OVERVIEW OF EXISTING AND INNOVATIVE BATTERIES

IMPACT OF THE STORAGE ON THE RENEWABLE ELECTRICITY LIFE CYCLE

Science for energy scenarios | Fabien Perdu

1. Why considering the environmental impact of batteries ?

2. Battery essential parameters

3. Overview of batteries

4. Material availability

5. Impact of battery production

6. Interpretation of battery production impacts

7. Conclusion

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

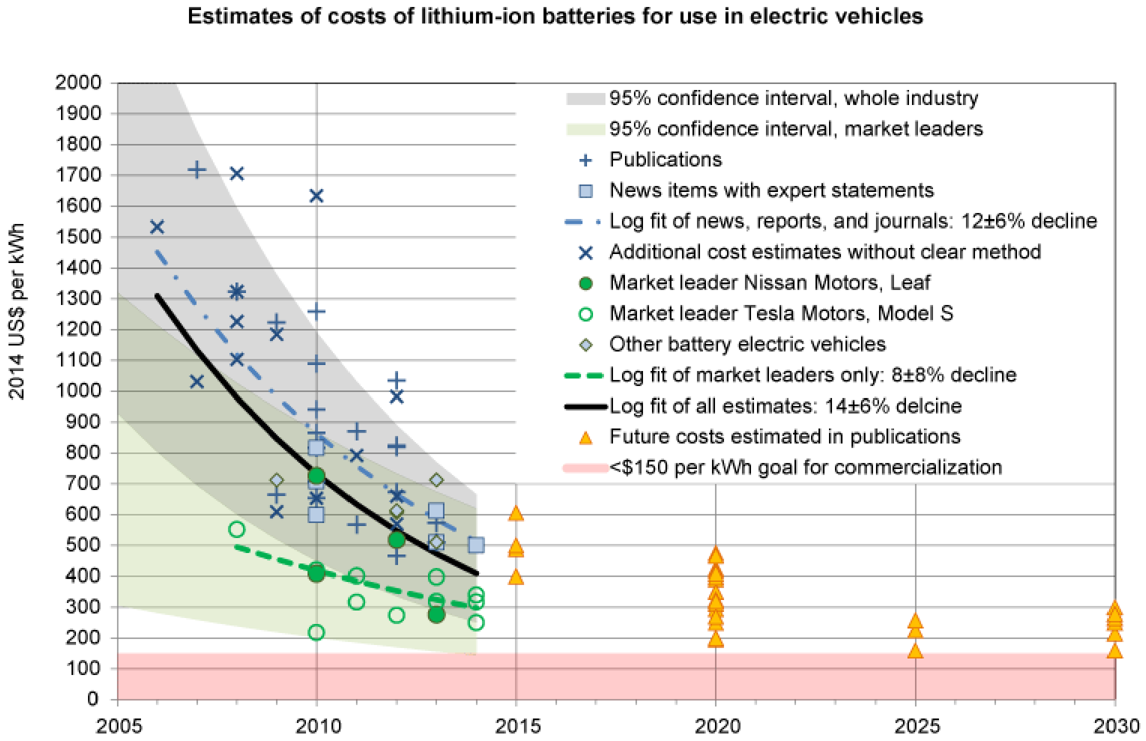
- Batteries are already everywhere

- If it were bad, we would know it !

Let’s look at the numbers…

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

Battery price is falling down at 8%/year



Björn Nykvist and Måns Nilsson, 2015

The market-acceptable prices will be attained soon.

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

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

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

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).

1. Vehicles

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

2. Renewable energy storage

Barnhardt&Benson 2013:
for 50-80% renewables mix, global storage capacity
should be ~4 to 12 hours of world average power demand.
World electric consumption = 20,450 TWh in 2014 (indexmundi.com)
4-12 hours = **9-30TWh of storage**
Consistent with Tesla estimation of 7-10 kWh/home.

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

This is not an extreme value as it does not include long term storage for which batteries are not well suited

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

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

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

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- 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

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

1 gigafactory = 1,3km²
= 35GWh/year

WHY CONSIDERING THE ENVIRONMENTAL IMPACT OF BATTERIES ?

“If a battery's energetic cost is too high, its overall contribution to global warming could negate the environmental benefits of the wind or solar farm it was supposed to support”

Barnhardt & Benson, 2013

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BATTERY ESSENTIAL PARAMETERS

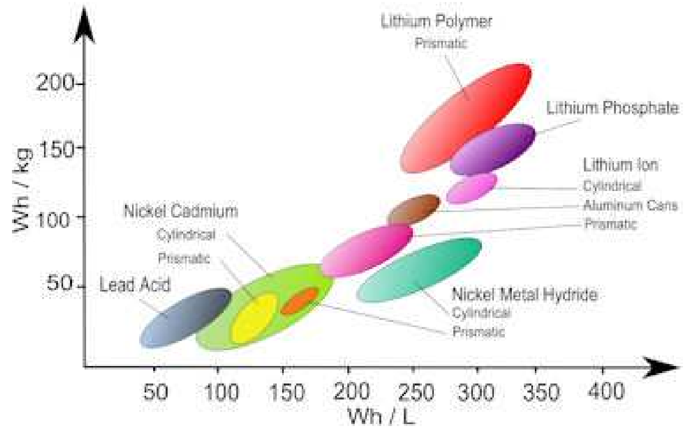
- Performances
  - Energy density
  - Power density
  - Cycle and calendar life
- Operating conditions
  - Temperature
  - Flexibility,…
- Costs and externalities
  - Financial cost
  - Security
  - Environmental impact

More data

Less data

Most common representations :

- Volumetric energy density vs gravimetric energy density

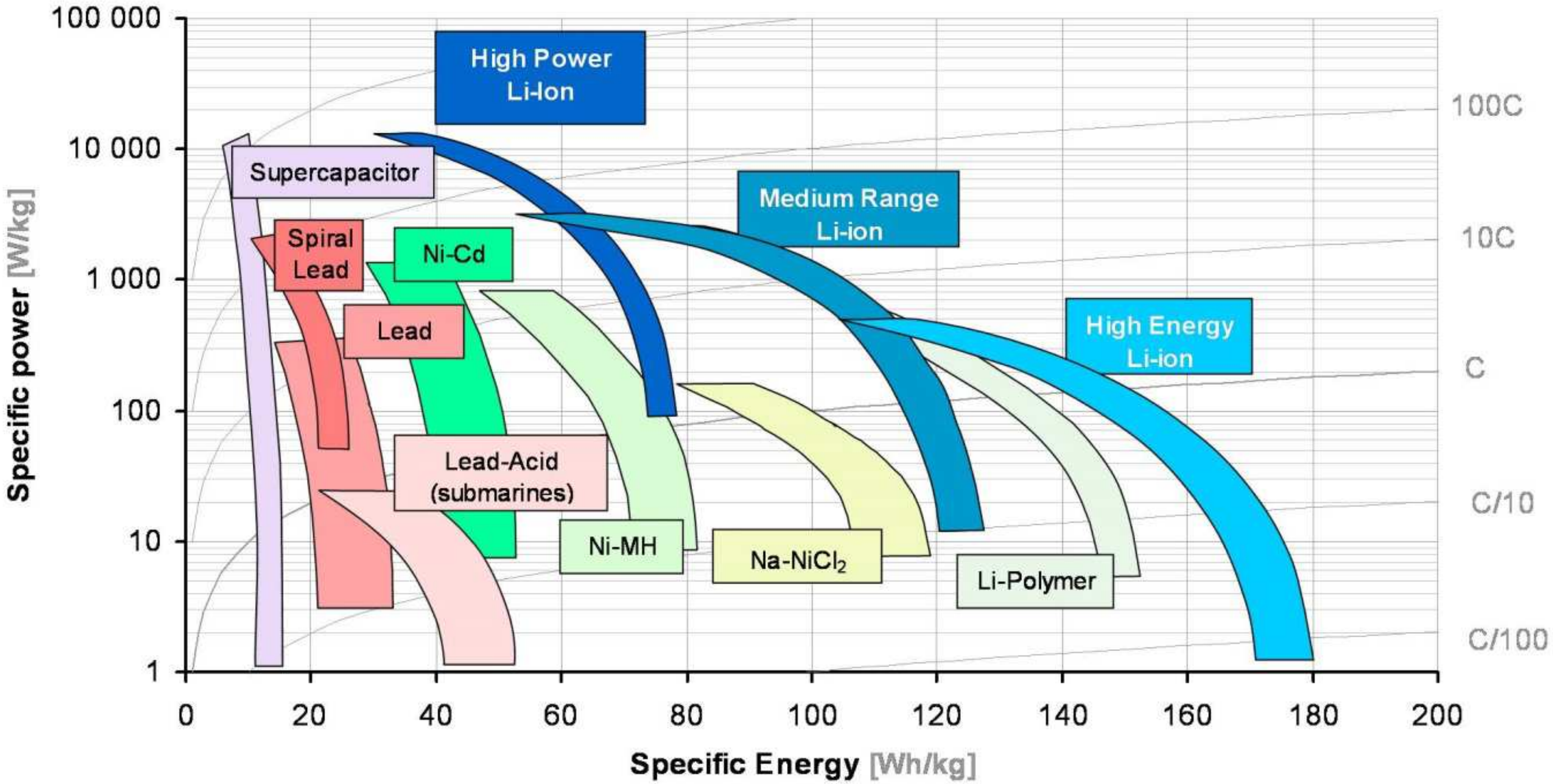


Not that interesting…

- 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…

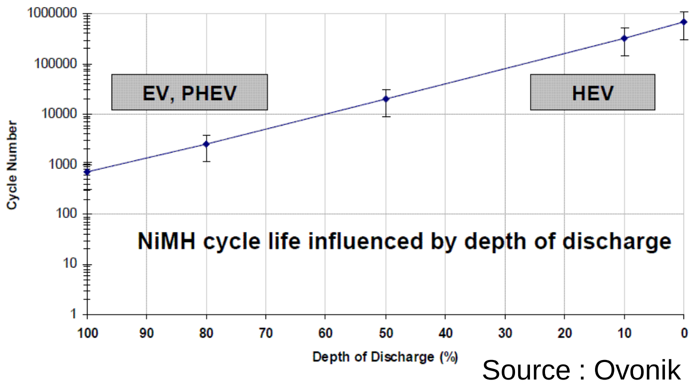


BATTERY ESSENTIAL PARAMETERS

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

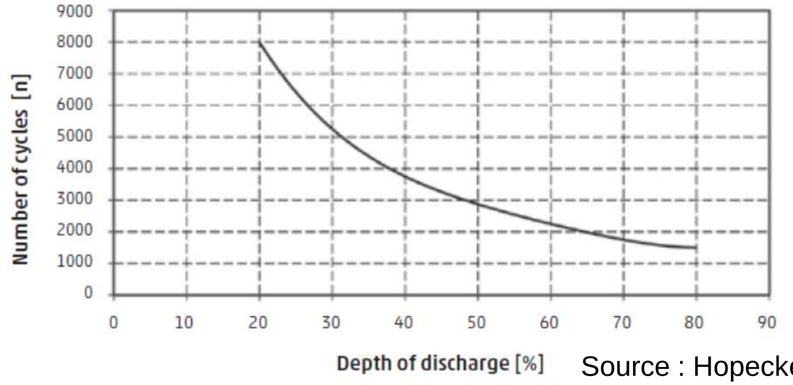
    ⇔ greater investment for a given energy but better return on investment.

