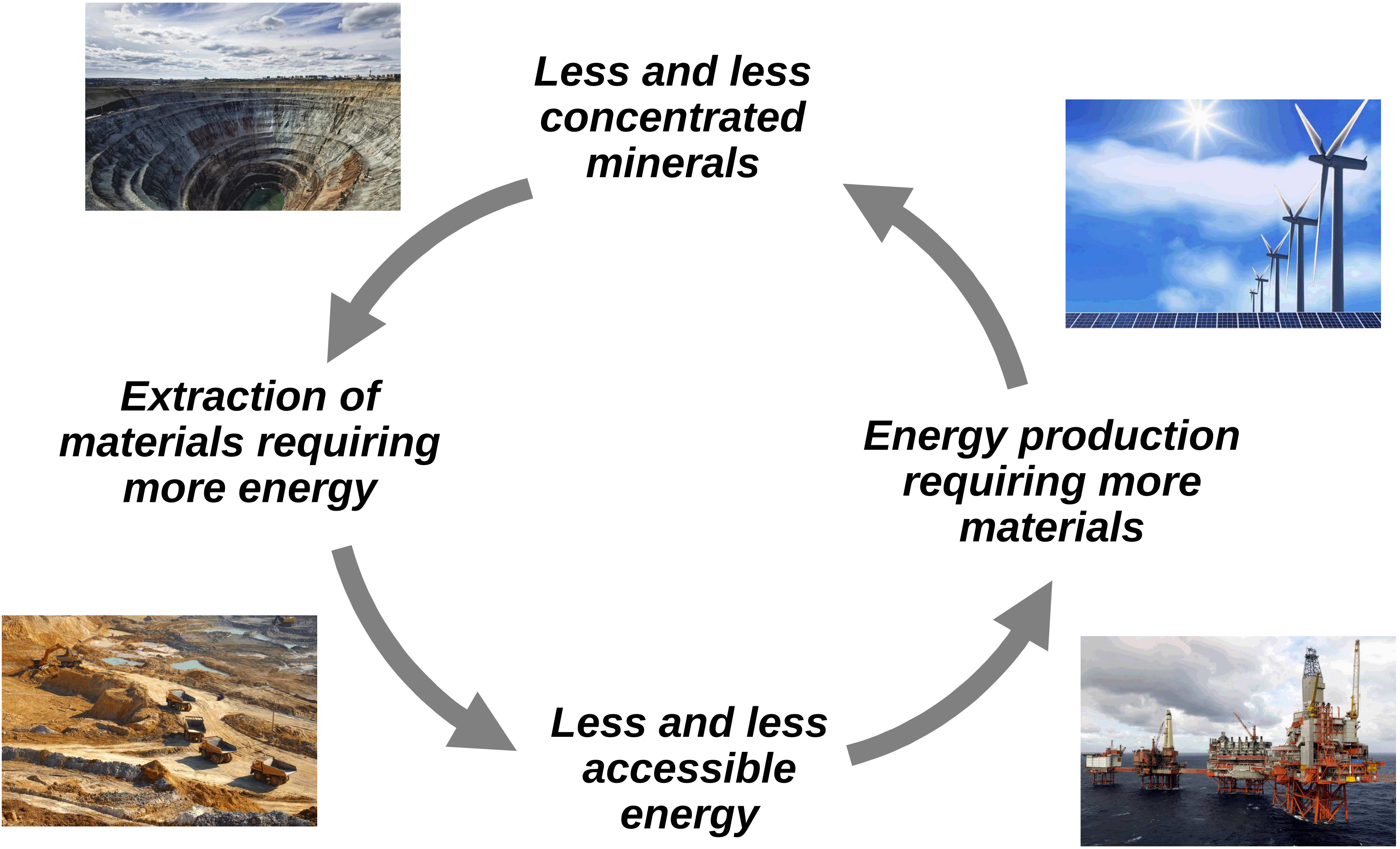
downstream : storage, networks,…

***At least* consider matter and energy needs**

Beware of beliefs on what is ‘unlimited’, ‘free’, or ‘clean’

MATTER AND ENERGY NEXUS

Source : Philippe Bihouix



Less and less concentrated minerals

Extraction of materials requiring more energy

Less and less accessible energy

Energy production requiring more materials

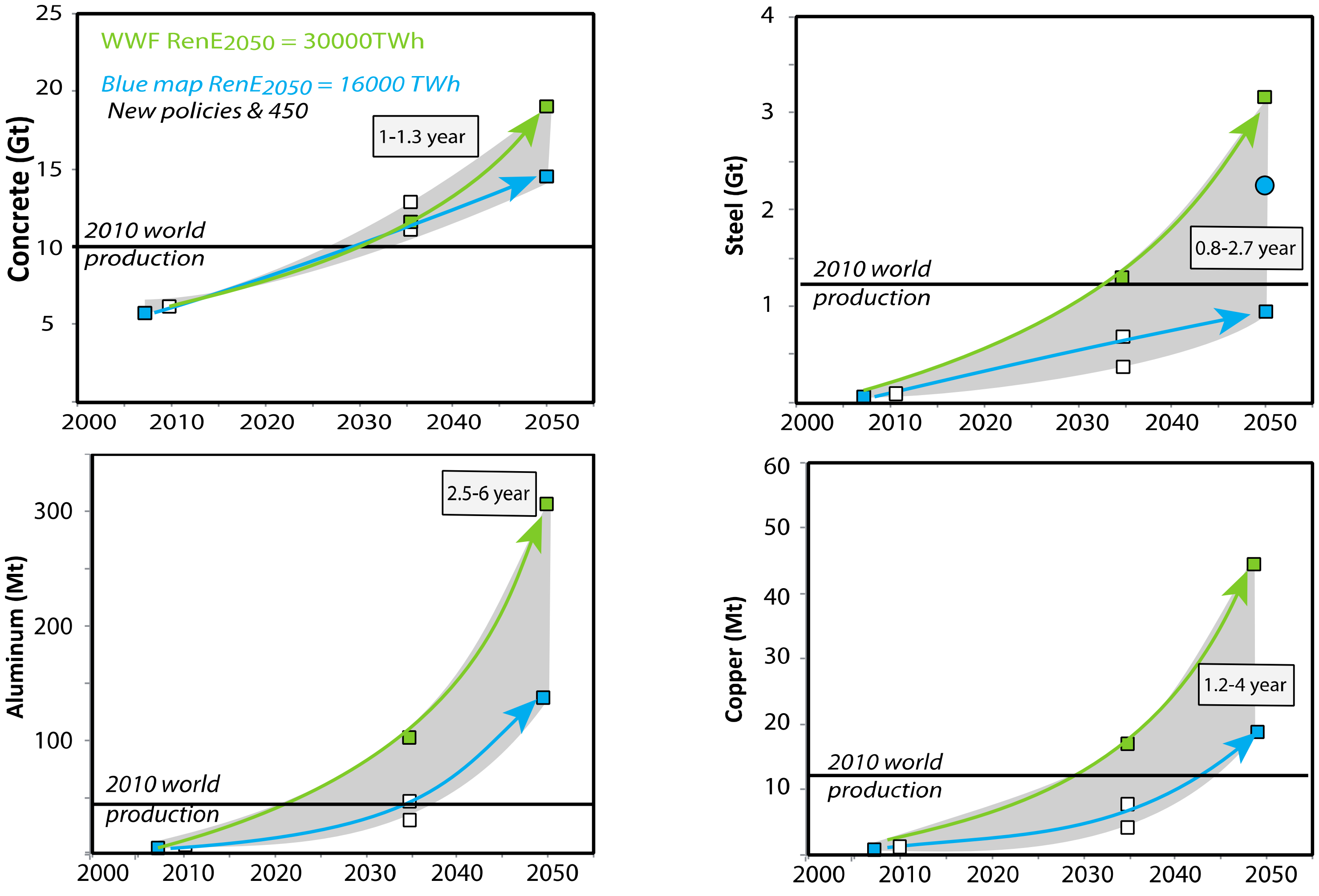
CO2 emissions from industry : 50% come from iron, cement, aluminium
Energy consumption by industry : 21% for steel & cement

THE MATTER ISSUE

Source : Olivier Vidal

Cumulative material requirements for renewable electricity production facilities

Case of a high renewable energy fraction in 2050



THE MATTER ISSUE

Source : Olivier Vidal

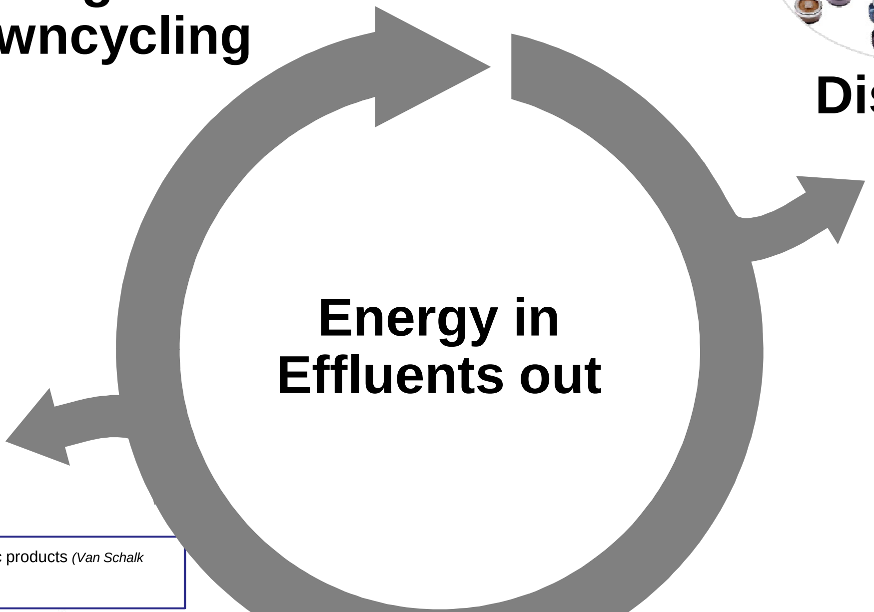
Material use (Al, Cu, Fe, concrete) for renewables
is high because they are diffuse :
between 1 and 6 years of global 2010 production

Energy use for those materials alone
could be 1.5 years of global crude oil production 2012

(case of a high renewable energy fraction in 2050)

THE MATTER ISSUE: RECYCLING LIMITS

Source : Philippe Bihouix



Recycling without downcycling

Energy in Effluents out

Dissipative usages

Recycling with downcycling

The increase in the complexity of metal assemblages in generic products *(Van Schalk and Reuter, 2012; adapted from Achzel and Reller)*

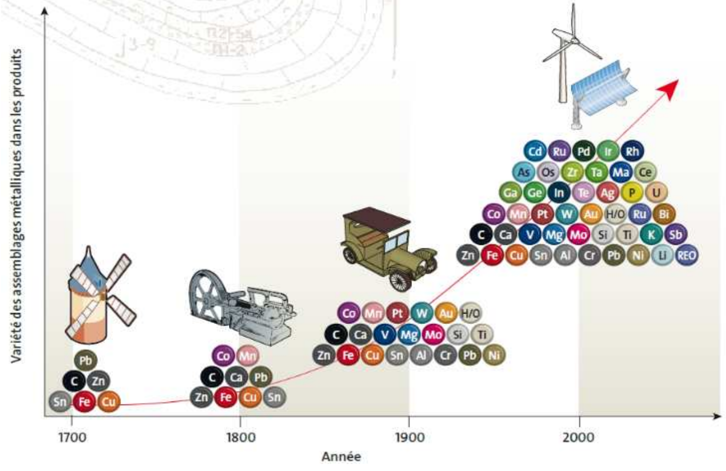


Fig. 6 : Augmentation de la complexité des assemblages métalliques dans des produits génériques.

Source : Van Schaik et Reuter, 2012 (adapté d'Achzet et Reller).

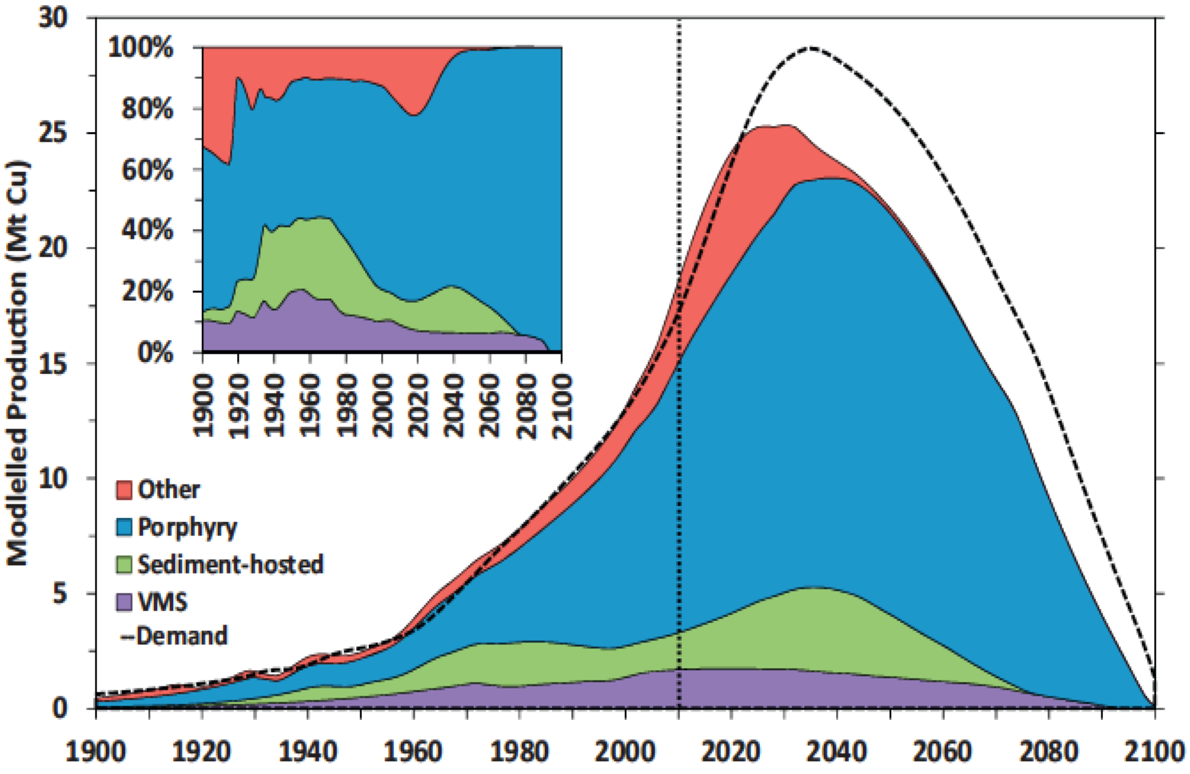
Fig. 6: The increase in the complexity of metal assemblages in generic products.

Source: Van Schaik and Reuter, 2012 (adapted from Achzet and Reller).

Mechanical loss, landfill (imperfect recycling)

THE MATTER ISSUE: CASE OF COPPER

Source : Olivier Vidal



It is a hard time to build large material intensive infrastructures.

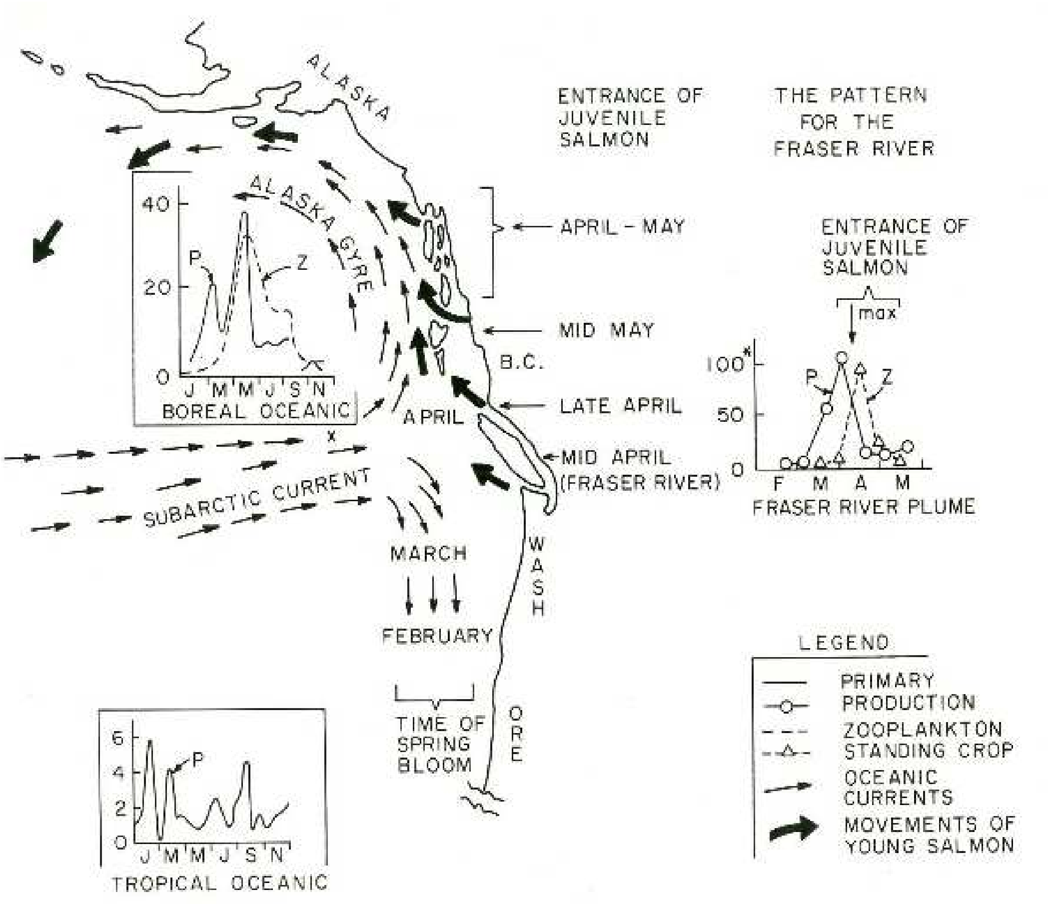
Recycling is not relevant during the buildup phase.

THE ENERGY ISSUE: CONCEPT OF EROI

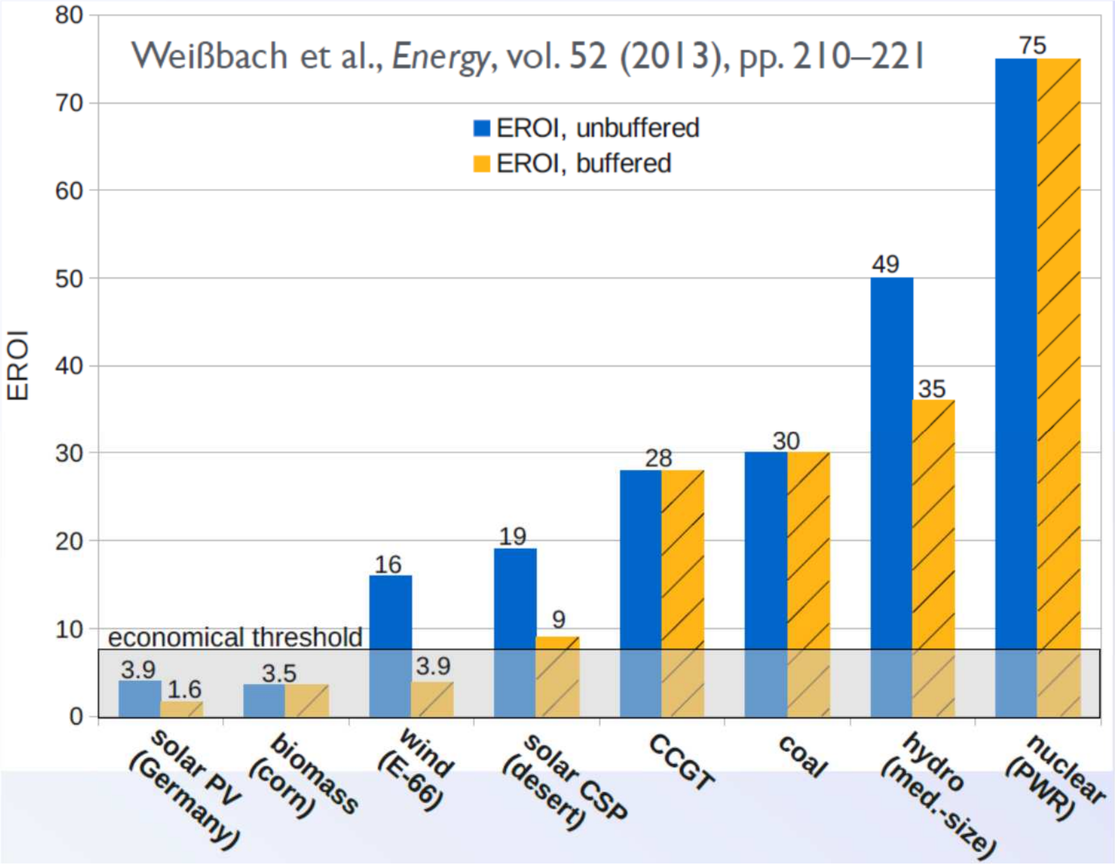
- **Introduced by Charles Hall for fish:**

They migrate if each calory invested in migration earns at least 5 calories of food

Energy Return On Investment
> 5:1



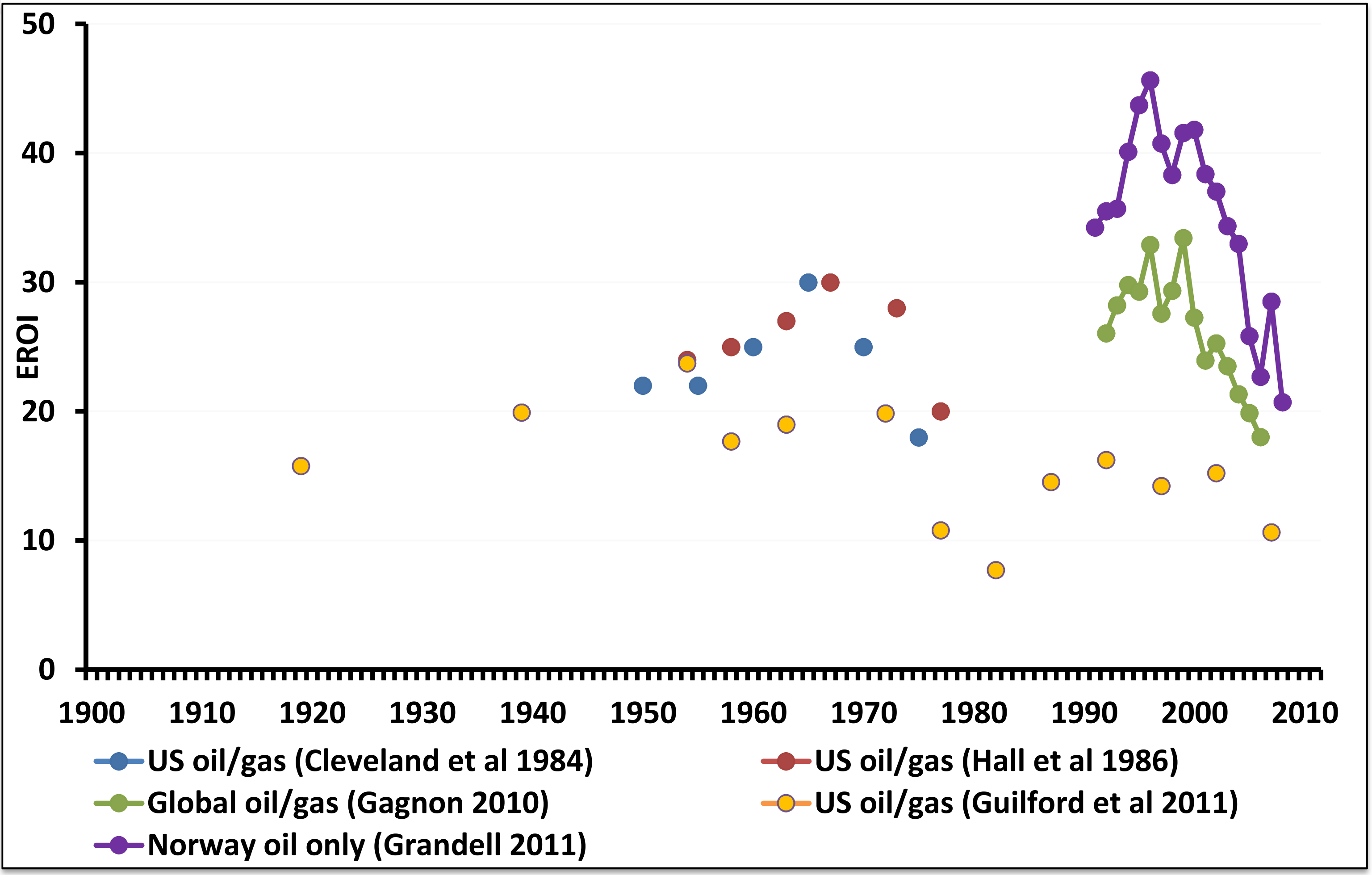
THE ENERGY ISSUE



MJ(elec)
/ MJ(primary)

