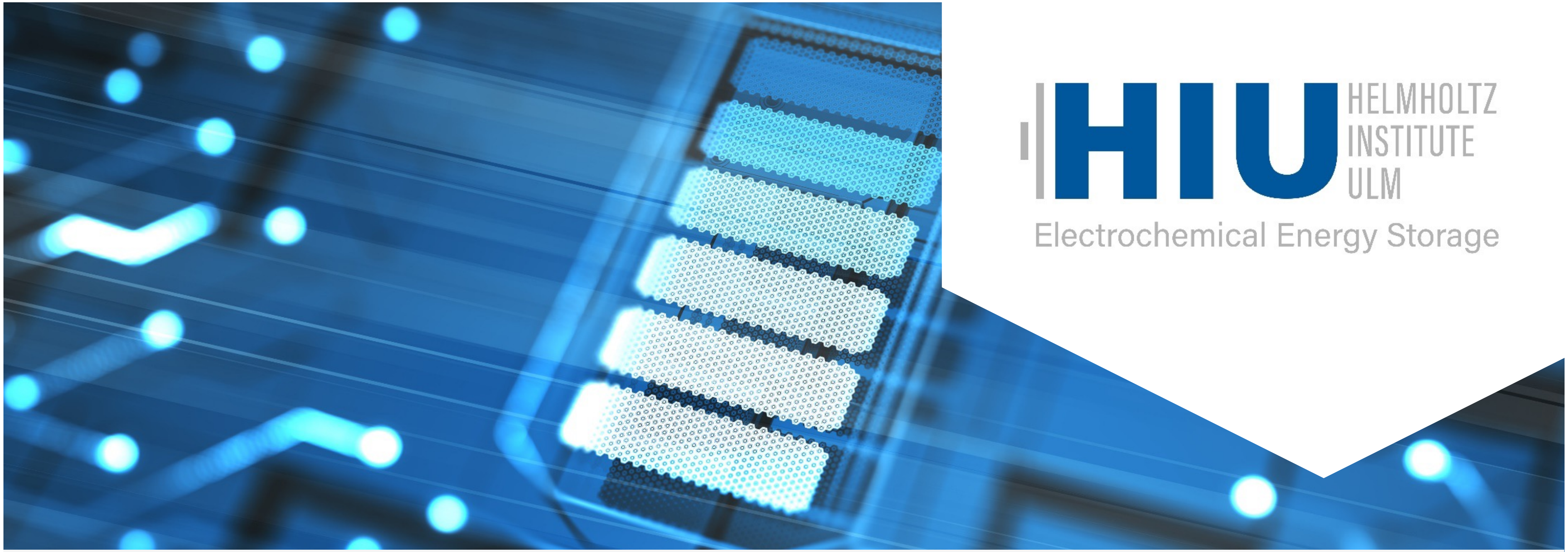

HIU HELMHOLTZ INSTITUTE ULM
Electrochemical Energy Storage

Stefano Passerini

An approach to the Energy Transition: From the Oil Barrel to Reactive Metals

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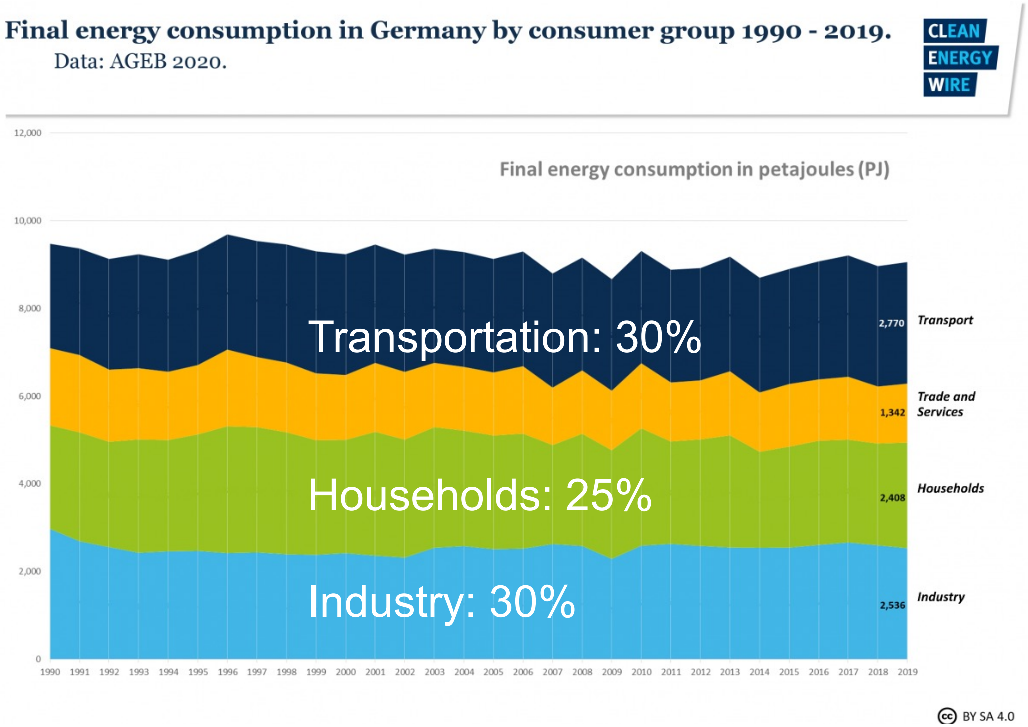
KIT Karlsruhe Institute of Technology · ulm university universität uulm · ZSW · DLR

Decarbonising Europe by 2050

EU Energy players propose one broad ambitious mission for Europe
"Decarbonising Europe by 2050".
A new framework programme has been created "Horizon Europe". This coalition gathers the most important energy players in Europe covering electrical, heat and gas sector

On 28 **November 2018**, the Commission presented its **strategic long-term vision for a climate-neutral economy by 2050** (emissions are balanced by methods of removing warming gases from the atmosphere)

Source: ETIP SNET Website https://ec.europa.eu/clima/policies/strategies/2050_en



Secure Energy Needs for:

Transportation

Residential

Industry

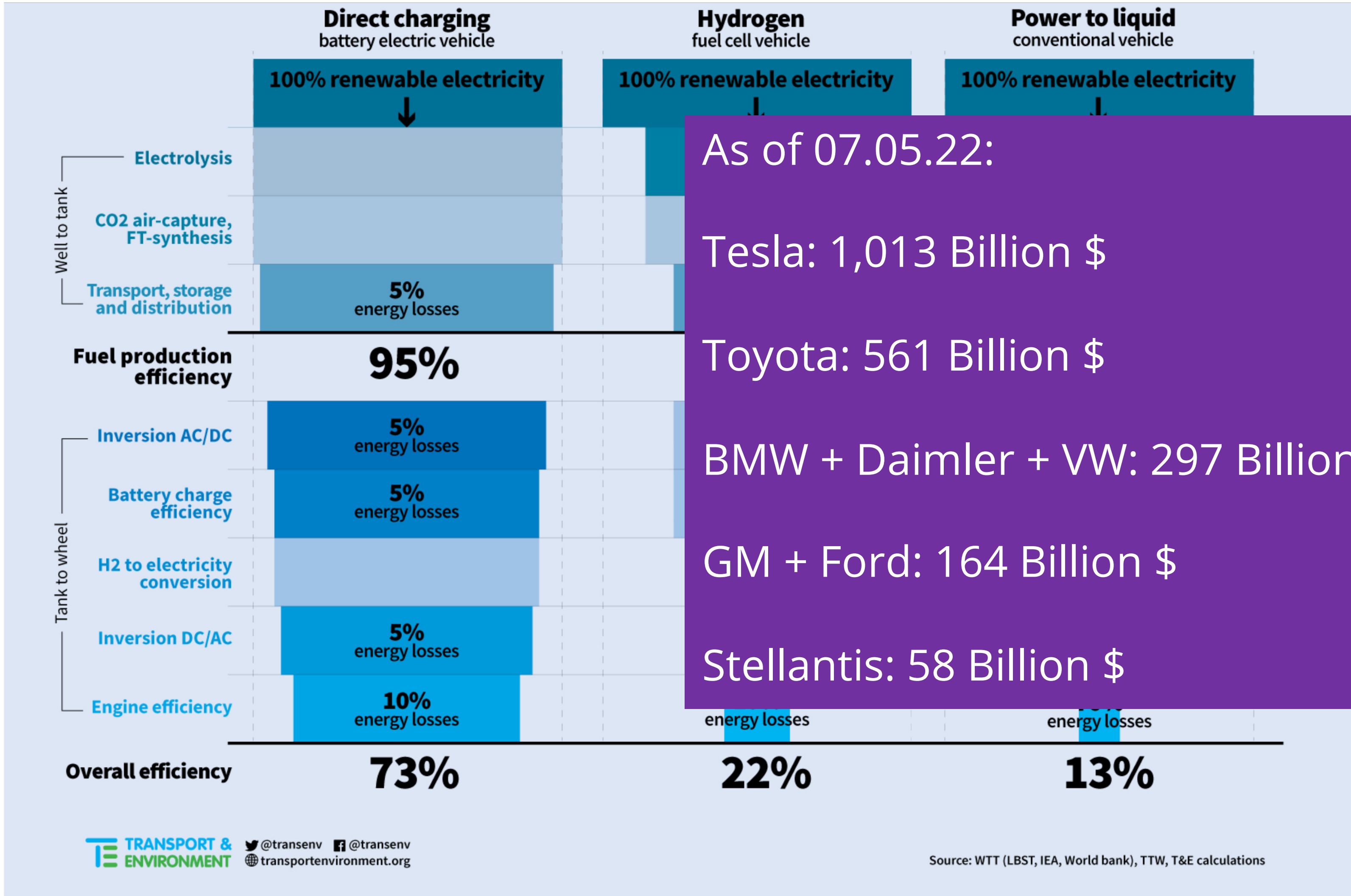
“Der Weg nun, auf welchem diese grösste aller technischen Fragen, die Beschaffung billiger Energie, zu lösen ist, dieser Weg muss von der Elektrochemie gefunden werden.”