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

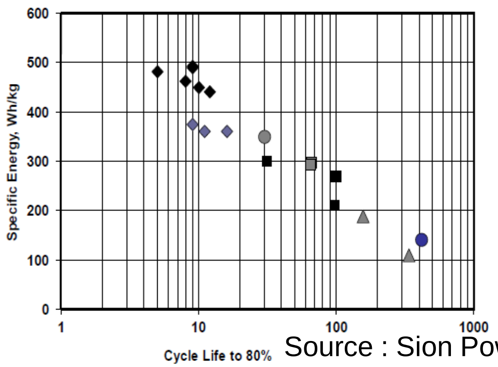


Source : Ovonik

PbA cycle life vs DoD



Source : Hopecke



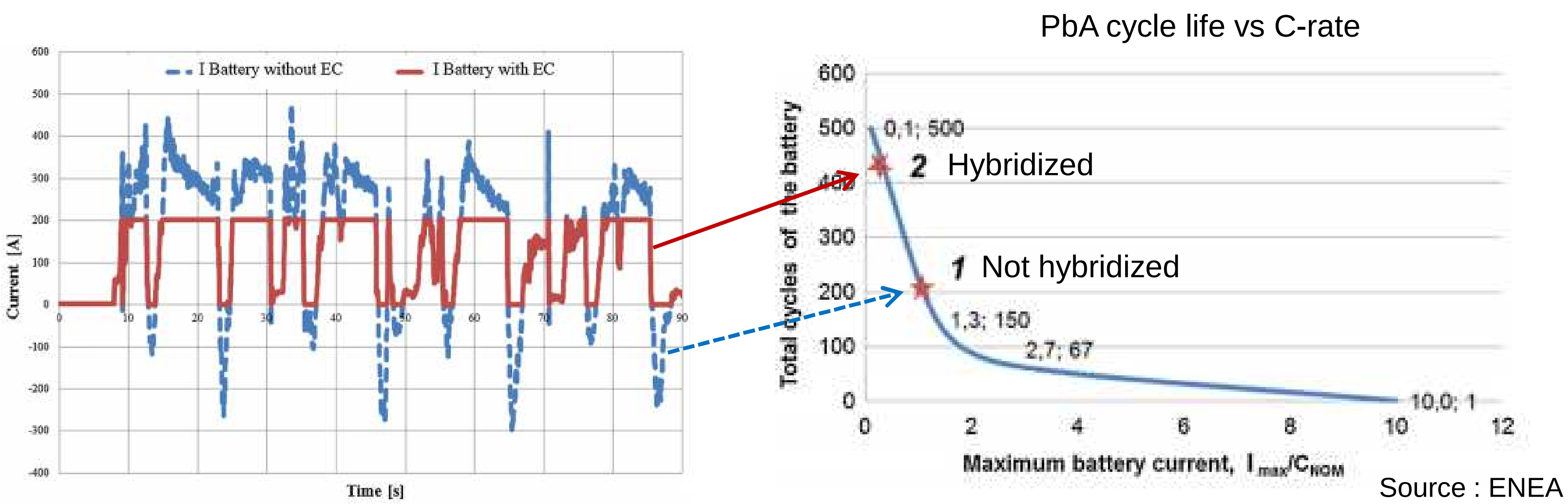
Source : Sion Power

Li-S cycle life vs Energy density

Effect of electrolyte amount

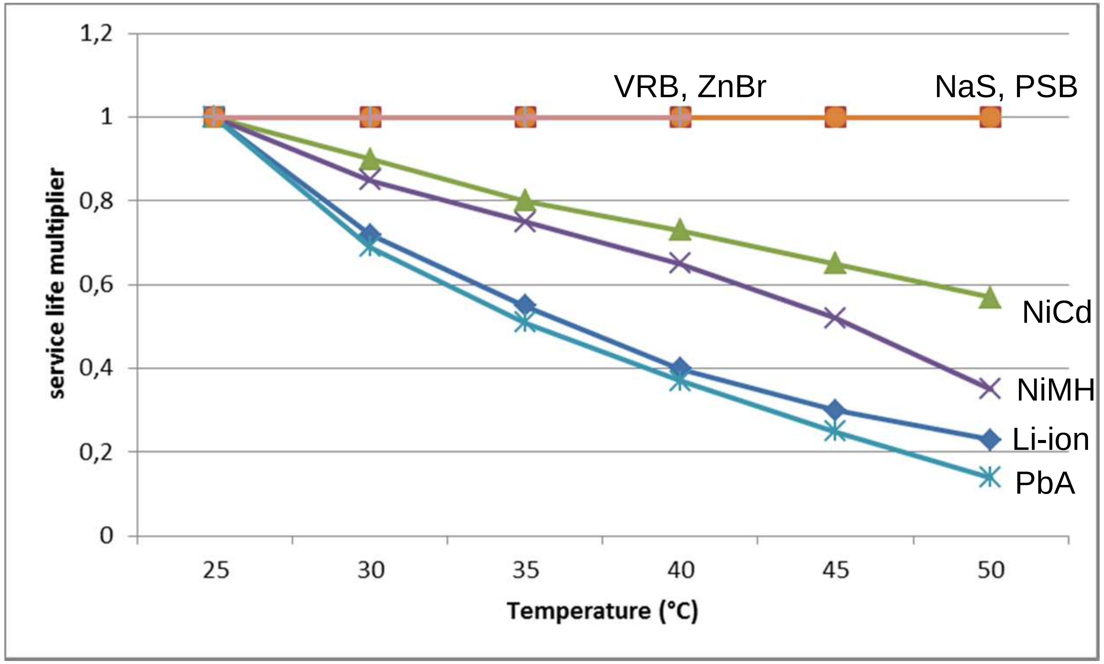
BATTERY ESSENTIAL PARAMETERS

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



BATTERY ESSENTIAL PARAMETERS

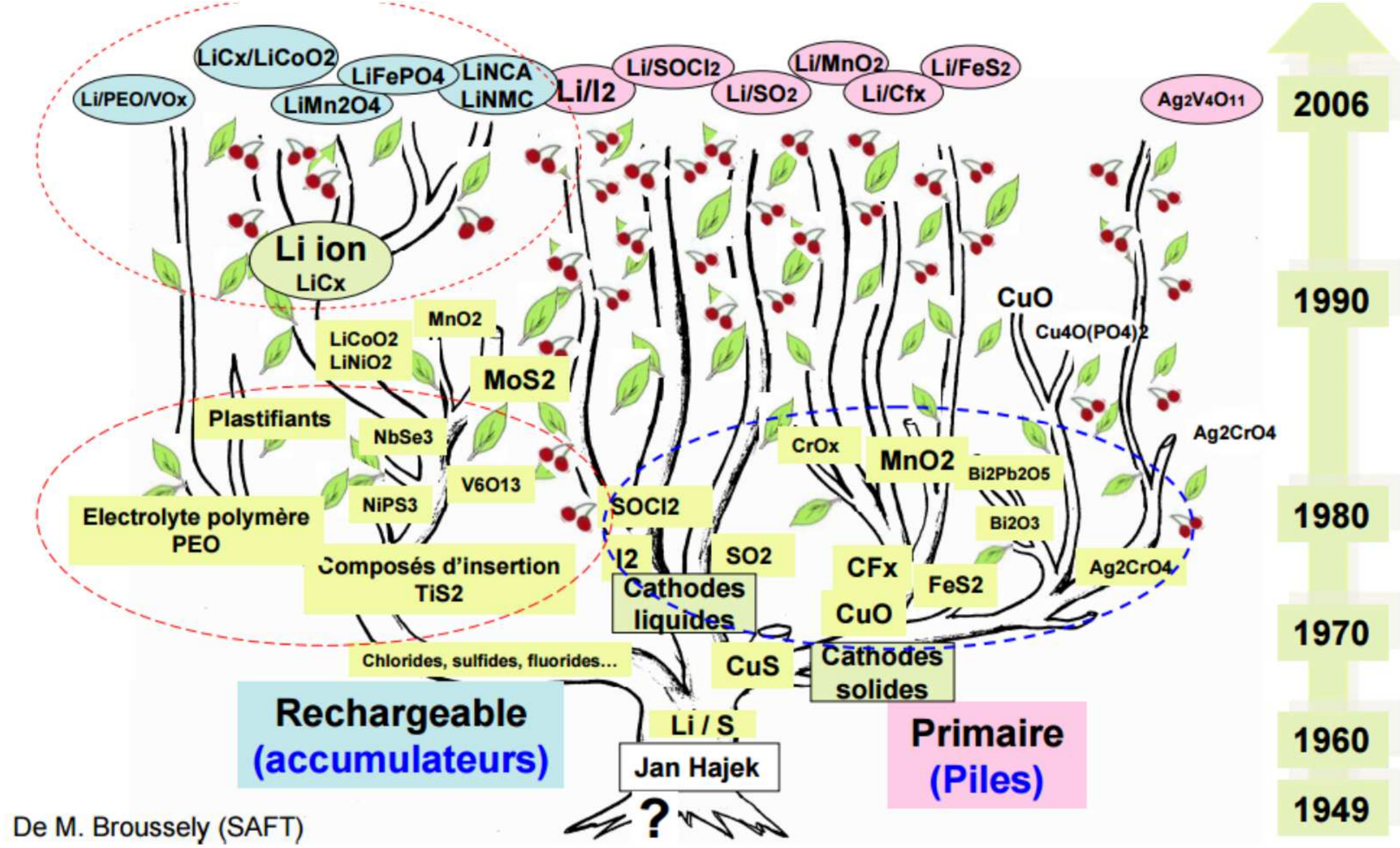
- **Effect of temperature on cycle life**
  - Extreme temperatures usually reduce calendar and cycle life
  - Exceptions are high temperature batteries (NaS, $NaNiCl_2$)
  - Active temperature control is more efficient than reduced calendar life
    (Rydh & Sanden, 2005)



Data from Rydh & Sanden, 2005

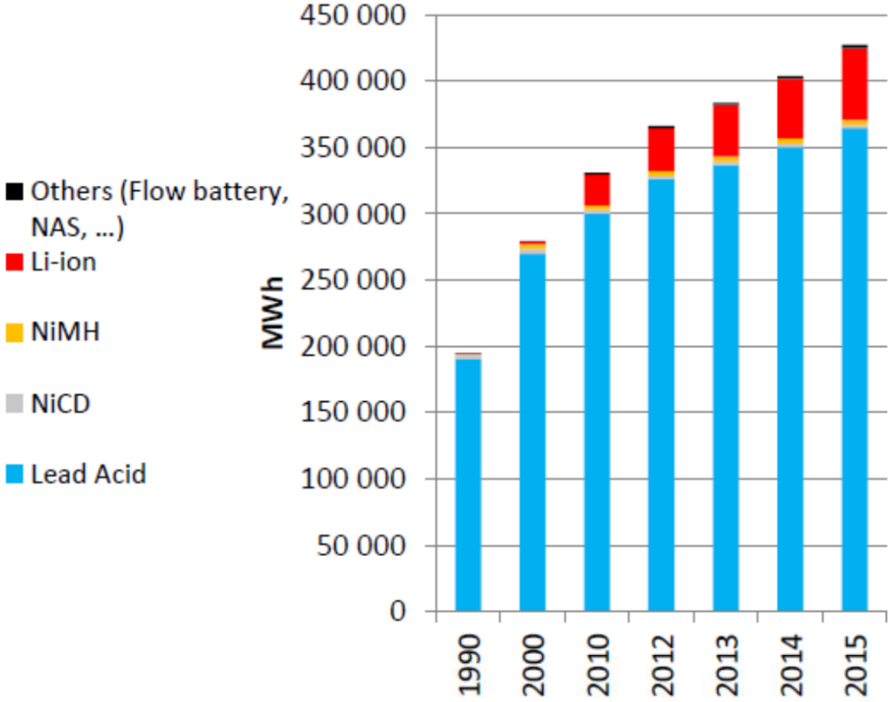
OVERVIEW OF BATTERIES

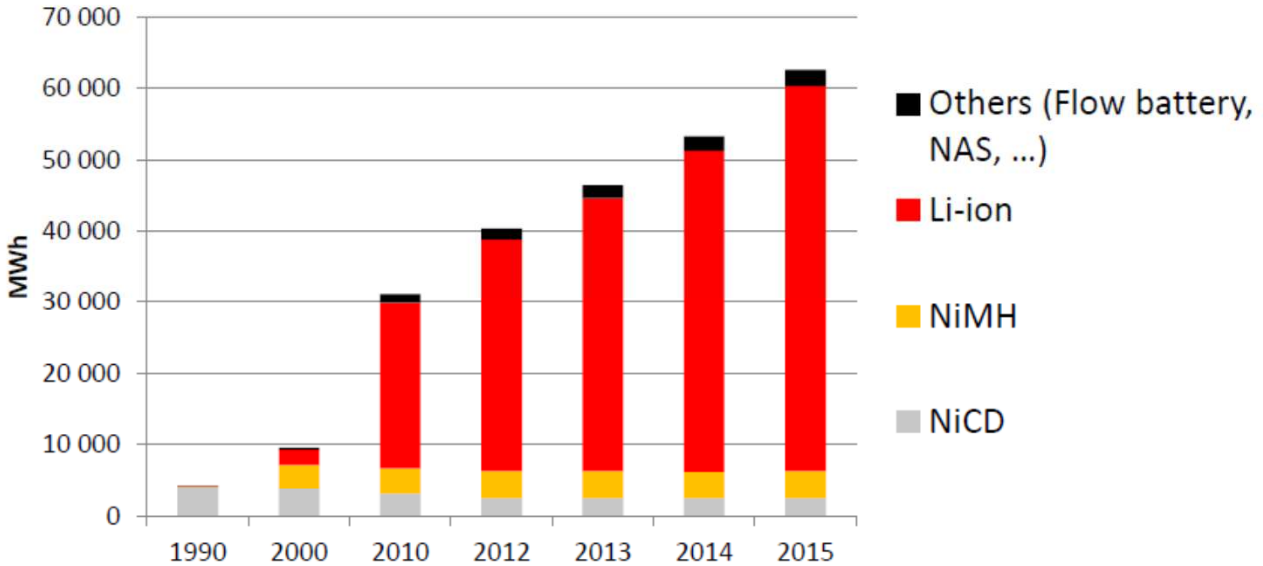
- Batteries have a long history
- A lot of different chemistries and many more to come
- Each one has its well advertised advantages, but also its drawbacks.



EXISTING BATTERIES

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





Source: AVICENNE ENERGY, 2015

2015: Estimations

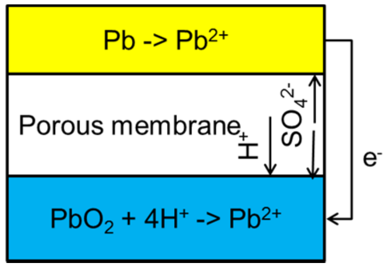
EXISTING BATTERIES : LEAD-ACID

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

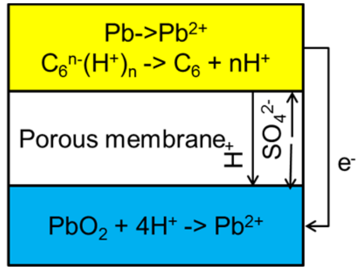
Main benefits
- **Lowest capital cost**
- Very mature, observed service life 9-15 years
- Abundant materials and **very efficient recycling (96%)**
- Very safe, except end of charge electrolysis
  and dendrite risk in case of sulfatation

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)

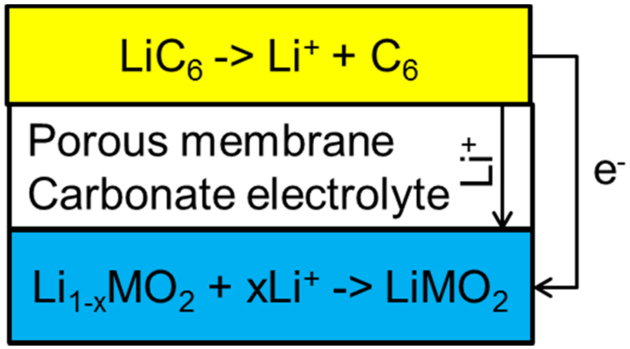
Furukawa 300kW (Japan)
'ultrabattery'

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°C
- 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



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

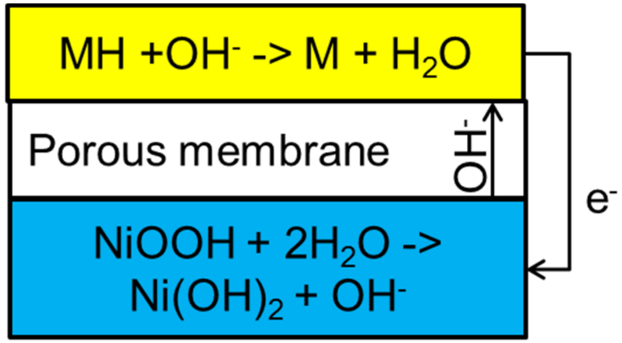
- Mature
- High power
- No Cd => replace progressively NiCd batteries.
- Easy recycling

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



1,2V

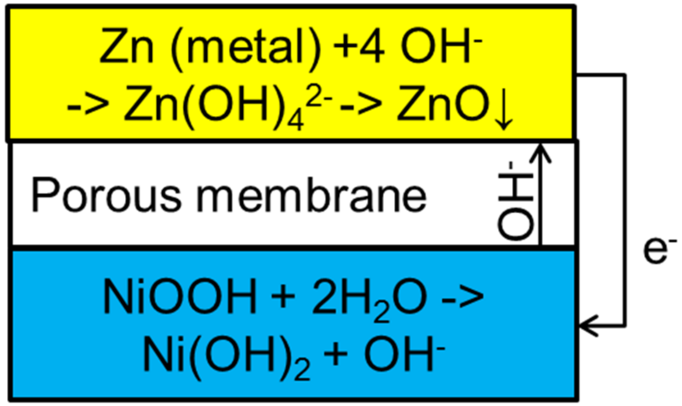
EXISTING BATTERIES : NI-ZN

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

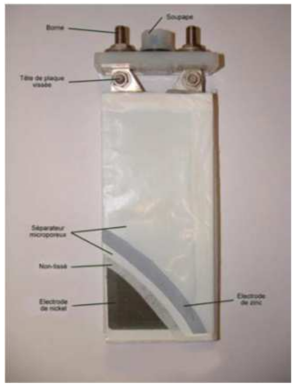
Main benefits
- **Higher energy density than NiMH**
- **Low cost**
- **Abundant materials**
- **Easy recycling**

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



1,65V



SCPS

Powergenix

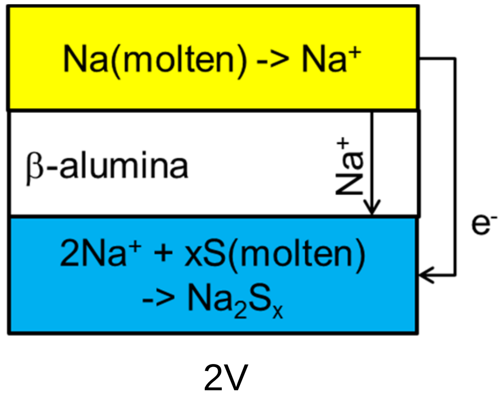
EXISTING BATTERIES : SODIUM-SULFUR

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°C => 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



EXISTING BATTERIES : ZEBRA

<u>Basic data</u>

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

<u>Main benefits</u>

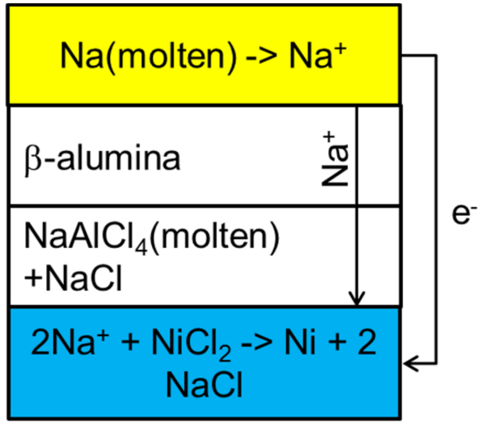
- Can operate in any external temperature
- **Less dangerous than Na-S**
- **Good energy density and cycle life**
- Ni easily recycled (and pays the recycling)

<u>Main problems</u>

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

<u>Actors and realisations</u>

- 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°C technology with 1000 cycles



2,58V

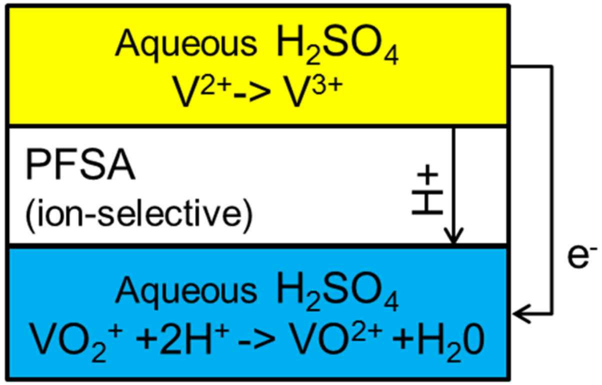
EXISTING BATTERIES : VANADIUM FLOW BATTERY

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°C-40°C

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

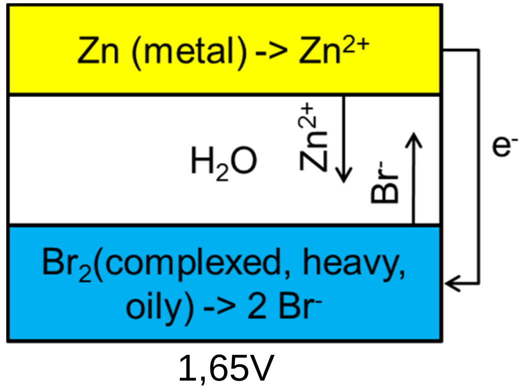
Main problems
- **High operating costs**
- **Complex auxiliaries**
- Self-discharge
- Corrosive electrolyte
- precipitation of V_2O_5 near 50°C-60°C
- **Low real world efficiency**
- Research focuses on temperature range and electrolyte concentration

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



1,4V

EXISTING BATTERIES : ZN-BR HYBRID FLOW BATTERY

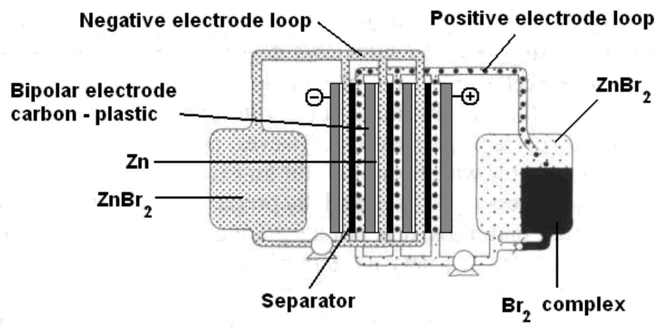


Basic data

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

Main benefits

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



Main problems

- **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

Actors and realisations

- 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

<u>Basic data</u>

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

<u>Main benefits</u>

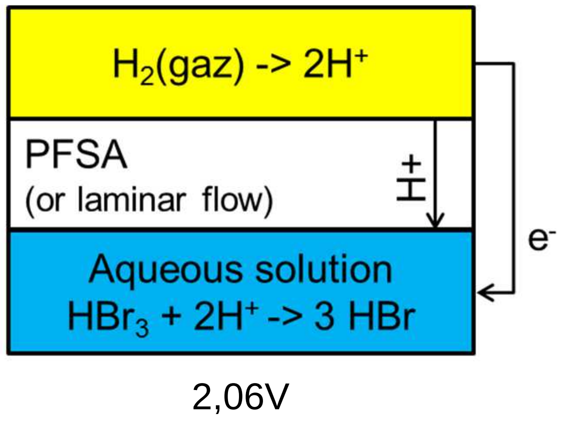
- **E / P decoupling**
- **Abundant and low cost materials**
- **Large operating temperature range**
- No DoD limit
- **Long cycle life**
- Tolerance to overcharge / overdischarge

<u>Main problems</u>

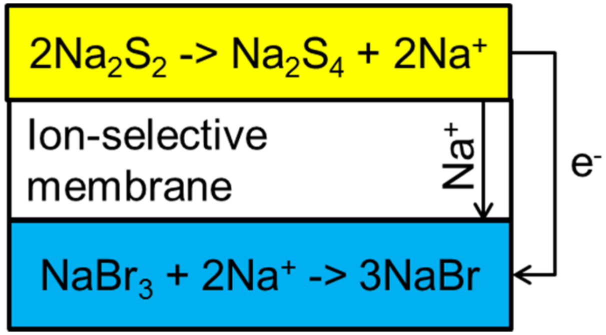
- **HBr and Br_2 highly toxic and corrosive**
- Loss of capacity by Br_2 crossing
- **Environmental impact**
- System cost

<u>Actors and realisations</u>

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



EXISTING BATTERIES : BR-POLYSULFIDES FLOW BATTERY



1,36V

Basic data

- Energy density : 20-30 Wh/l
- Power : 40 mA/cm²
- Efficiency : 65%-75%
- Cycle life : 3000-5000

Main benefits

- **E/ P decoupling**
- **Low cost and abundant materials**
- Aqueous electrolyte and high solubility

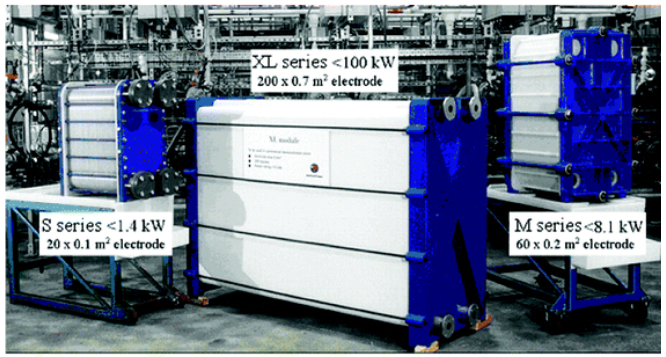
Main problems

- 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

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.