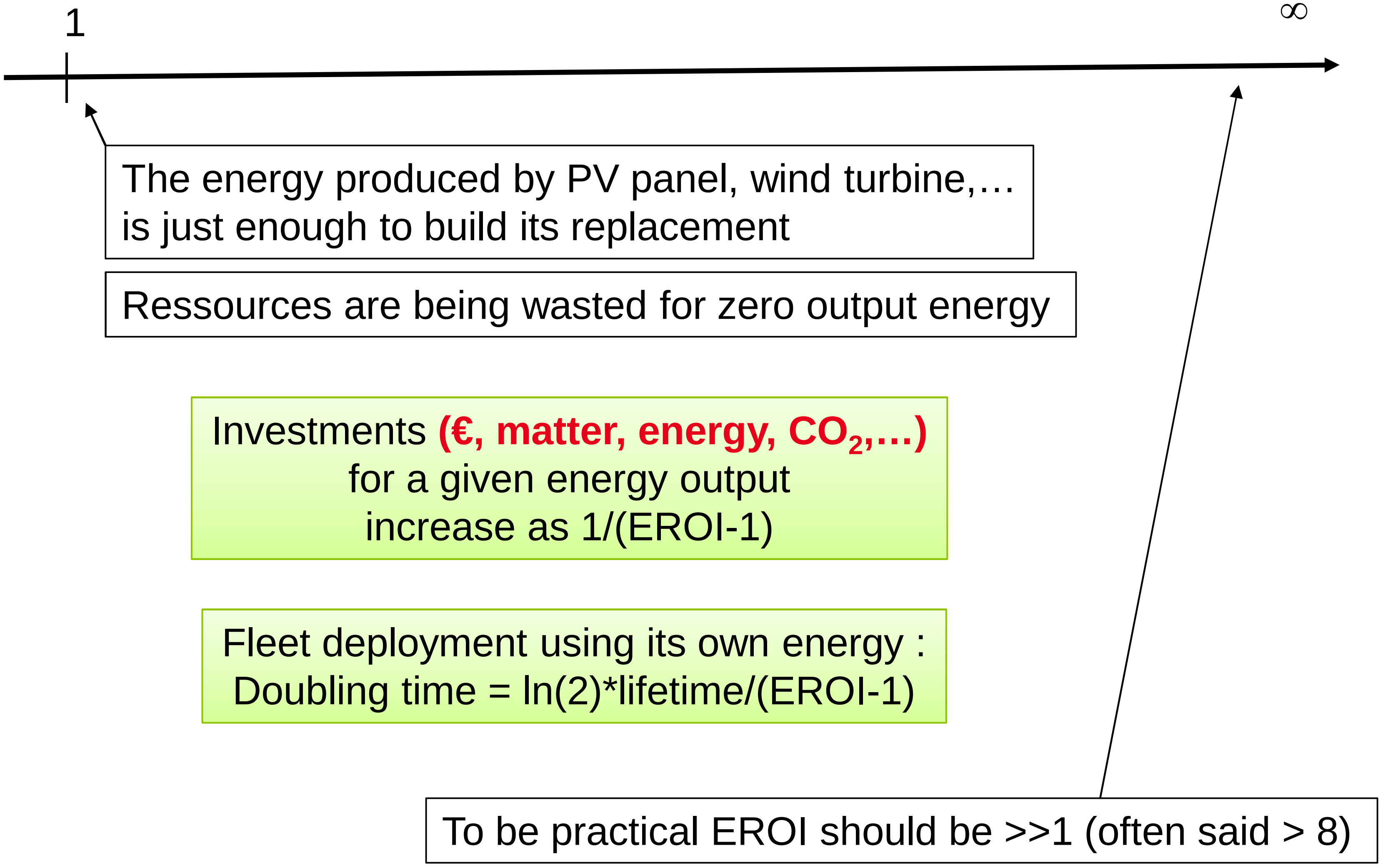
EROI is useful to compare energy sources.
EROI is low when energy is diffuse and difficult to manage
e.g. corn ethanol : not even sure EROI>1 (Murphy, Hall and Powers, 2011)

THE ENERGY ISSUE



Even for fossile fuels, EROI is declining, as easiest resources are exploited first. More and more oil is needed to extract oil…

THE ENERGY ISSUE: IMPLICATIONS OF LOW EROI



The energy produced by PV panel, wind turbine,…
is just enough to build its replacement

Ressources are being wasted for zero output energy

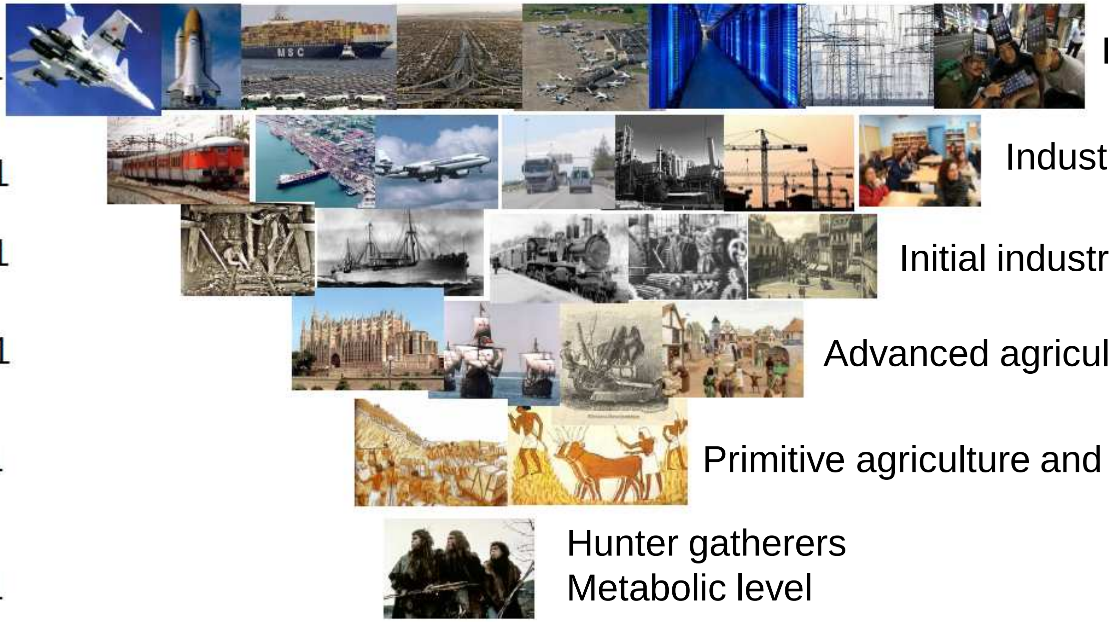
Investments **(€, matter, energy, CO_2,…)**
for a given energy output
increase as 1/(EROI-1)

Fleet deployment using its own energy :
Doubling time = ln(2)*lifetime/(EROI-1)

To be practical EROI should be >>1 (often said > 8)

THE ENERGY ISSUE: IMPLICATIONS OF LOW EROI

EROI has been linked to the society development level

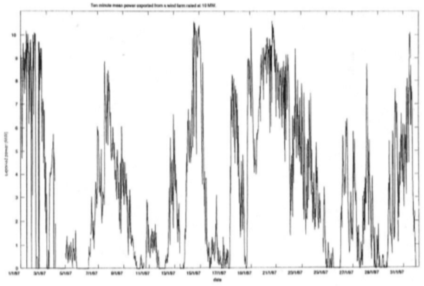


12-25:1	Industrial & technological society
8-15:1	Industrial developed society
6-13:1	Initial industrial society
5-6:1	Advanced agricultural society
4-5:1	Primitive agriculture and cattle
2-3:1	Hunter gatherers Metabolic level

Source: Pedro Prieto

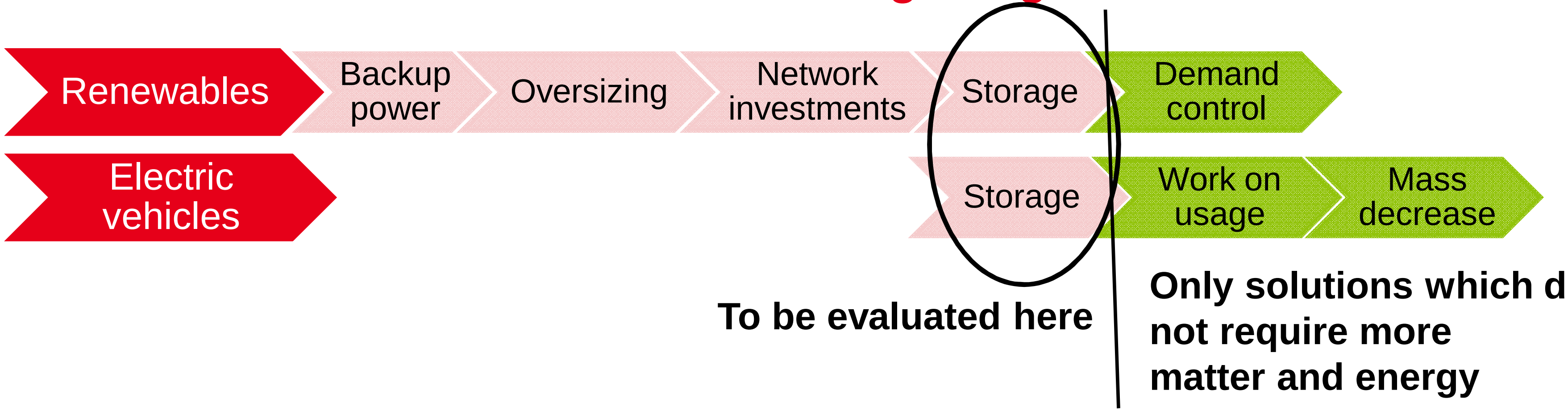
WHICH SUSTAINABLE ENERGY SCENARIO ?

- Renewables suffer from high matter and energy use but also
  - intermittency
  - lack of predictability
  - high correlation
  - low capacity factor
  - large difference between installed / guaranteed power



- Vehicles also use matter (>1 t) and energy (75 GJ_{prim}, 4 t_{CO2}), and
  - bring energy onboard

- How to deal with this **without making things worse** ?



Renewables

Backup power

Oversizing

Network investments

Storage

Demand control

Electric vehicles

Storage

Work on usage

Mass decrease

To be evaluated here

Only solutions which do not require more matter and energy

1. Context

2. Batteries : the size of the problem

3. Battery essential parameters

4. Material availability

5. Impact of battery production

6. From battery production to EROI

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BATTERIES : THE SIZE OF THE PROBLEM

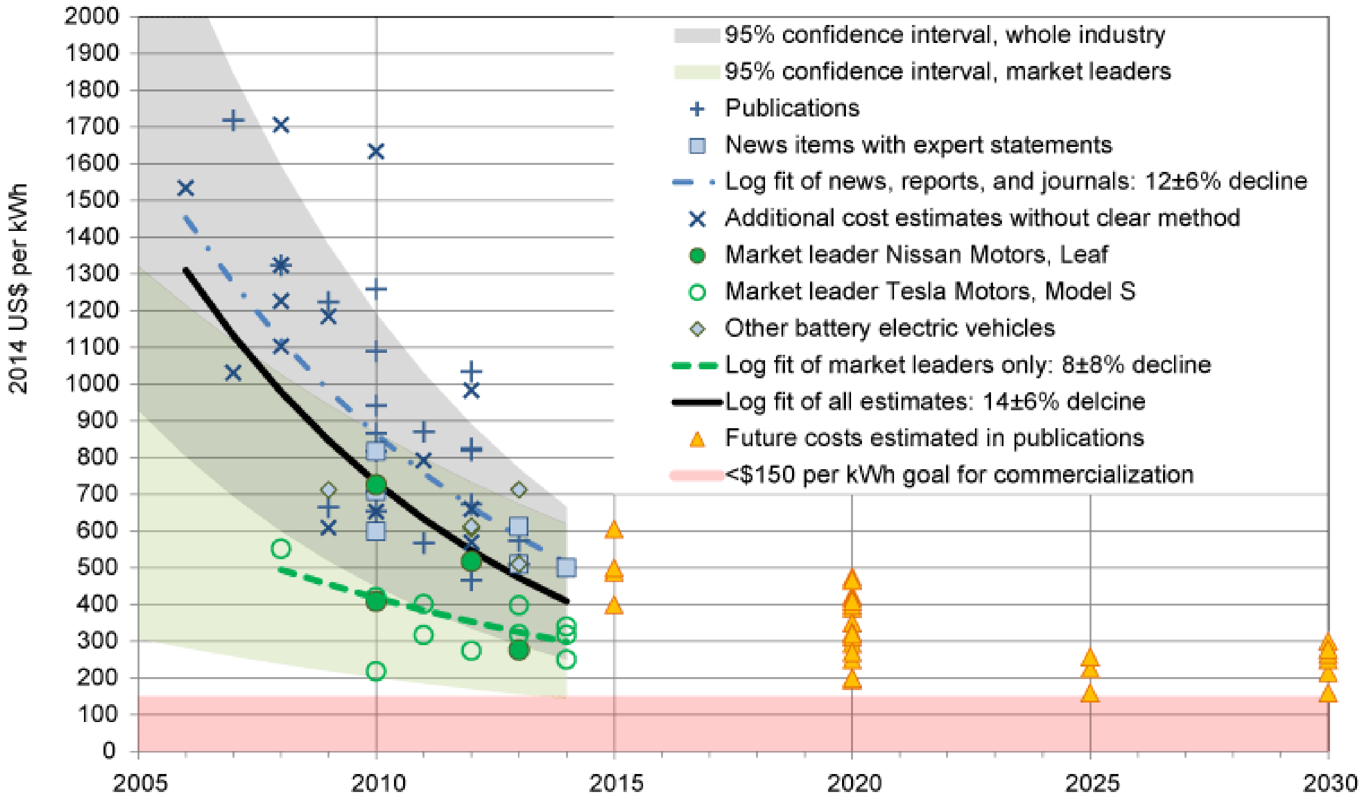
- Batteries are already everywhere

- If it were bad, we would know it !

Let’s look at the numbers…

BATTERIES : THE SIZE OF THE PROBLEM

Battery price is falling down at 8%/year



Estimates of costs of lithium-ion batteries for use in electric vehicles

Björn Nykvist and Måns Nilsson, 2015

The market-acceptable prices will be attained soon.

BATTERIES : THE SIZE OF THE PROBLEM

Everyone predicts an acceleration in battery production

- **GDF Suez :**

  In 2050, 75 TWh of intermittency surplus in France
  (=annual production of 10 nuclear reactors)
- **Larcher & Tarascon 2015 :**

  14 TW worldwide electrical production in 2015, 28 TW in 2050
- **Siemens :**

  In 2030, 12,5 GW of storage in Germany
- **IMS research :**

  PV energy storage $200 million in 2012 -> $19 billion in 2017
- **IHS** :

  Energy storage installation 0,34 GW in 2013, 6GW/y in 2017, 40 GW/y in 2022
- **Avicennes :**

  NiMH and Li-ion : from 60GWh/an today to 200GWh/an in 2020 of which 70 GWh/an in cars
- **United Nations :**

  1 billion cars in the world in 2007, 3 billion expected in 2050
- **JRC IPTS :**

  110,000 to 638,000 EV in Europe in 2020

BATTERIES : THE SIZE OF THE PROBLEM

What is the foreseeable battery fleet ?

Scenario :

- getting rid of fossile fuels to drastically decrease GHG emissions.
- no increase in worldwide energy consumption and cars (contrary to the predictions which are between x2 and x3 in 2050).

BATTERIES : THE SIZE OF THE PROBLEM

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1. Vehicles

Massive electrification of vehicles with no increase in their number.
10^9 vehicles * 30kWh/vehicle = **30 TWh of storage**

BATTERIES : THE SIZE OF THE PROBLEM

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Scenario :

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2. Renewable energy storage

for 50-80% renewables mix, global storage capacity
should be ~4 to 12 hours of world average power demand. (Source: Barnhardt&Benson 2013)

World electric consumption = 20,450 TWh in 2014 (indexmundi.com)

4-12 hours = **10-30TWh of storage**

Consistent with Tesla estimation of 7-10 kWh/home.

BATTERIES : THE SIZE OF THE PROBLEM

30 TWh

10-30 TWh

We thus consider a global battery fleet of **~50 TWh**

With conservative assumptions…

BATTERIES : THE SIZE OF THE PROBLEM

What is 50 TWh of batteries ?

- It is **140 years** of current production rate of PbA batteries
- Or nearly **1000 years** of current production rate of every other type of battery

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- To produce 50 TWh in 10 years (must be shorter than battery life…), we will need **140 gigafactories.**

1 gigafactory = 1,3km²
= 35GWh/year

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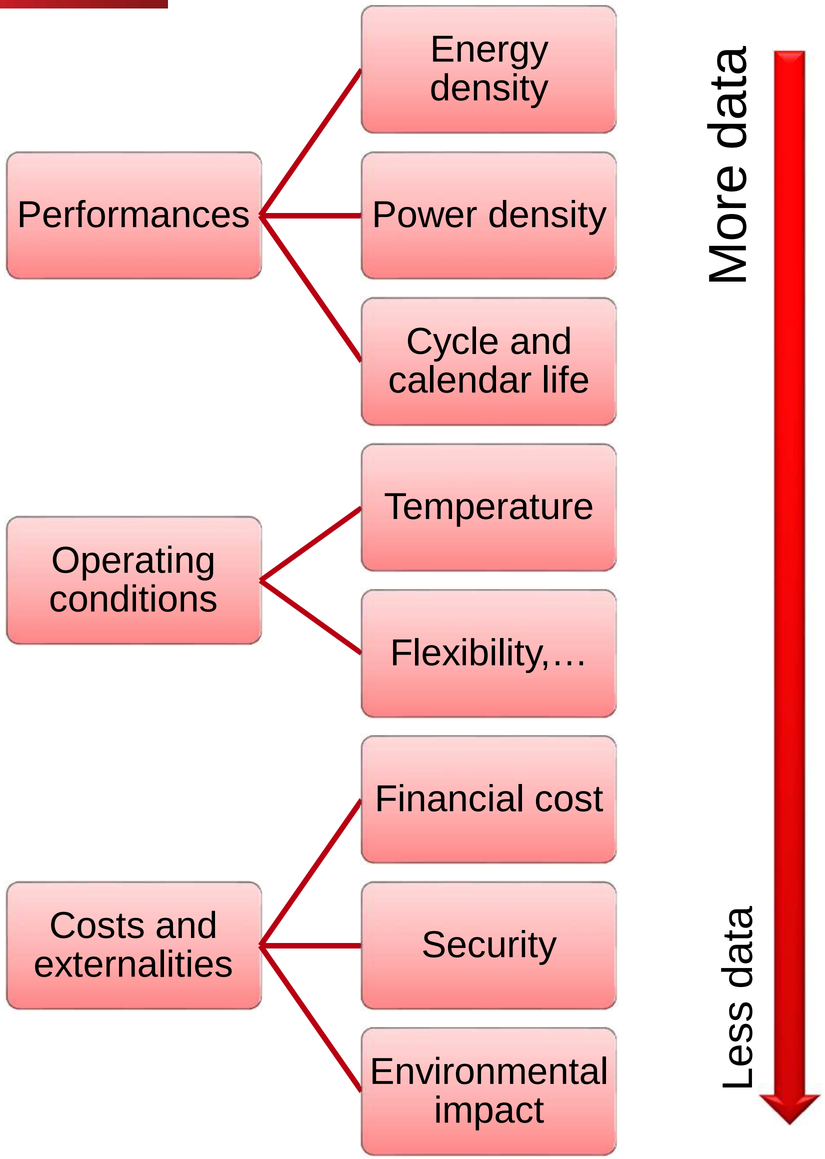
BATTERY ESSENTIAL PARAMETERS



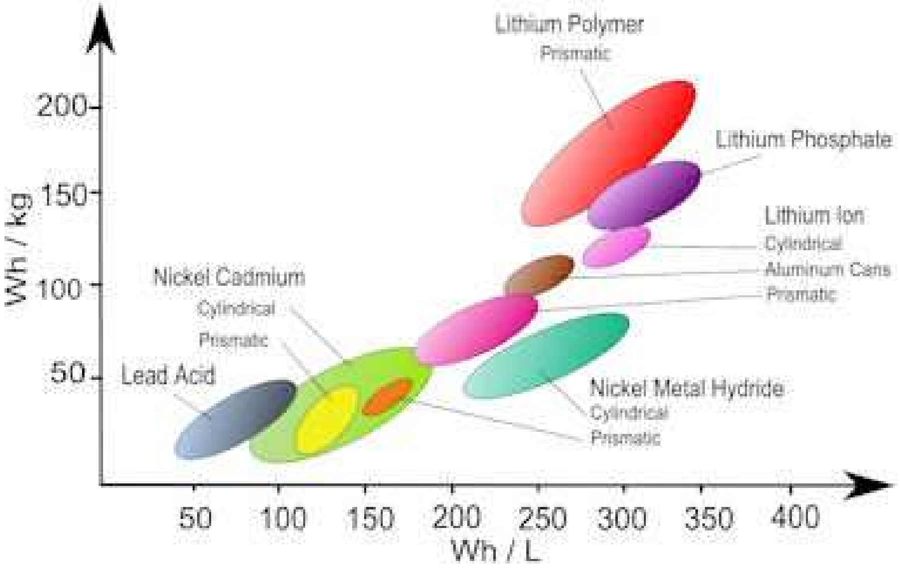
Performances
- Energy density
- Power density
- Cycle and calendar life

Operating conditions
- Temperature
- Flexibility,…

Costs and externalities
- Financial cost
- Security
- Environmental impact

Most common representations :

- Volumetric energy density
  vs gravimetric energy density

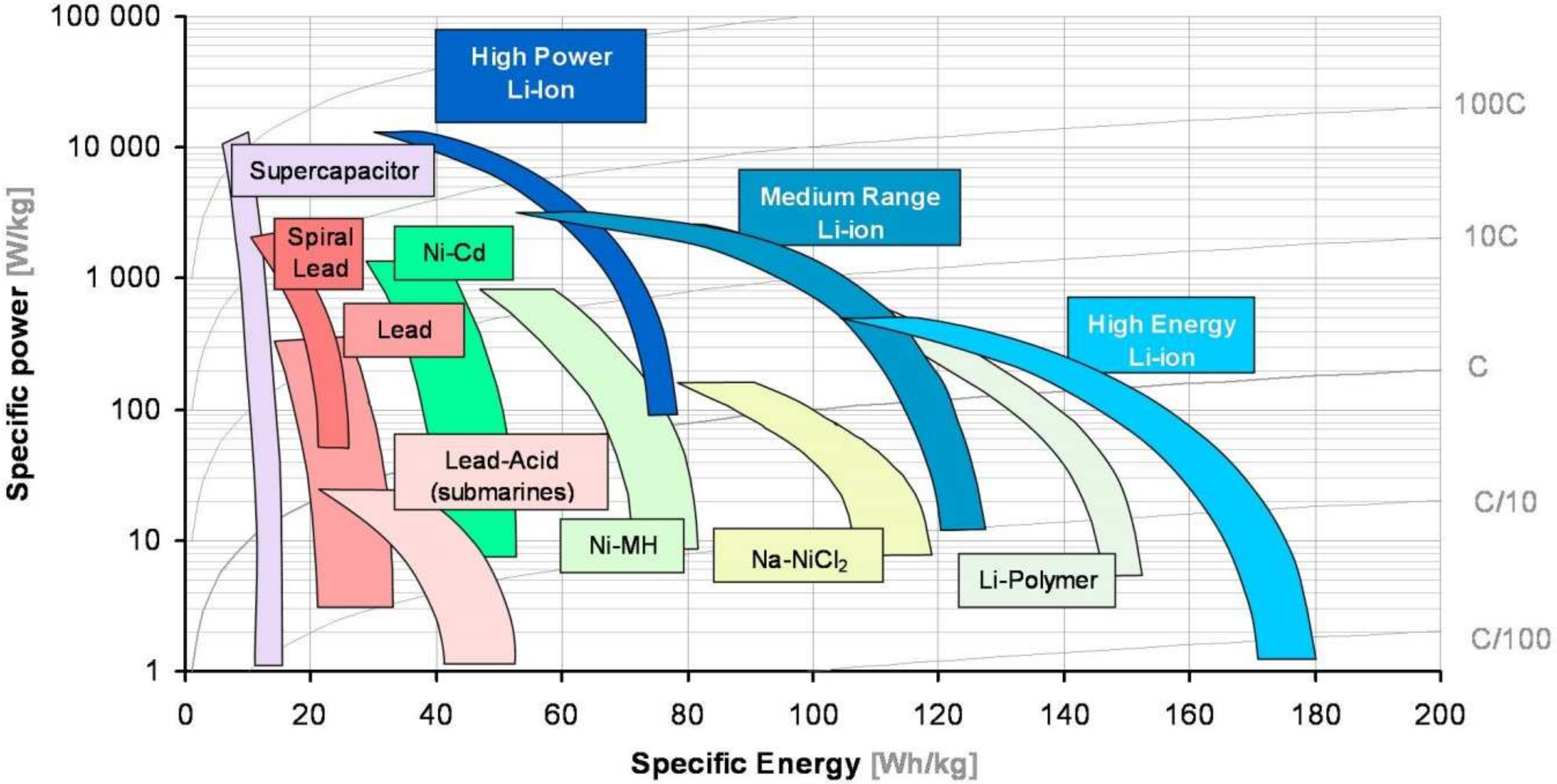


Not that interesting…

- Energy density
  vs power density

BATTERY ESSENTIAL PARAMETERS

- **Tradeoff Energy / Power : Ragone plot**
  - More energy : thicker electrodes, thinner current collectors
  - Many companies are marketting ‘long duration’ what is in fact low power…

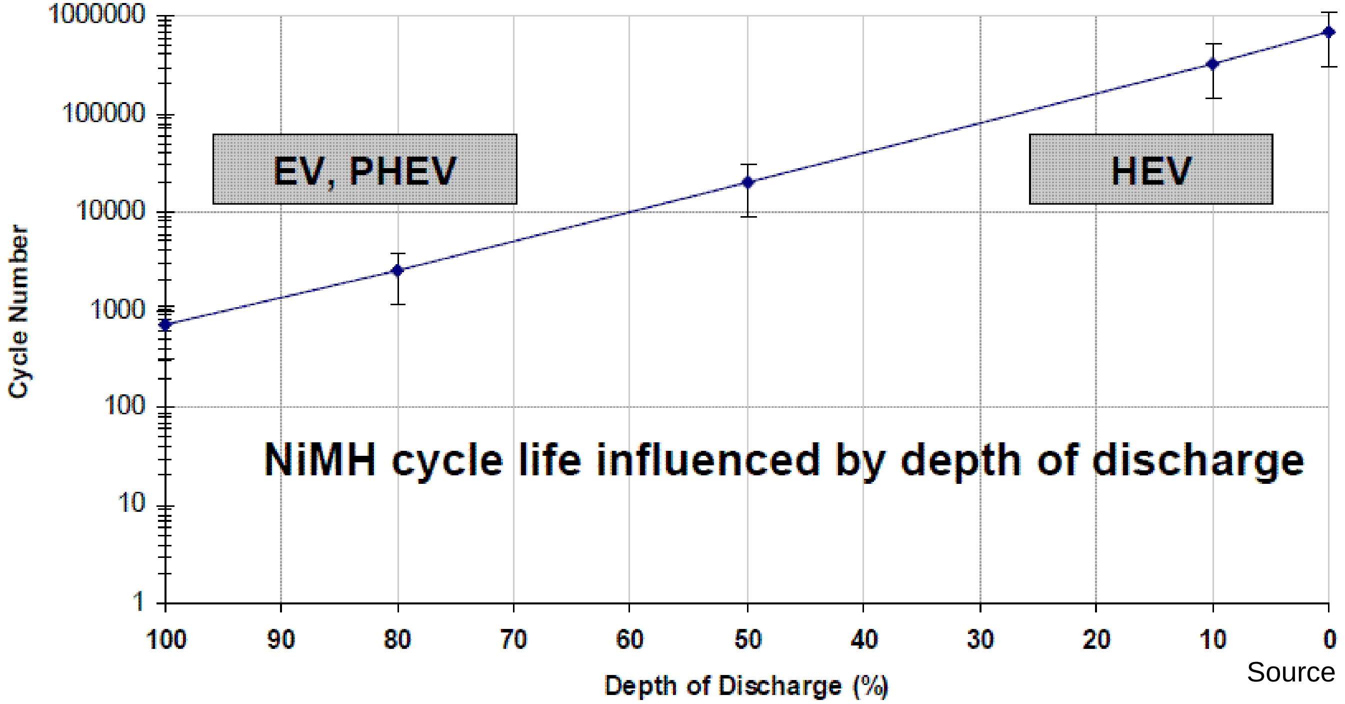


BATTERY ESSENTIAL PARAMETERS

- **Tradeoff Energy / Cycle life**
  - Less data available.
  - Less depth of discharge

    ⇔ greater investment for a given energy but better return on investment.