“The path leading to the solution of the most difficult of all technological questions - the delivery of cheap energy - must be discovered by Electrochemistry”

F.W. Ostwald, Z. Elektrotechnik und Elektrochemie, 1894

One of the most important missions for electrochemistry is to enable a sustainable energy future

Decarbonising the Transportation Sector



As of 07.05.22:

Tesla: 1,013 Billion $

Toyota: 561 Billion $

BMW + Daimler + VW: 297 Billion $

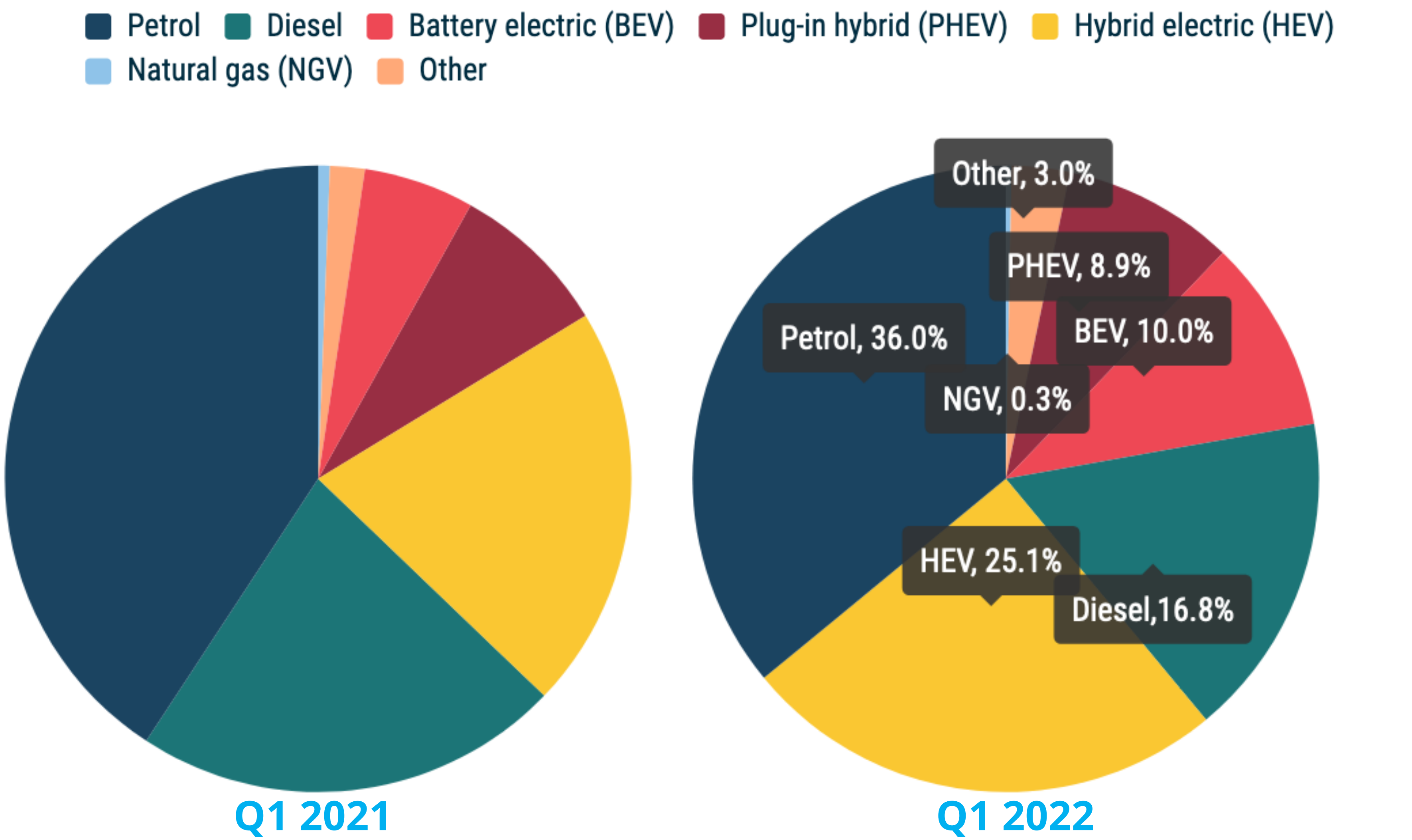
GM + Ford: 164 Billion $

Stellantis: 58 Billion $

Energy storage in batteries is way more efficient than in hydrogen and liquid fuels.

No wonder Tesla capitalizes more than Toyota as well as the three German carmakers altogether !!!

HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

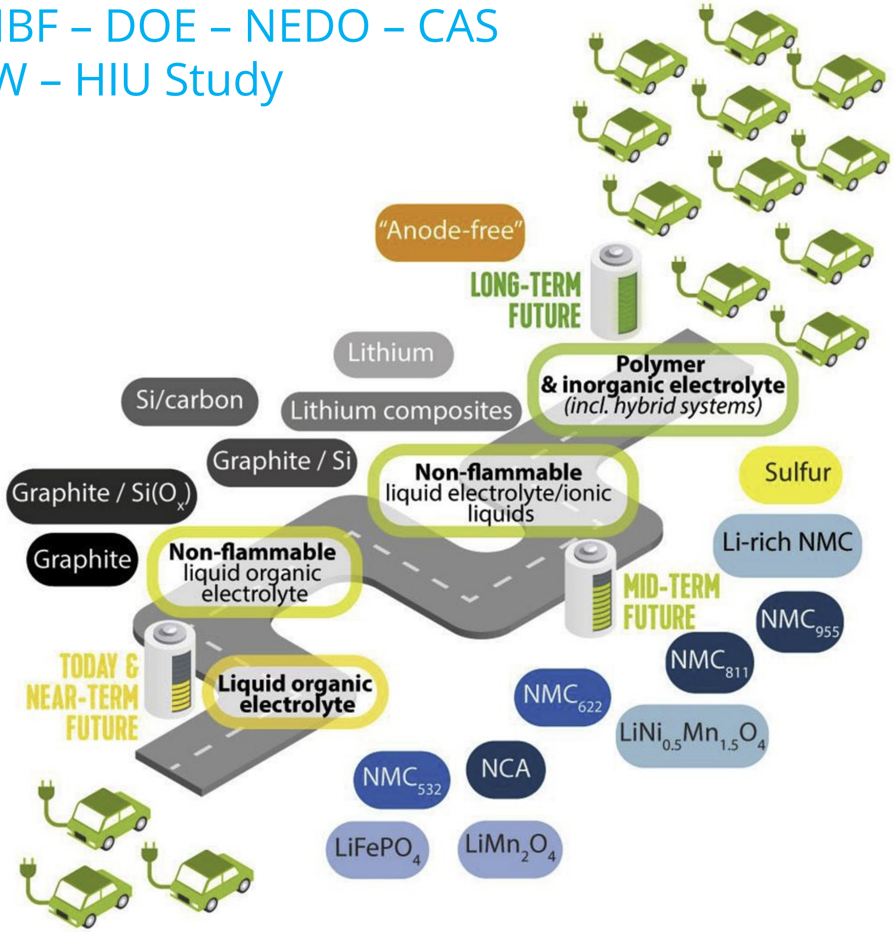


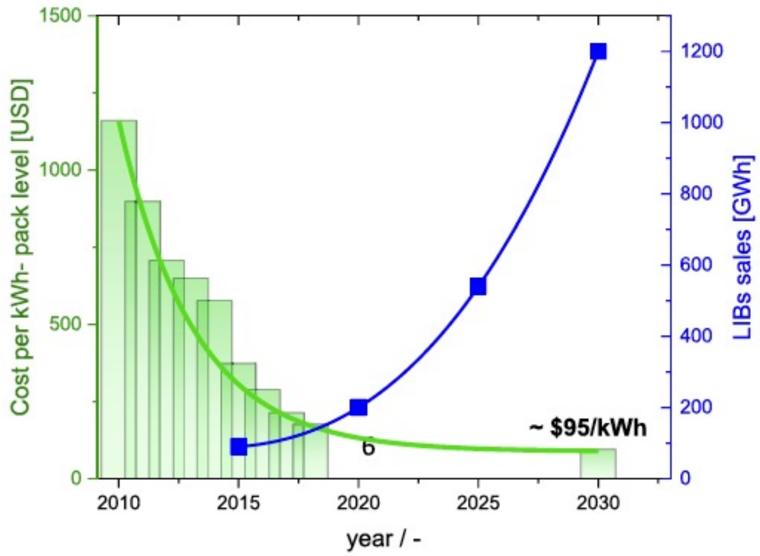
Share of HEV, PHEV and EV in the EU is growing fast. **44% in Q1 2022**

https://www.acea.be/

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

BMBF – DOE – NEDO – CAS
ZSW – HIU Study

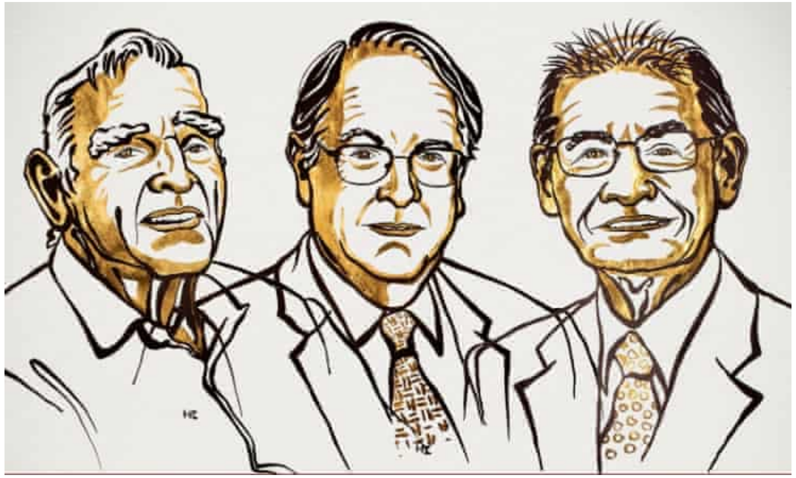




A Behind the Scenes Take on Lithium-ion Battery Prices" –bloombergNEF-; predicted costs for 2030 kindly provided by NEDO.