(a)



(b)

EXISTING BATTERIES : FE-FE HYBRID FLOW BATTERY

<u>Basic data</u>

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

<u>Main benefits</u>

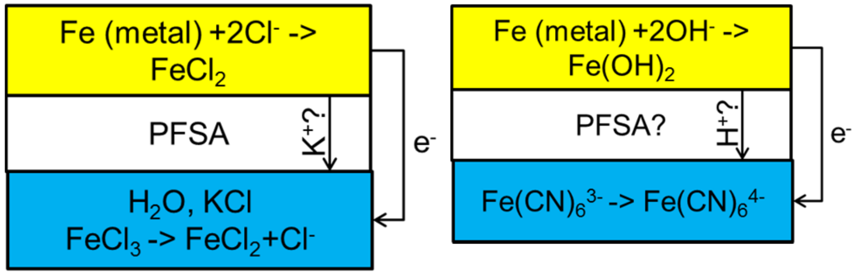
- Partial E/P decoupling
- **Abundant and low cost materials**
- **Very high cycle life**
- Can use twice the same electrolyte

<u>Main problems</u>

- **Low energy density**

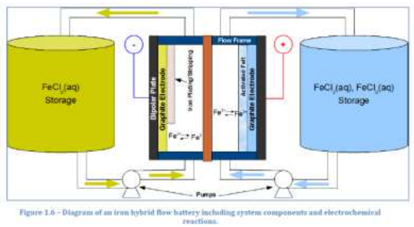
<u>Actors and realisations</u>

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

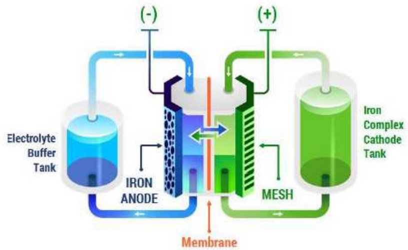


1,2V

Energy Storage Systems



Arotech



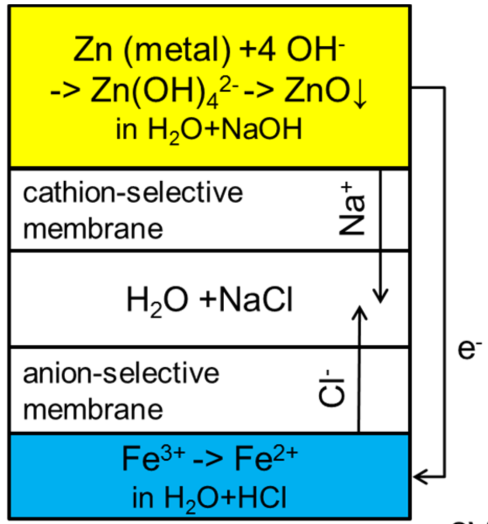
EXISTING BATTERIES : ZN-FE HYBRID FLOW BATTERY

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



2V

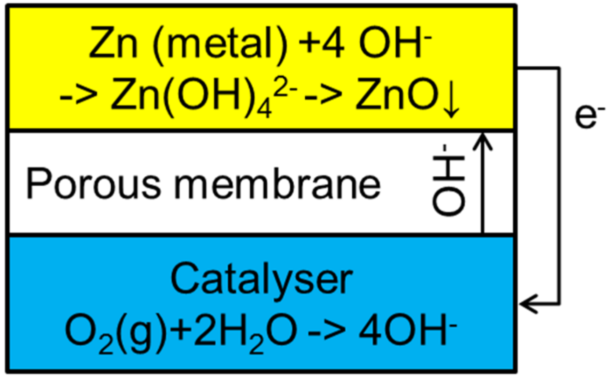
Energy Environ. Sci., 2015, 8, 2941

ViZn : 1,64V

EXISTING BATTERIES : ZN-AIR

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



1,32V

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

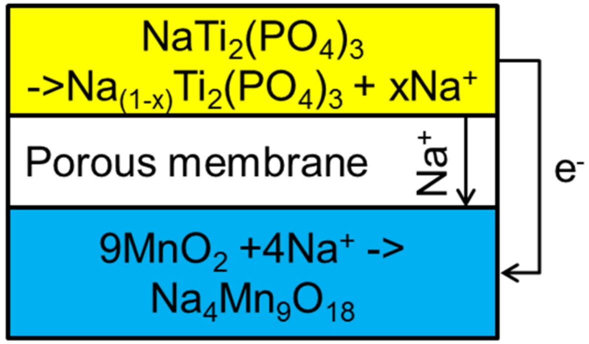
- **Abundant and low cost materials**
- **High cyclability**
- **Easy recycling**
- **Very safe**

Main problems

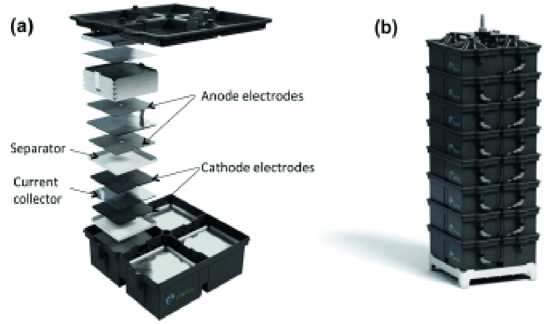
- **Low energy density**
- Low power (C/2)

Actors and realisations

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



1,5V



UPCOMING BATTERIES : LITHIUM-SULFUR

Basic data

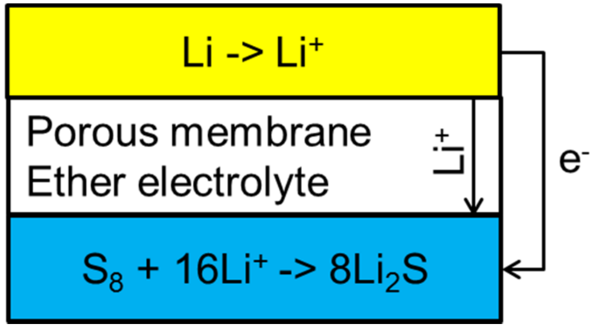
Energy density : 300 Wh/kg_{cell}, practical target 400-600 Wh/kg
Efficiency : 80-85%
Cycle life : 100-300, target >1000

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



2,2 V

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

UPCOMING BATTERIES : SOLID STATE BATTERIES

Basic data

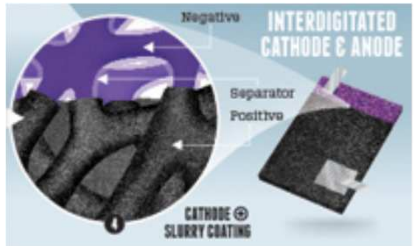
- Same chemistry as Li-ion, Li-S,… but solid electrolyte :
  - ceramic, glass, polymer, or gel
- Today 100 Wh/kg, target 400 Wh/kg
- Temperature range highly dependent on the electrolyte

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

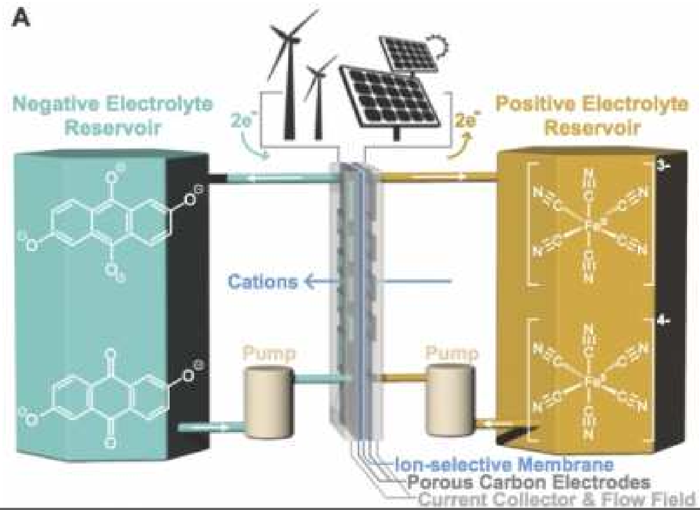
- The only available today is **POE working above 60°C**
- Most others have either **low conductivity** or **low processability**



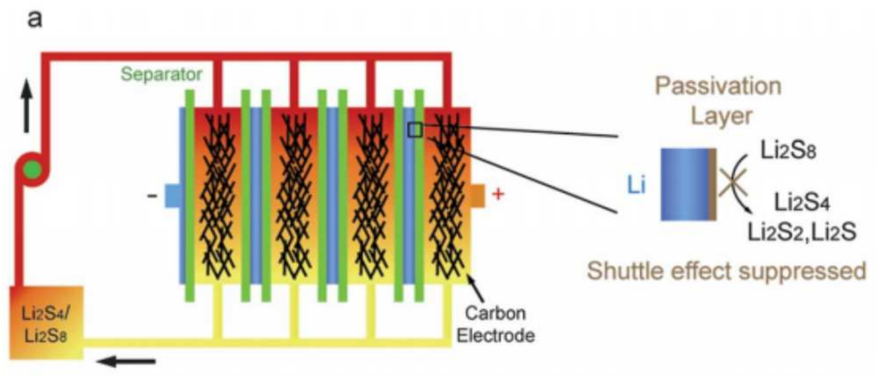
Actors and realisations

- 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

MATERIAL AVAILABILITY

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

- **Reserves** = ‘accessible’ amount,
- **Ressources** = existing amount, but not accessible (technically, economically, or because of regulations)

For most elements, ressources = 2 to 3 x reserves

We will use reserve values from USGS 2016 as

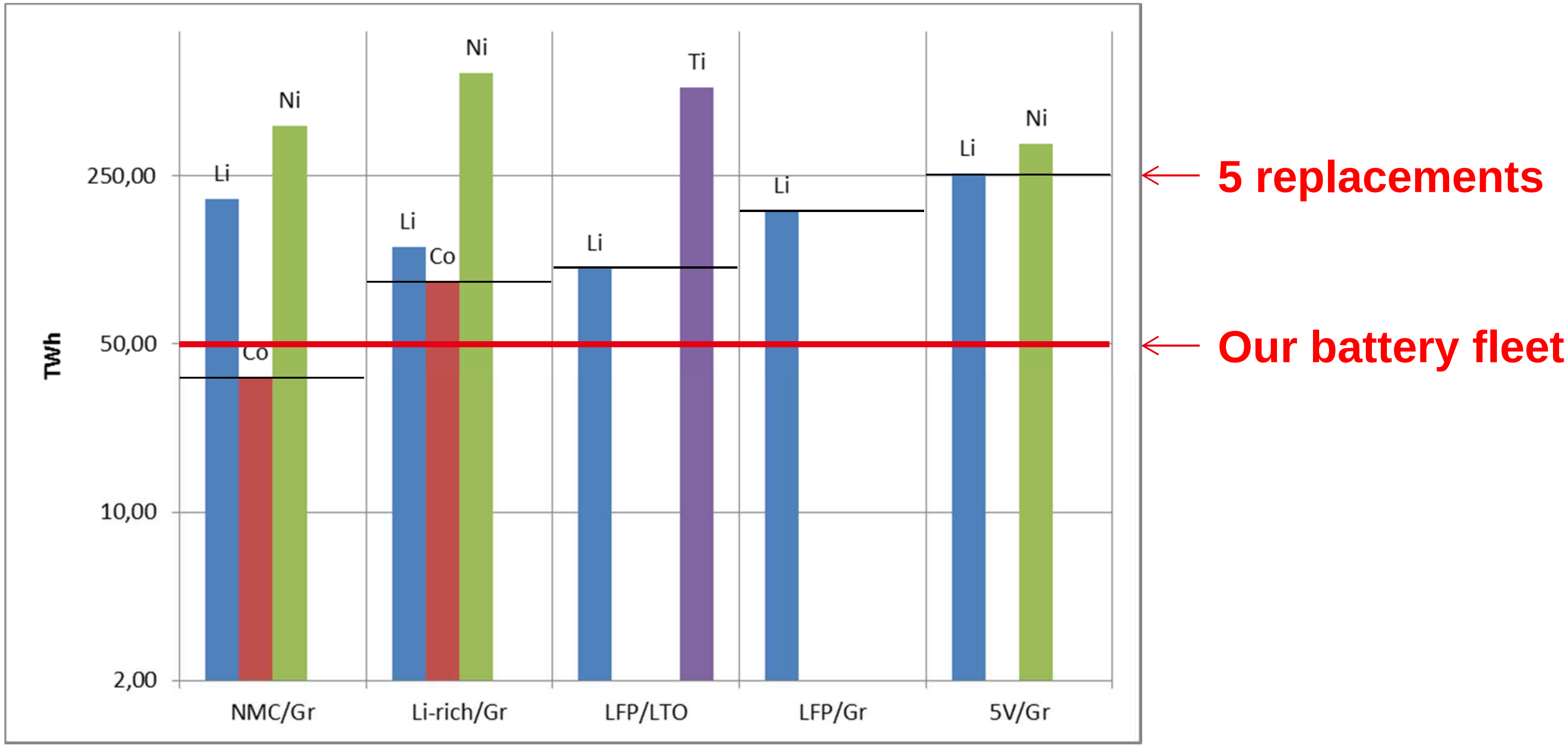
- We do not not want to transform all the earth crust into batteries
- We want to keep the possibility to replace the batteries at end of life even with a not 100% recycling process

We consider rather optimistic cell compositions

MATERIAL AVAILABILITY

For lithium-ion systems :

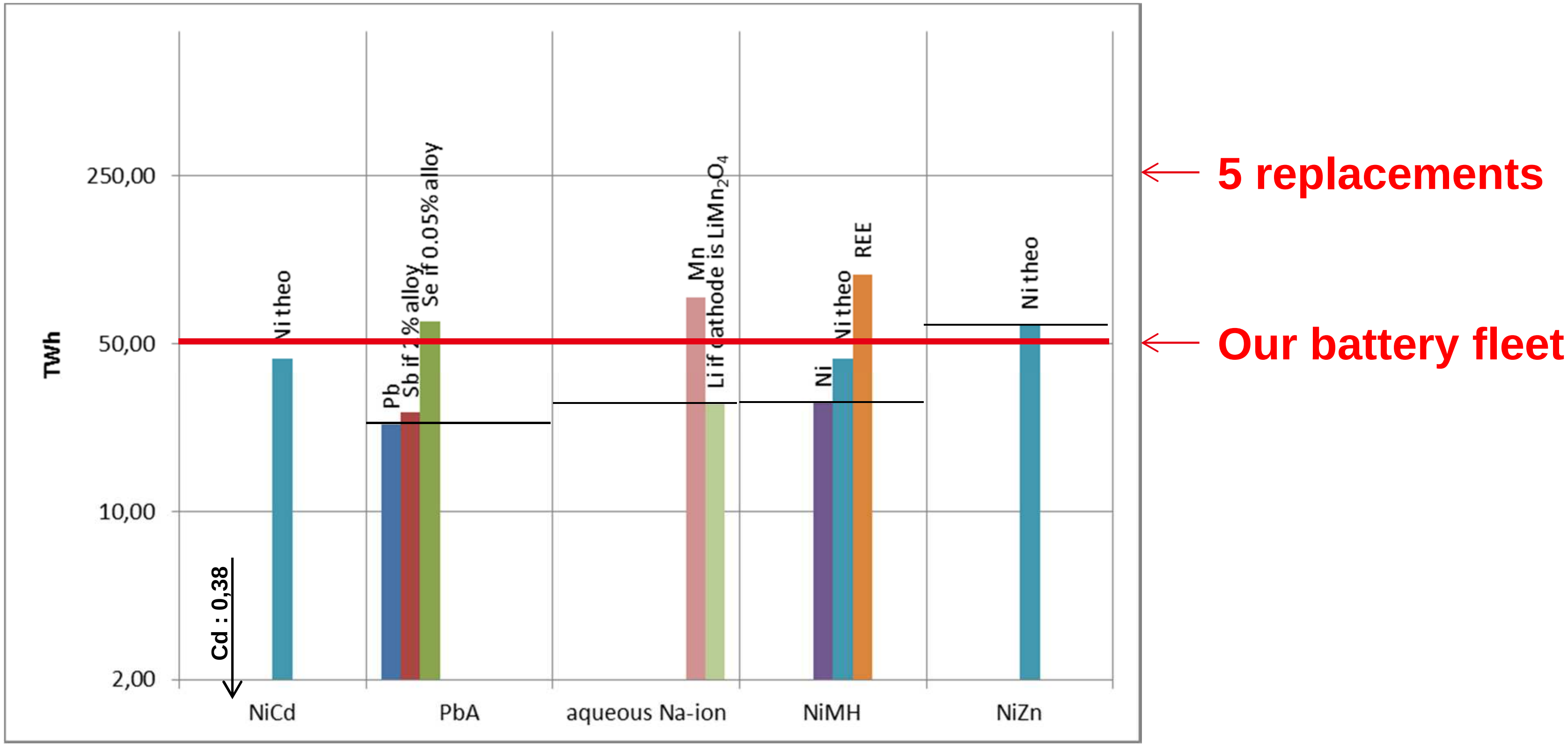
- Lithium is limiting for cobalt-free systems
- Nickel is not far above, except for nickel-free system (LFP)
- Higher voltages allows more efficient use of lithium
- Fluorine is not limiting in electrolyte (would be different in active materials)