There is a **limit linked to calendar life** : 1 cycle/day for 20 years =7300 cycles



Source : Ovonik

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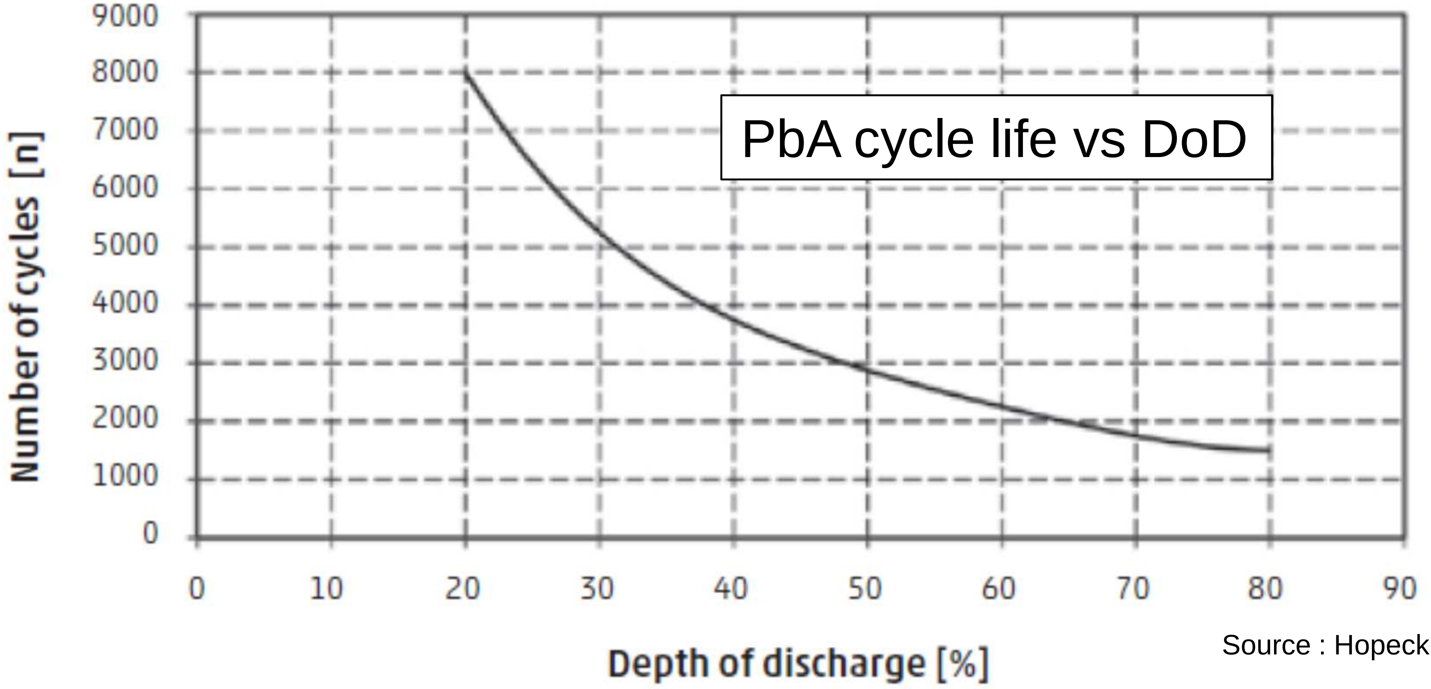

Source : Hopecke

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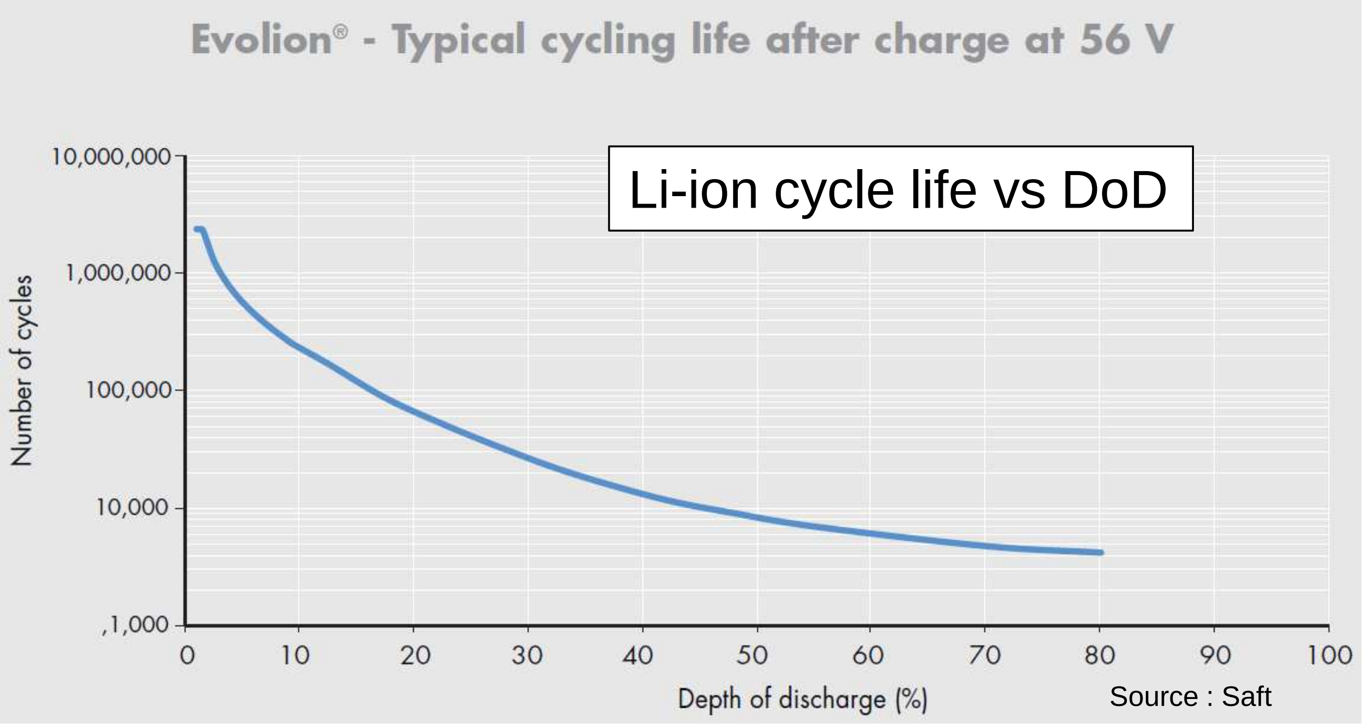

Source : Saft

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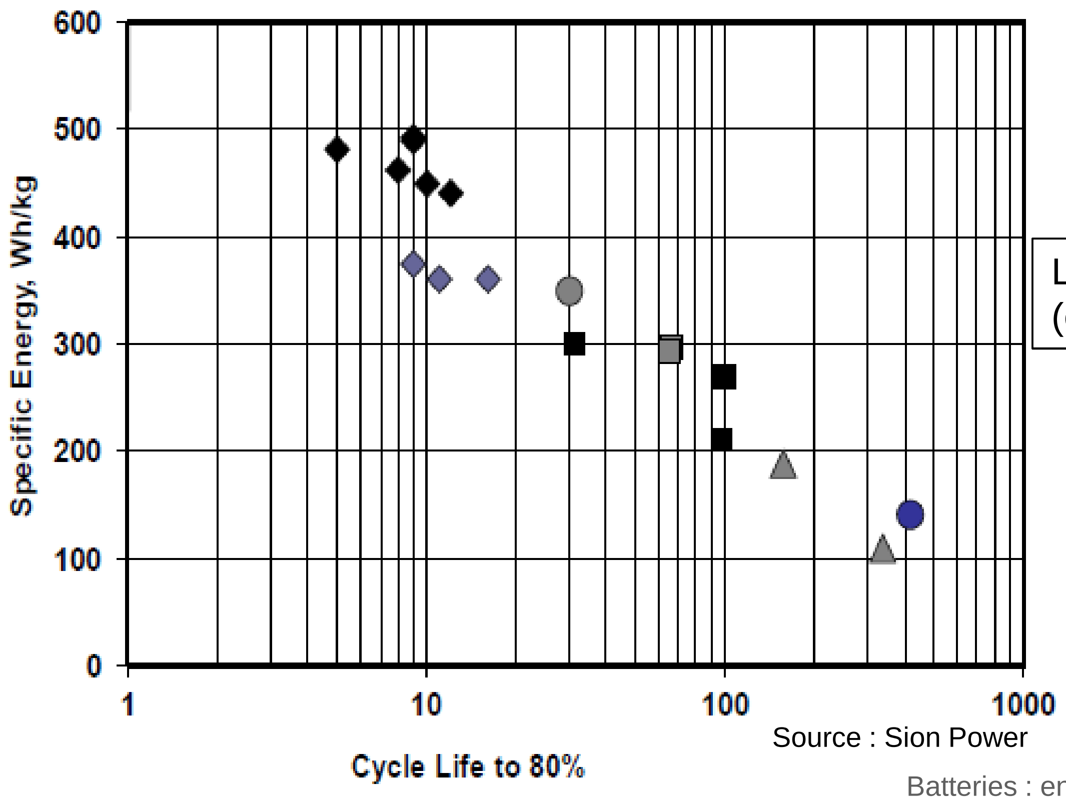
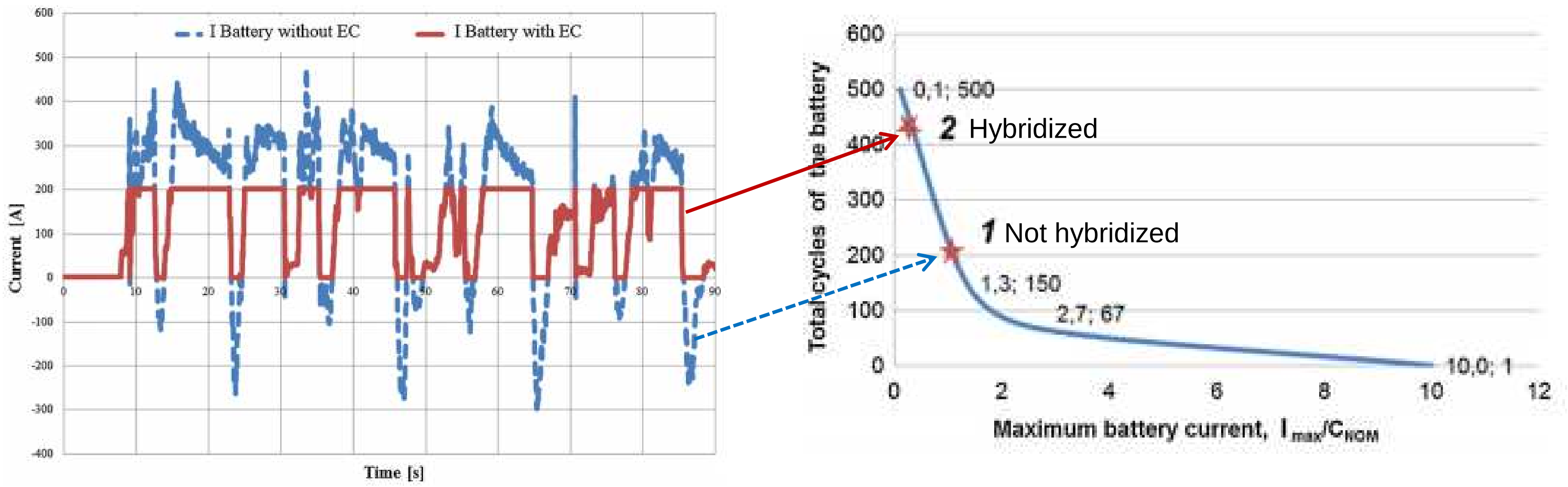


Li-S cycle life vs energy density (effect of electrolyte amount)

Source : Sion Power

BATTERY ESSENTIAL PARAMETERS

- **Tradeoff Power / Cycle life**
  - A highly sollicited battery has lower cycle life
  - **Hybridizing** batteries with high power systems (supercapacitors, flywheels,…) help enhance cycle life.



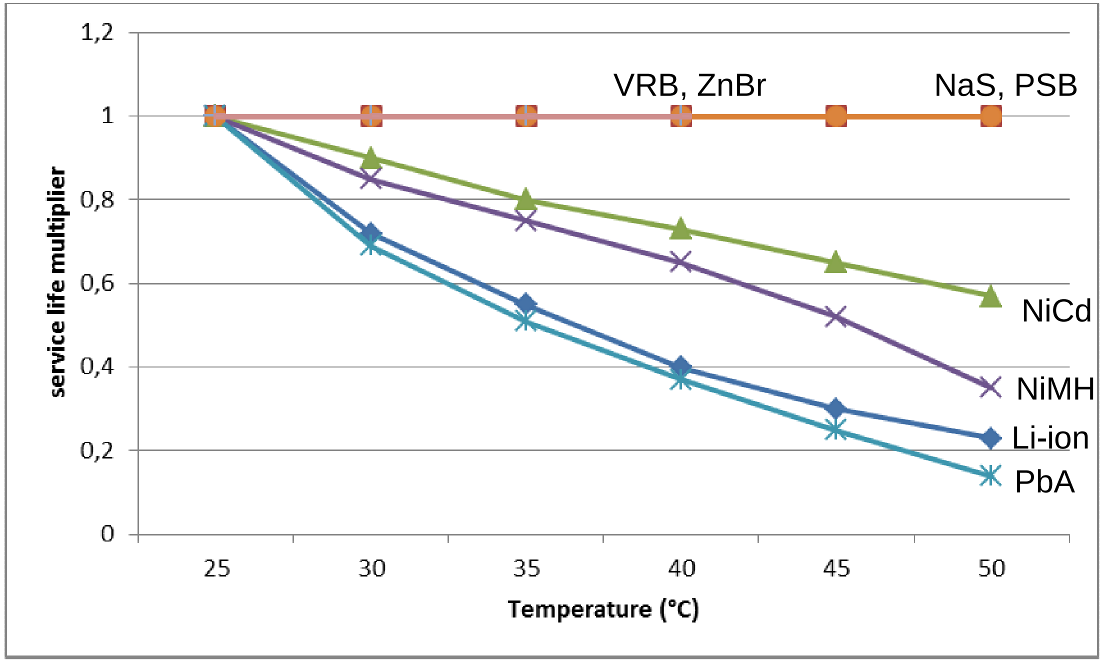
Source : ENEA

PbA cycle life vs C-rate

BATTERY ESSENTIAL PARAMETERS

- **Effect of temperature on cycle life**
  - Extreme temperatures usually reduce calendar and cycle life
  - Exceptions are high temperature batteries (NaS, $NaNiCl_2$)
  - Active temperature control is more efficient than reduced calendar life

  (Rydh & Sanden, 2005)



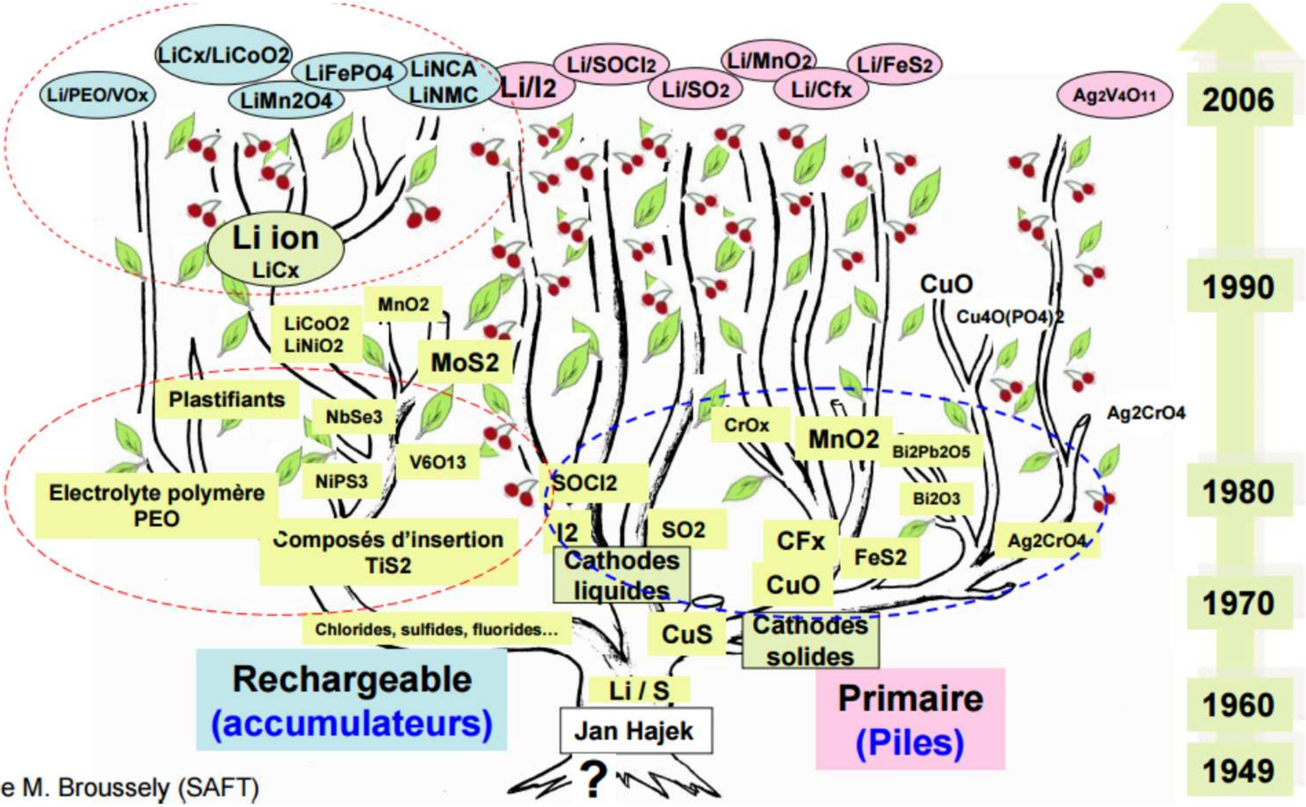
Data from Rydh & Sanden, 2005

BATTERY ESSENTIAL PARAMETERS

- **Environmental impact is yet another parameter to take into account…**

BATTERY ESSENTIAL PARAMETERS

- Batteries have a long history
- A lot of different chemistries and many more to come
- Each one has its well advertised advantages, but also its drawbacks.

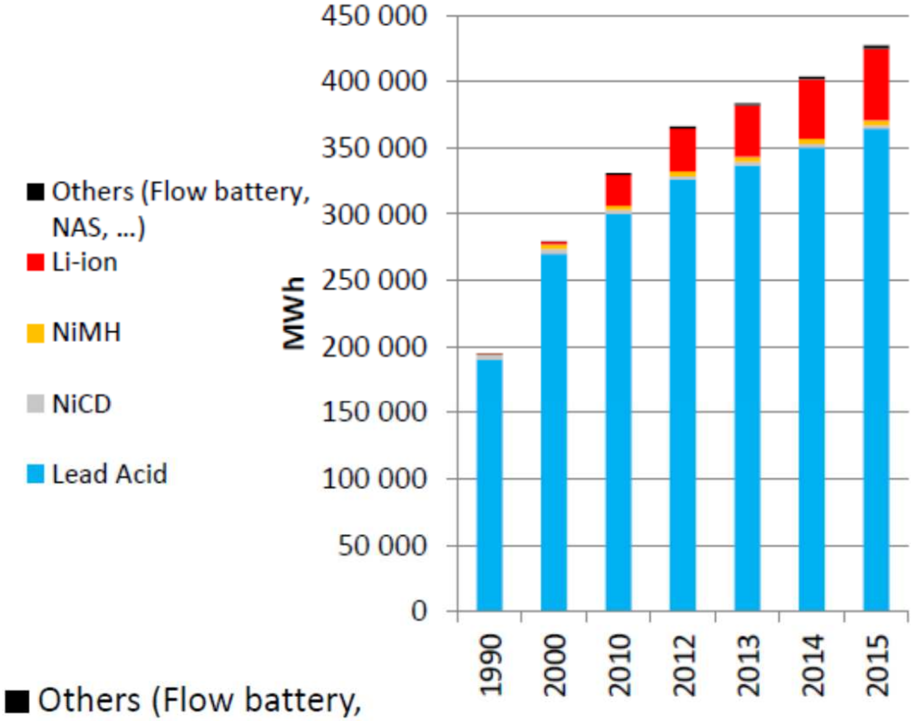


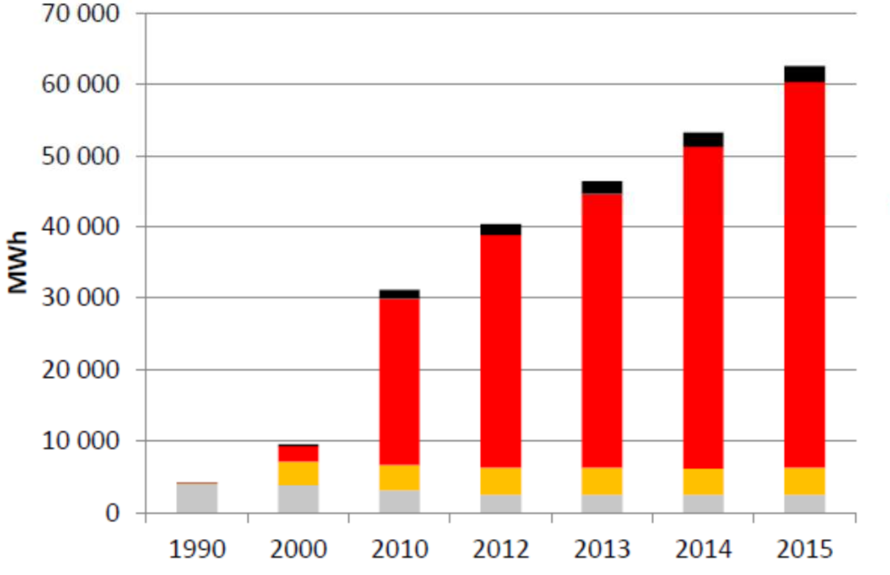
De M. Broussely (SAFT)

BATTERY ESSENTIAL PARAMETERS

Today

- Battery = lead-acid
- Other battery = lithium-ion





Source: AVICENNE ENERGY, 2015

2015: Estimations

Battery ID cards are available at the end of the document for a wide range of technologies

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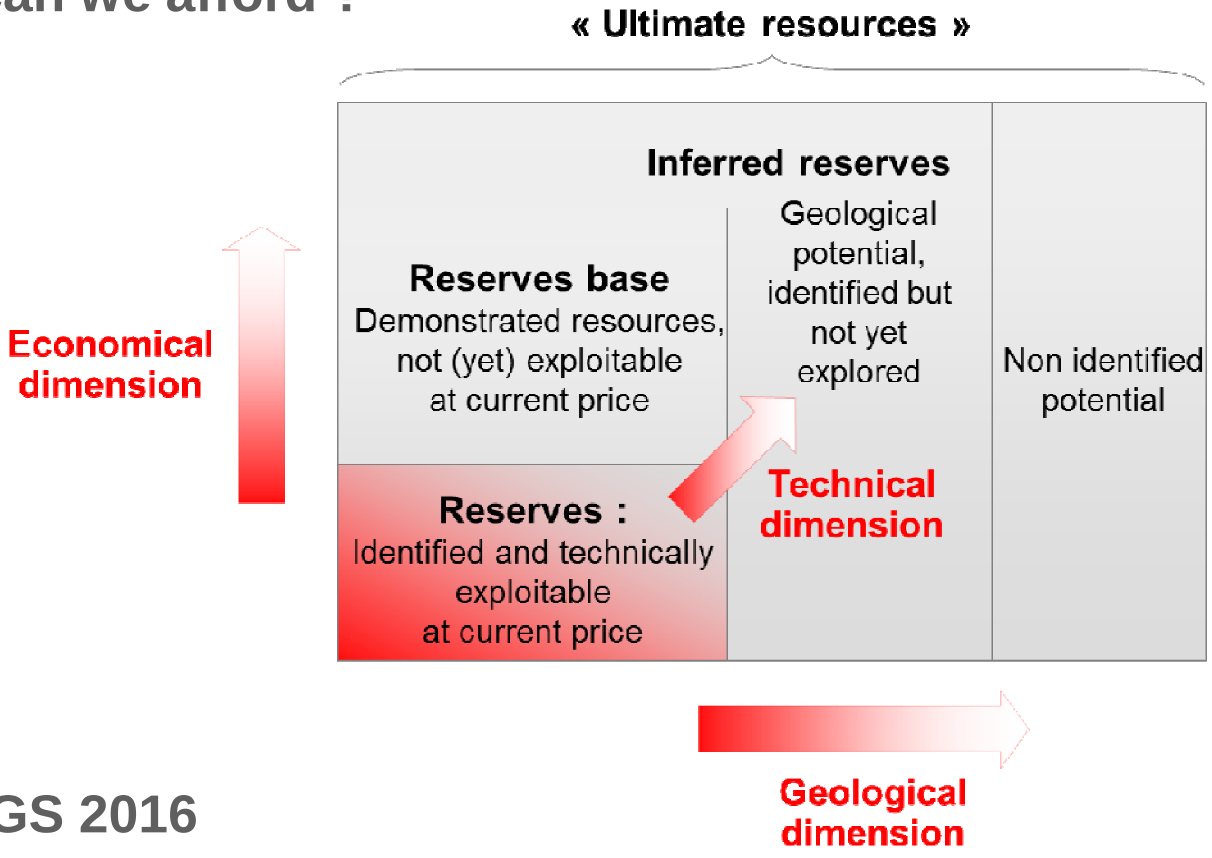
MATERIAL AVAILABILITY

Batteries use scarce materials.
How many batteries can we afford ?