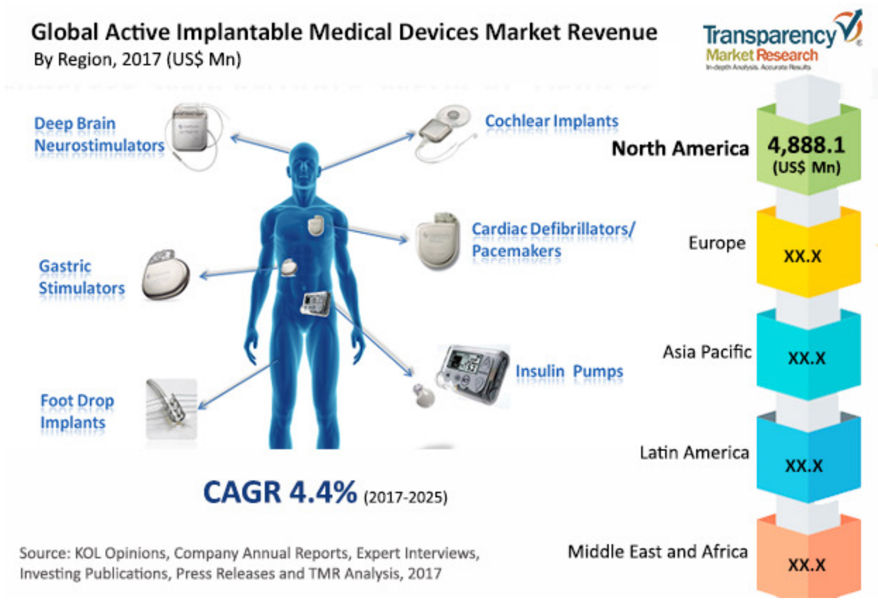
Lithium batteries (LIBs and LMBs) will lead the EV market for the next 10-15 years (at least).

M. Marinaro et al., J. Power Sources (2020) 10.1016/j.jpowsour.2020.228073



Nobel Prize in Chemistry 2019

John B. Goodenough,
M. Stanley Whittingham
and Akira Yoshino.



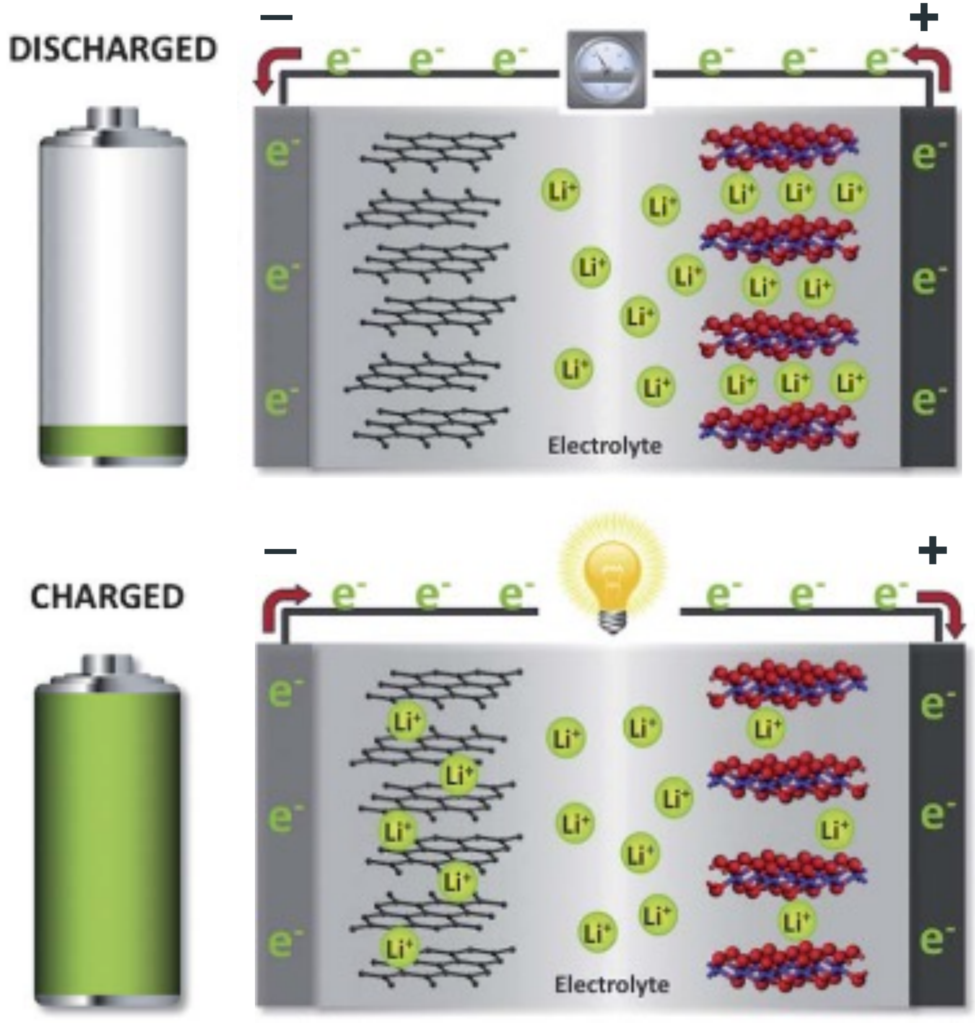
Source: https://www.theguardian.com/science/2019/oct/09/nobel-prize-in-chemistry-awarded-for-work-on-lithium-ion-batteries.

Lithium-ion Batteries – operating principle

Negative electrode (Carbon)

Electrolyte (organic solvent + Li salt)

Positive electrode (Layered metal oxide)



$$yC + LiMO_2 \underset{\text{discharge}}{\overset{\text{charge}}{\rightleftharpoons}} Li_xC_y + Li_{(1-x)}MO_2$$

Average Cell Voltage ~ 3.6 V

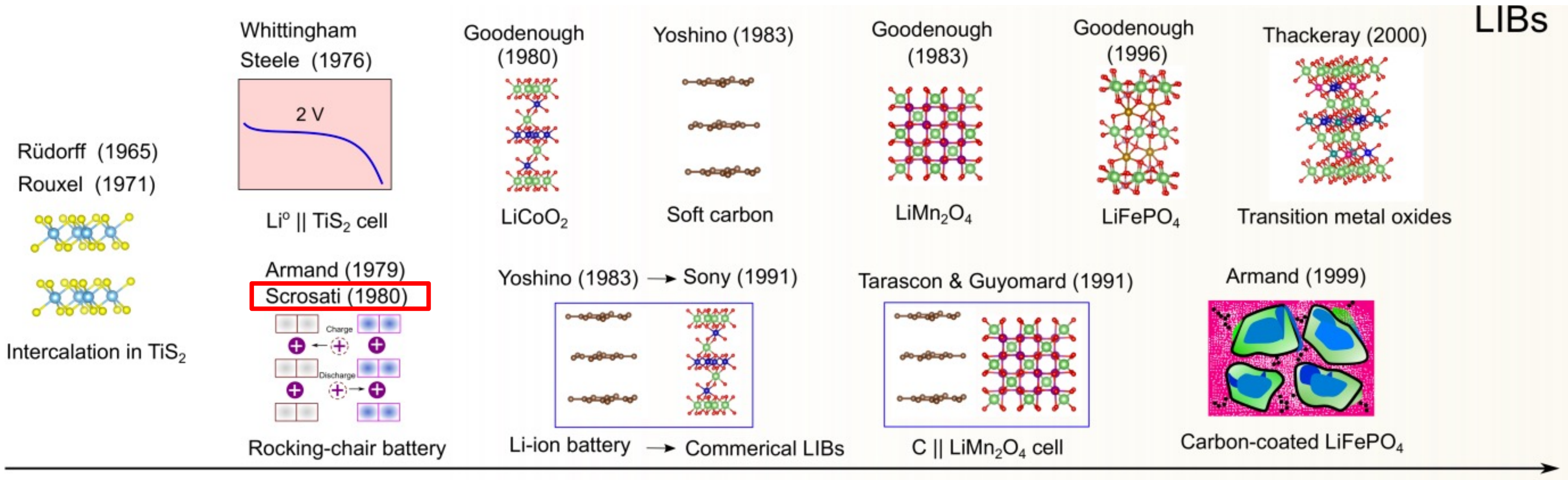
Energy (Wh) = Voltage (V) x Capacity (Ah)

System	Nominal Voltage / V	Energy*	
		Gravimetric / Wh kg^{-1}	Volumetric / Wh L^{-1}
Pb-Acid	2.1	40	90
Ni-Cd	1.2	60	130
Ni-MH	1.2	80	215
Li-ion	**3.6**	**300**	**700**

*Practical values on battery pack level

The Li-ion performance has more than doubled in the past 30 years, „just“ by optimizing cell design...

M.M. Thackeray et al., Energy Environ. Sci., 2012, 5, 7854



1980 - First report on Lithium-ion (Rocking Chair) Battery

1991- First commercial Lithium-ion Battery

Journal of the Electrochemical Society • Volume 127, Issue 3, Pages 773 - 774 • 1980

A Cyclable Lithium Organic Electrolyte Cell Based on Two Intercalation Electrodes

Lazzari M.[a]; Scrosati B.[b]