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

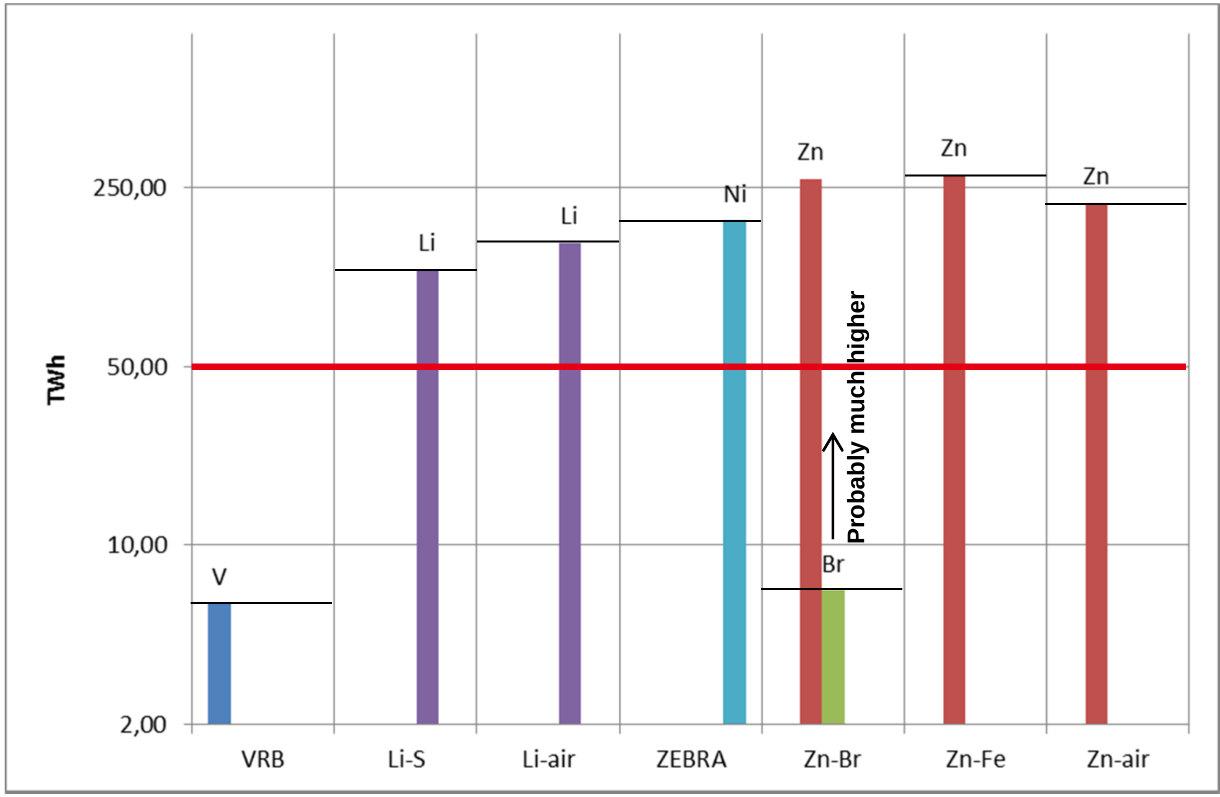


MATERIAL AVAILABILITY

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



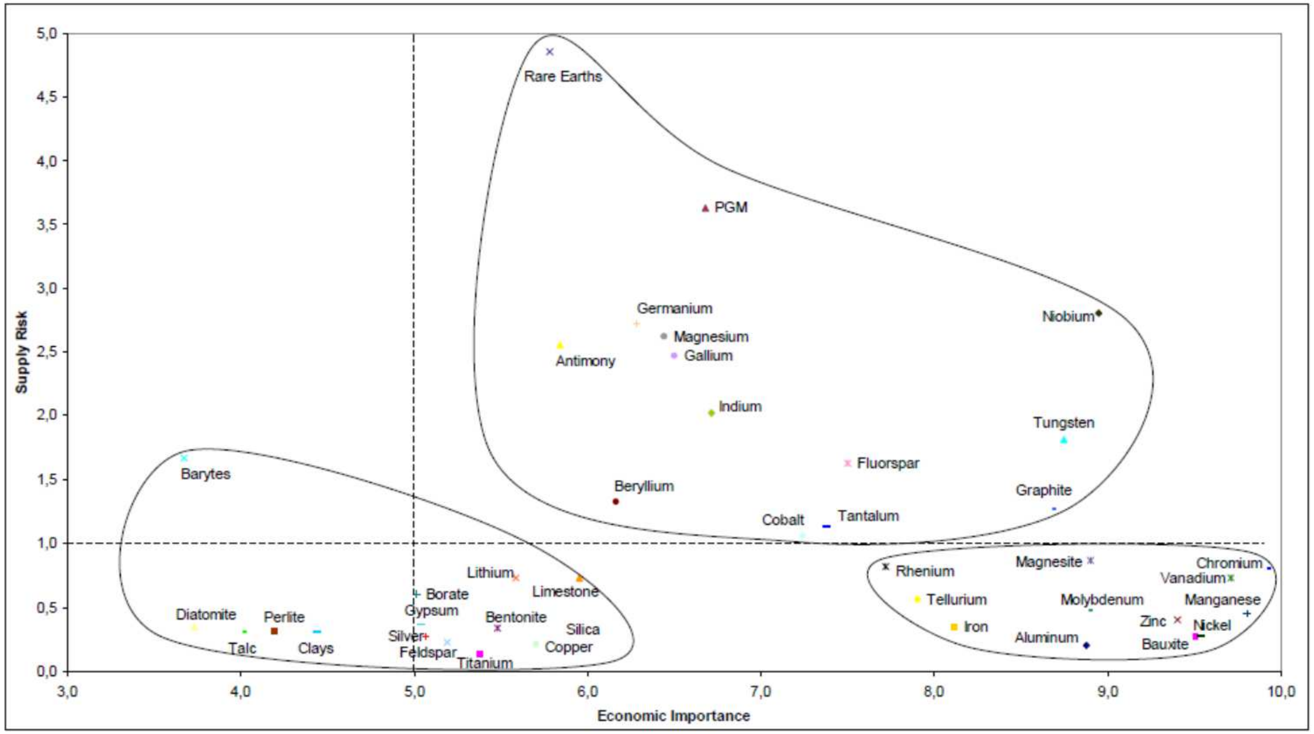
5 replacements

Our battery fleet

MATERIAL AVAILABILITY

At EU level:

- A list of critical raw materials has been established, taking into account
  - Every present usage (not only batteries, but no extrapolation)
  - Geopolitical constraints
- This is different from our approach, leading to different results.



For large scale batteries, additional critical materials are :
Cd, V, then Pb, Ni,
(then Li, Zn, Ti)

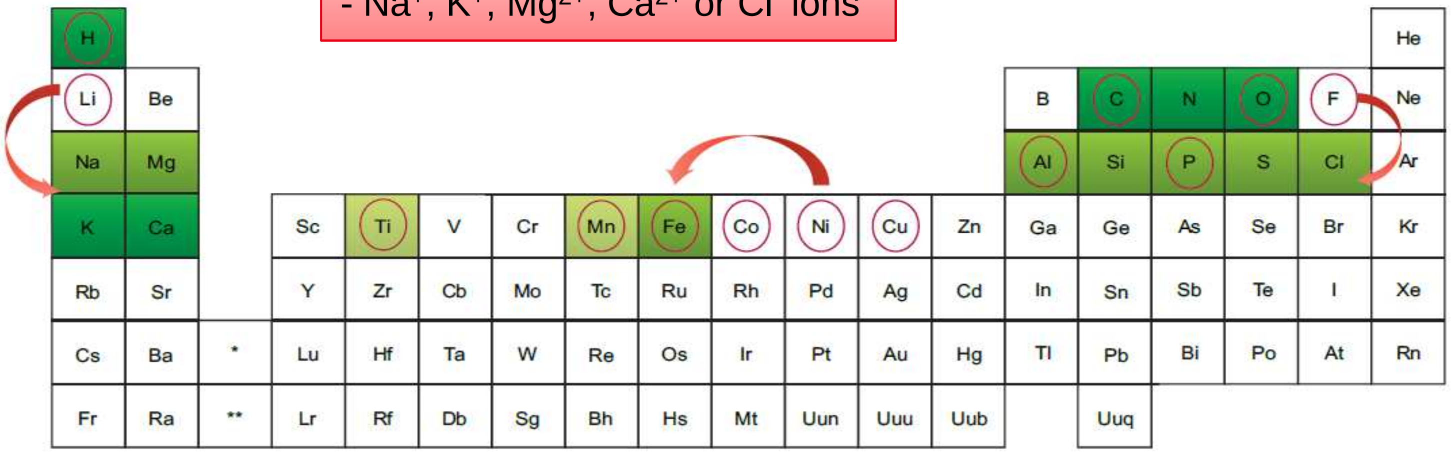
MATERIAL AVAILABILITY

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 much higher thanLi-ion.

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

- Organic active materials
- Oxygen or sulfur 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. Why considering the environmental impact of batteries ?

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7. Conclusion

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
  - CO2 emissions
  - Primary energy consumption
  - 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

- **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

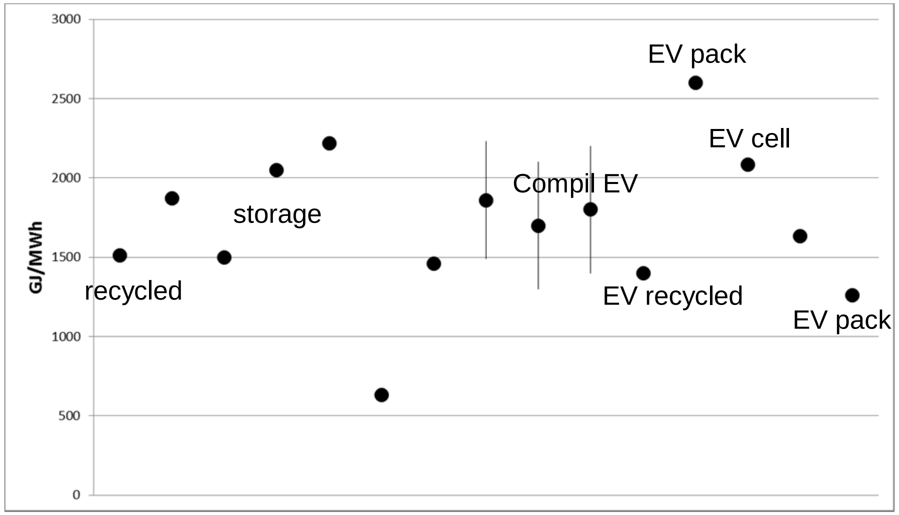
-20% -25% in case of recycling

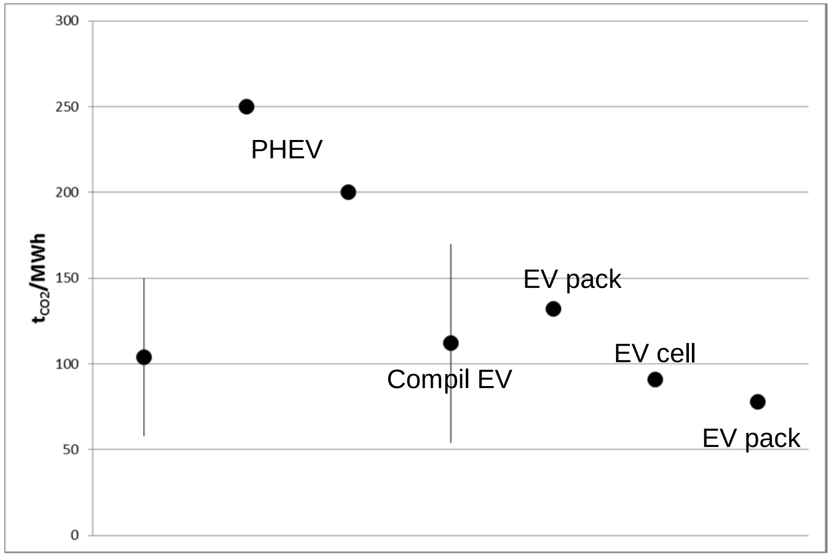
Cell ~ 80% of pack

Cathode = 35-45% of pack

Manufacturing ~25% of pack

BMS ~13% of pack





IMPACT OF BATTERY PRODUCTION

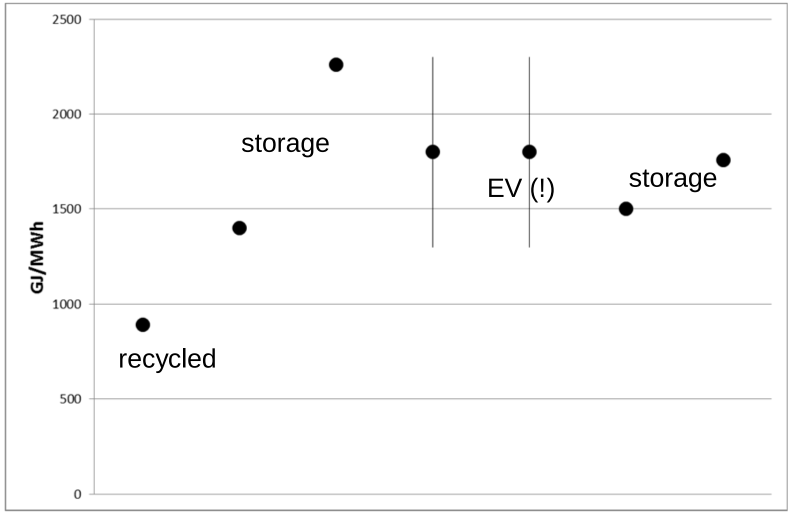
- **Sodium-sulfur**

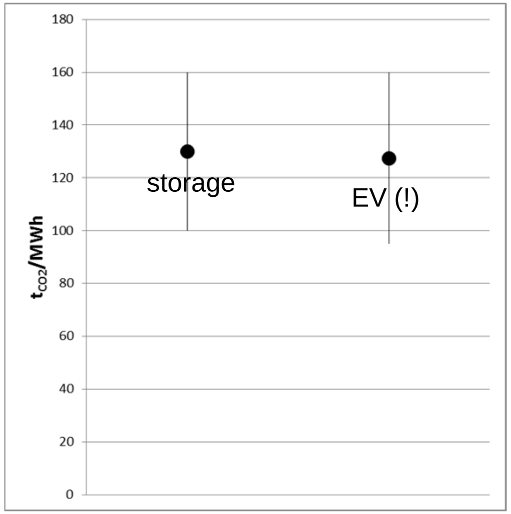
1500-2000 GJ/MWh

~2/3 material, 1/3 manufacturing

-35% in case of recycling

100-150 t_{CO2}/MWh





IMPACT OF BATTERY PRODUCTION

- **Lead-acid**

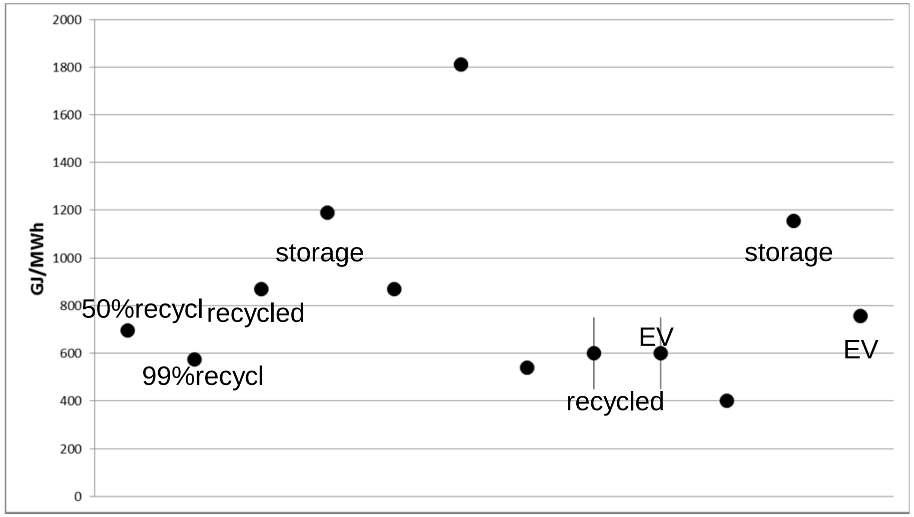
800-1200 GJ/MWh

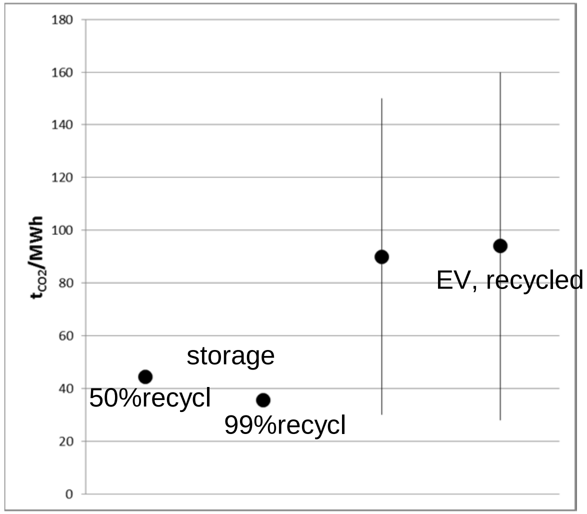
~2/3 material, 1/3 manufacturing

-25% in case of recycling

50-150 t_{CO2}/MWh

-30% in case of recycling





IMPACT OF BATTERY PRODUCTION

- **Vanadium redox flow**

2000-3000 GJ/MWh

~3/4 materials, 1/4 manufacturing

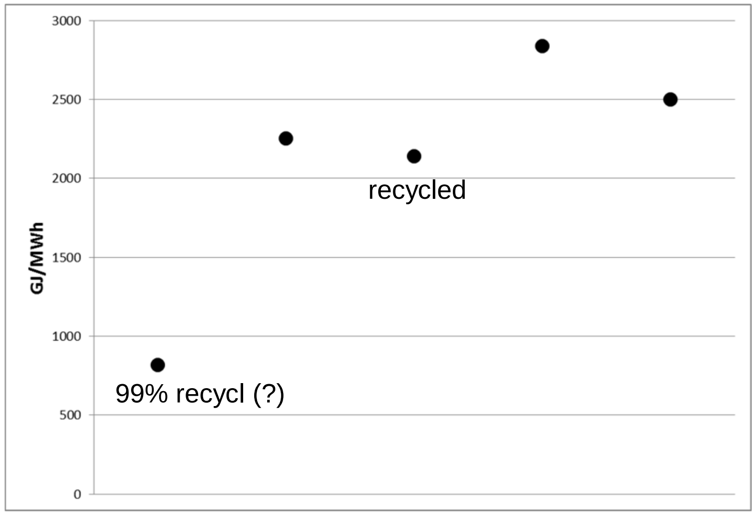
impact of recycling ?