« Ultimate resources »

Economical dimension

Inferred reserves

Reserves base
Demonstrated resources, not (yet) exploitable at current price

Geological potential, identified but not yet explored

Non identified potential

Reserves :
Identified and technically exploitable at current price

Technical dimension

Geological dimension

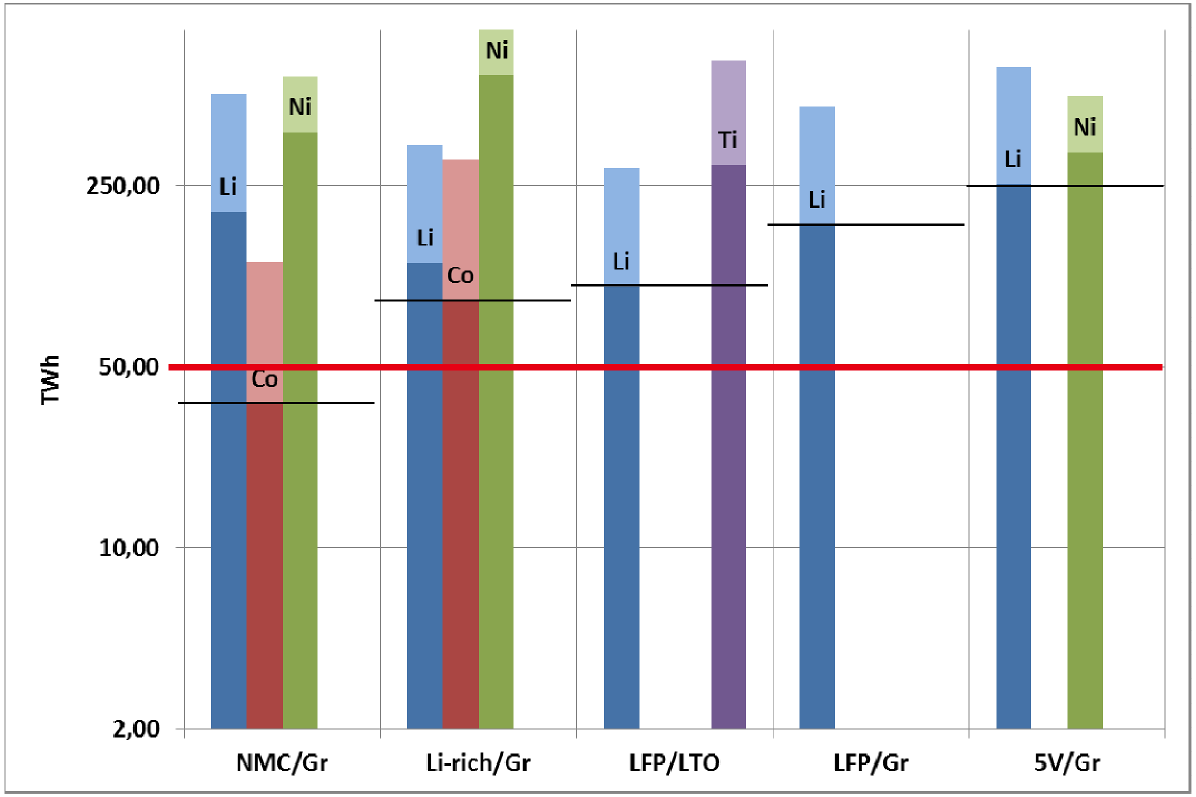
We use data from USGS 2016

We consider rather optimistic cell compositions

MATERIAL AVAILABILITY

For lithium-ion systems :

- Lithium is limiting for cobalt-free systems
- Nickel is not far above, except for nickel-free system (LFP)
- Higher voltages allows more efficient use of lithium
- Fluorine is not limiting in electrolyte salt (would be different in active materials)



← **5 replacements**

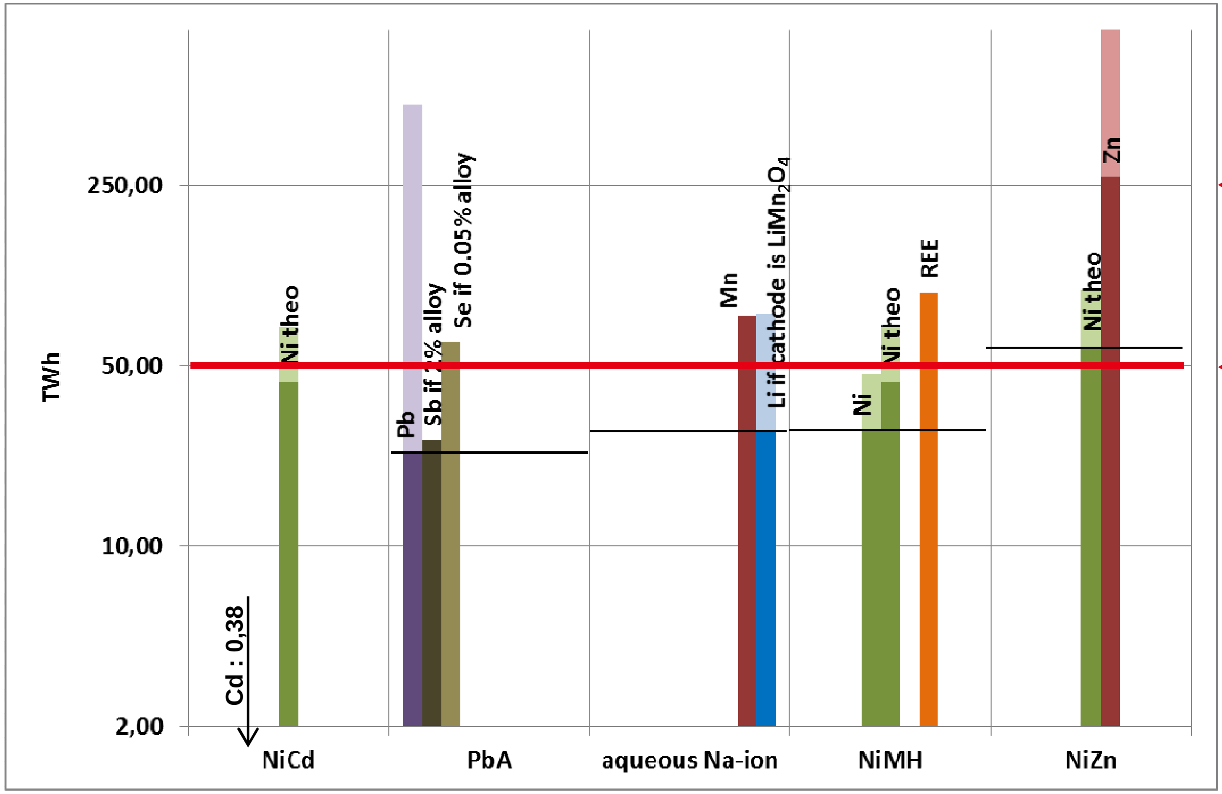
← **Our battery fleet**

Storable energy with reserves
in dark colors, and with
ressources in pale colors

MATERIAL AVAILABILITY

For aqueous systems :

- The material limit is even lower for aqueous system mainly due to lower voltage
- Even aqueous Na-ion is not that abundant due to very inefficient use of Mn
- At small energy densities, even low concentration additives can put a stringent limit



← **5 replacements**

← **Our battery fleet**

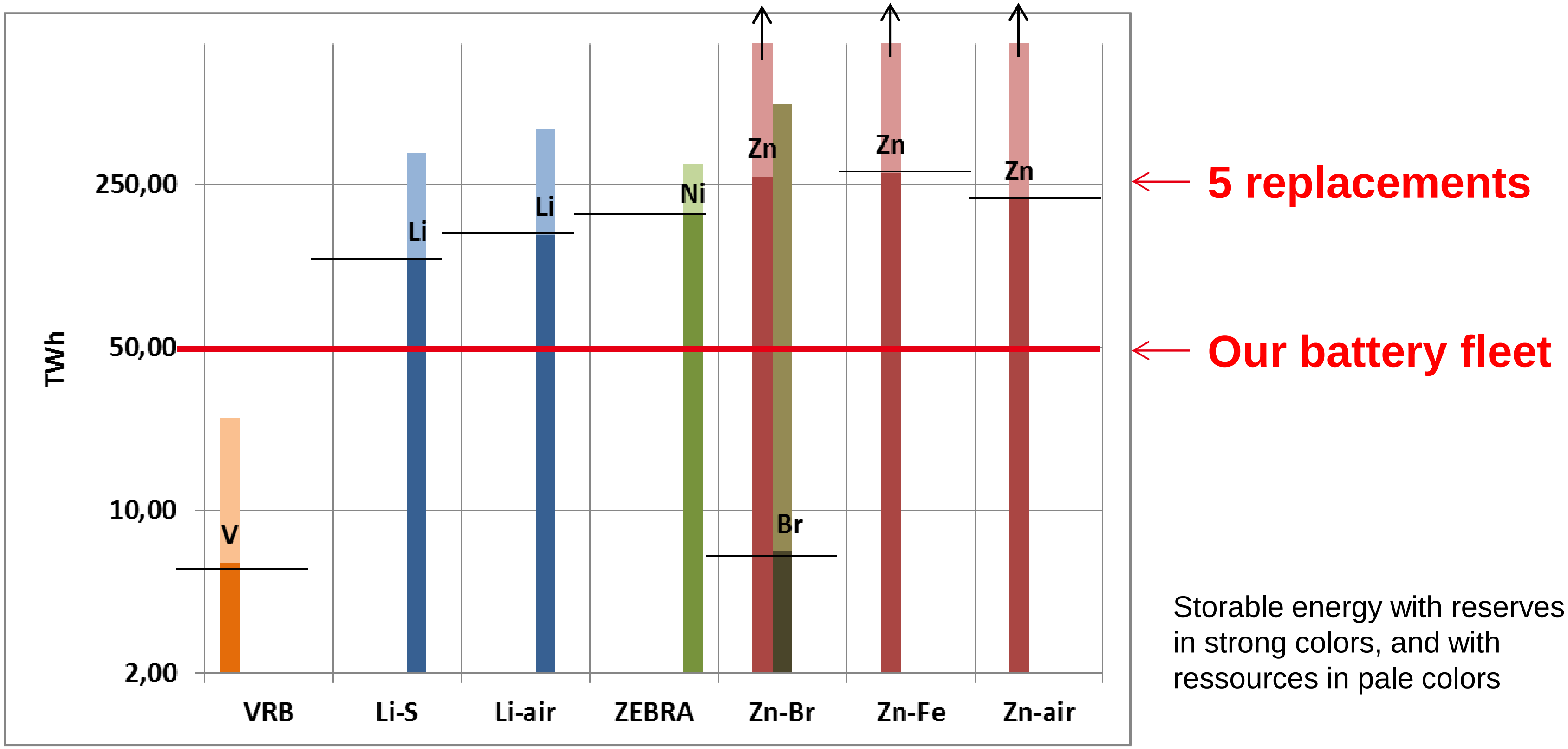
Storable energy with reserves in strong colors, and with ressources in pale colors

MATERIAL AVAILABILITY

For other systems :

- The vanadium redox battery has a very small potential.
- Lithium-metal technologies are a bit more limited than LFP/G and 5V Li-ion due to voltage

Few existing technologies have really high material limits :
Na-S, Fe-Fe, supercapacitors



Storable energy with reserves in strong colors, and with ressources in pale colors

MATERIAL AVAILABILITY

Differences with EU critical raw materials approach:

- We consider only batteries (no other use)
- We consider future battery production (much higher than present)
- We do not consider geopolitical constraints

This explains why we get different results.
Apart from identified CRM (Co, F), limits will come from

- Cd, V
- then Pb, Ni for aqueous technologies
- then Li, Zn, Ti

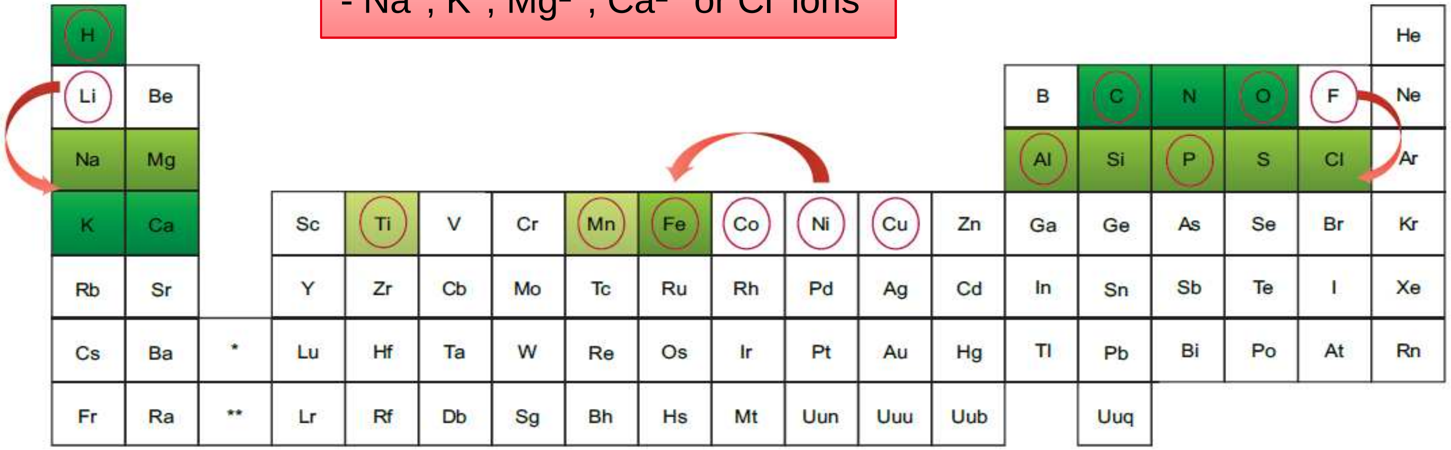
MATERIAL AVAILABILITY

Conclusion :

- There is a strong need for finding substitution chemistries with abundant elements
- Even supposedly green batteries with aqueous electrolyte or Zn anode have deployment potentials not higher than Li-ion.

- Research should focus on **substitution of Ni at positive and Li at negative** electrode.
- Active research areas able to tackle this limitation include :

- Organic active materials
- Sulfur or oxygen cathode
- Na^+, K^+, Mg^{2+}, Ca^{2+} or Cl^- ions



Elements constituting biomass in green
Elements constituting batteries are red circled
Larcher & Tarascon 2015

1. Context

2. Batteries : the size of the problem

3. Battery essential parameters

4. Material availability

5. Impact of battery production

6. From battery production to EROI

7. Some comparisons

8. Conclusion

9. Battery ID cards

IMPACT OF BATTERY PRODUCTION

- **Data is scarce, dated, and values are widely spread.
  They depend upon**
  - the application (EV vs storage) through energy / lifetime tradeoff
  - the scale considered (cell / EV pack / 40ft container)
  - the location (US/Europe) through transport, energy mix,…

  When 2 values match, they often come from the same source…

  Units differ and conversion is not straightforward (/kg vs /Wh, GJ_{th} vs MWh_e)

- **We focus on**
  - Battery technologies for which data exists (!)
  - Cradle to gate values
    Life cycle, EROI,… will be calculated afterwards
  - Primary energy consumption and CO_2 emissions
  - Values are normalised by nominal energy
  - Whole system excluding inverter as not always necessary
    (e.g. near PV farm). Inverter efficiency ~92-94%

All following values are to be taken as orders of magnitude

IMPACT OF BATTERY PRODUCTION

- **Lead-acid**

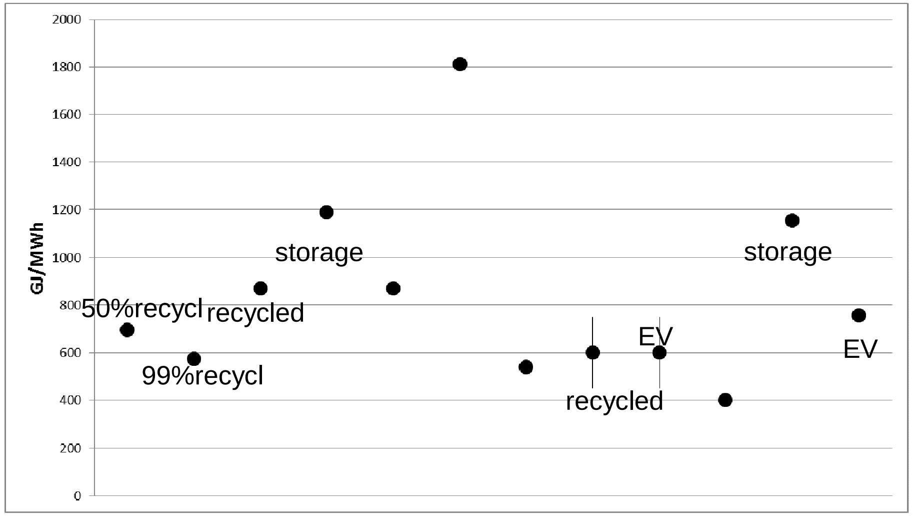
800-1200 GJ/MWh

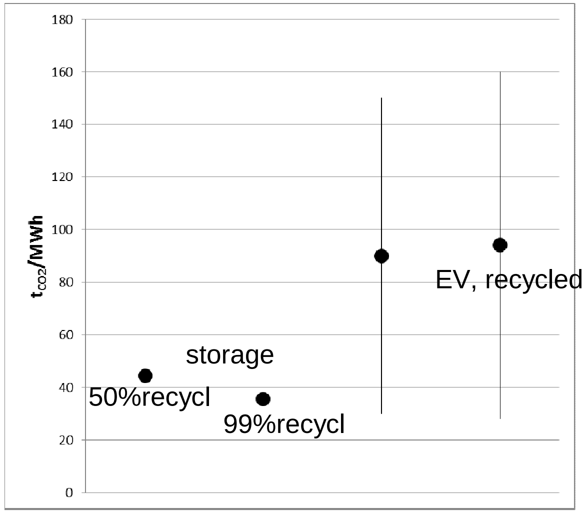
~2/3 material, 1/3 manufacturing

-25% in case of recycling

50-150 t_{CO2}/MWh

-30% in case of recycling





IMPACT OF BATTERY PRODUCTION

- **Lithium-ion**

1500-2000 GJ/MWh

-20% -25% in case of recycling

Cell ~ 80% of pack

Biggest contributions from cathode material, manufacturing and aluminium

No consensus on their relative weights

100-150 t_{CO2}/MWh

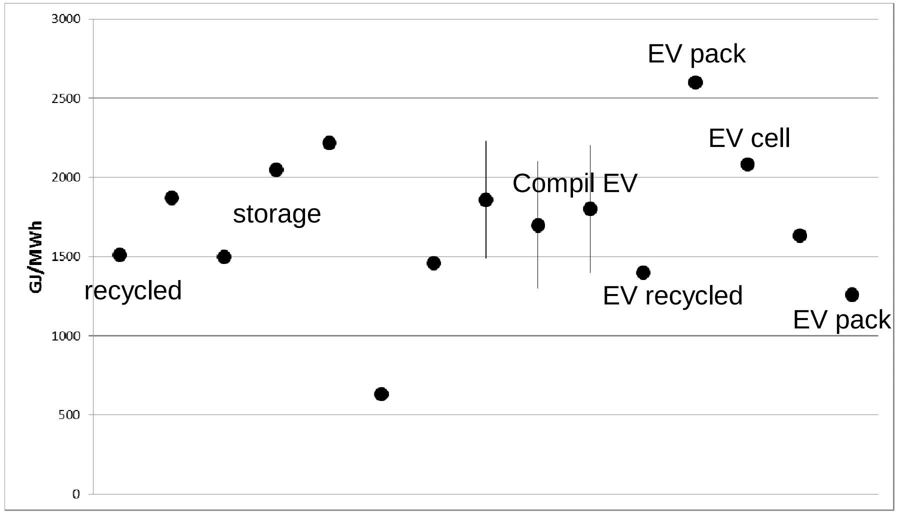
-20% -25% in case of recycling

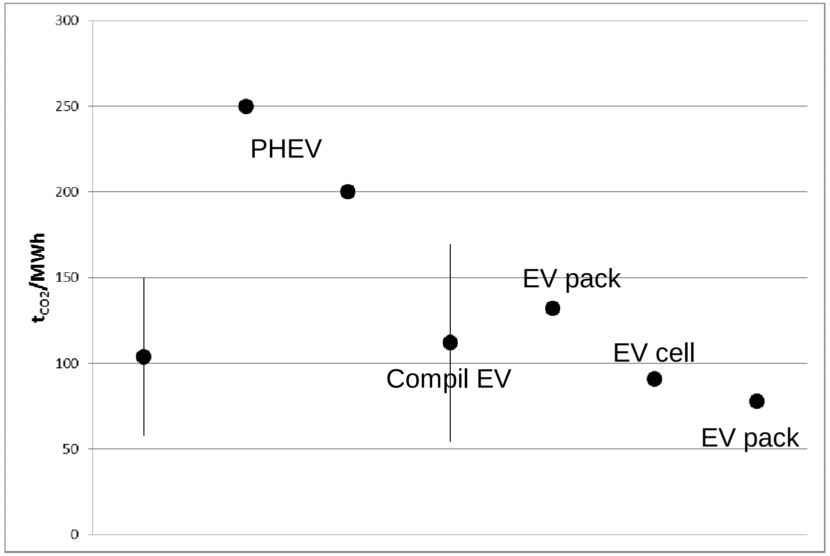
Cell ~ 80% of pack

Cathode = 35-45% of pack

Manufacturing ~25% of pack

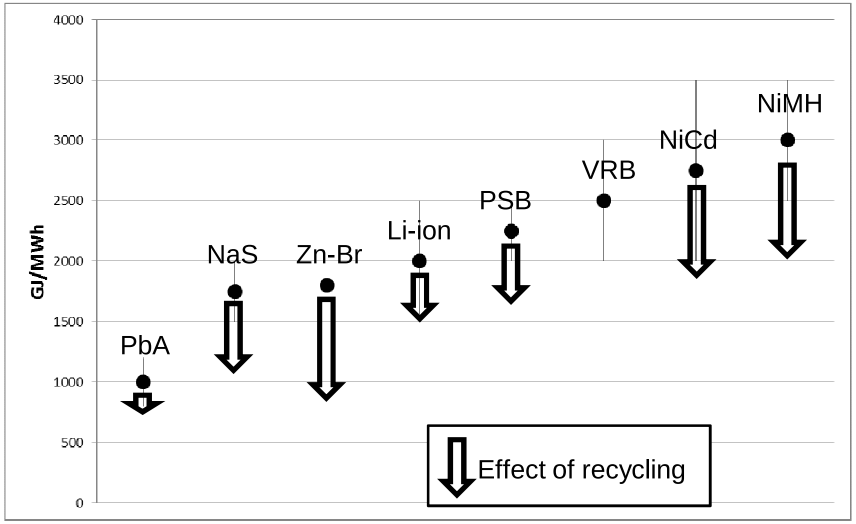
BMS ~13% of pack

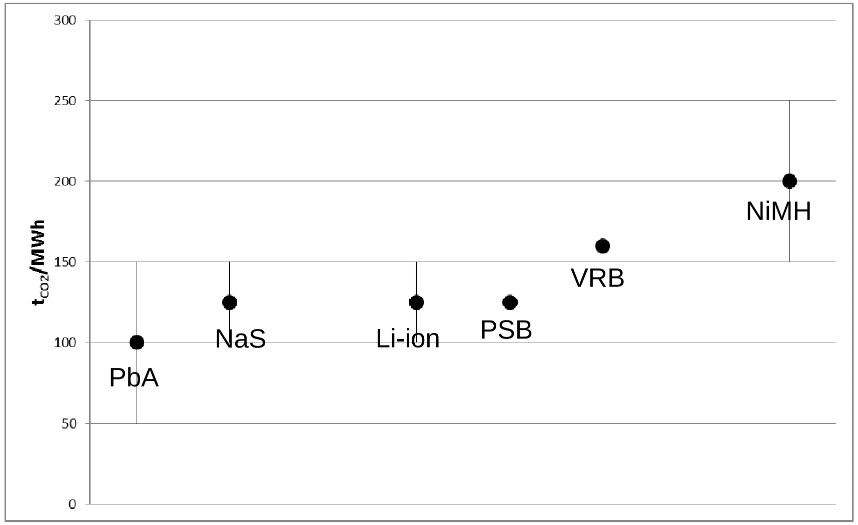




IMPACT OF BATTERY PRODUCTION

- **Synthesis**
  - All technologies lie in a factor 3 for production impact /MWh
  - **Higher energy density compensates for higher impact /kg**
    => EV and stationary storage needs are not so far from one another
  - Energy consumption and GWP are correlated
  - PbA has lowest impact per MWh, NiMH and NiCd the highest
  - Recycling effect is limited, and non-existent during build-up phase