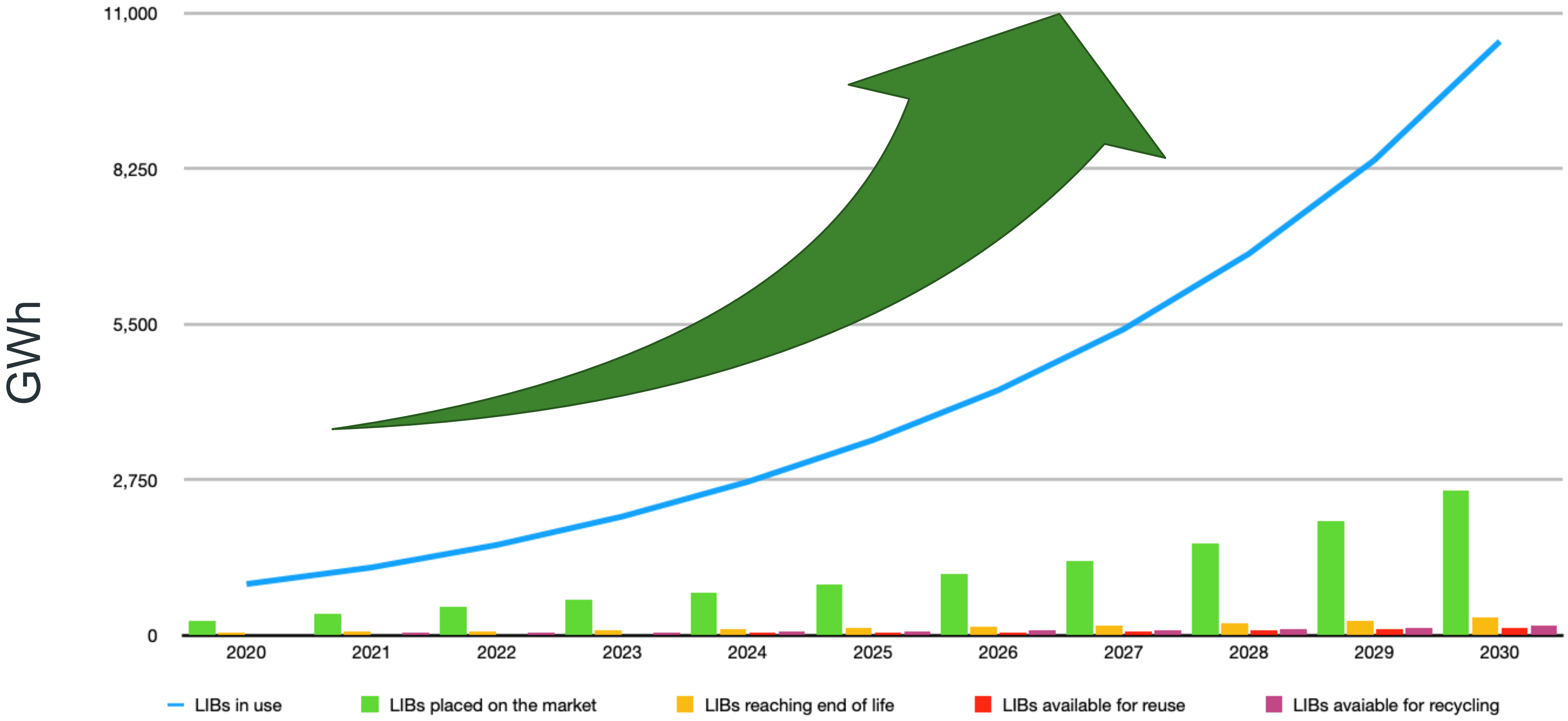
Save all to author list

[a] Centro Studio Processi Elettrodici del C.N.R, Polytechnic of Milan, Milan, Italy

[b] Istituto di Chimica Fisica, University of Rome, Rome, Italy

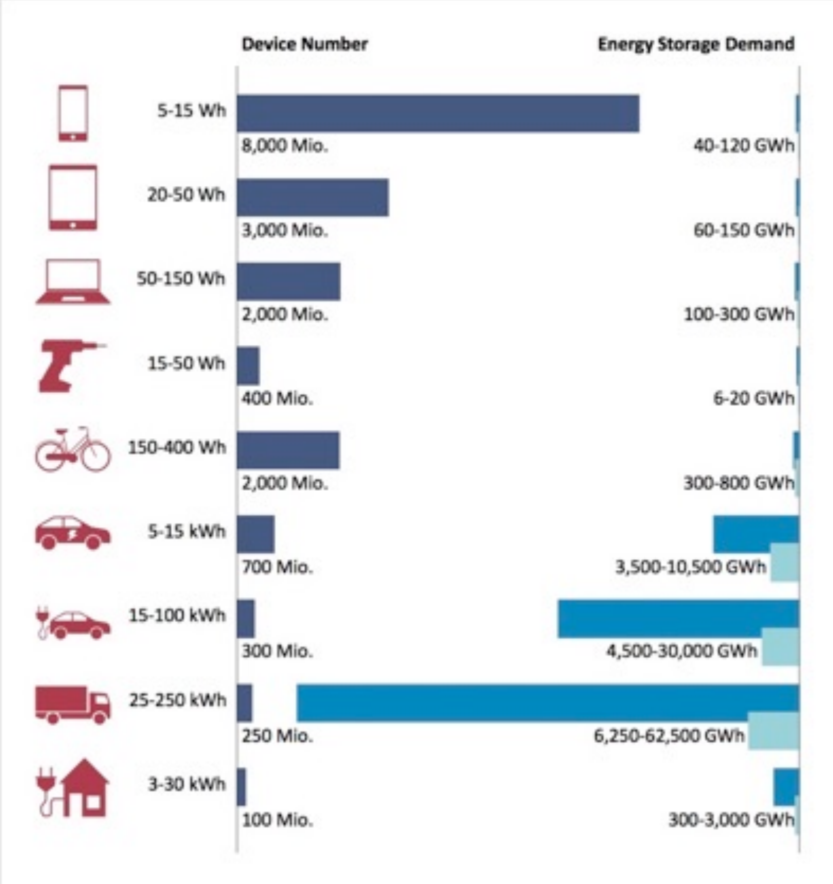
H. Zhang et al., Angew. Chem. Int. Ed. 10.1002/anie.201913923

LIBs production grows extremely fast because of EV



The 2021 forecast on LIBs production in 2030 was two times higher than the 2020 forecast.

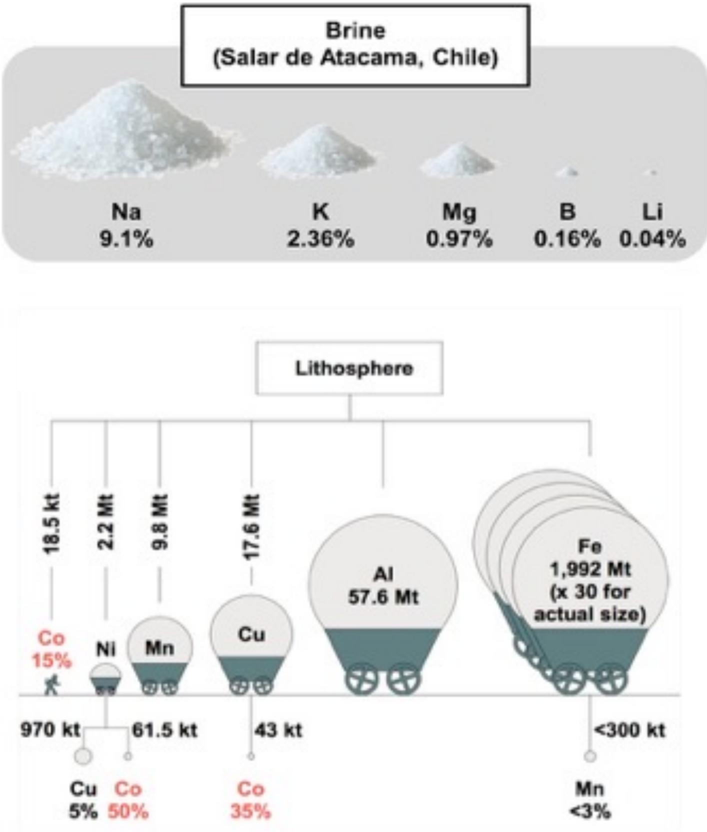
Battery Energy Storage
2050 Scenario



Cumulative capacity demand in 2050: 14-107 TWh

Production 2016: 44 GWh (1540 GWh by 2050)

Availability of Resources

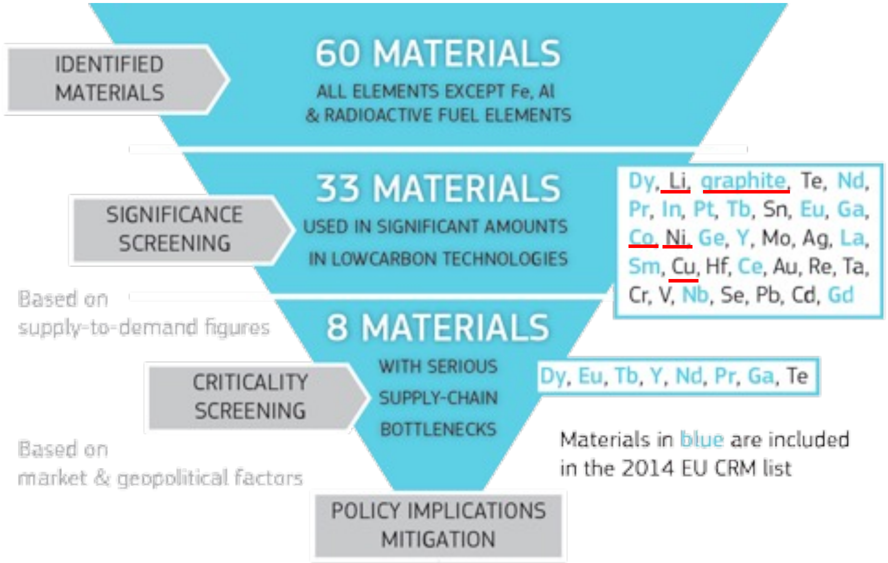


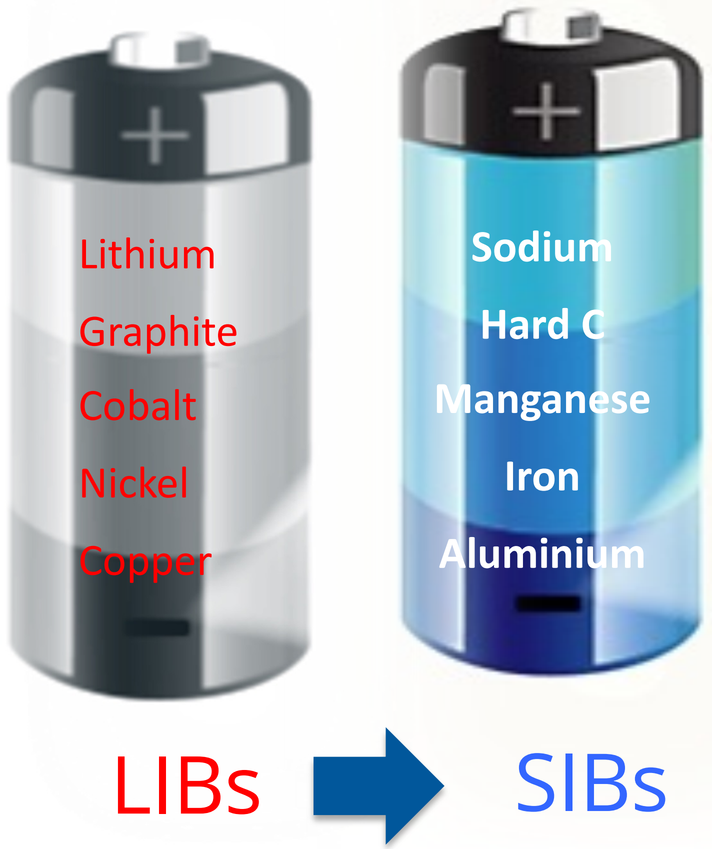
Lack of Cobalt (soon) then Nickel and, eventually, Lithium !!!!