+10% to include operating energy use

160 t_{CO2}/MWh

Single value…

+10% to include operating energy use



IMPACT OF BATTERY PRODUCTION

- **Polysulfide bromine**

2000-2500 GJ/MWh

~3/4 materials, 1/4 manufacturing

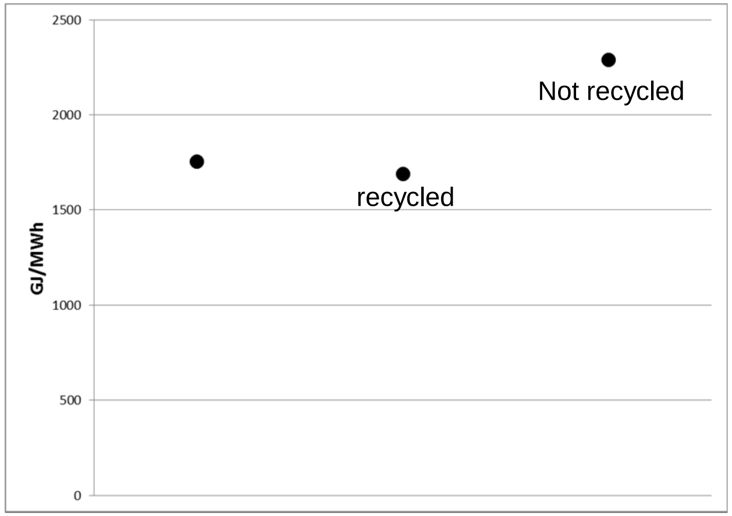
-25% in case of recycling

+10% to include operating energy use

125 t_{CO2}/MWh

Single value…

+10% to include operating energy use



IMPACT OF BATTERY PRODUCTION

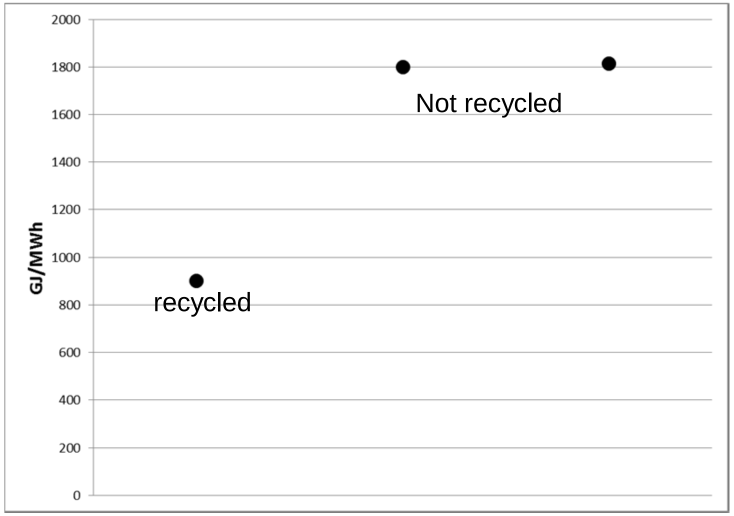
- **Zinc Bromine**

~1800GJ/MWh

~2/3 materials, 1/3 manufacturing

-50% in case of recycling

No GWP data found



IMPACT OF BATTERY PRODUCTION

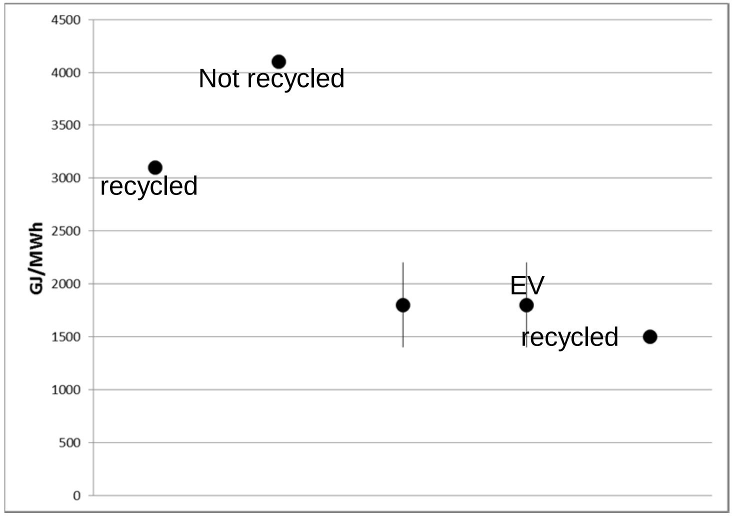
- **Nickel Cadmium**

2000-3500GJ/MWh

~2/3 materials, 1/3 manufacturing

-30% in case of recycling

No GWP data found



IMPACT OF BATTERY PRODUCTION

- **Ni-MH**

2500-3500GJ/MWh

~1/2 materials, 1/2 manufacturing

-30% in case of recycling

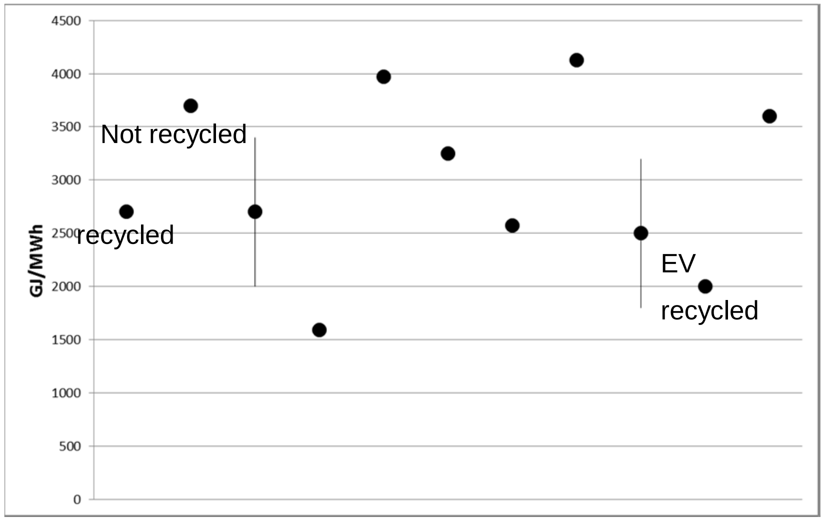
150-250 t_{CO2}/MWh

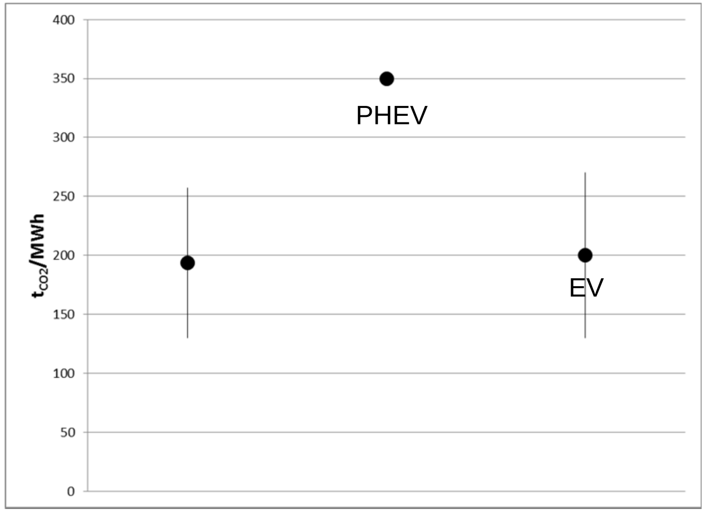
~35% manufacturing

25% negative electrode

20% collectors

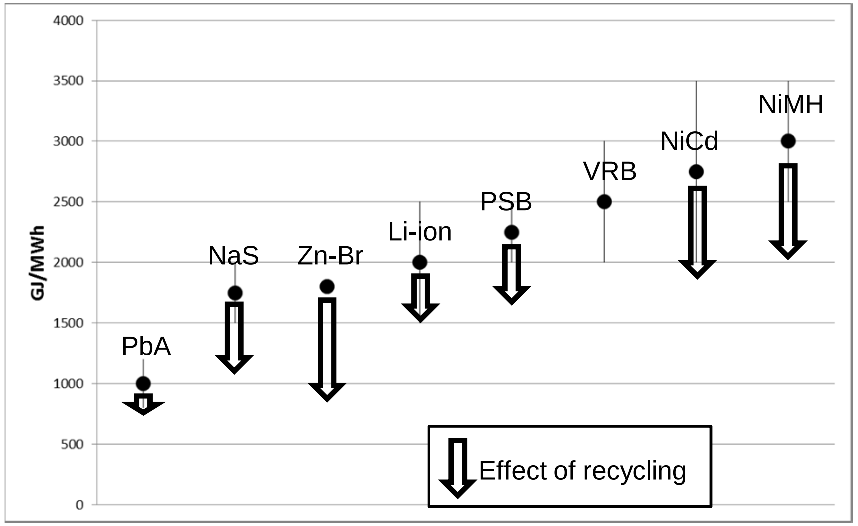
12% positive electrode

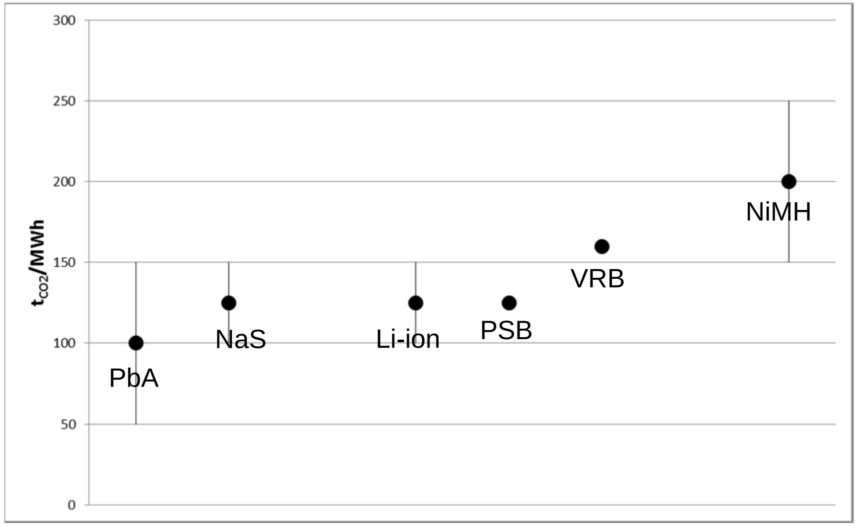




IMPACT OF BATTERY PRODUCTION

- **Synthesis**
  - All technologies lie in a factor 3 for production impact /MWh
  - **Higher energy density compensates for higher impact /kg**
  - Energy consumption and GWP are correlated
  - PbA has lowest the impact per MWh, NiMH and NiCd the highest
  - Recycling will not solve all the problems



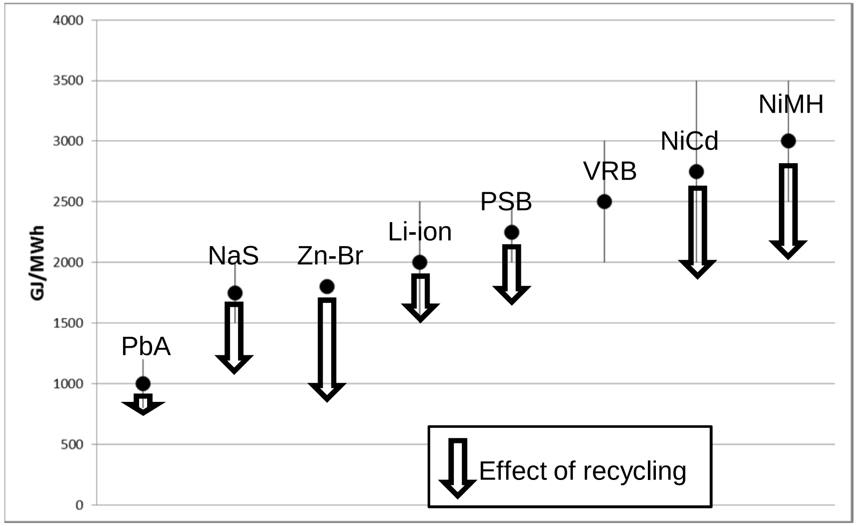


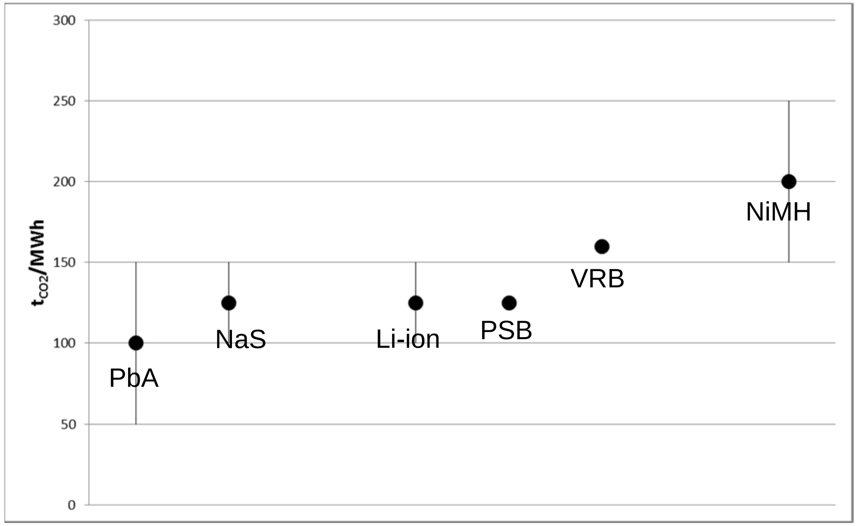
Lack of data for interesting technologies such as
ZEBRA, ZnFe, FeFe, Zn-air, supercapacitors, Lithium-sulfur

IMPACT OF BATTERY PRODUCTION

- **Synthesis**

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





1. Why considering the environmental impact of batteries ?

2. Battery essential parameters

3. Overview of batteries

4. Material availability

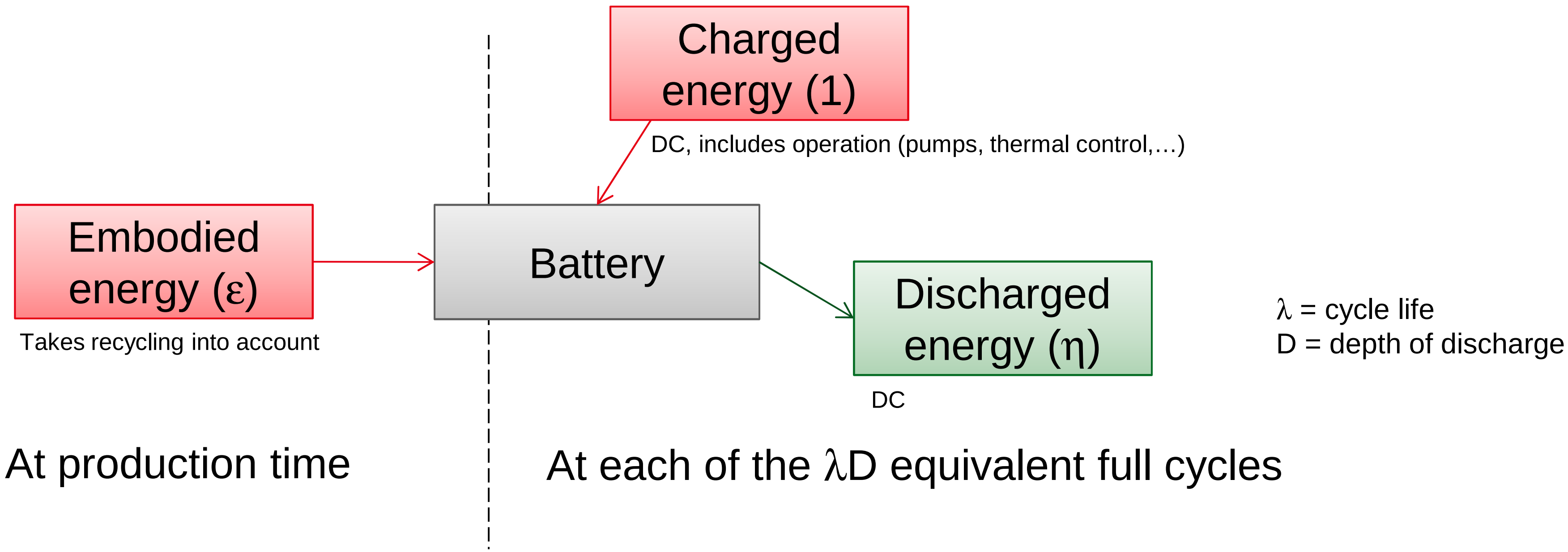
5. Impact of battery production

6. Interpretation of battery production impacts
   1. ESOI
   2. Net storage efficiency
   3. Timescale based EROI analysis
   4. Some comparisons

7. Conclusion

INTERPRETATION OF BATTERY PRODUCTION IMPACTS

- **Consider embodied energy, CO_2,… as <u>costs</u>**
  - Then economic concepts can be applied to them in particular concerning **investments** (pay today, get the return later)
  - Embodied energy is specific as it is comparable to
    - The performance of the battery (nominal energy stored)
    - The function delivered by the battery over its life