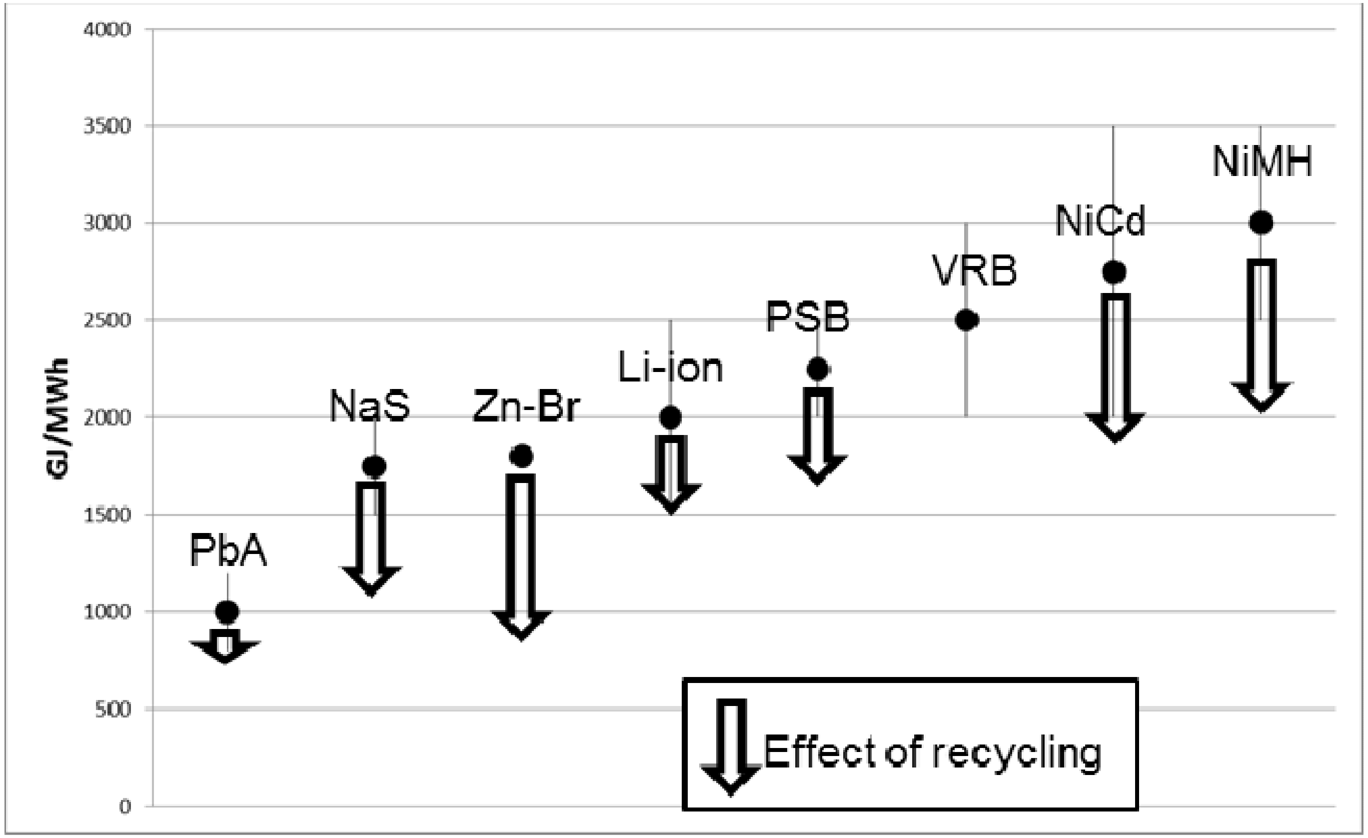


Lack of data for interesting technologies such as
ZEBRA, ZnFe, FeFe, Zn-air, supercapacitors, Lithium-sulfur

IMPACT OF BATTERY PRODUCTION

- **Synthesis**

Building 50TWh of batteries in 10 years with 2000GJ$_t$/MWh
will use 2% of world total energy production



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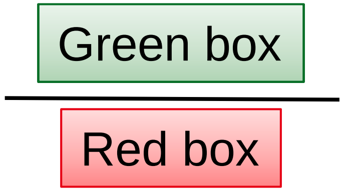
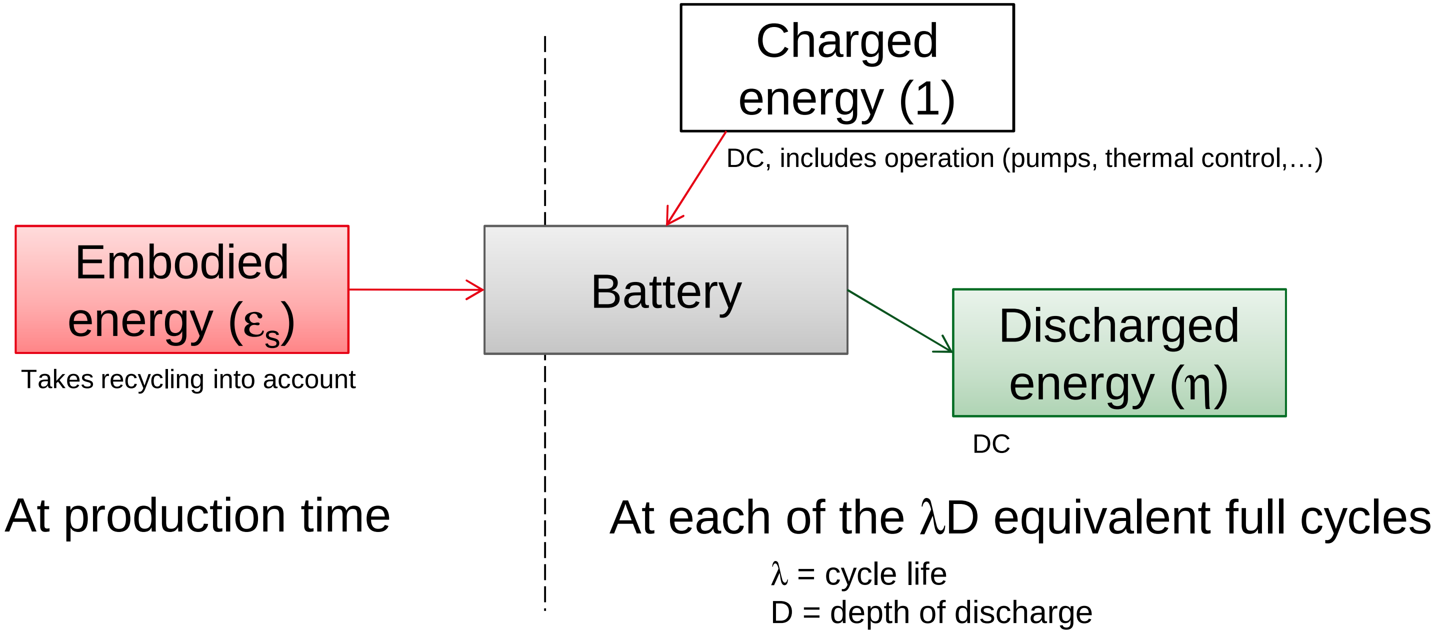
FROM BATTERY PRODUCTION TO EROI

- **Concept of ESOI (energy stored over invested)**
  - Introduced by Stanford in 2013 (very new!)
  - Energy Stored On Invested



$$\boxed{\text{ESOI} = \lambda D\, \eta\, /\, \varepsilon_S}$$



DC, includes operation (pumps, thermal control,…)

Takes recycling into account

DC

At production time

At each of the λD equivalent full cycles

λ = cycle life
D = depth of discharge

FROM BATTERY PRODUCTION TO EROI

1. ESOI

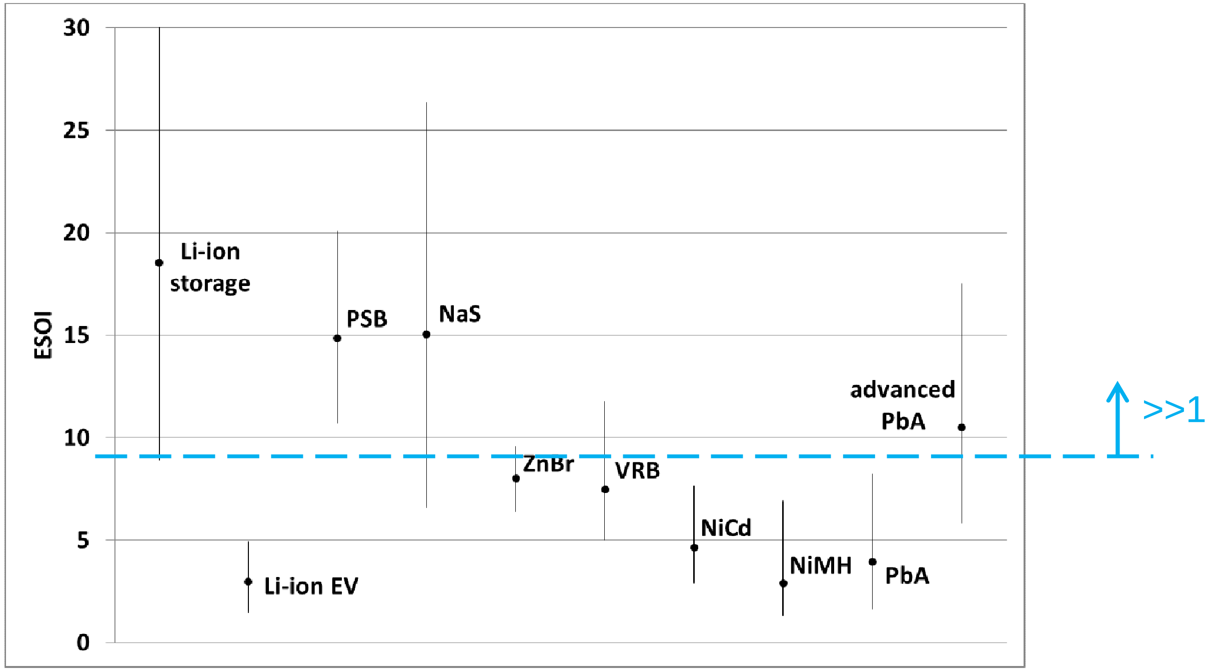
- **Batteries ESOI calculation**
  - Performance parameters used are the following :

	efficiency	Depth of discharge	cycles
PbA	80%	80%	300-1000
advanced PbA	85%	80%	1000-2000
NaS	80%	80%	2000-6000
ZnBr	70%	80%	2000-3000
Li-ion storage	90%	80%	3000-7000
Li-ion EV	90%	80%	500-1000
PSB	65%	100%	4000-6000
VRB	65%	80%	2800-4400
NiCd	75%	33%	4000-6000
NiMH	80%	70%	800-3000

  - Depth of discharge is chosen to optimise full cycles equivalent.
    Cycle number is limited by calendar life (1/day => 15 years = 5000 cycles).
  - No accelerated ageing due to temperature, power,… is considered.
  - Embodied primary energy is converted to electrical using
    1GJ$_t$ <-> 0,0972 MWh$_e$ (35% Carnot efficiency).
    Otherwise all ESOI values would be 3 times lower.

FROM BATTERY PRODUCTION TO EROI
1. ESOI

- **Batteries ESOI calculation**
  - We see best results for Li-ion, followed by Na-S and redox flow
  - NiMH, NiCd, and PbA have insufficient ESOI values
  - Advanced lead-acid with higher cycle life has far better EROI



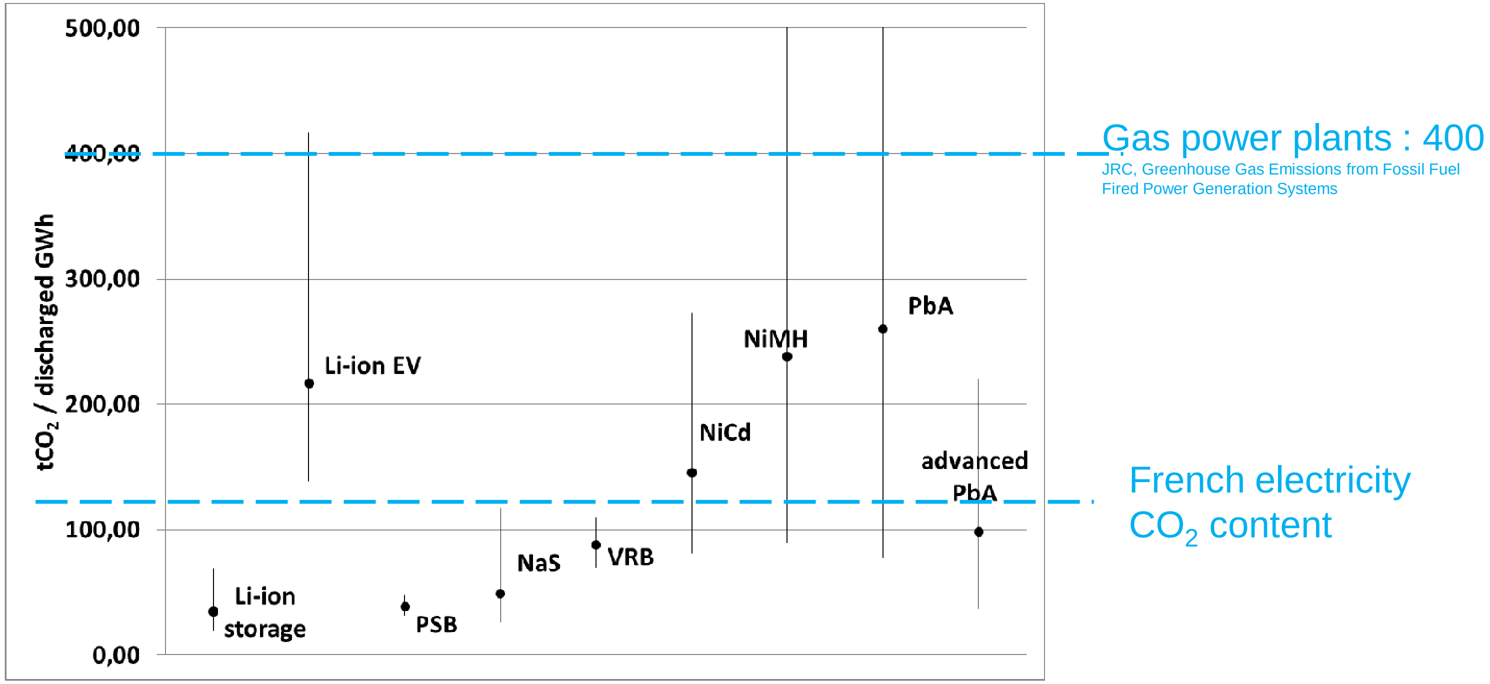
  - Uncertainties included : embodied energy, cycle life
  - Sensitivity to energy efficiency and discount rate (here 0%) are small

FROM BATTERY PRODUCTION TO EROI

1. ESOI

- **CO2 content of stored electricity**
  - We can also estimate the equivalent CO_2 content of stored electricity :

    CO_2 embodied in storage / total discharged energy



Very few data => real uncertainty is huge

But some solutions should not impair too much the benefit of low carbon electricity

FROM BATTERY PRODUCTION TO EROI
2. EROI (RENEWABLE+STORAGE)

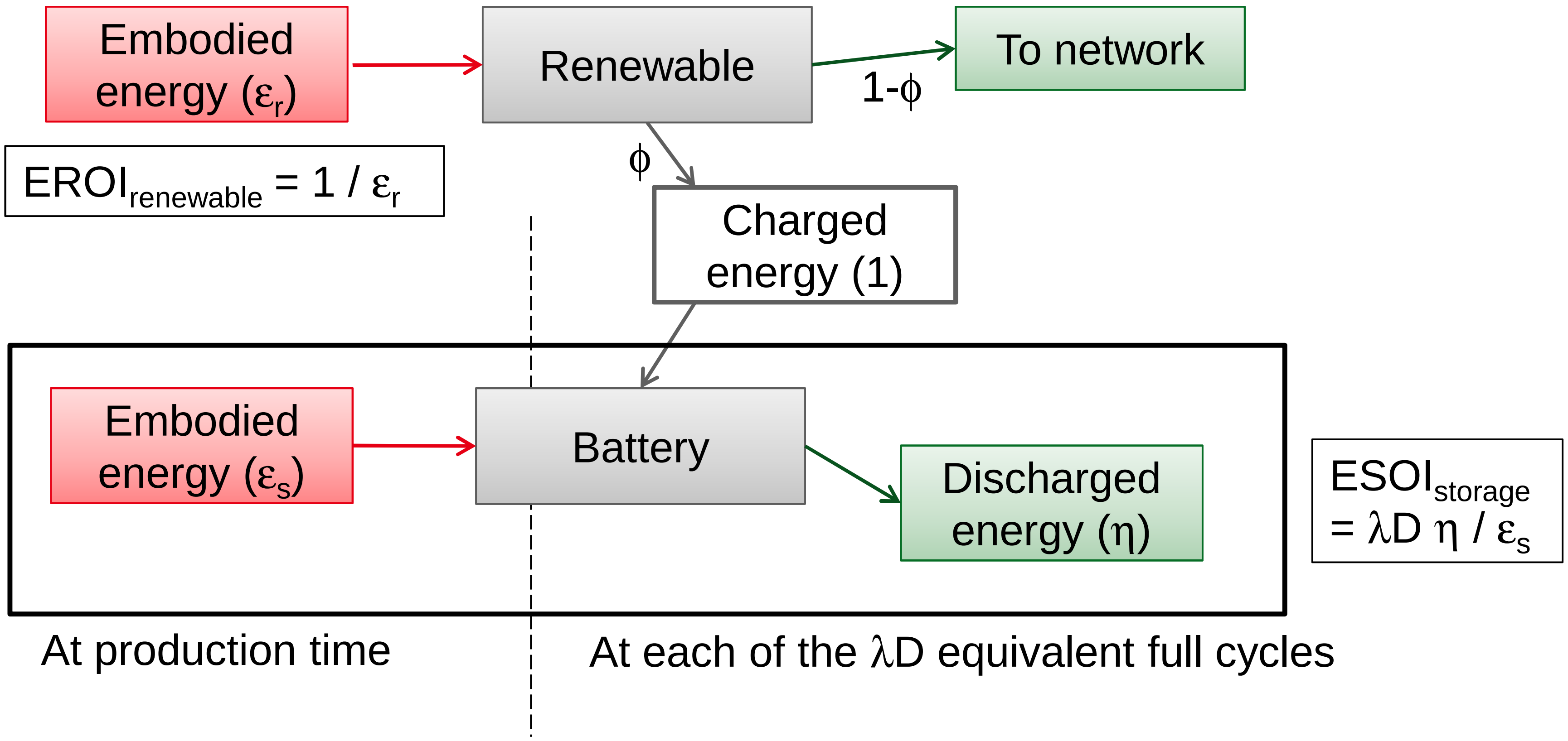
- Barnhardt & al, 2013 use ESOI of the storage to compute the global EROI of a system (renewable production + storage)

- The renewable source is supposed to present a waste ratio ϕ, fraction of its production which is not directly usable and has to be stored
  (e.g. for wind turbines today ϕ=1-16%, increases a lot at >30% renewables)

FROM BATTERY PRODUCTION TO EROI
2. EROI (RENEWABLE+STORAGE)

$$\frac{\text{Green boxes}}{\text{Red boxes}}$$

$$EROI_{renewable+storage} = \frac{1-\phi+\eta\phi}{1/EROI_{renewable} + \eta\phi/ESOI_{storage}}$$



Embodied energy (ε_r)

Renewable

$1-\phi$

To network

$EROI_{renewable} = 1 / \varepsilon_r$

ϕ

Charged energy (1)

Embodied energy (ε_s)

Battery

Discharged energy (η)

$ESOI_{storage} = \lambda D \eta / \varepsilon_s$

At production time

At each of the λD equivalent full cycles

FROM BATTERY PRODUCTION TO EROI
2. EROI (RENEWABLE+STORAGE)

- This $\text{EROI}_{\text{renewable+storage}}$ is greater than the curtailment scenario (waste ratio ϕ is simply discarded) if :

$$\text{ESOI}_{\text{storage}} > (1-\phi)\ \text{EROI}_{\text{renewable}}$$

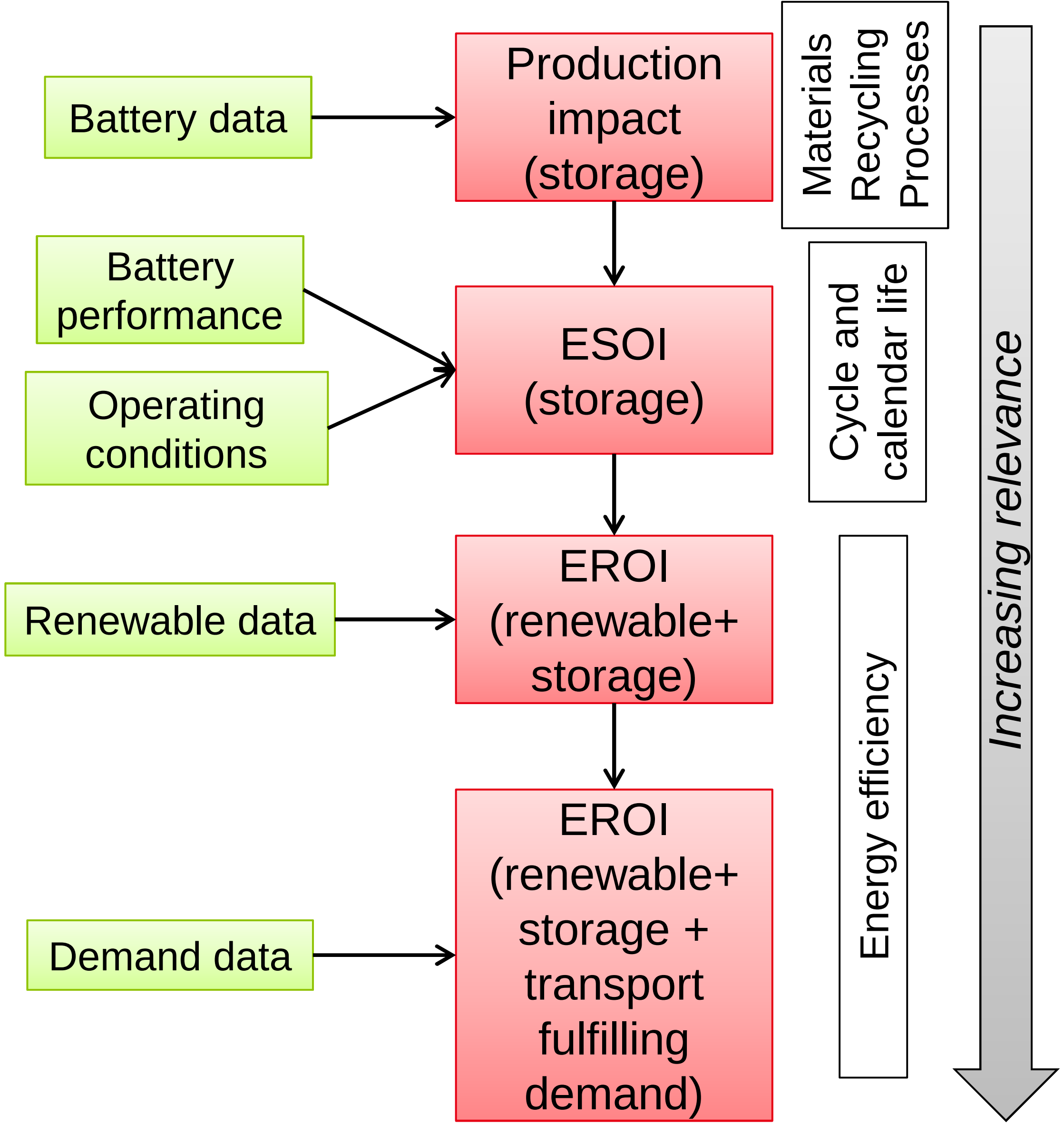
- This indicator takes into account the storage efficiency in a far better way than $\text{ESOI}_{\text{storage}}$

- However, this analysis lacks a link with the demand :
  It is possible to conclude that we should not store energy,
  while the production does not meet the demand.