C. Vaalma, D. Buchholz, M. Weil, S. Passerini, Nature Materials Reviews (2018)

NEED TO REDUCE DEPENDENCE ON CRITICAL MATERIALS (EU)

In 2014, the EU issued a revised list of 54 raw materials, among which 20 were identified as critical in terms of supply risk and economic importance.





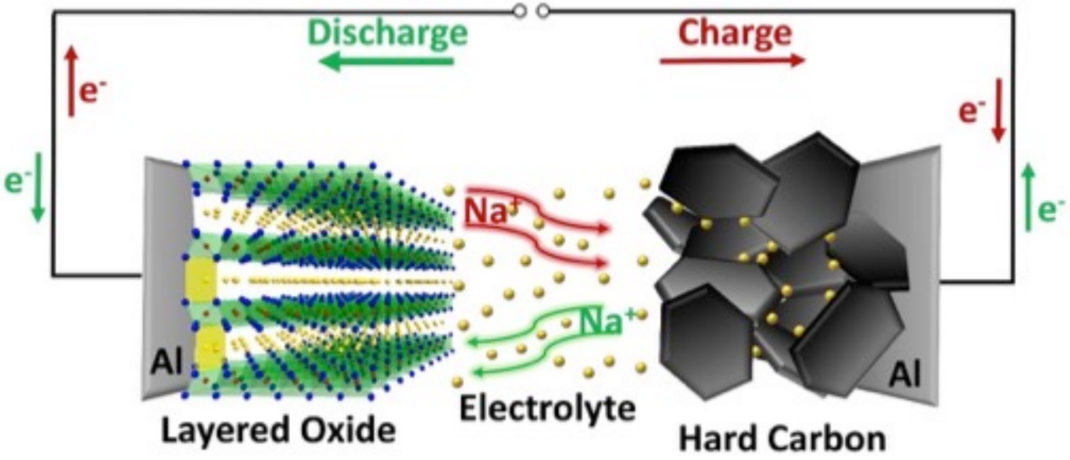
- ❑ Supply risks (geopolitical);
- ❑ Supply restrictions (importance and substitutability);
- ❑ Environmental implications (human health and ecosystems);

https://setis.ec.europa.eu/setis-reports/setis-magazine/materials-energy/critical-materials-energy-technologies-evangelos
IDTechEx USA2017Masterclass13Copyright © IDTechEx. www.IDTechEx.com
Graedel, et al. "On the materials basis of modern society" PNAS 2015 112 (20) 6295-6300.

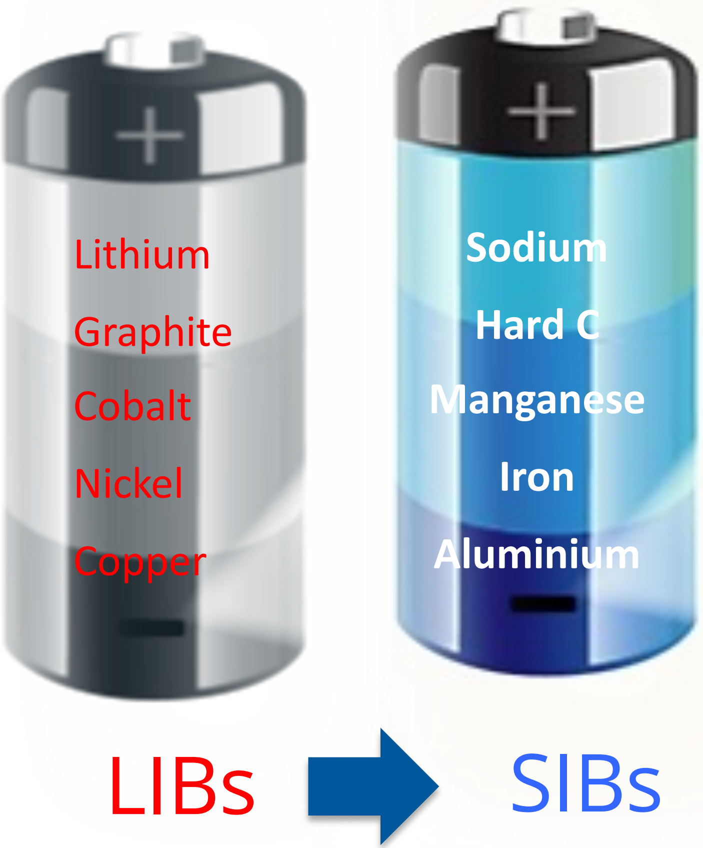
Sodium-ion Battery philosophy:

- Use of low-cost & environmentally friendly raw materials;
    - Reduce dependency on critical materials

"Drop-in" technology

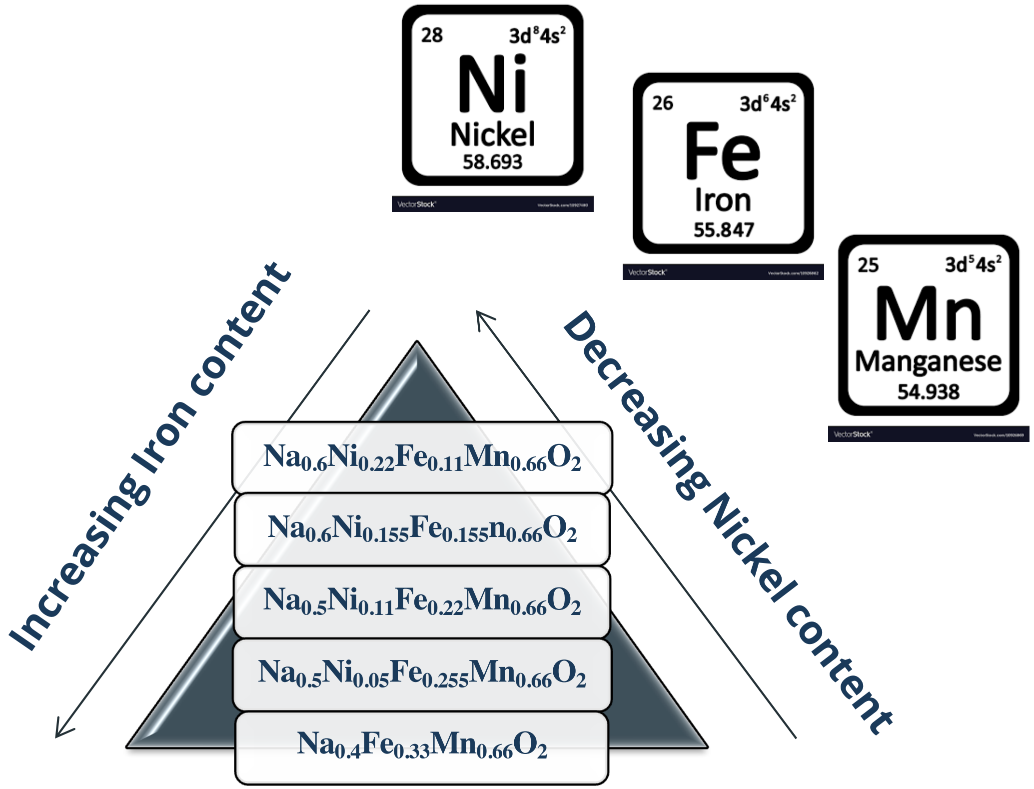


Foreseen applications for Sodium-ion batteries:
Scooters
Light-duty vehicles
City buses
Stationary energy storage



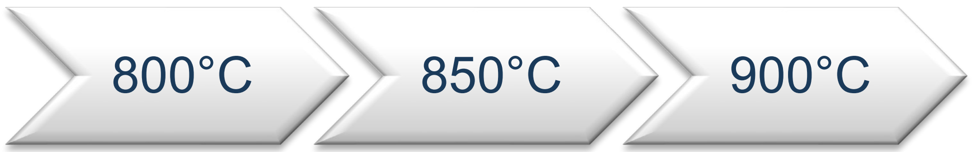
https://setis.ec.europa.eu/setis-reports/setis-magazine/materials-energy/critical-materials-energy-technologies-evangelos
IDTechEx USA2017Masterclass13Copyright © IDTechEx. www.IDTechEx.com
Graedel, et al. "On the materials basis of modern society" PNAS 2015 112 (20) 6295-6300

Toward Cobalt free cathodes:
Ni-Fe-Mn based transition metal layered oxides

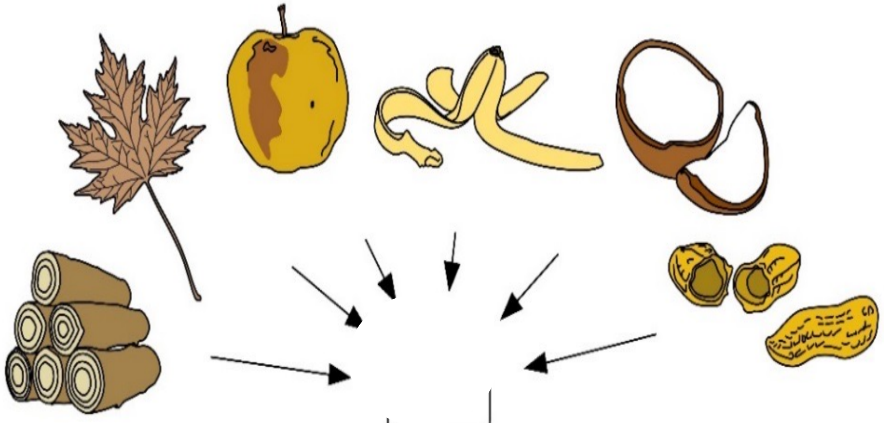


Nickel to Iron Ratio in the layers of the transition metal oxide

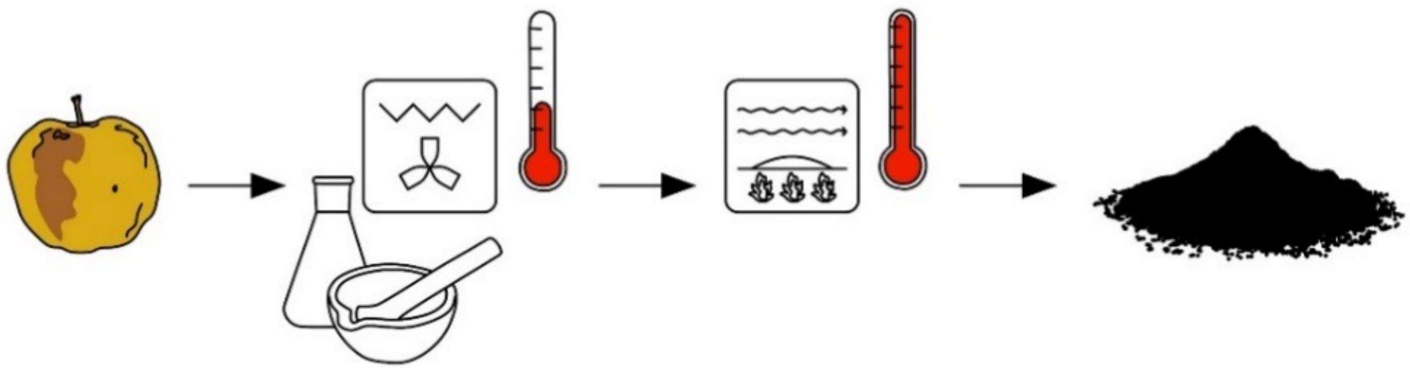
Annealing condition: thermal treatment temperature