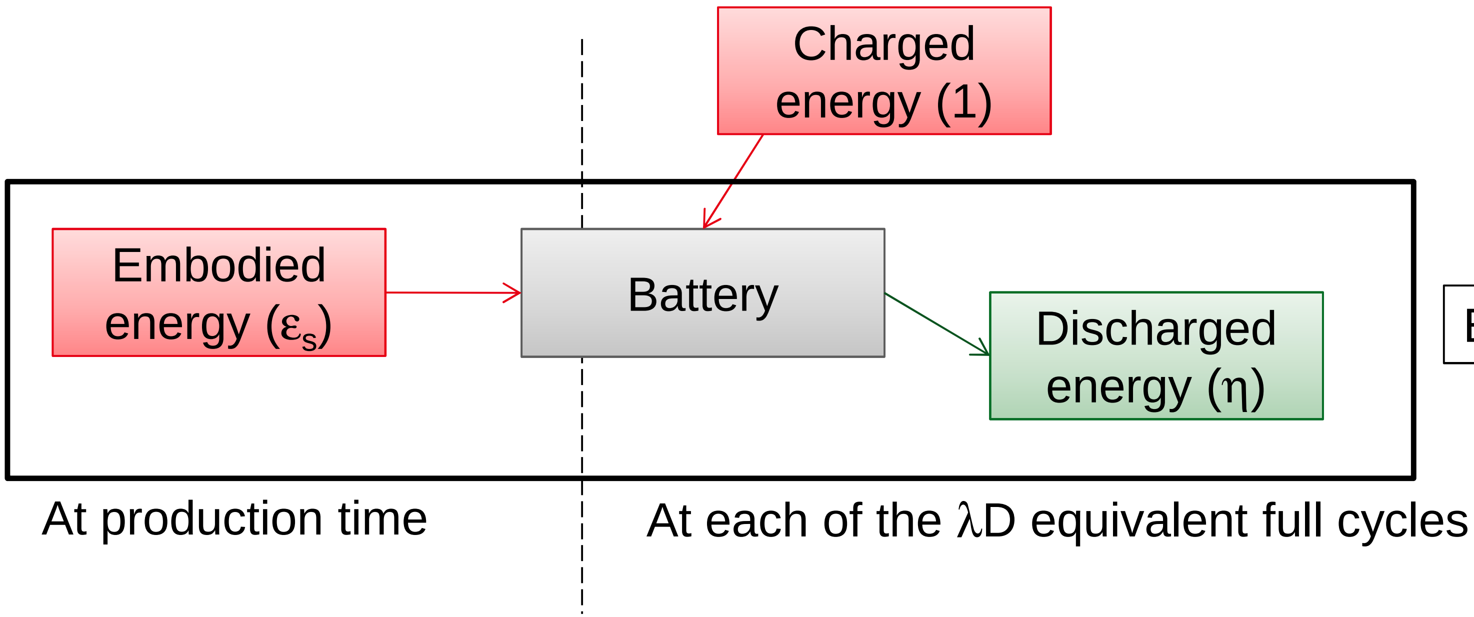
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **For energy sources, EROI = Energy return on investment**
  - Very useful to detect cliff effects
  - When EROI→1
    - The energy produced by a source unit (PV panel, wind turbine,…) is just enough to build its replacement
    - We keep building and exhausting the resources for zero usable energy output
  - The invested costs (€, energy, CO_2) for a given energy output increase as 1/(EROI-1)
    => EROI is a good proxy for costs !
  - The faster we want to deploy a fleet using its own energy,
    the higher EROI should be : doubling time is ln(2)*lifetime / (EROI-1)

=> To be practical EROI should be >>1 (typically >10)
Values for renewables are ~10 for PV, ~80 for wind turbines

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **First approach for storage : ESOI**
  - Introduced by Stanford in 2013 (very new!)
  - Energy Stored On Invested
  - Does not count charged energy, as it is supposed to be free (surplus from intermittency)



$ESOI = \lambda D \, \eta / \varepsilon_s$

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

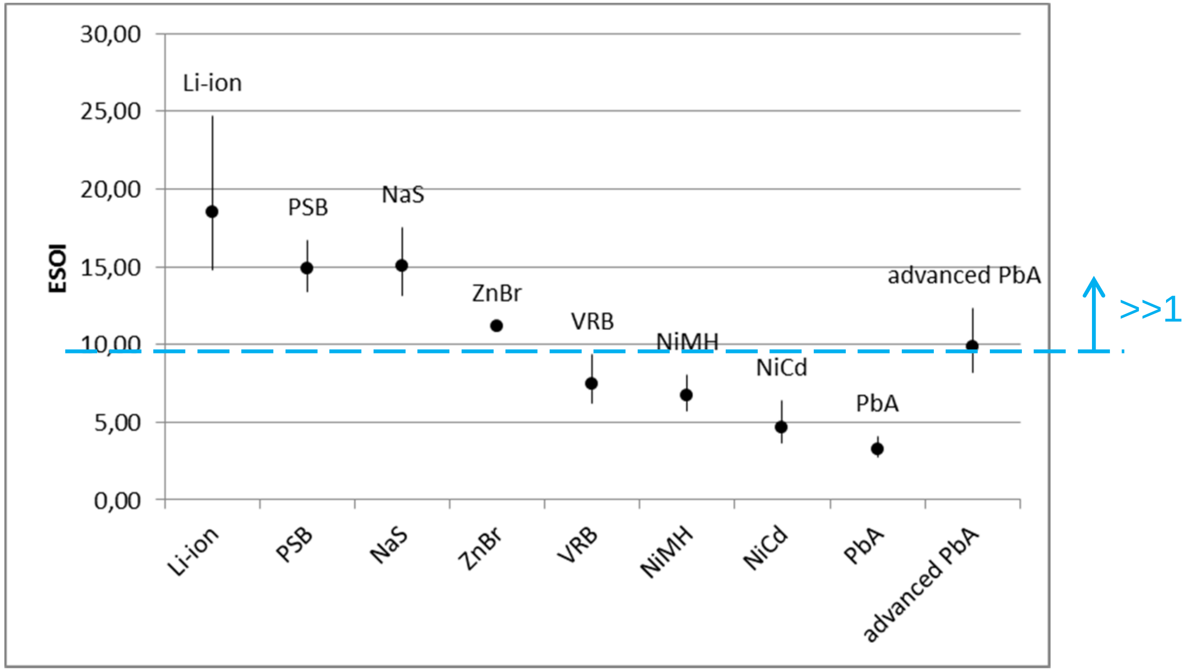
- **Batteries ESOI calculation**
  - Performance parameters used are the following :

	efficiency	Depth of discharge	cycles
PbA	80%	80%	500
advanced PbA	80%	80%	1500
NaS	80%	80%	4000
ZnBr	70%	80%	3500
Li-ion	90%	80%	5000
PSB	65%	100%	5000
VRB	65%	80%	3500
NiCd	75%	33%	5000
NiMH	80%	70%	3500

  - We choose DoD for each technology to optimise full cycles equivalent. We consider 1 cycle/day and limit the number of cycles by calendar life (e.g. 15 years = max. 5000 cycles). Lower DoD increases full cycle equivalents but also the installed capacity and so the initial investment (price, energy, CO_2, materials,…)
  - No accelerated ageing due to temperature, power,… is considered.
  - Embodied energy is primary whereas discharged energy is electrical We suppose the equivalence $1GJ_t$ <-> 0,0972 MWh_e corresponding to 35% primary->electrical efficiency.

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

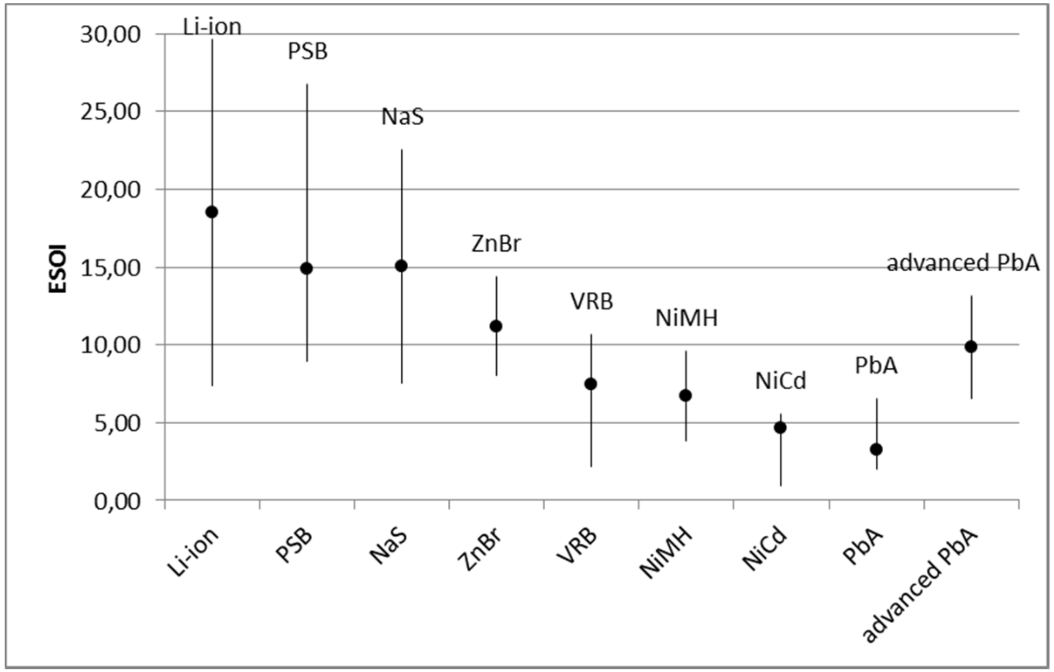
- **Batteries ESOI calculation**
  - We see best results for Li-ion, followed by Na-S and redox flow
  - NiMH, NiCd, and PbA have insufficient ESOI values
  - Advanced lead-acid with higher cycle life has far better EROI



  - Error bars correspond only to the uncertainty in embodied energy
  - How do these results depend on the performance parameters ?

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

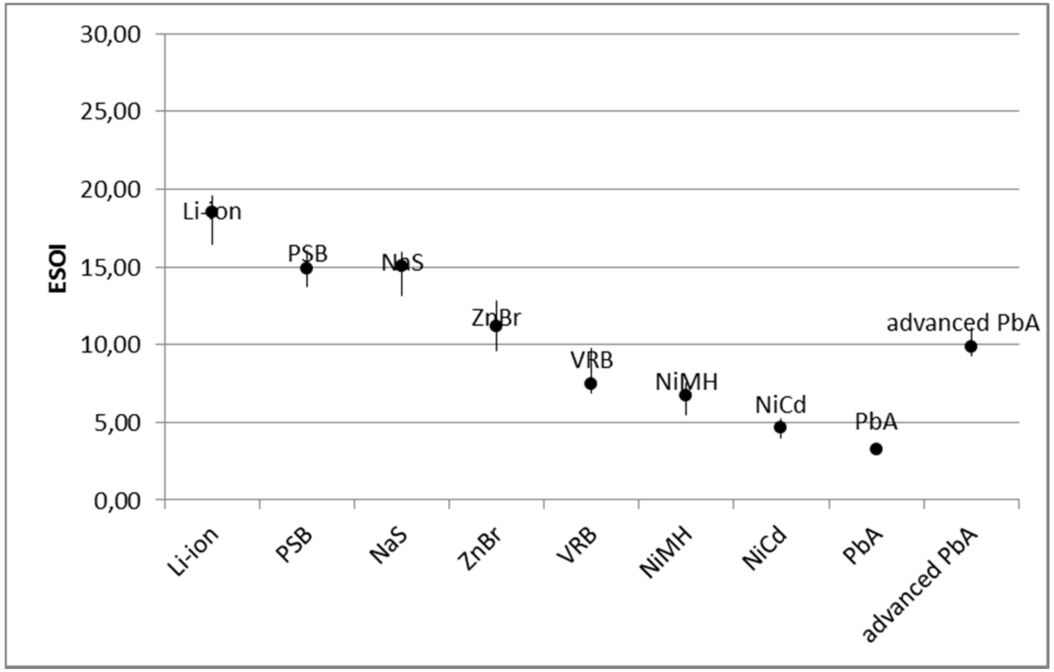
- **Sensitivity to cycle life**
  - Central value considered for embodied energy, without recycling
  - Error bars correspond to the uncertainty in cycle life



Impact of cycle life on ESOI is huge

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

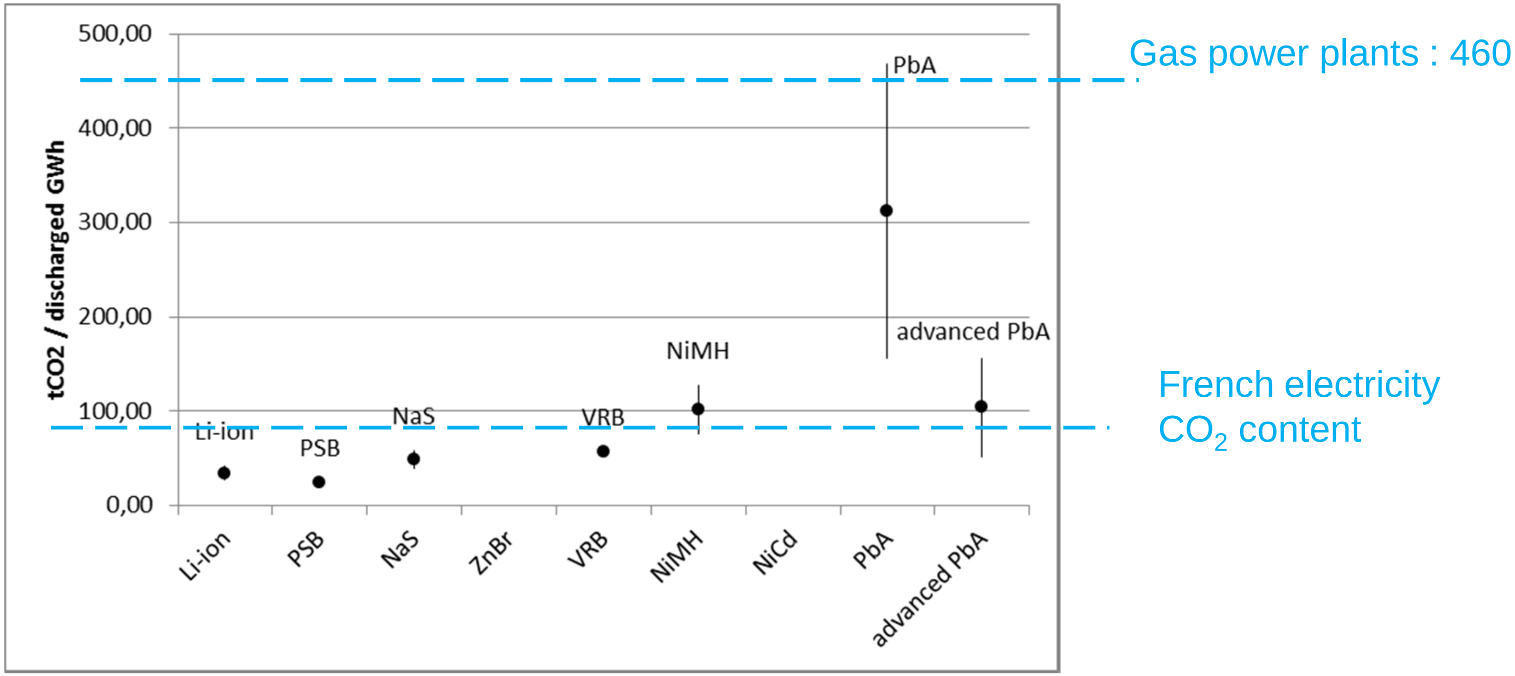
- **Sensitivity to energy efficiency**
  - Central value considered for embodied energy, without recycling
  - Error bars correspond to the uncertainty in energy efficiency



  - Very small effect of energy efficiency on ESOI

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Batteries ESOI calculation**
  - 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 storage could not impair too much the benefit of low carbon energy sources

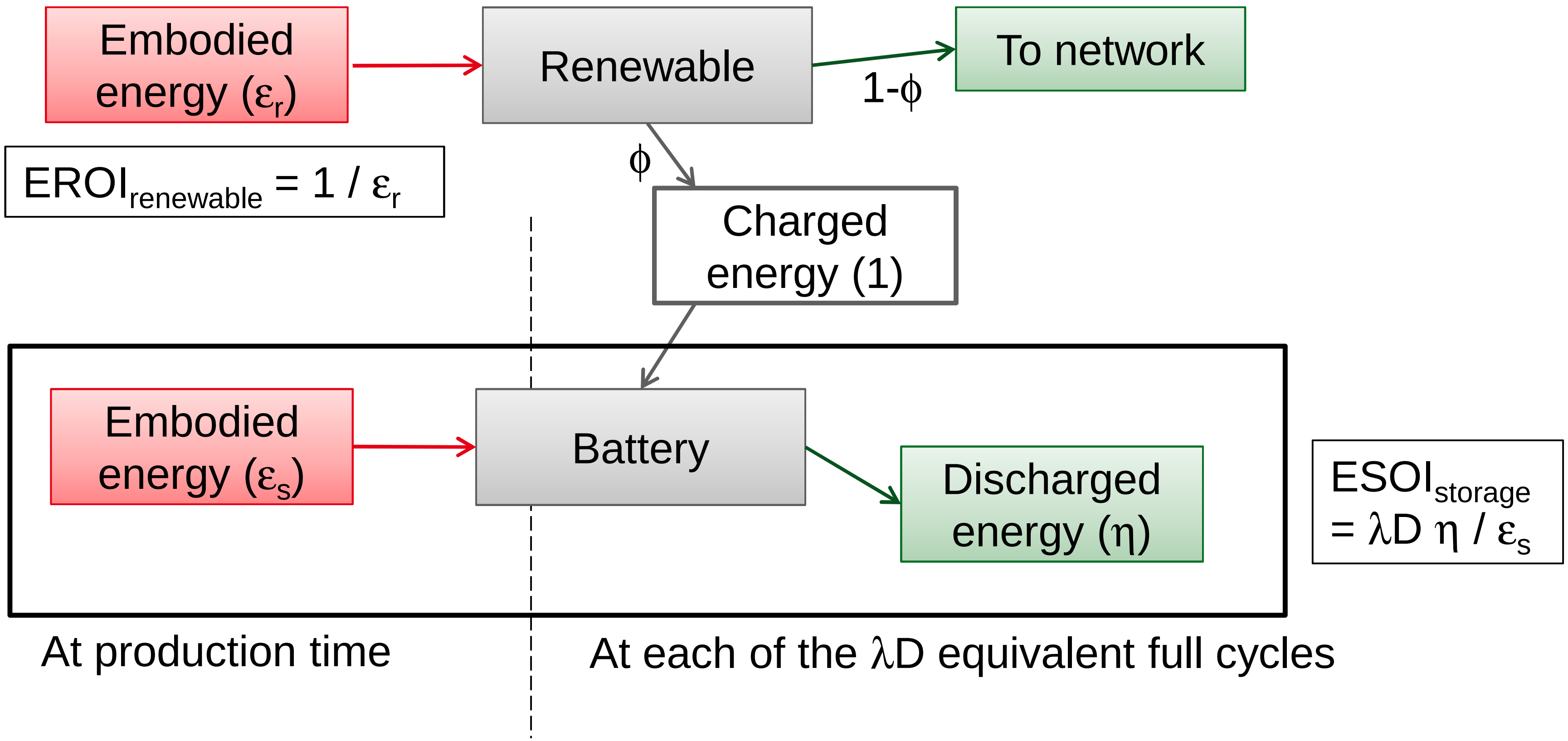
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **ESOI use and interpretation**
  - 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)