- In fact, discharged energy has a higher value than direct output energy in that it is manageable

$\text{EROI}_{\text{renewable+storage}}$ is a powerful indicator but should only be used to compare systems which fulfill the same demand

FROM BATTERY PRODUCTION TO EROI
A FULL ANAYSIS IS NECESSARY

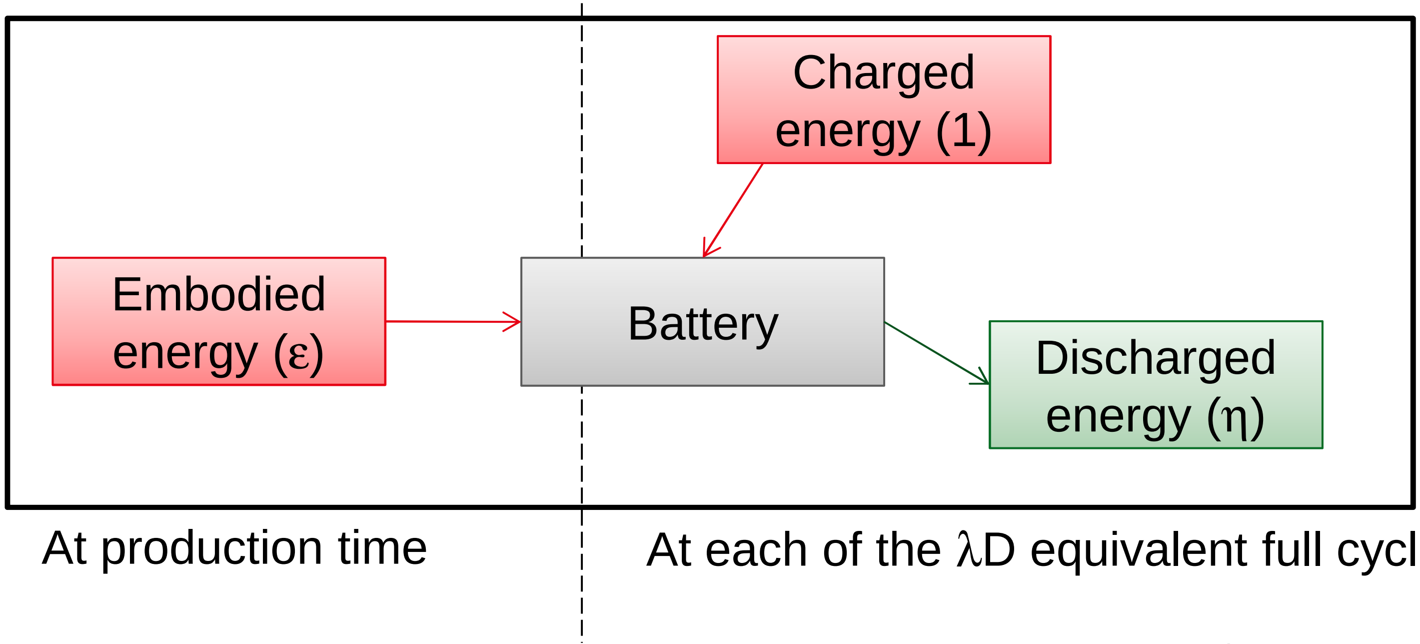


- **Operating conditions** (temperature, timescales) have a huge impact on ESOI partly through **calendar life**
- It is not satisfying to compare storage technologies on ESOI, nor even on $\text{EROI}_{\text{renewable+storage}}$
- The full renewable+storage +network+demand analysis is necessary
- Don't forget to come back to physical impact ($CO_{2\ eq}$,…)

FROM BATTERY PRODUCTION TO EROI
3. NET STORAGE EFFICIENCY

- **A simpler indicator depending only on battery parameters**
  - Used for example by Denholm & Kulcinski 2003
  - Includes both ESOI and energy efficiency effects
  - Net storage efficiency = discharged energy / (embodied + charged)
  - It is easily calculated from ESOI and energy efficiency

$$1/\eta_{eff} = 1/\eta + 1/ESOI$$



Charged energy (1)

Embodied energy (ε)

Battery

Discharged energy (η)

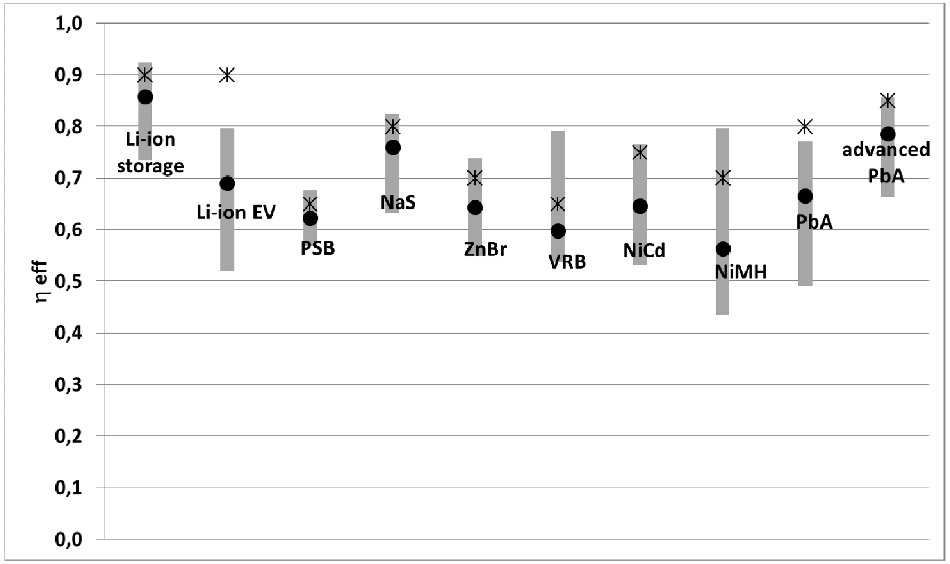
$$\eta_{eff} = \lambda D\eta / (\varepsilon+\lambda D)$$

At production time

At each of the λD equivalent full cycles

FROM BATTERY PRODUCTION TO EROI
3. NET STORAGE EFFICIENCY

- Batteries net storage efficiency calculation



Crosses = efficiency
Rounds and error bars : net efficiency

- Net efficiency is close to trditionnal efficiency except for really low ESOI (<5-10)
- Contrary to ESOI, this indicator gives a too strong importance to efficiency as embodied energy (typ. fossile) and charged energy (typ. renewable) are considered equally.

FROM BATTERY PRODUCTION TO EROI
4. TIMESCALE BASED EROI ANALYSIS

- **Previous examples assumed 1 cycle / day**
  Real application needs span a large timescale range

- **For short times (high power)**
  - Available energy decreases
  - Energy efficiency decreases
  - Cycle life decreases

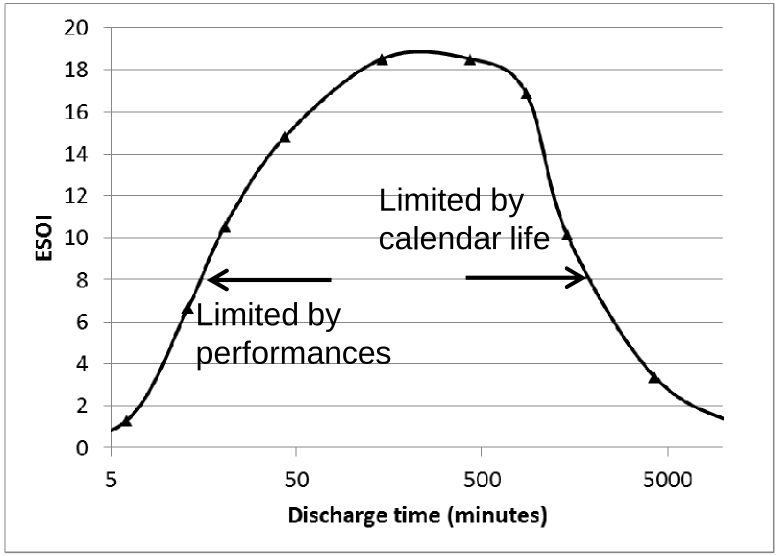
- **For long times**
  - Calendar life limits the number of cycles

- **In both cases the indicators get worse**

FROM BATTERY PRODUCTION TO EROI
4. TIMESCALE BASED EROI ANALYSIS

- **Simple model of Li-ion battery**
  - Limited cycle life : 5000 cycles
  - Limited calendar life : 15 years
  - Available energy decreasing sharply around 5C
  - Embodied energy 2000 GJ/Wh

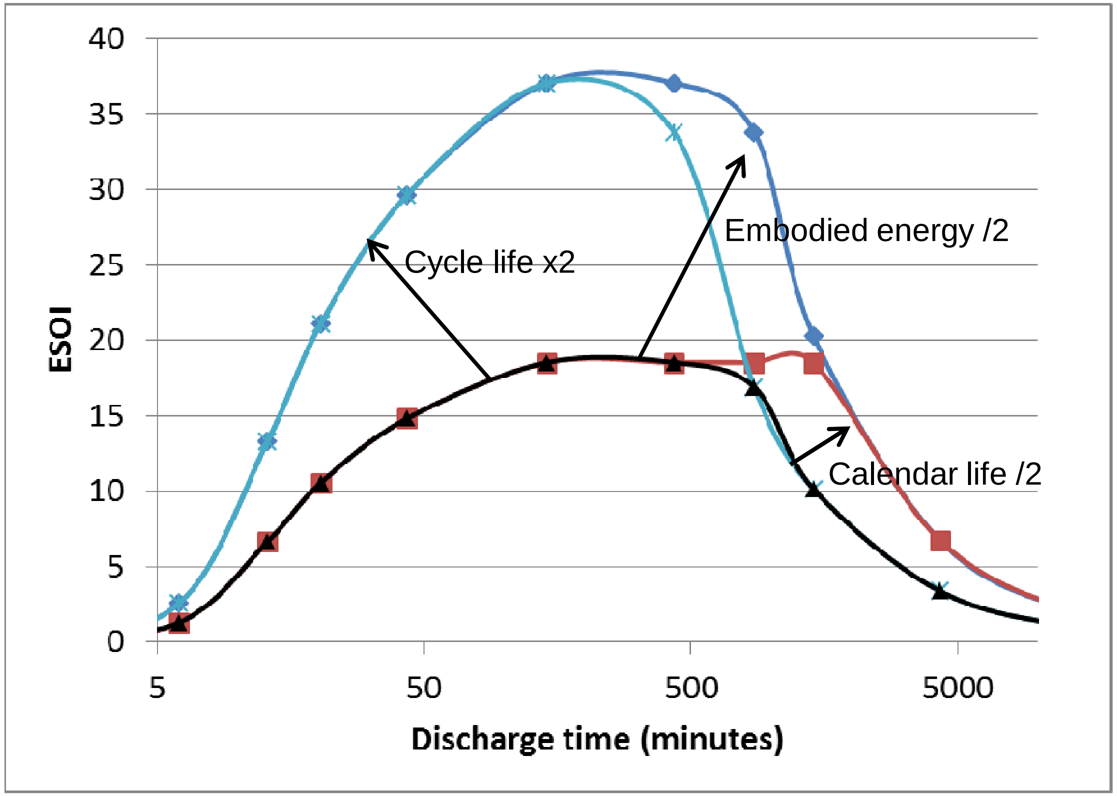
- **Variable parameter = time for charge and discharge**
  - We assume full cycles, and no pause between cycles



ESOI is only optimal in the **1h-12h range** (range where it is tested in lab…)

FROM BATTERY PRODUCTION TO EROI
4. TIMESCALE BASED EROI ANALYSIS

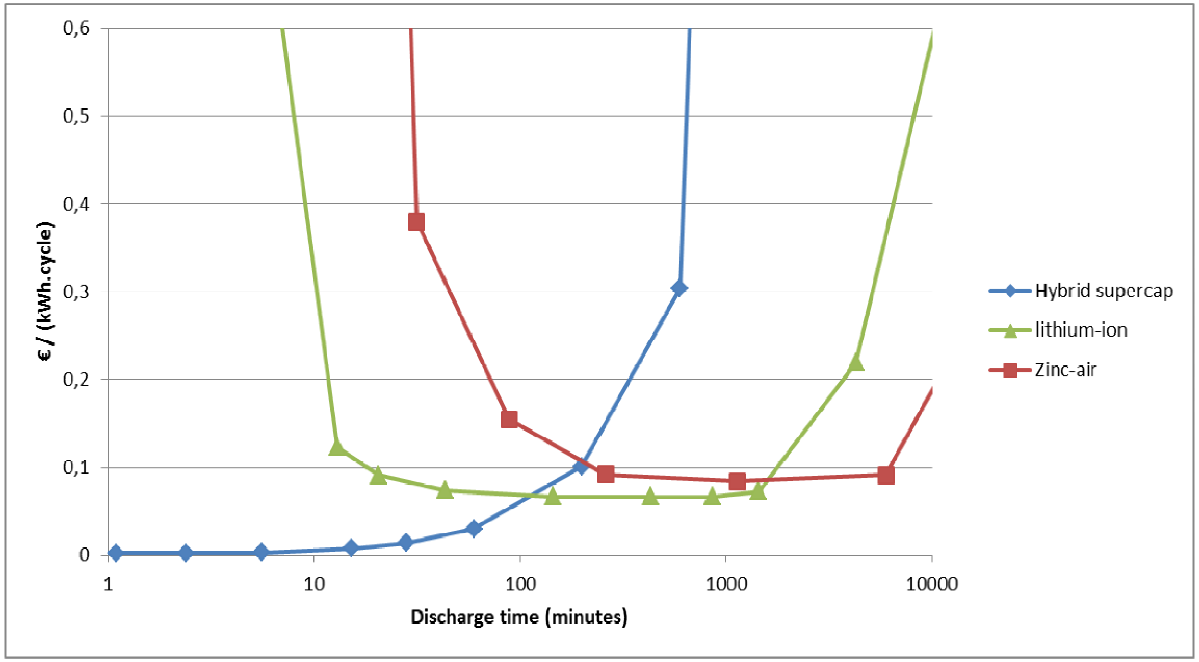
- What should we do to improve ESOI ?



To improve ESOI at short timescales : Cycle life and embodied energy
To improve ESOI at large timescales : Calendar life and embodied energy

FROM BATTERY PRODUCTION TO EROI
4. TIMESCALE BASED EROI ANALYSIS

- **Each technology has its 'preferred' timescale**
  - Below graph is computed with costs (€) instead of ESOI but methodology is the same



Values are very approximate for methodology only…

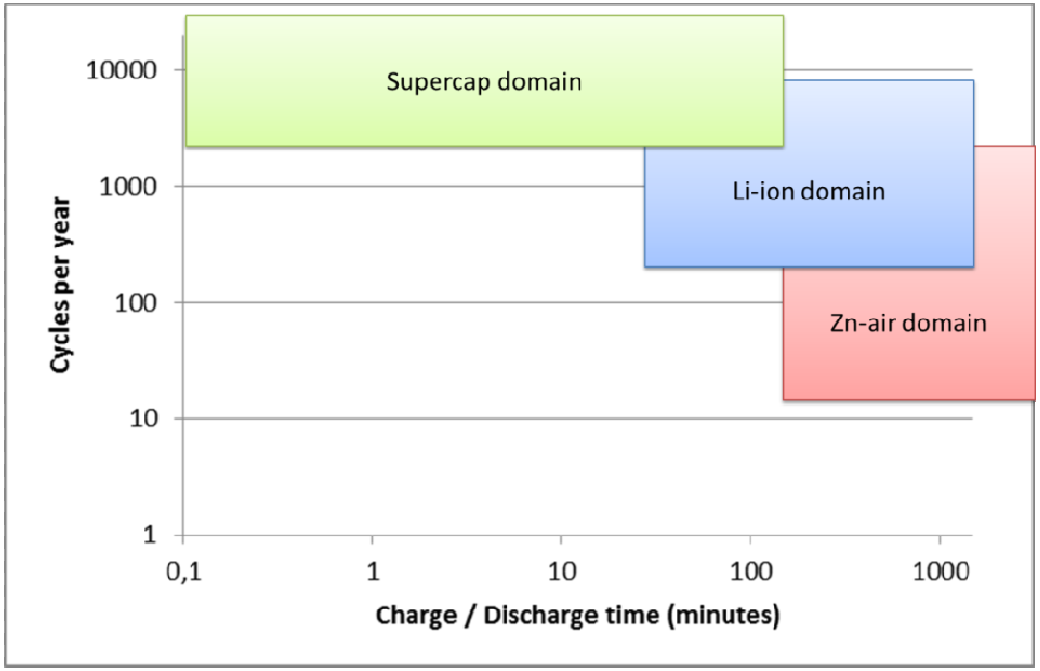
With such a tool, the various technologies can be ranked at each timescale

Possibility to size each technology for the timescale range where it is most suitable (according to €, EROI, CO_2,…)

FROM BATTERY PRODUCTION TO EROI
4. TIMESCALE BASED EROI ANALYSIS

- **Each technology has its 'preferred' timescale**
  - If the system stays idle a large part of the time, two axis are necessary :
    - charge / discharge time
    - cycles per year

Values are very approximate for methodology only…



With such a tool, the network needs could be analysed at different time scales.

Possibility to size each technology for the timescale range where it is most suitable (according to €, EROI, CO_2,…)

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SOME COMPARISONS

- **Hydrogen and the importance of efficiency**

  - Pellow, 2015 compares two strongly different storage technologies :

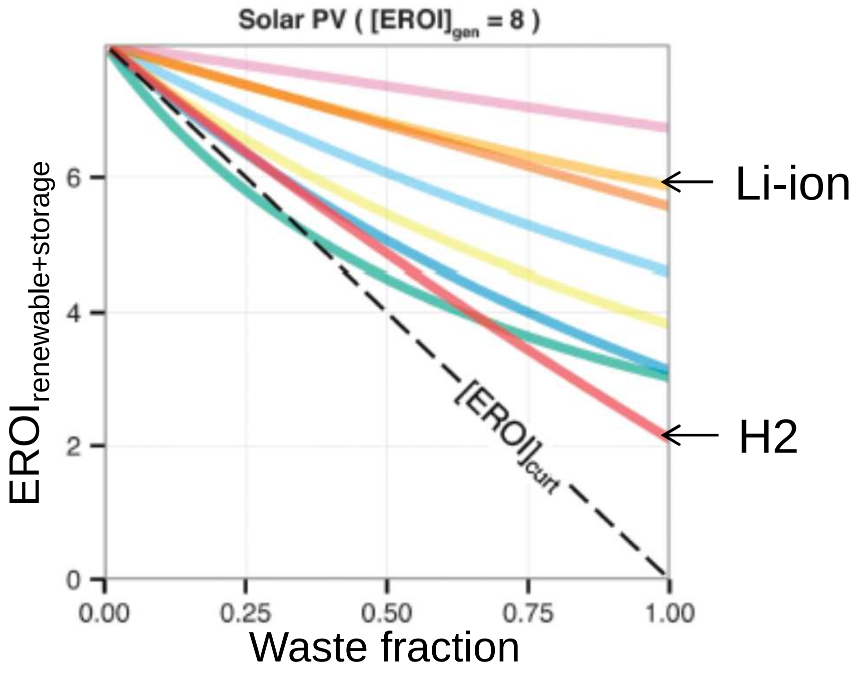
Techno	ESOI	Net energy efficiency
Li-ion	35	**83%**
Regenerative fuel cell	**59**	30%

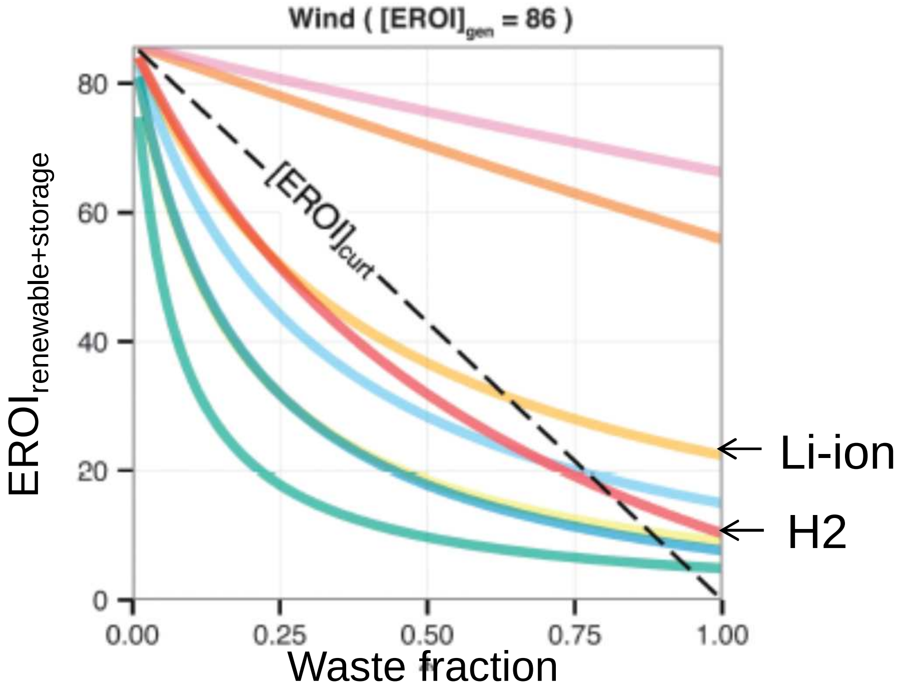
Both ESOI figures are on the optimistic side.

  - They are coupled to a wind farm with EROI=86 or a PV farm with EROI=8 (also optimistic values)

SOME COMPARISONS

- **Hydrogen and the importance of efficiency**
  - Despite its higher ESOI, the H_2 system has similar or lower $EROI_{renewable+storage}$ values than lithium-ion batteries, due to poor efficiency.

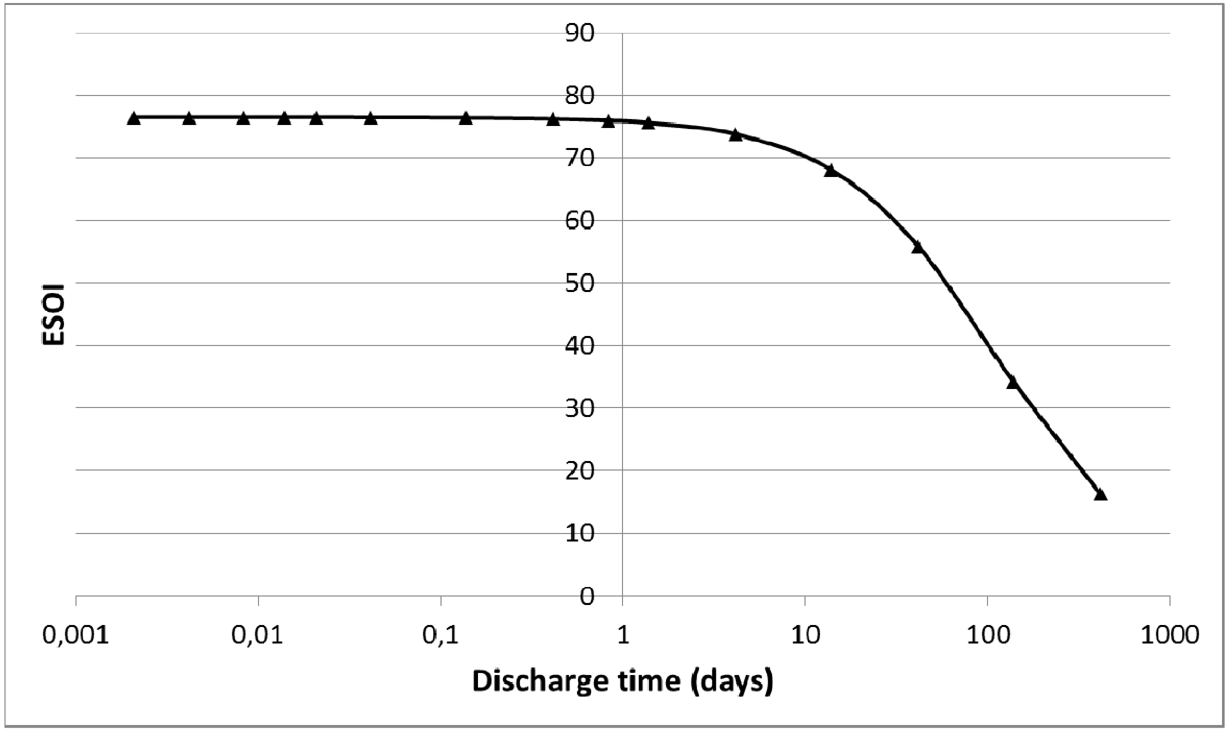




  - Efficiency = 30% means 3 times higher installed renewable capacity for the stored fraction (=> 3 times more €, matter, energy, CO_2,…).
  - Ratio high spot price / low spot price must be >3 for storage (even if the system was free !).

SOME COMPARISONS

- **Hydrogen and timescale analysis**
  - Timescale analysis : the ability to size energy vs power and the low energy embedded in storage gives high ESOI up to timescales where batteries are discarded.