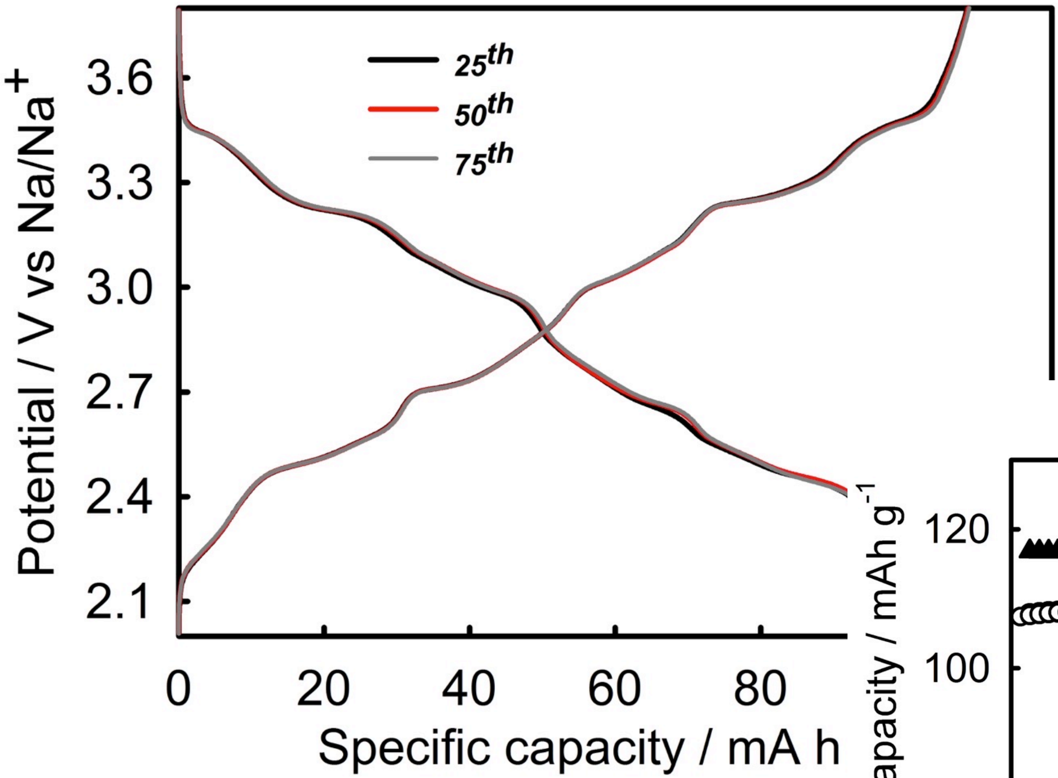
I. Hasa, D. Buchholz, S. Passerini, B. Scrosati, J. Hassoun, Adv. Energy Mater. 2014, 4, 1400083
I. Hasa, S. Passerini, J. Hassoun, RSC Advances 2015, 5, 48928-48934;
I. Hasa , D. Buchholz, S. Passerini, J. Hassoun, ACS Appl. Mater. Interfaces, 2015, 7, 5206–5212.



Biowaste is an abundant and cheap raw material for Hard Carbon



Peters, J.; Buchholz, D.; Passerini, S.; Weil, M. Energy Environ. Science, 2016, 9, 1744-1751.
Vaalma, C.; „Functional Materials with Apple Biowaste“, GIT Laboratory Journal;

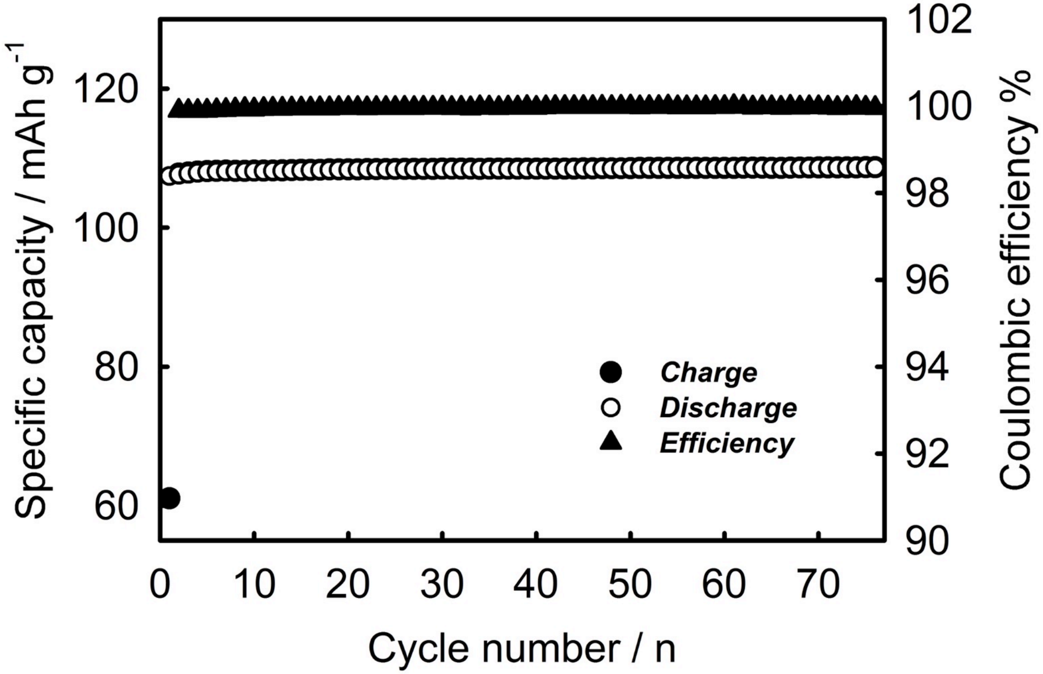


HC/ Na_xMnO_2

Hard Carbon from corn cobs

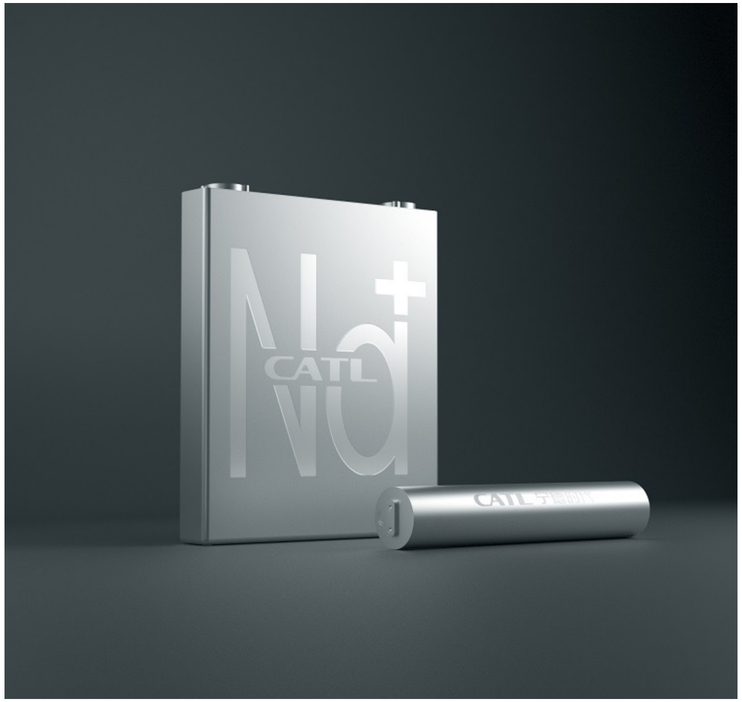
Ni- and Co-free cathode

Both electrodes made with a cellulose-derived aqueous binder

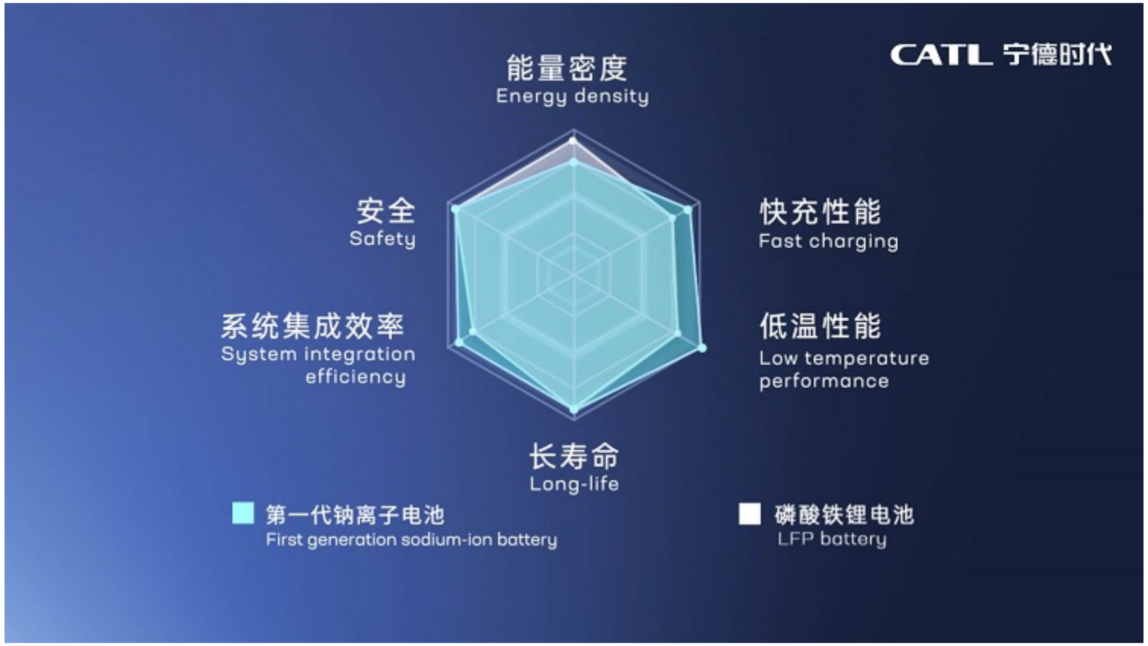


Excellent cyclability
Acceptable capacity

Dall'Asta, V; Buchholz, D; Chagas, L; Dou, X; Ferrara, C; Quartarone, E; Tealdi, C; Passerini, S, ACS AM&I 2017, DOI: 10.1021/acsami.7b09464



See Mr. A. Innocenti presentation on LCC of Na-ion Batteries.