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

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

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



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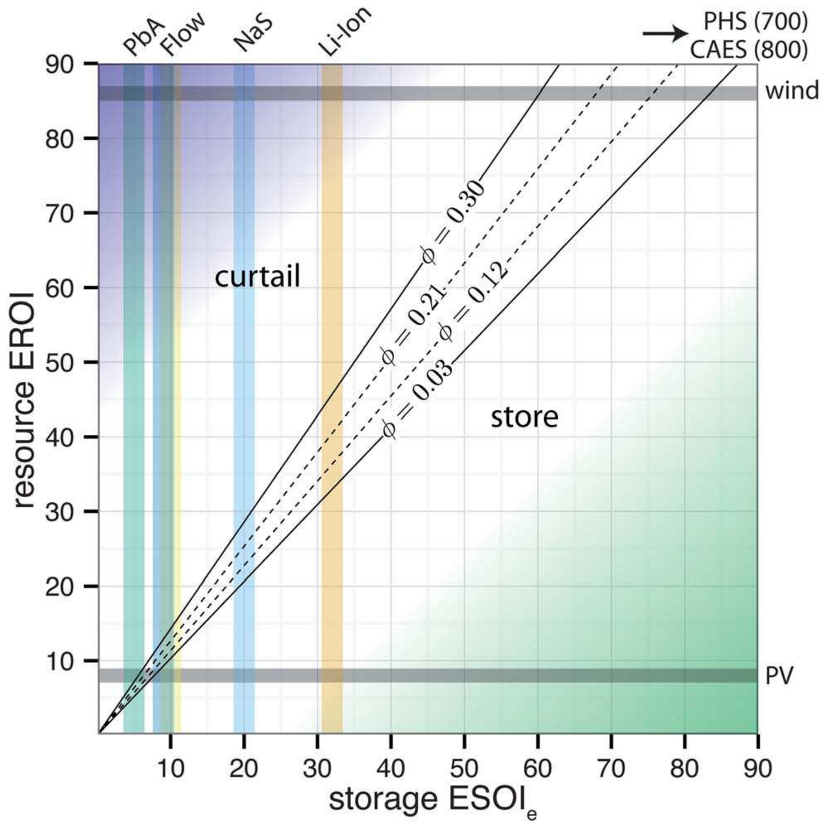
$$EROI_{global\_system} = \frac{1-\phi+\eta\phi}{1/EROI_{renewable} + \eta\phi/ESOI_{storage}}$$

  - Then they compare $EROI_{global\_system}$ to a curtailment scenario and deduce that it is increased if and only if

$$ESOI_{storage} > (1-\phi)EROI_{renewable}$$

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- They deduce that
  - all battery technologies except PbA are relevant for storing PV energy (EROI=8)
  - none are relevant for storing wind energy (EROI=86), which would better be curtailed.

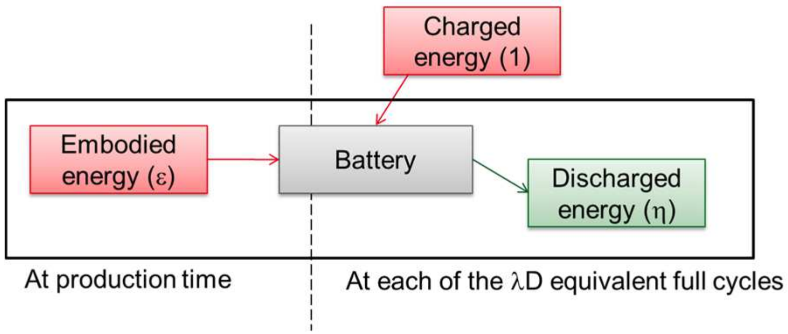


INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Discussion of this approach**
  - ESOI calculation is built upon more or less implicit assumptions
    - **The energy used to charge the storage has zero cost**

This excludes any other use than storing or curtailing
(e.g. lower value usage such as demand shifting, heat or cold storing,…)

We will see later another metric (net storage efficiency) taking it into account



INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Discussion of this approach**
  - ESOI calculation is built upon more or less implicit assumptions
    - Storing energy has two objectives
      1. Not wasting it
      2. Having it available when it is needed
    - In the calculation, the energy discharged from battery has the same value as any energy delivered directly to the network or the energy used to produce the system.

So **the waste is well taken into account, but not the availability**.

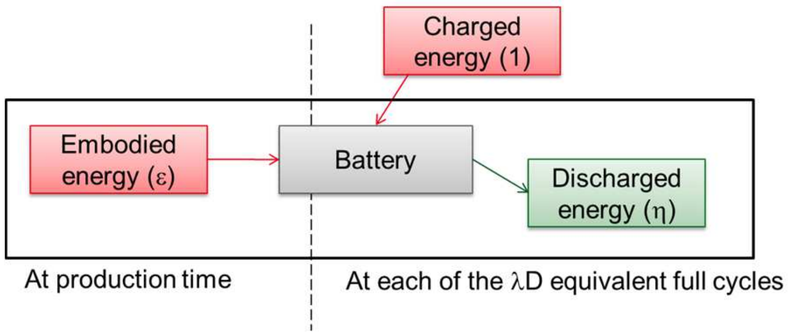
Problem 1 with curtailment : there is **no energy available off-peak**.
Implicitely in-peak and off-peak energy have the same *value*, as if a free storage system existed.

Problem 2 with curtailment : if storage is to be replaced by increased renewable installed power, then **additional transmission capacity** should be installed too, with associated energy cost.

=> In reality even a decreased global EROI can hide an increased energy ‘value’. Economic assessments better describe this part of the problem.

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Discussion of this approach**
  - ESOI calculation is built upon more or less implicit assumptions
    - Each kWh of battery installed can be used up to its full cycle life.
    - In reality, the first installed kWh of batteries will be used everyday, the last ones will be very seldom used are their ESOI very low
    - The implicit assumption is **infinite calendar life**
    - In this case, there would be no penalty to oversize the system
    - Denholm & Kulcinski 2003 : Service life is more often limited by calendar life than by cycle life (except in case of daily and high DoD cycles)
    - We will see later a time-based analysis to overcome this limitation



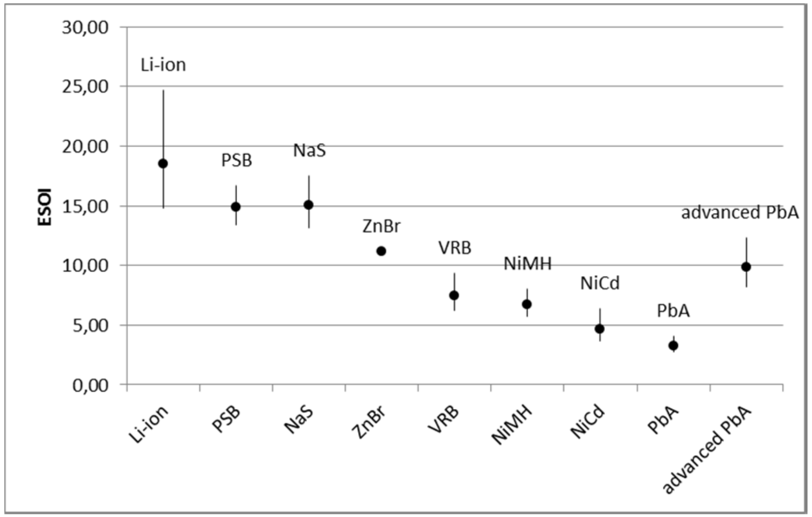
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Discussion of this approach**
  - ESOI calculation is built upon more or less implicit assumptions
    - Energy today is supposed to have the same 'value' as energy later, as **no discount rate is used**
    - In economy, discount rate accounts for various phenomena :
      - Impatience : present is preferred over future
      - Growth : future generations are supposed to be wealthier than current one and discount rate allows to redistribute wealth from future to present. This is for from obvious concerning energy…
      - Uncertainty : initial cost is sure, future reward is only probable. N. Stern uses 0,1%/year discount rate to account for the possibility of human race extinction…
    - Usual rates are in the range 2-5%/year, and 1% less for environmental services

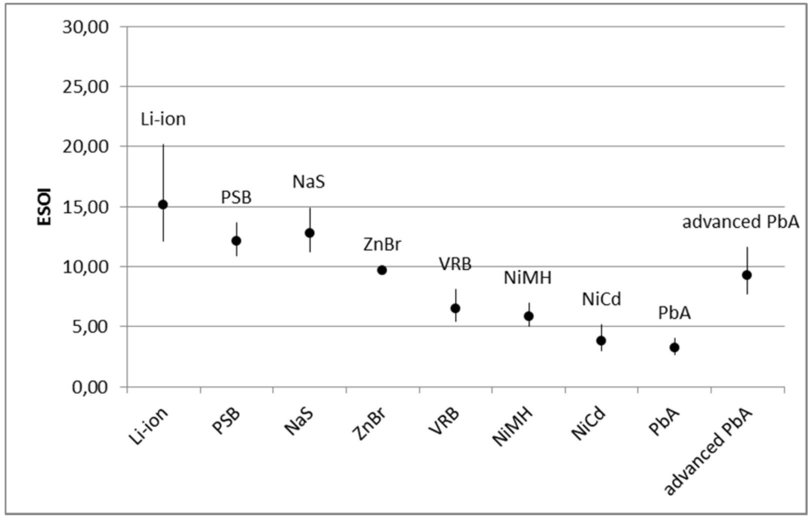
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
1. ESOI

- **Discussion of this approach**
  - For technologies with similar ESOI, including a discount rate will favor those with lower investment and shorter life.
  - This is desirable : In the transitory phase of fleet buildup, there is a risk of very high power consumption for battery production

In practice discount rate has small impact on ESOI and does not change the relative position of the batteries



0% discount rate

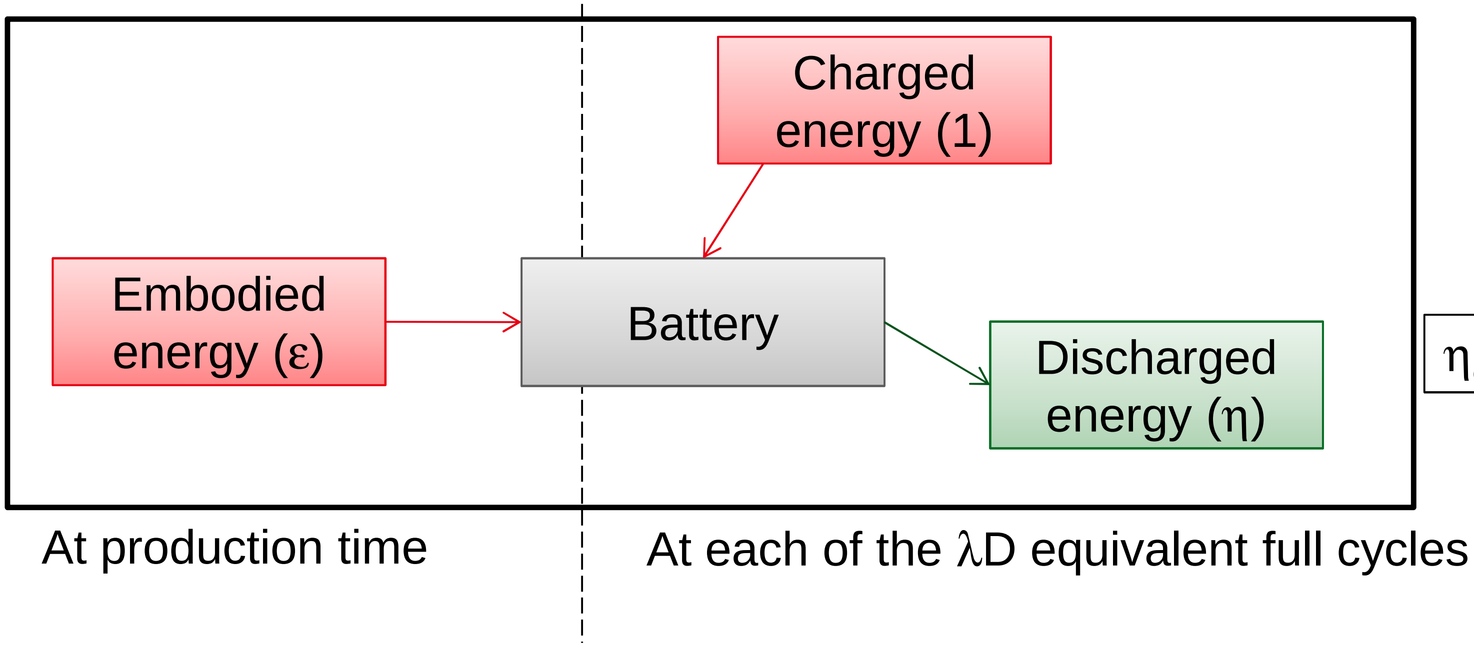


3% discount rate

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
2. NET STORAGE EFFICIENCY

- **Second approach for storage : net storage efficiency**
  - Used for example by Denholm & Kulcinski 2003
  - Studies the impact of battery production on the efficiency
  - Net storage efficiency = discharged energy / (embodied + charged)
  - It is easily calculated from ESOI and energy efficiency

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



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

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
2. NET STORAGE EFFICIENCY

- **Batteries net storage efficiency calculation**

	Efficiency	ESOI	Net efficiency
Li-ion	90%	18,51	86%
PSB	65%	14,86	62%
NaS	80%	15,05	76%
ZnBr	70%	11,20	66%
VRB	65%	7,49	60%
NiMH	80%	6,72	71%
NiCd	75%	4,63	65%
PbA	80%	3,29	64%
advanced PbA	80%	9,87	74%

- The results are only a few percent less than traditional energy efficiency except for really low ESOI (<5-10)

- So if we consider charged energy as a cost together with embodied energy

Efficiency is the main influencing factor as long as EROI > 5-10

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
2. NET STORAGE EFFICIENCY

- **Discussion on ESOI and net energy efficiency**

Approach	Cost of energy used to charge	Main parameter
ESOI	0	Cycle life
Net energy efficiency	Full	Efficiency

- Truth may be somewhere in between according to the usefulness of the curtailed energy…

- If we consider another *cost*, e.g. CO_2 emissions, supposed to be proportional to energy used, then $EROI_{global\_system}$ is a good indicator of the *cost* of electricity delivered to the network.

- However, it does not account for the fact that the energy provided meets the need at right time or not.

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

Higher *value* because time can be controlled

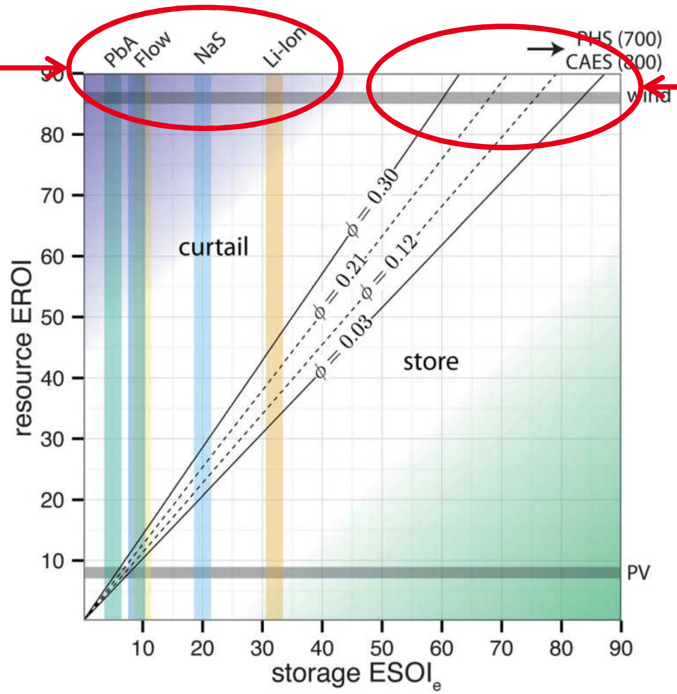
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
2. NET STORAGE EFFICIENCY

- **Discussion on ESOI and net energy efficiency**

  - Both arguments tend to show that $EROI_{global\_system}$ gives too low emphasis on energy efficiency.