Combined heat and power could help improve the efficiency

SOME COMPARISONS

- **Which solution for seasonal storage ?**

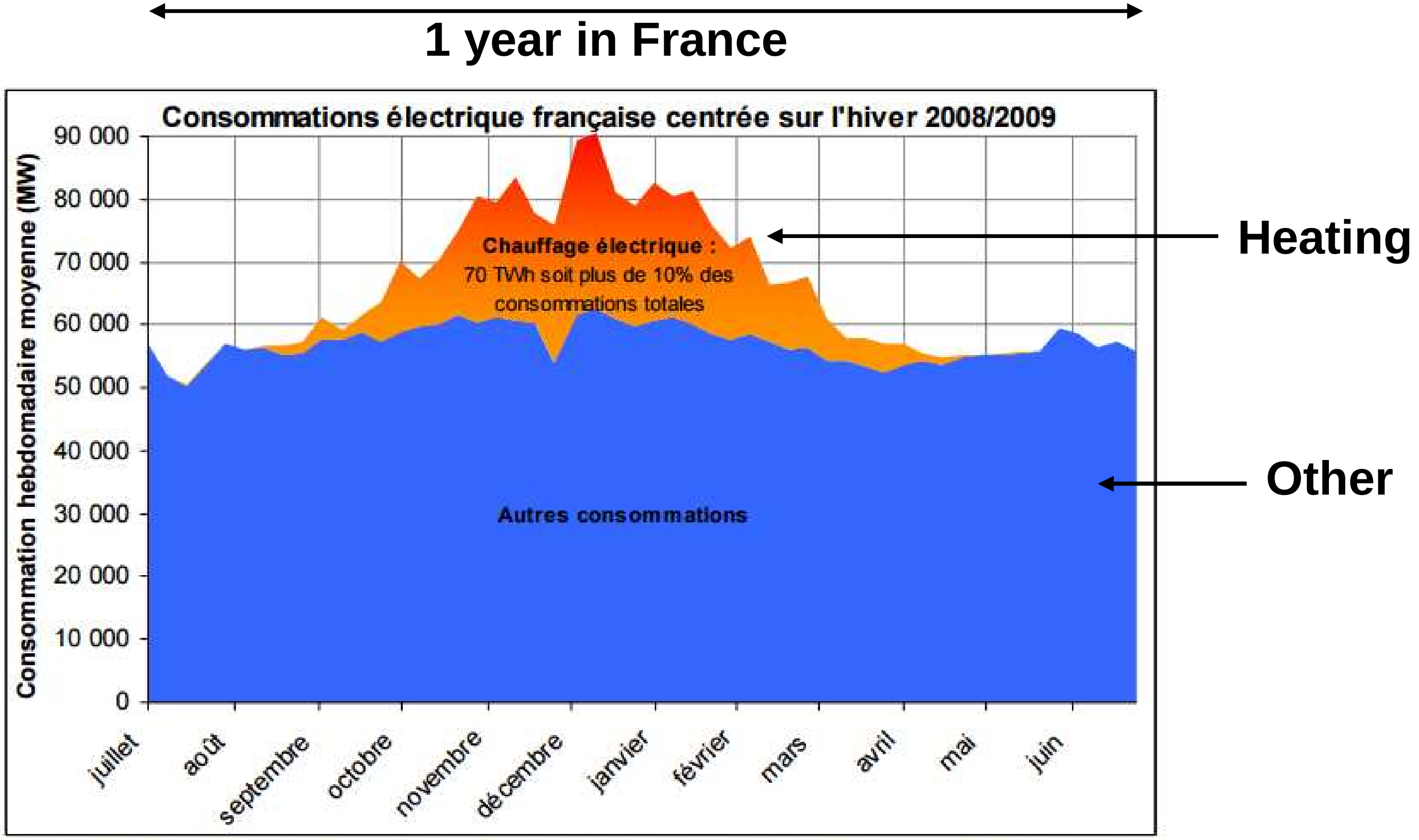
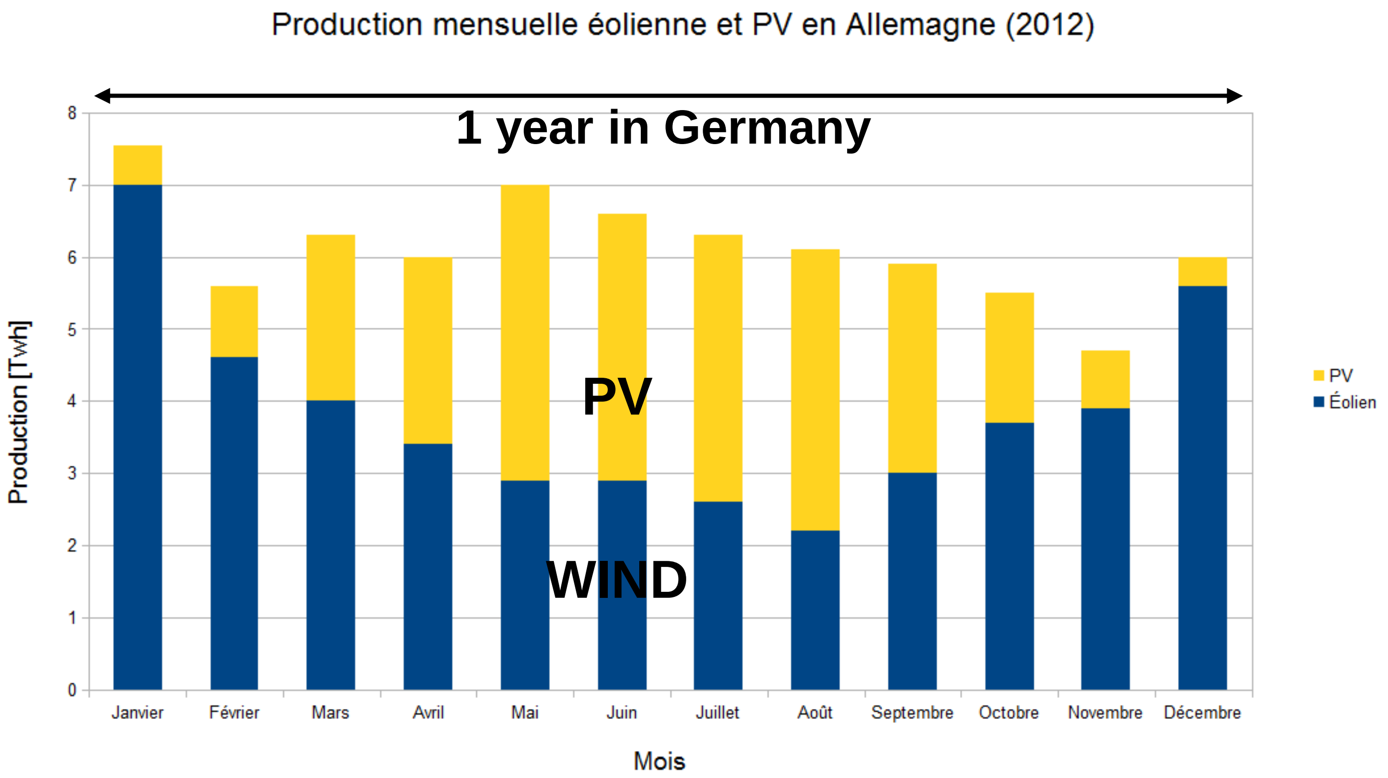


Figure 7 : variation saisonnière de la consommation d'électricité en France liée au chauffage électrique
Source : Données RTE, analyse association négaWatt

The main seasonal consumption pattern is for heating.

SOME COMPARISONS

- Which solution for seasonal storage ?



Seasonal production patterns may be adjusted using wind / power

=> Perhaps there is no need for *electrical* seasonal storage.

SOME COMPARISONS

- **Which solution for seasonal storage ?**

Example of very low tech *seasonal* thermal storage : hot water.

Pit storage
STES in Munich

Need 50-100m^3 of water for a house.
Energy density : >50 Wh/kg
Heat cost with solar thermal panels : ~0,2€/kWh

SOME COMPARISONS

- **Batteries vs PHS (Pumped Hydro Storage)**

Considering for PHS 60 years at 20% capacity factor and E/P=11, with as before 35% thermal -> electric conversion efficiency

	Embodied CO_2 t_{CO2}/MWh_e	Embodied energy GJ_t/Mwh_e	ESOI (incl operation)	CO_2 content of electricity t_{CO2}/GWh_e (incl operation)	Net energy efficiency
Li-ion best estimate (previous slides)	125	2000	18	34,72	86%
Pumped hydro (Denholm & Kulcinsky 2004)	35,7	373	**155**	**5,6**	**74%**

According to these data, pumped hydro is highly desirable.
But :

- Values are very dependent on particular project
- Best sites are chosen first
- EU PHS potential is very variable according to hypothesis chosen (distance between sites, type of sites,…)

Prefer use of pumped hydro where and while **good** sites are available

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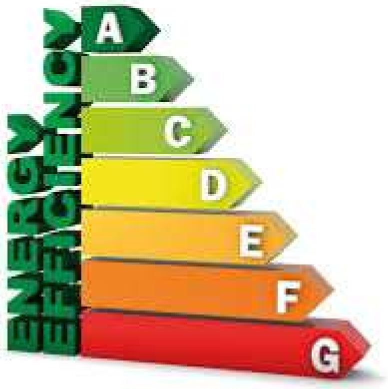
CONCLUSION
1. SIZE DOES MATTER

- We can foresee the need for **very large amount** (50TWh) of daily storage for mobility and renewable integration.
- Resource use and environmental impact will be significant
- We should balance performance with resource consumption

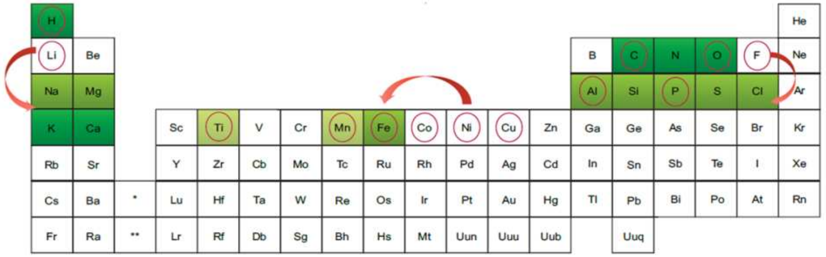
⇒ **Answer n°1 is energy saving** , not technology



CONCLUSION
2. MATERIAL AVAILABILITY

- **Most existing technologies will be limited by material availability, even considering recycling**
- Notable exceptions are Supercapacitors, Na-S, Fe-Fe
- Apart from identified CRM (**Co**), limits will come from **Cd** and **V**, then **Pb** and **Ni**, perhaps from Li, Zn, Ti

- Research should focus on **substitution of Ni at positive then Li at negative** electrodes
- Active research areas able to tackle this limitation include :
  - Organic active materials
  - Sulfur or oxygen cathode
  - Na^+, K^+, Mg^{2+}, Ca^{2+} or Cl^- ions



CONCLUSION

3. IMPACT OF BATTERY PRODUCTION

- Data is insufficient and totally lacks for several interesting technologies (e.g. ZEBRA, Zn-Fe, Fe-Fe, Zn-air, Supercapacitors, Li-S)
  Structured and validated data are needed
  - For impact of battery production
  - But also for perfomance depending on operating conditions

Meanwhile, following conclusions are a bit hasty, yet useful

- **Urgent improvements** to reduce embodied energy (and CO_2)
  1. Materials (1/2 – 3/4 of total)
  2. Processes (1/4 – 1/2 of total)
  3. Recycling (potential gain ~30%)

CONCLUSION
3. IMPACT OF BATTERY PRODUCTION

1. Materials (1/2 – 3/4 of total)

- **Organic or abundant materials**
- **Low temperature synthesis**
  - Hydro-, solvo-, iono- thermal, microwave processes, biomineralization
- Research on **solid / polymer** electrolytes and membranes to unlock metal anode chemistries and improve cycle life
- **Energy density** helps through inactive mass and transport (in VRB main contributors are steel and plastic)
- **Beware of additives** with high embodied energy (e.g. carbon fibers or nanotubes)

2. Processes (1/4 – 1/2 of total)

- **Solvent-less processes** (quit NMP and PVdF)
- New electrolytes to **avoid use of dry room**

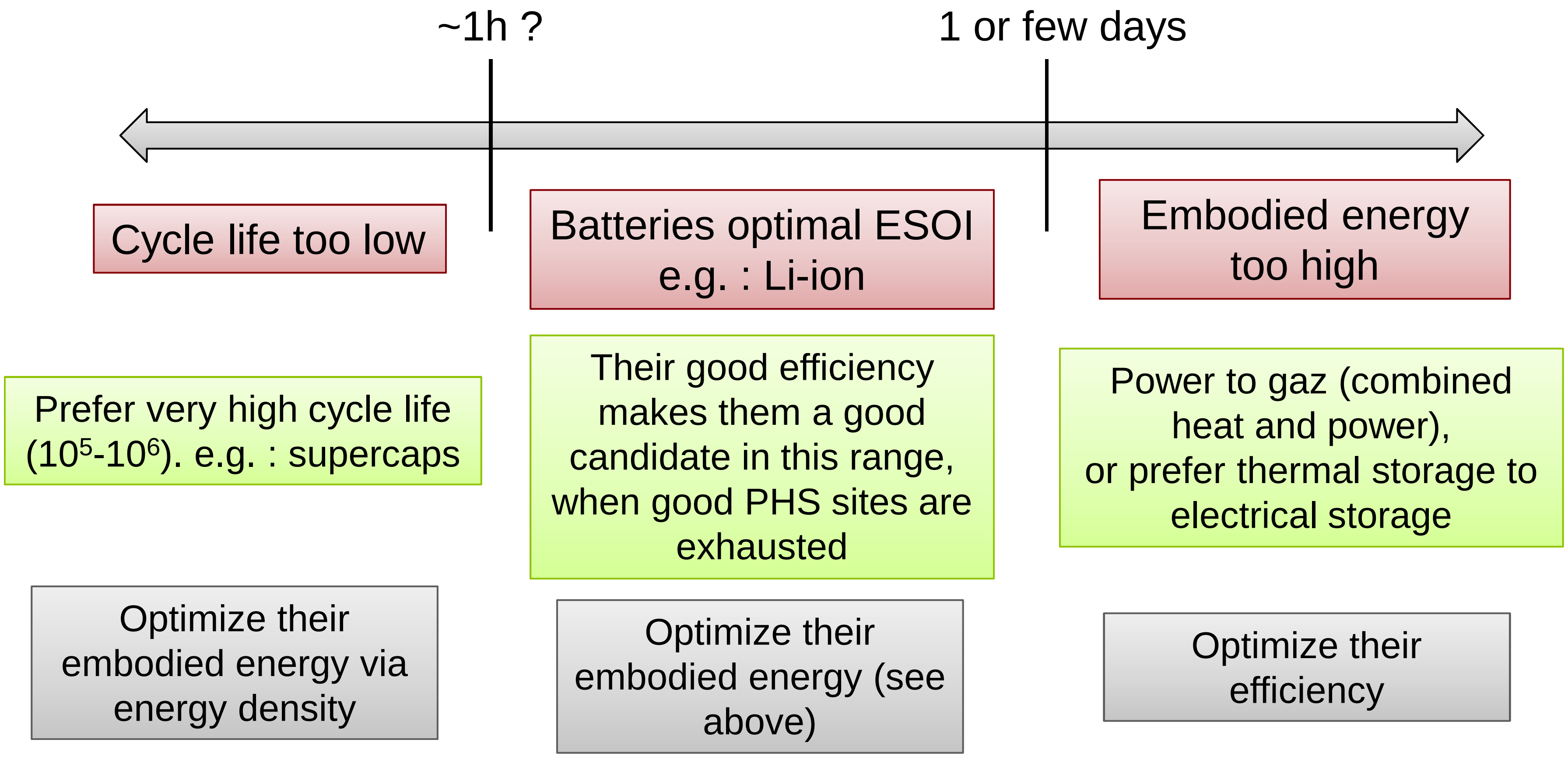
3. Recycling (potential gain ~30%)

- Develop **low impact recycling processes**
- **Standardize** batteries to optimize recycling

cf Larcher & Tarascon, 2015

CONCLUSION
4. ENVIRONMENTAL EVALUATION OF STORAGE

- Study of ESOI at different time scales suggests :



Cycle life too low

Prefer very high cycle life (10^5-10^6). e.g. : supercaps

Optimize their embodied energy via energy density

Batteries optimal ESOI e.g. : Li-ion

Their good efficiency makes them a good candidate in this range, when good PHS sites are exhausted

Optimize their embodied energy (see above)

Embodied energy too high

Power to gaz (combined heat and power), or prefer thermal storage to electrical storage

Optimize their efficiency

Hybridizing is necessary to accomodate all time scales but also to optimize the service life of each system

MERCI POUR VOTRE ATTENTION

THANKS FOR YOUR ATTENTION

Commissariat à l’énergie atomique et aux énergies alternatives
17 rue des Martyrs | 38054 Grenoble Cedex
www-liten.cea.fr

Établissement public à caractère industriel et commercial | RCS Paris B 775 685 019

BATTERY TECHNOLOGIES
ID CARDS

EXISTING BATTERIES : LEAD-ACID

Basic data

Energy density : 30-40 Wh/kg
Power : 10C
Efficiency : 70-80%
Cycle life : 300-500 full cycles for standard PbA
1000-1500 for advanced PbA

Main benefits

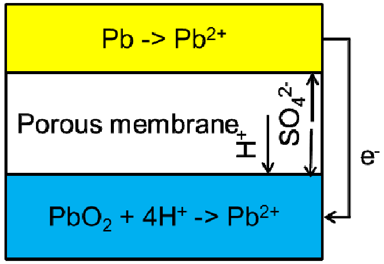
Lowest capital cost
Very mature, observed service life 9-15 years
Abundant materials and **very efficient recycling (96%)**
Very safe, except end of charge electrolysis
and dendrite risk in case of sulfatation

Main problems

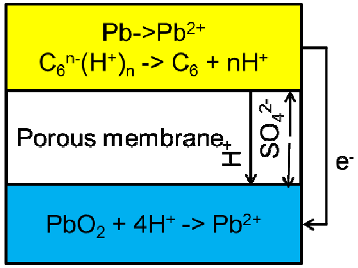
Low cycle life under real conditions, except with carbon anode
Low energy density
Lead toxicity
Sulfatation : cristallisation of $PbSO_4$ if stays discharged

Actors and realisations

Exide / GNB : 1.5MWh in Alaska (1997-12y) 40MWh in California (1988-9y)
C&D batteries :14 MWh in Puerto Rico. Hagen OCSM 14 MWh à Berlin
Hoppecke : aim at 8000 microcycles of 20%DoD in Micronésia
For ultrabatteries :
Xtreme power 24MW 36MWh Ultrabatt in Texas, acquired by Younicos
Furukawa / Ecoult 250kW 1MWh Ultrabatt in New Mexico
Ecoult announces a ‘UltraFlex’ system 5000$ 11kWh 25kW for microgrids
Axion Power



2V



‘Ultrabattery’ variant
with carbon anode

Exide/GNB
1MW (Alaska)

Furukawa 300kW (Japan)
‘ultrabattery’

EXISTING BATTERIES : LI-ION

Basic data (very dependent on particular chemistry)

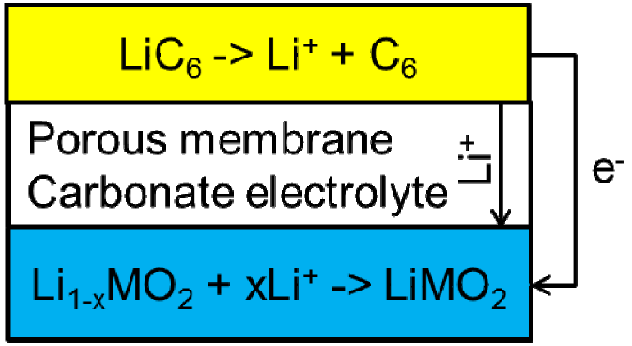
Energy density : 70-250Wh/kg cell (pack/1.4)
Power : 200-3000 W/kg cell
Efficiency : 85-95%
Cycle life : 500-5000

Main benefits

Very good energy density
Good cycle life
Good energy efficiency

Main problems

Security : thermal runaway after ~80℃
No tolerance to overcharge nor overdischarge
Large pack **overmass, overvolume, overcost** to deal with security
Fast charge impossible in particular when cold
Complex BMS necessary
Recycling not yet convincing
Cost is now mostly linked to materials



$LiC_6 \rightarrow Li^+ + C_6$

Porous membrane
Carbonate electrolyte

Li^+

e^-

$Li_{1-x}MO_2 + xLi^+ \rightarrow LiMO_2$

3,7V (3.3-4V)

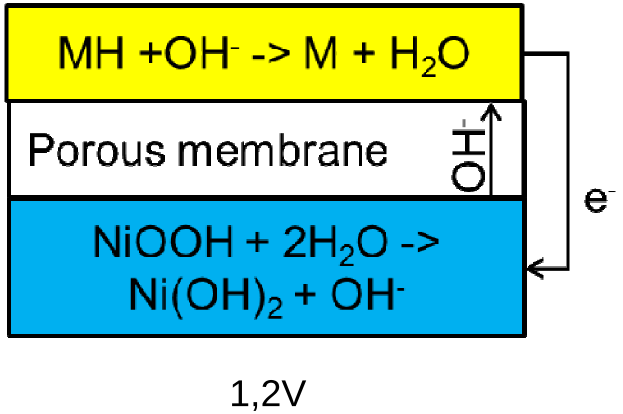
Variants of cathode (LFP, spinels,…), anodes (Si, Li metal, LTO), electrolyte

Variants with Na (~~Li~~) and Al (~~Cu~~)

Actors and realisations

Panasonic, Sony, Samsung, LG Chem, A123, AESC, BYD, Johnson Control, Saft, Amperex, Lishen, Atm, Toshiba, Leclanché, Microvast,…
NEC : Wind storage 4,3 MWh 11MW on Maui.
Given for 80-85% AC efficiency, 8000 cycles and 20 years
Saft : 500 kW 1MWh on Gran Canaria. 95% eff, 20 years daily cycles at 60%DoD
Tesla : announced Powerwall in 2015 at 350\$/kWh
Followed by annouces by Schneider, Electrovaya, Younicos
Xalt energy announced in 2016 NMC/LTO cells of 60 Ah with 16000 full cycles
LG Chem sold for 400MWh of stationary storage systems in 2015.(half of world total)

EXISTING BATTERIES : NI-MH



Basic data
- Energy density : 50-70 Wh/kg
- Power : 700-1000 W/kg
- Efficiency : 80-90%
- Cycle life : 2000 at 80%DoD, 100,000 at 5%DoD
- Self-discharge : 30%/month

Main benefits
- Mature
- High power
- No Cd => replace progressively NiCd batteries.
- Easy recycling

Main problems
- High self discharge through H_2 crossover. Sanyo/Panasonic sells Eneloop low self discharge cells since 2008.
- **Use of rare earth materials**
- **Relatively expensive**
- Need for cooling

Actors and realisations
- Saft (FR) 15 MWh at Fairbanks since 2003.
- Kawasaki Gigacell 150 kW 28kWh at Ishikawa since 2008 and 39 kWh at Amagasaki in 2012.
- Used in Toyota Prius with 5%-10% microcycles*
- BASF announces 140Wh/kg, and aims for 700 Wh/kg (!?!) licensed their patents to Kawasaki Heavy Industries in 2015

EXISTING BATTERIES : NI-ZN

Basic data

Energy density : 70-100 Wh/kg
Power : 600-1400 W/kg
Efficiency : 80%
Cycle life : 500

Main benefits

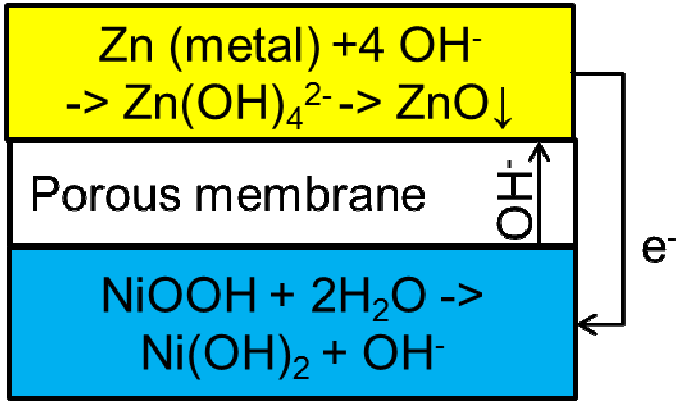
Higher energy density than NiMH
Low cost
Abundant materials
Easy recycling

Main problems

Low maturity level
Limited cyclability, depending on cycling conditions
Zinc dendrites
Sensitive to overdischarge

Actors and realisations

Powergenix (US) realized a NiZn Prius pack 30% lighter than NiMH
SCPS (FR) obtains >1000 cycles
ZAF (US) is a new entrant



Zn (metal) +4 OH^-
-> $Zn(OH)_4^{2-}$ -> ZnO↓

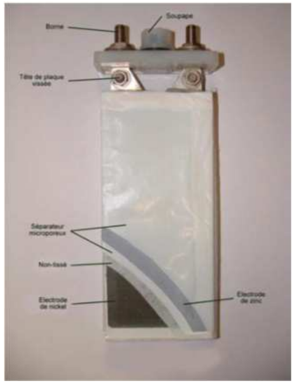
Porous membrane

OH^-

e^-

NiOOH + $2H_2O$ ->
$Ni(OH)_2$ + OH^-

1,65V



SCPS

Powergenix

EXISTING BATTERIES : SODIUM-SULFUR

Basic data

Energy density : 110-150 Wh/kg
Efficiency : 85%-90% -thermal losses
Cycle life : 3000-6000