Industrial Sodium-Ion Batteries are already available on the market

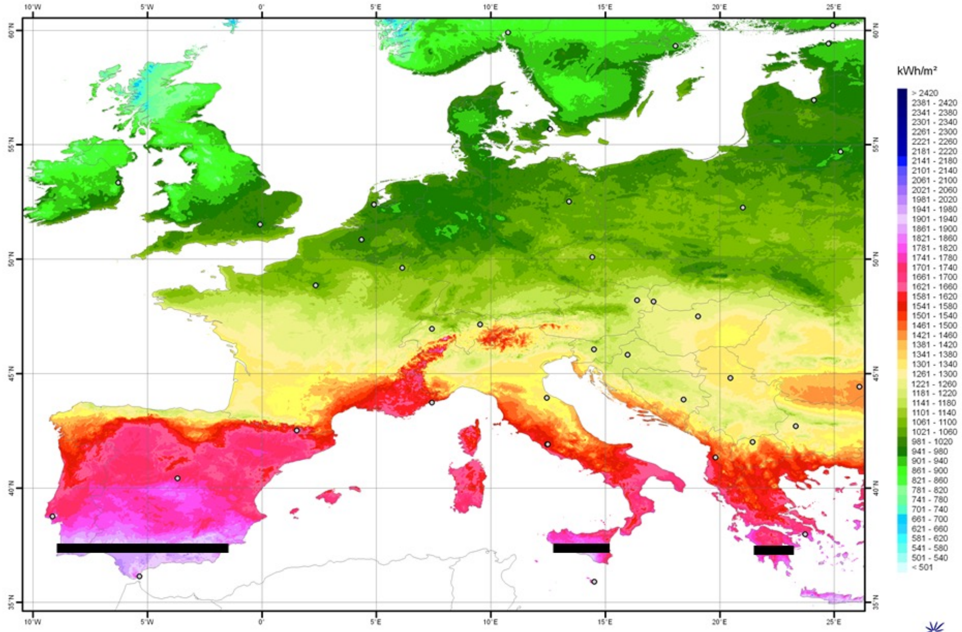
CATL recently announced interest in large-scale production

However, they are still not competitive with Lithium-ion Batteries.

Y. Hu, S. Komaba, M. Forsyth, C. Johnson, T. Rojo, Small Methods. 3 (2019) 1900184. doi:10.1002/smtd.201900184.
Y. Lu, C. Zhao, X. Rong, L. Chen, Y. Hu, Acta Phys. Sin. 67 (2018) 120601.

Primary Energy needs

Europe: 21,400 TWh (2018)
Italy: 1,807 TWh (2019)



Globalstrahlung: Langjähriges Mittel 1986 - 2005

Area of photovoltaic systems to meet energy needs

Europe:

62,600 km^2 (Sicilia + Sardegna + ½ Puglia)

Italy:

6,000 km^2 (9% of Sicilia + Sardegna + Puglia)

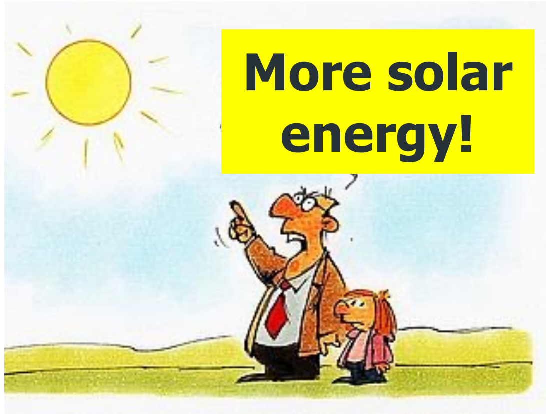
Assumptions

- Energy through renewable energy from PV only (20% collection efficiency)
- Solar radiation˜1,500 kWh/m^2 (Perugia)

Italy:

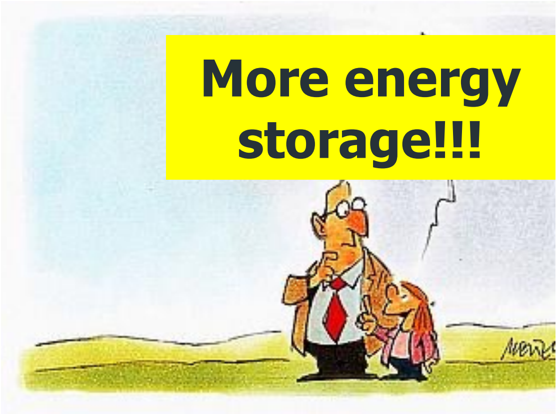
20,000 km^2 of urbanised territory (Buildings, Railways, Roads and Motorways)

https://mapsontheweb.zoom-maps.com/post/83907154436/solar-irradiation-map-of-europe
https://yearbook.enerdata.net/total-energy/world-consumption-statistics.html

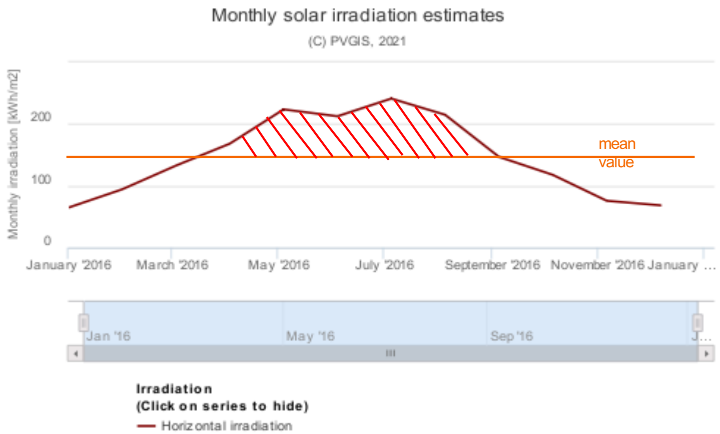


Seasonal/annual energy storage –

The KEY to
renewable energy,
energy independence,
and decarbonisation.



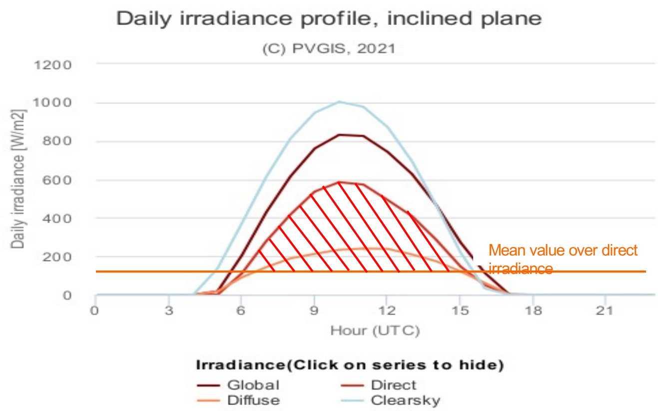
STORAGE NECESSARY FOR ENERGY INDEPENDENCE