$EROI_{global\_system}$ is a powerful metrics but should only be used to compare systems which fulfill the same demand

Storage :
Lower $EROI_{global}$
but demand fulfilled



Curtailment :
Higher $EROI_{global}$
but demand not fulfilled

Satisfying the need at the right time has an energetic and environmental cost

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
3. TIMESCALE BASED EROI ANALYSIS

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

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

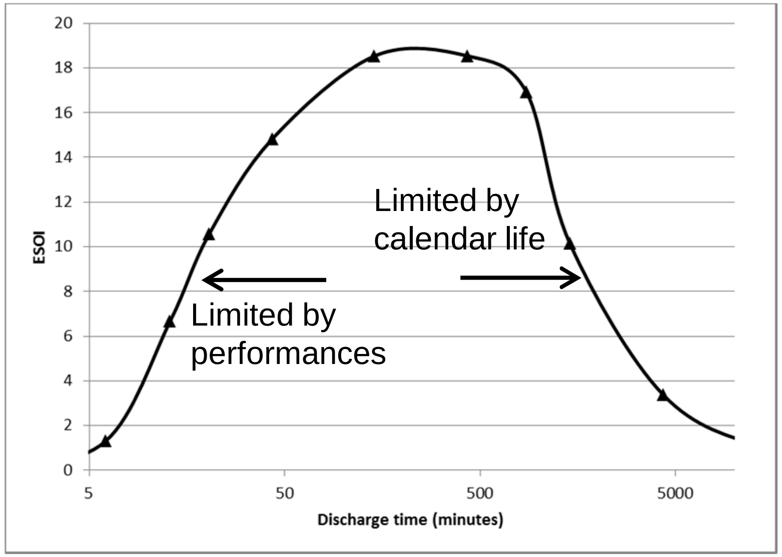
- **For long times**
  - Calendar life limits the number of cycles

- **In both cases ESOI, $EROI_{global\_system}$,… worsen**

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
3. 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

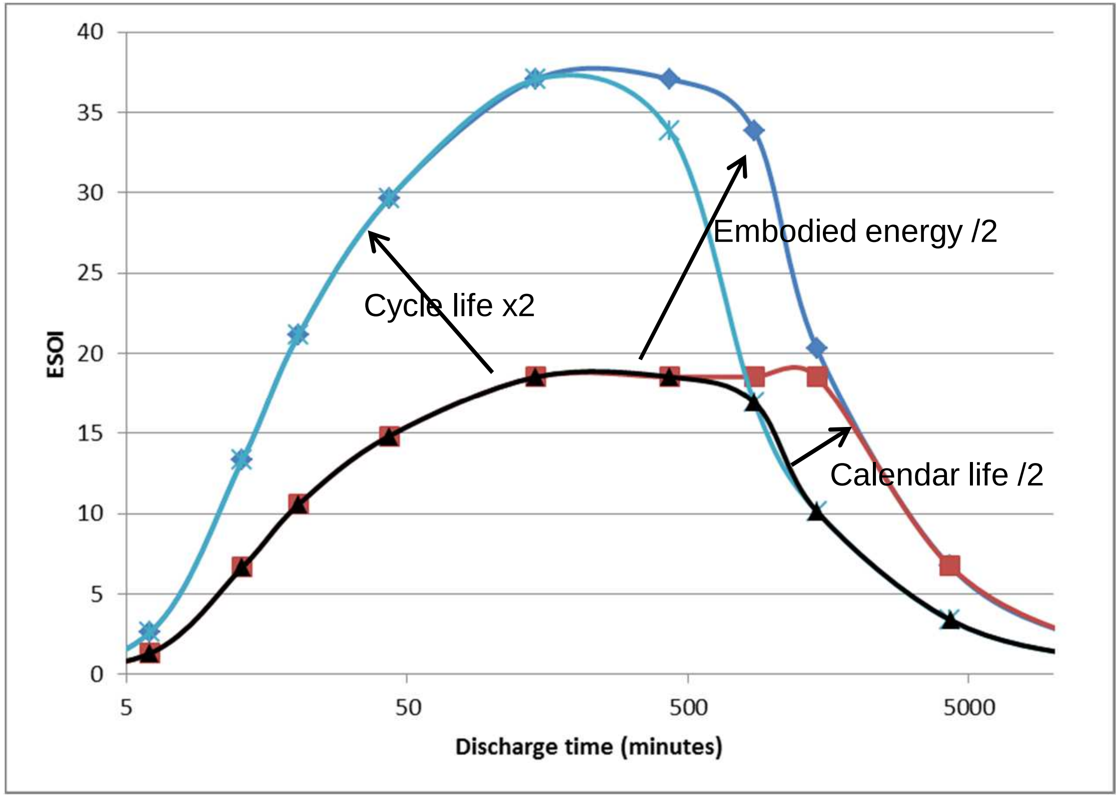
- **Variable parameter = time for charge and discharge**
  - We assume full cycles, and no pause between cycles



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

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
3. TIMESCALE BASED EROI ANALYSIS

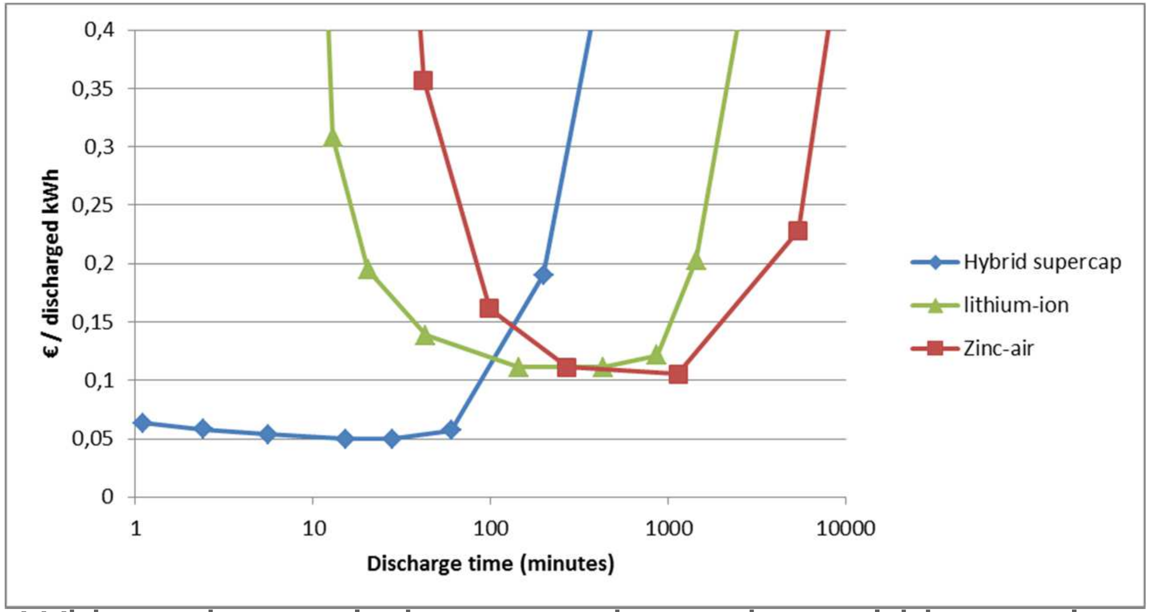
- **What should we do to improve ESOI ?**



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

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
3. 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 network needs could be analysed at different time scales. For systems like flow batteries or fuel cells, E/P ratio can be optimized at each point.

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

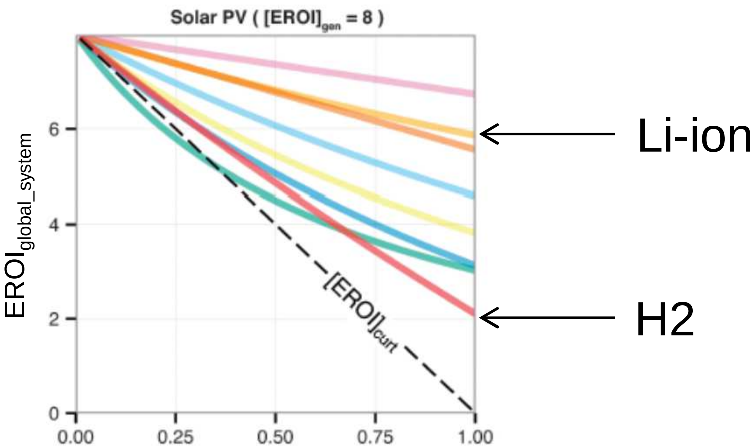
INTERPRETATION OF BATTERY PRODUCTION IMPACTS
4. SOME COMPARISONS

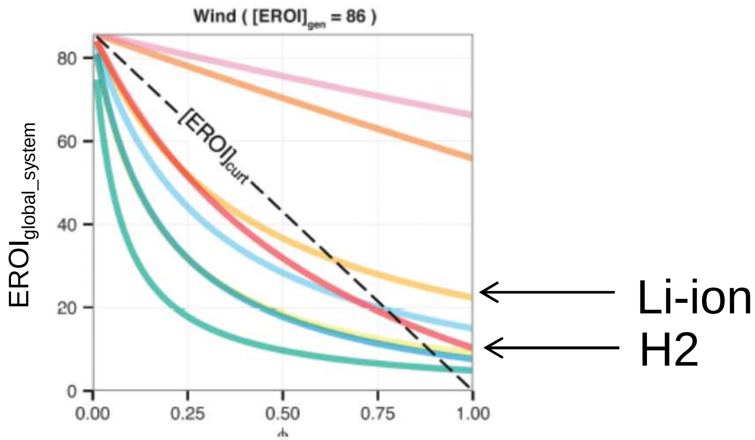
- **Batteries vs H2**
  - Pellow, 2015 compares two strongly different storage technologies :

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

All the figures are on the optimistic side.

  - They are coupled to a wind farm with EROI=86 or a PV farm with EROI=8
  - Despite its higher ESOI, the H_2 system has similar or lower $EROI_{global\text{-}system}$ values than lithium-ion batteries, due to poor efficiency.

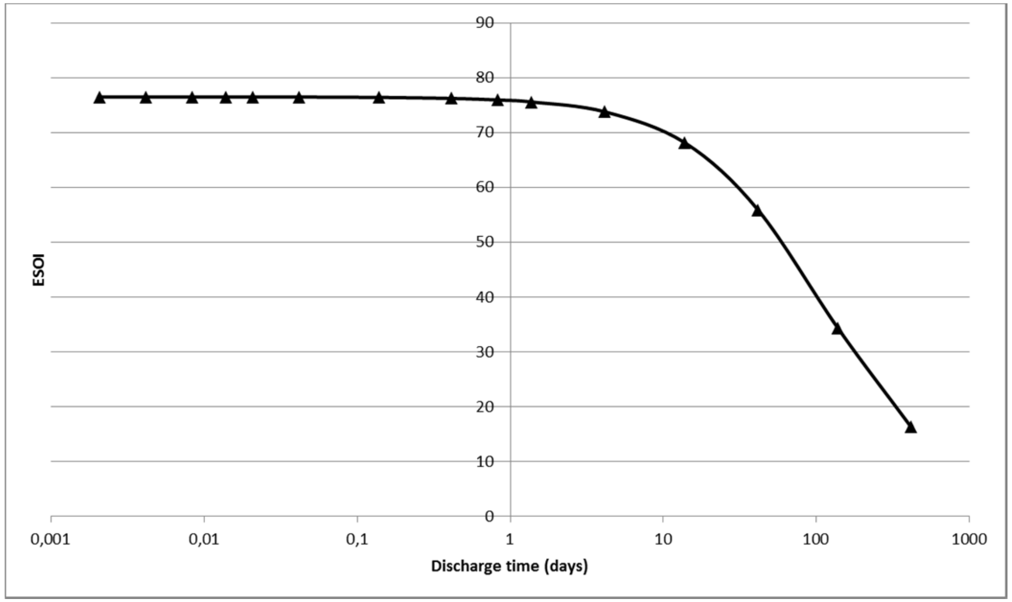




INTERPRETATION OF BATTERY PRODUCTION IMPACTS
4. SOME COMPARISONS

- **Batteries vs H2**
  - Furthermore, even with similar $EROI_{global\_system}$, **the energy available off-peak would be three times lower** with H_2.
  - 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.

H_2 with cheap storage (geological?) may be a good solution for seasonal storage, despite low efficiency



Combined heat and power could help improve the efficiency

INTERPRETATION OF BATTERY PRODUCTION IMPACTS
4. SOME COMPARISONS

- **Batteries vs PHS**

  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,…)
  How much would provide a good ESOI ?

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

1. Why considering the environmental impact of batteries ?

2. Battery essential parameters

3. Overview of batteries

4. Material availability

5. Impact of battery production

6. Interpretation of battery production impacts

7. Conclusion

CONCLUSIONS
1. SIZE DOES MATTER

- We can foresee the need for **very large amount** (50TWh) of daily storage

- Resource use and environmental impact will be significant

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

liten
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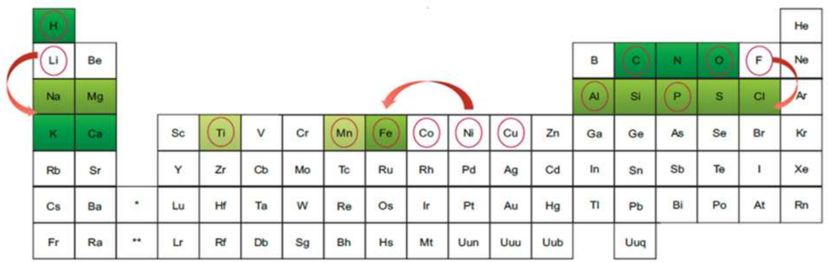
CONCLUSIONS
2. MATERIAL AVAILABILITY

- **Most existing technologies will be limited by material availability, even considering recycling**
- Notable exceptions are Supercapacitors, Na-S, Fe-Fe

- Apart from identified CRM, limits will come from **Cd** and **V**, then **Pb** and **Ni**, perhaps from Li, Zn, Ti
- Research should focus on **substitution of Li at negative and Ni at positive** electrodes
- Active research areas able to tackle this limitation include :
  - Organic active materials
  - Air or sulfur cathode
  - Na^{+}, K^{+}, Mg^{2+}, Ca^{2+} or Cl^{-} ions



CONCLUSIONS
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. Recycling (potential gain ~30%)
  3. Processes (1/4 – 1/2 of total)

CONCLUSIONS
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. Recycling (potential gain ~30%)

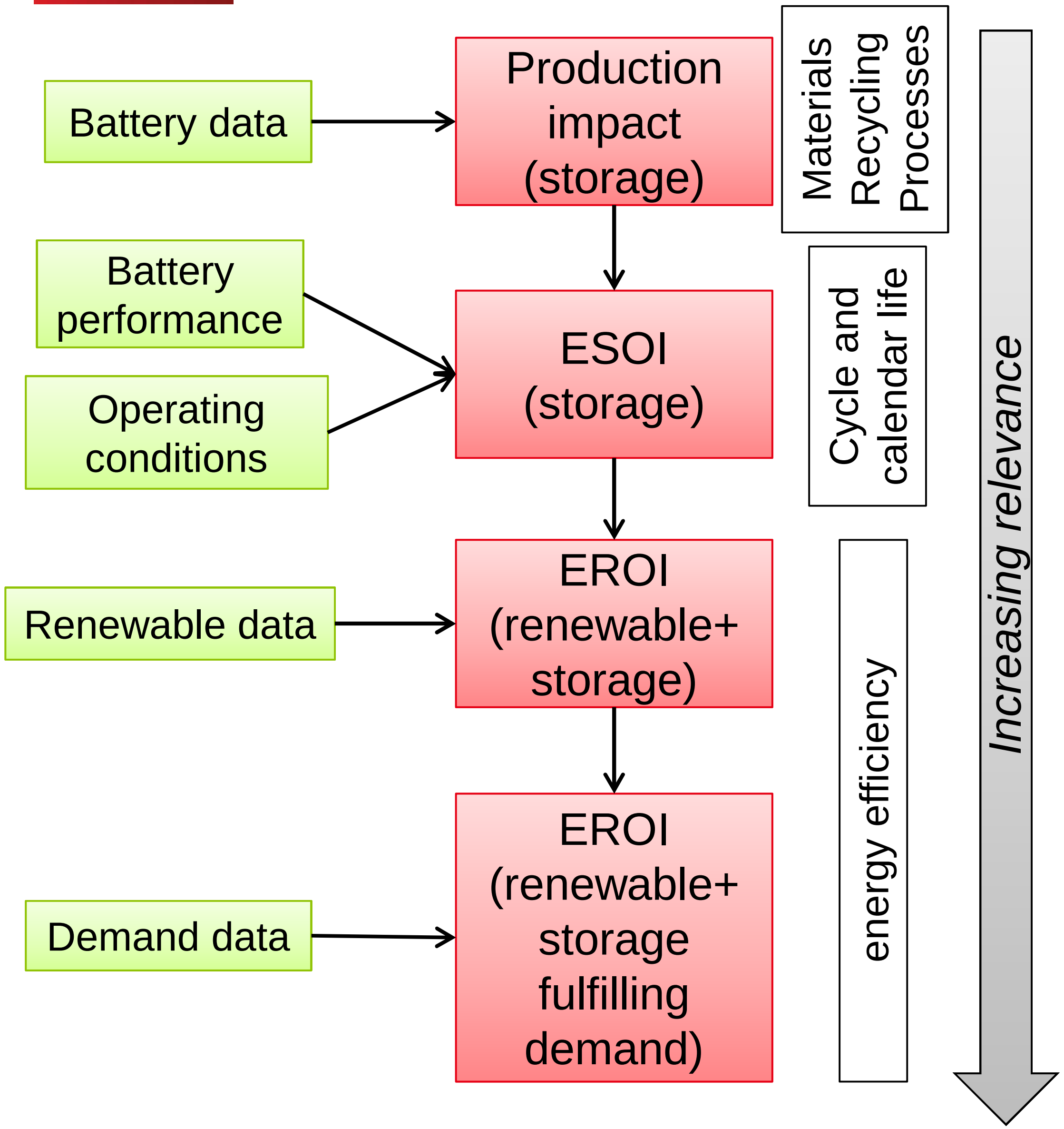
- Develop **low impact recycling processes**
- **Standardize** batteries to optimize recycling

3. Processes (1/4 – 1/2 of total)

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

cf Larcher & Tarascon, 2015

CONCLUSIONS
4. ENVIRONMENTAL EVALUATION OF STORAGE



- **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 $EROI_{global\_system}$
- A **new tool** is needed to couple EROI evaluation with **timely meeting the demand**
- Don’t forget to come back to physical impact (GWP,…)

CONCLUSIONS

4. ENVIRONMENTAL EVALUATION OF STORAGE

- Study of ESOI at different time scales suggests :

~1h ?

1 or few days

< ~1h	~1h – 1 or few days	> 1 or few days
Cycle life too low	Batteries optimal ESOI e.g. : Li-ion	Embodied energy too high
Prefer very high cycle life (10^5-10^6). e.g. : supercaps	Their good efficiency makes them a good candidate in this range, when good PHS sites are exhausted	Prefer P/E decoupled systems with very low embodied energy for E. e.g : H2, some flow batteries
Optimize their embodied energy via energy density	Optimize their embodied energy (see above)	Optimize their efficiency

Hybridizing is necessary to accomodate all time scale 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

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