Main benefits

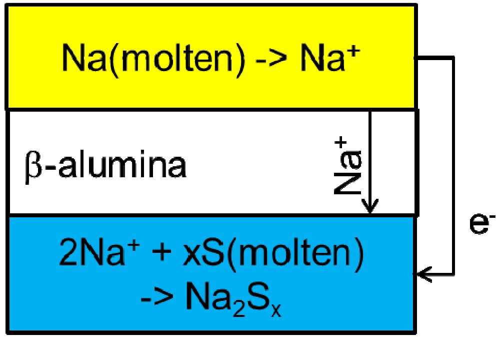
Among the most mature technologies
Abundant and low cost materials
Good energy density and cycle life
Can operate in any external temperature

Main problems

300-350℃ => thermal losses 20%/day
Long term water tightness (corrosion)
Safety : liquid Na, fire risk if failure of alumina
e.g. fire in Tsukuba 2011 for 2 weeks
Low tolerance to stop / restart

Actors and realisations

NGK (JP) : 450 MW installed
Space shuttle mission STS-87 in 1997
34MW in a wind farm, Rokkasho Village, 2008



Na(molten) -> Na^+

β-alumina

Na^+

e^-

$2Na^+ + xS$(molten) -> Na_2S_x

2V

EXISTING BATTERIES : ZEBRA

Basic data

- Energy density : 90-100 Wh/kg
- Efficiency : 85%-90% -thermal losses
- Cycle life : 2000-3000, 15 years

Main benefits

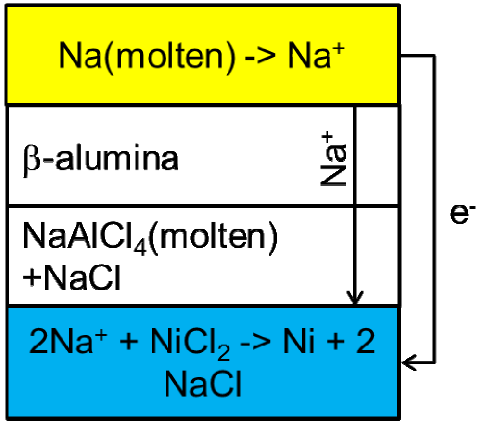
- Can operate in any external temperature
- **Less dangerous than Na-S**
- **Good energy density and cycle life**
- Ni easily recycled (and pays the recycling)

Main problems

- **250-350℃ => thermal losses 15%/day**
- **Safety : liquid Na**
- 24h heating before use

Actors and realisations

- Developed in South Africa, 1985
- GE Durathon (US) 115Wh/kg, 3000 cycles at 80%DoD, 20 years. seems abandoned
- FIAMM Group (IT) for 250 EV Kangoo (La Poste)
- Sumitomo (JP) announced 90℃ technology with 1000 cycles



Na(molten) -> Na^+

β-alumina

Na^+

$NaAlCl_4$(molten) +NaCl

$2Na^+ + NiCl_2$ -> Ni + 2 NaCl

e^-

2,58V

EXISTING BATTERIES : VANADIUM FLOW BATTERY

Basic data

Energy density : 10-30 Wh/kg
Power : 100 mW/cm²
Efficiency : 60%-80% in best operating range
Cycle life : 3000-10000
Operating temp : 10℃-40℃

Main benefits

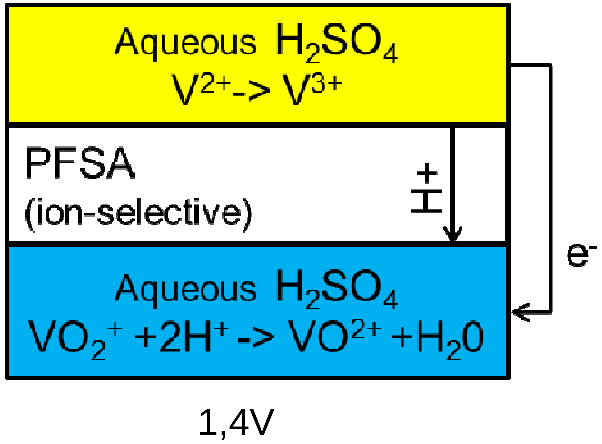
E / P decoupling
Long service life
Safety
Tolerance to overcharge / overdischarge
Cross contamination = self discharge

Main problems

High operating costs
Complex auxiliaries
Self-discharge
Corrosive electrolyte
precipitation of V_2O_5 near 50℃-60℃
Low real world efficiency
Research focuses on temperature range and electrolyte concentration

Actors and realisations

Gildemeister (DE) 8000 install worldwide
Imery (US)
Prudent Energy (CN)
Sumitomo (JP)
Rongke Power (CN) 5MW 10 MWh at Woniushi



Aqueous H_2SO_4
$V^{2+} \rightarrow V^{3+}$

PFSA
(ion-selective)

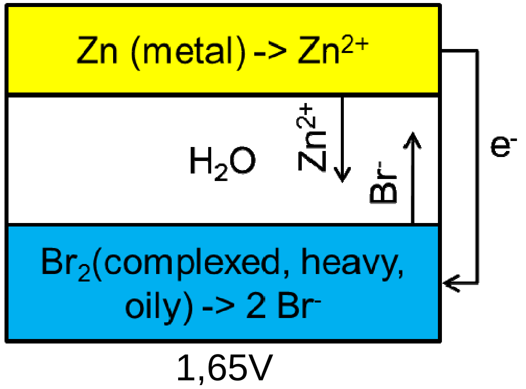
H^+

e^-

Aqueous H_2SO_4
$VO_2^+ + 2H^+ \rightarrow VO^{2+} + H_20$

1,4V

EXISTING BATTERIES : ZN-BR HYBRID FLOW BATTERY



<u>Basic data</u>

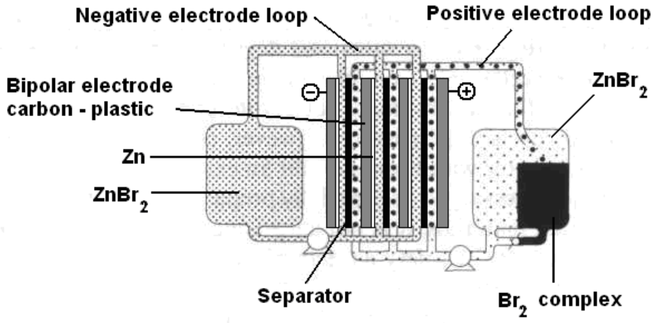
- Energy density : 60-90 Wh/kg
- Power : 200 mW/cm²
- Efficiency : 70%-75%
- Cycle life : >3000

<u>Main benefits</u>

- Partial E/ P decoupling
- No DoD limit
- **Long cycle life**
- Tolerance to overcharge / overdischarge
- **0V on commissionning, and possible anytime**

<u>Main problems</u>

- **Br_2 highly toxic and corrosive** => use of complexing agents
- **Zn dendrites => full discharge every few days**
- **Complex auxiliaries**
- Br^- and Zn^{2+} concentrations increase during discharge



<u>Actors and realisations</u>

- Redflow (AU) guarantees 10 years and 3000 cycles on 11kWh modules for 8800$
  - Launches home storage in 2016
- Ensync Energy Systems (US) 55kWh/12.5kW/2.2t modules
- Primus Power (US) 100MWh/25MW project in Kazakhstan

EXISTING BATTERIES : H2-BR FLOW BATTERY

Basic data

- Energy density : 90-100 Wh/kg
- Power : > 1W/cm²
- Efficiency : 70%-80% at 100mW/cm²
- Cycle life : >10000
- Operating temp : -20℃ +55℃

Main benefits

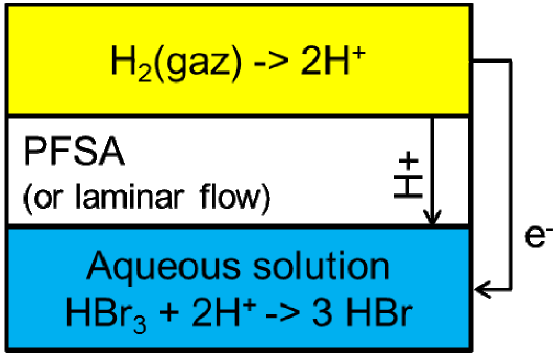
- **E / P decoupling**
- **Abundant and low cost materials**
- **Large operating temperature range**
- No DoD limit
- **Long cycle life**
- Tolerance to overcharge / overdischarge

Main problems

- **HBr and Br_2 highly toxic and corrosive**
- Loss of capacity by Br_2 crossing
- **Environmental impact**
- System cost

Actors and realisations

- Enstorage (IS) project with AREVA, EdF, CEA,… for
  - 900 kWh 150 kW
- Publications from MIT with laminar flow



H_2(gaz) -> $2H^+$

PFSA

(or laminar flow)

H^+

e^-

Aqueous solution

$HBr_3 + 2H^+ \rightarrow 3\,HBr$

2,06V

EXISTING BATTERIES : BR-POLYSULFIDES FLOW BATTERY

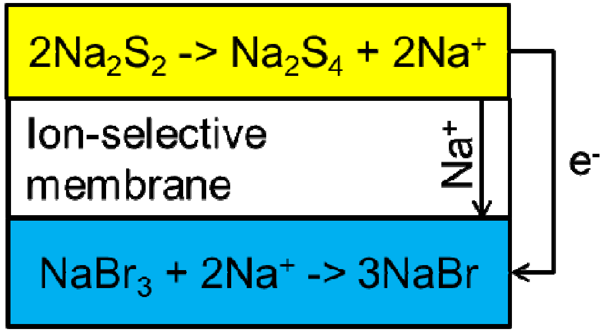
Basic data

Energy density : 20-30 Wh/l

Power : 40 mA/cm²

Efficiency : 65%-75%

Cycle life : 3000-5000



$2Na_2S_2 \rightarrow Na_2S_4 + 2Na^+$

Ion-selective membrane

Na^+

e^-

$NaBr_3 + 2Na^+ \rightarrow 3NaBr$

1,36V

Main benefits

E/ P decoupling

Low cost and abundant materials

Aqueous electrolyte and high solubility

(a)

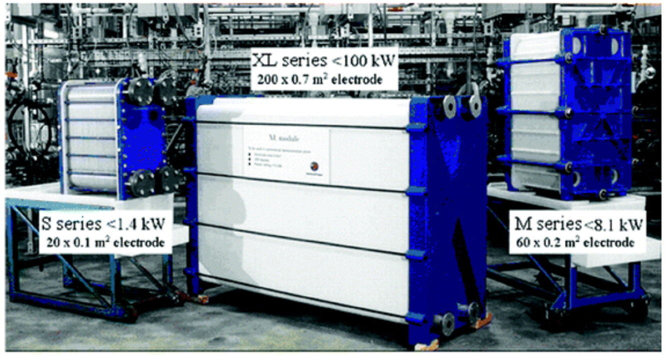
Main problems

Cross-contamination of the electrolytes

Br_2 and H_2S released if electrolytes are mixed

Br^- is very corrosive

Buildup of sulfur species in the stack



(b)

Actors and realisations

Regenesys (acquired by Prudent Energy)

1MW successfully demonstrated in South Wales.

15 MW prototypes in Little Barford Power Station (UK) and Tenessee Valley were never commissionned / finished.

EXISTING BATTERIES : FE-FE HYBRID FLOW BATTERY

Basic data

Energy density : 11-18 Wh/kg
Power : 60 mW/cm²
Efficiency : 70% AC-AC
Cycle life : >10,000 cycles and 25 years

Main benefits

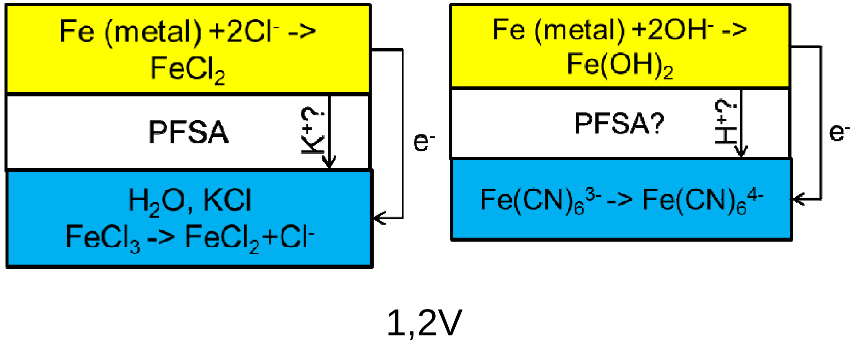
Partial E/P decoupling
Abundant and low cost materials
Very high cycle life
Can use twice the same electrolyte

Main problems

Low energy density

Actors and realisations

Arotech (IS)
Energy Storage Systems (US) 125kW 1MWh



Energy Storage Systems

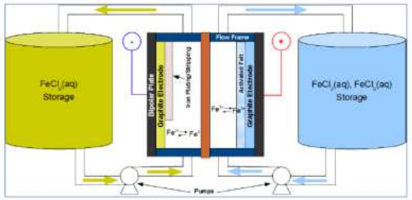
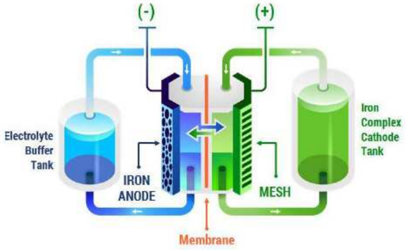


Figure 1.6 – Diagram of an iron hybrid flow battery including system components and electrochemical reactions.

Arotech



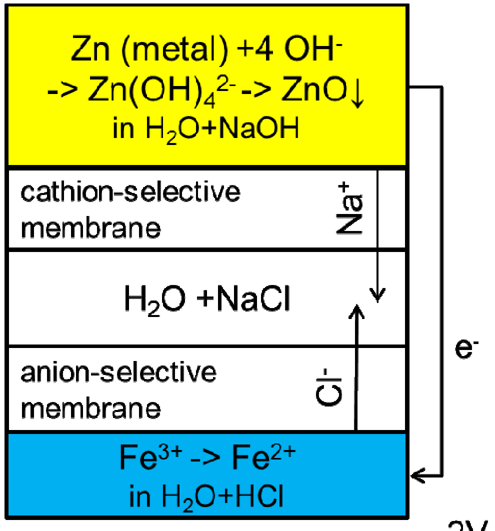
EXISTING BATTERIES : ZN-FE HYBRID FLOW BATTERY

Basic data
- Energy density : 7 Wh/kg at container scale
- Power : 600 mA/cm² with 3 electrolytes system
- Efficiency : 80% at C/2, 90% at C/7
- Cycle life : 10,000 and 20 years

Main benefits
- Partial E/P decoupling
- **Abundant, safe and non toxic materials**
- **Low cost** : 800 $/kWh in 2015, "300 in 2017"
- Easy recycling

Main problems
- **Energy density !**
- (Rejuvanation cycle after x1000 cycles)

Actors and realisations
- ViZn Energy (US), first shipping 2014
  - INL purchase for 320 kWh – 128 kW
  - Base stack 16 kW, Container 120-160 kWh



Zn (metal) +4 OH^- -> $Zn(OH)_4^{2-}$ -> ZnO↓ in H_2O+NaOH

cathion-selective membrane Na^+

H_2O +NaCl

anion-selective membrane Cl^-

Fe^{3+} -> Fe^{2+} in H_2O+HCl

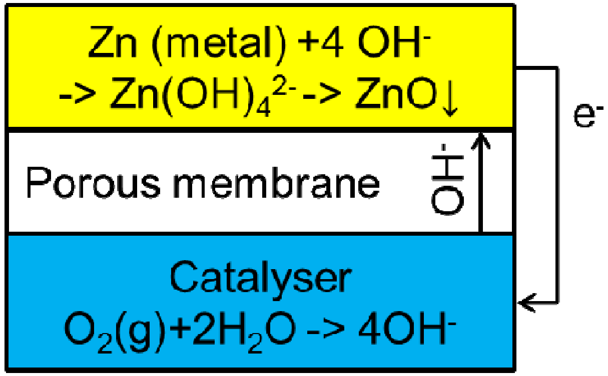
e^-

2V

Energy Environ. Sci., 2015, 8, 2941

ViZn : 1,64V

EXISTING BATTERIES : ZN-AIR



Zn (metal) +4 OH^- -> $Zn(OH)_4^{2-}$ -> ZnO↓

Porous membrane

OH^-

e-

Catalyser

$O_2(g)+2H_2O$ -> $4OH^-$

1,32V

Basic data

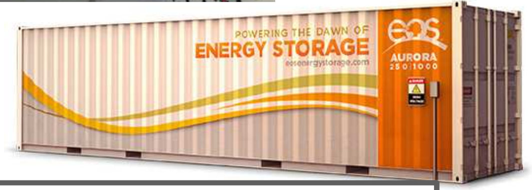
- Energy density : 200-250 Wh/kg, 50 mAh/cm²
- Power : 20 mA/cm²
- Efficiency : 60-75%
- **Cycle life : 100-200**, EOS claims 5000 and 15 years…
- Self-discharge 1%/day
- A flow variant exists with flowing Zn particles

Main benefits

- Most mature of high promise metal-air systems.
- **High energy density (air cathode), but beware of system**
- Particularly **low cost**
- **Abundant and non toxic materials**
- Easy recycling

Main problems

- Zn dendrites during charge => use of additives
- Air electrode stability during charge => use of third electrode
- Carbonatation of alcaline electrolyte -> K_2CO_3 which clogs the cathode
- ZnO precipitation => large electrolyte volume
- Electrolyte circulation and treatment, heat management
- Air / O2 crossover
- Low energy efficiency



Actors and realisations

- Many have died : Revolt, Power Air Corp, Leo Motors,…
- Phinergy (IS) carbon-free cathodes
- EOS Energy storage (US) pH-neutral electrolyte. Tested at Engie since 2014. Contract with NEC.
  - Recently don't talk anymore about air electrode but only zinc anode.
- EdF-SCPS collaboration (FR). Annouce 1500 cycles
- Fluidic Energy (US) uses ionic liquids 50000 cells installed for 10 MW.. MOU for 250 MWh in Indonesia.

EXISTING BATTERIES : AQUEOUS NA-ION

Basic data

Energy density : 15-30 Wh/kg
Efficiency : 80%
Cycle life : 5000

Main benefits

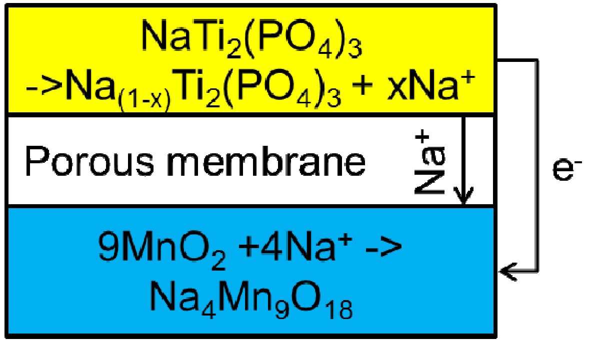
Abundant and low cost materials
High cyclability
Easy recycling
Very safe

Main problems

Low energy density
Low power (C/2)

Actors and realisations

Aquion Energy, 25 kWh modules
Installed 54 kWh at a ranch in California



$NaTi_2(PO_4)_3$ -> $Na_{(1-x)}Ti_2(PO_4)_3 + xNa^+$

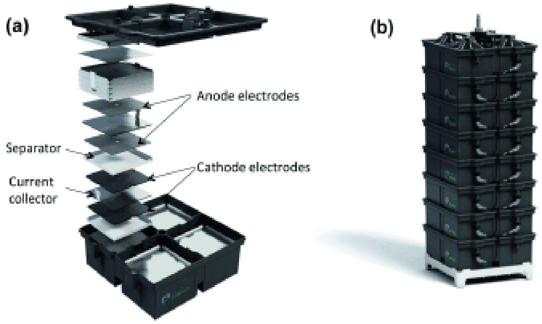
Porous membrane

Na^+

e^-

$9MnO_2 + 4Na^+$ -> $Na_4Mn_9O_{18}$

1,5V



UPCOMING BATTERIES : LITHIUM-SULFUR

Basic data

Energy density : 300 Wh/kg_{cell}, practical target 400-600 Wh/kg
Efficiency : 80-85%
Cycle life : 100-300, target >1000

Main benefits

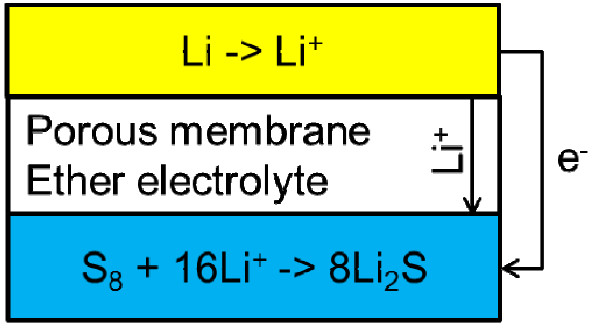
High energy density (transportation)
Cheap, abundant and non toxic materials
Anticipated low cost

Main problems

Today much lower energy and cycle life than expected :
S and Li_2S are insulating and clog the cathode
Intermediate polysulfides are soluble and induce self discharge
Electrode morphology changes with dissolution/precipitation
Dendrites and passivation of lithium metal anode
Same BMS need as Li-ion
Fire risks

Actors and realisations

Sion Power (US) / BASF : 350 Wh/kg on a solar drone in 2010
Oxis Energy (UK) 325 Wh/kg and 200 cycles or 220 Wh/kg and 1400 cycles of 80%DoD
Polyplus (US) with focus on protected lithium electrode and aqueous catholyte



$Li \rightarrow Li^+$

Porous membrane
Ether electrolyte

Li^+

e^-

$S_8 + 16Li^+ \rightarrow 8Li_2S$

2,2 V

UPCOMING BATTERIES : SOLID STATE BATTERIES

Basic data

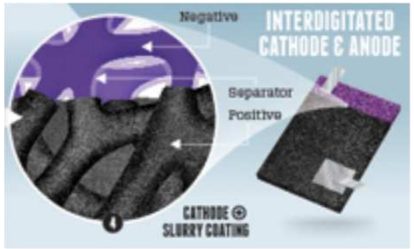
Same chemistry as Li-ion, Li-S,… but solid electrolyte :
ceramic, glass, polymer, or gel
Today 100 Wh/kg, target 400 Wh/kg
Temperature range highly dependent on the electrolyte

Main benefits

Solid electrolyte **unlocks safe use of metallic lithium**
High energy densities, hopefully **high calendar** and **cycle life**
Enables also **new architectures and processes**
- maybe no dry room, maybe no solvant
- maybe high power architectures

Main problems

The only available today is **POE working above 60°C**
Most others have either **low conductivity** or **low processability**



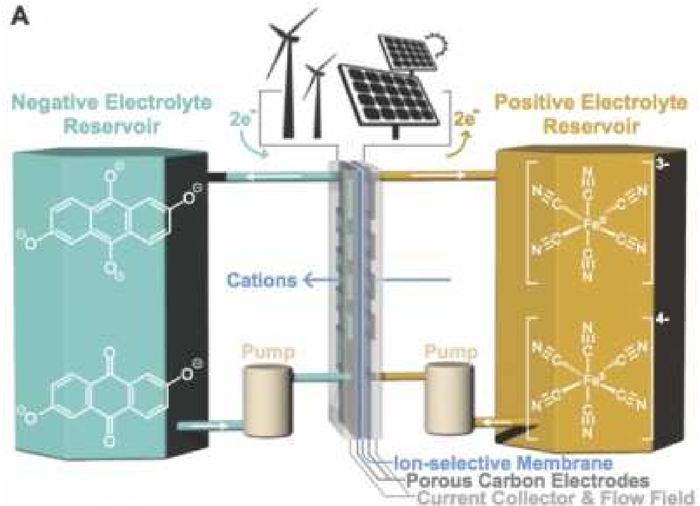
Actors and realisations

Blue Solutions (FR) uses POE electrolyte for Li/LFP cells in the Blue Car
- **always plugged** to stay hot

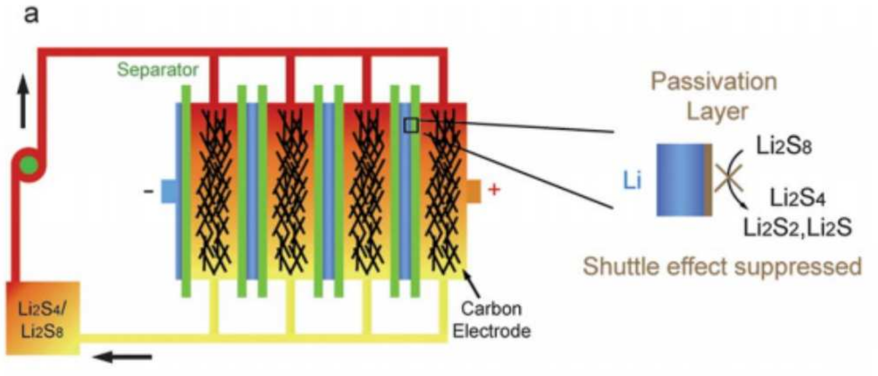
Seeo (US) developed a POE copolymer (hard/conducting domains).
- Acquired by Bosch, aims at 400 Wh/kg and 150$/kWh en 2018

Sakti3 , MIT spinoff acquired by Dyson, rather secretive…
Solid Energy (US) announced 1200Wh/l with polymer and ionic liquid electrolyte
Toyota (JP) has a long record on inorganic solid electrolytes, followed by BMW.
Prieto (US, Intel funding) explores 3D architectures with solid electrolyte

UPCOMING BATTERIES : NEW REDOX FLOW



Harvard **organic flow battery** published in 2014 gave rise to various research worldwide.
It uses **very cheap electrolyte and organic active material** (quinones) and demonstrates 100 cycles and 84% efficiency



Stanford lithium-polysulfide battery uses **low cost sulfur based catholyte**.
It is only hybrid flow battery due to lithium metal anode.
Proved 100 Wh/l of catholyte and 2000 cycles