Seasonal Storage

European needs: 4,059 TWh

Italian needs: 399 TWh



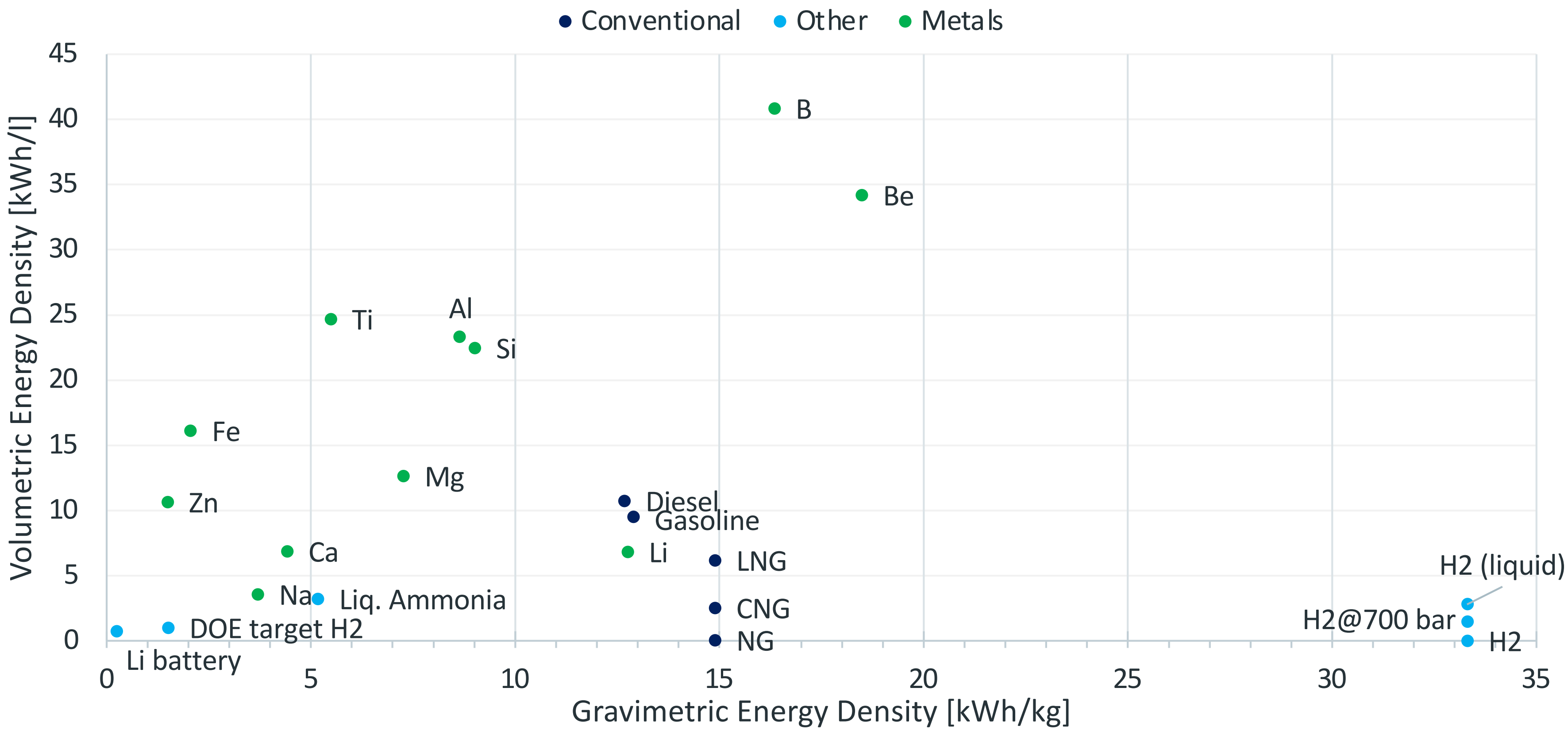
Daily Storage

European needs: 29 TWh

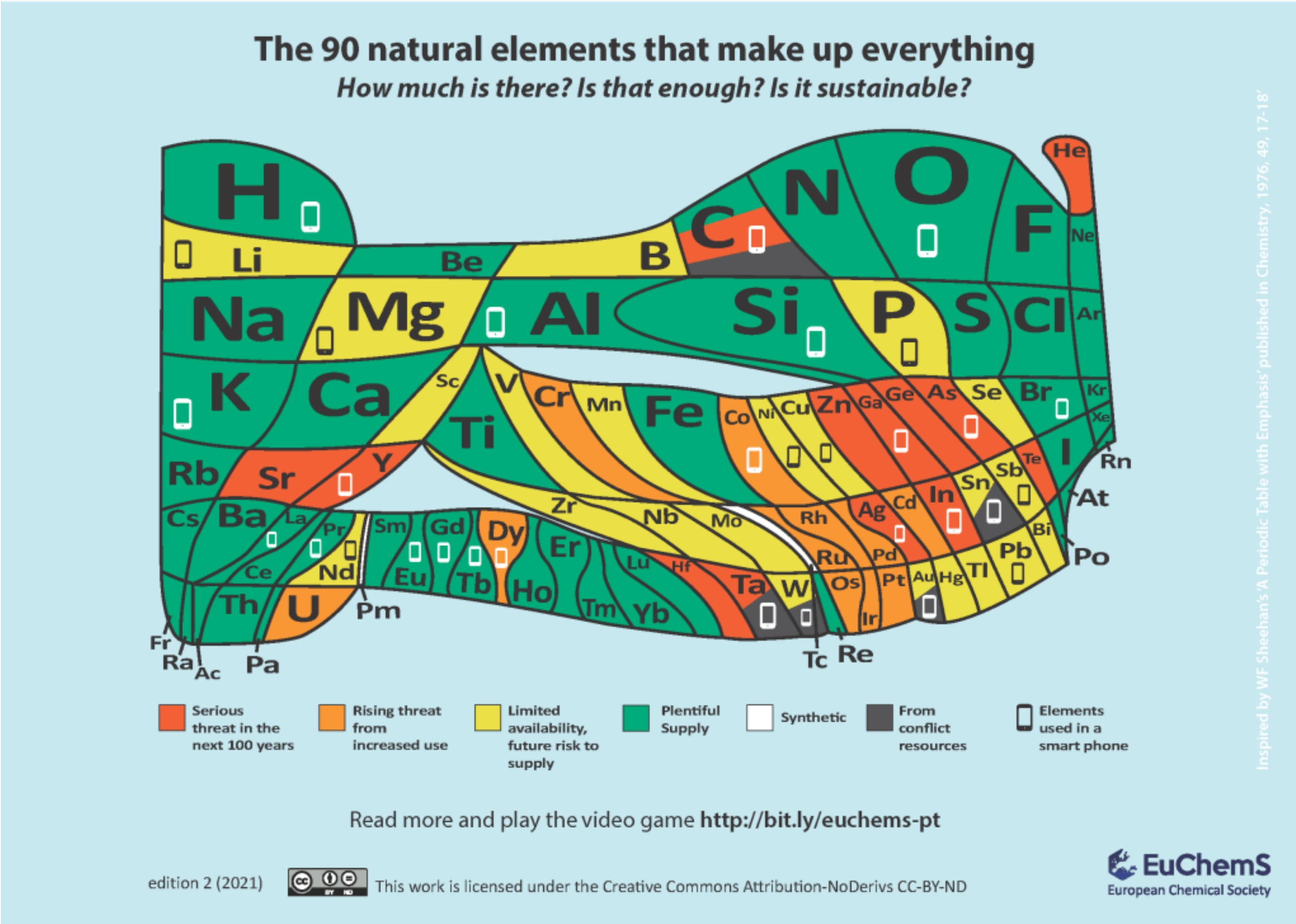
Italian needs: 3 TWh

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

Energy Storage - Substitution of Oil and Natural Gas



Reactive metals can store large amounts of energy in smaller volume than hydrogen



Some reactive metals (e.g., Al, Mg, Ca, Si Na, …) are rather abundant

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

Power-to-Al conversion:
Al production via Carbon-free (*inert anode*) Hall-Héroult (almost commercial)

Al-to-Power conversion:
- Electrochemical → **Primary batteries (see Mr. Chen Xu presentation)**

- Thermodynamic → **Combustion with water vapor** [2,3]

$$2Al(s)+3H_2O(g) \rightarrow Al_2O_3(s)+3H_2(g) \quad -815.4\ kJ/mol\ (298K,1atm)$$

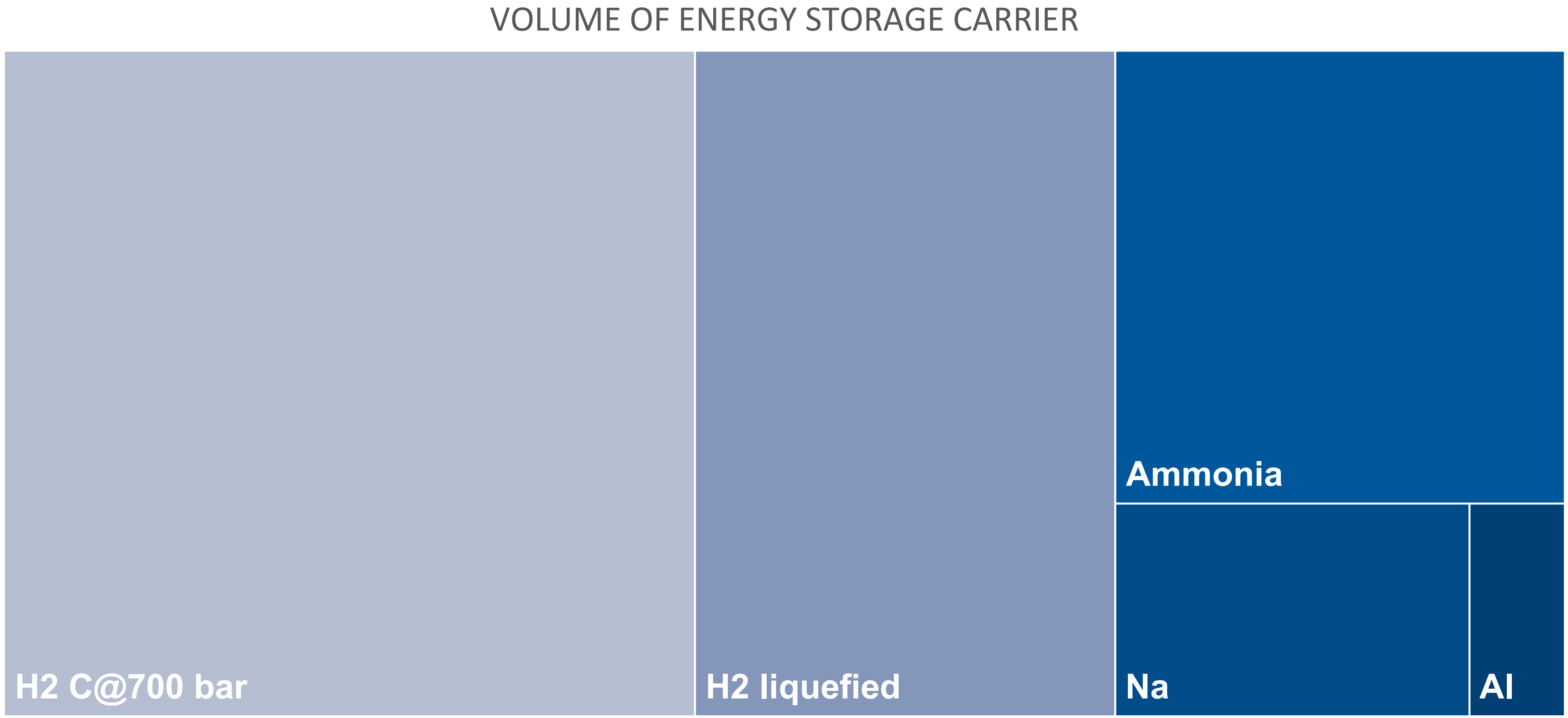
1 kg of Al produce:
15.1 MJ heat
0.11 kg H_2
1.9 kg Al_2O_3 → recyclable

1 TWh Energy Storage

	Volume	Weight
Al:	$42.5\ 10^3\ m^3$	$116\ 10^3$ Tons
H_2(liq):	$425\ 10^3\ m^3$	$30\ 10^3$ Tons
H_2(700 bar):	$714\ 10^3\ m^3$	$30\ 10^3$ Tons

[2]E. I. Shkolnikov, A. Z. Zhuk, M. S. Vlaskin, Renewable Sustainable Energy Rev. 2011, 15, 4611.
[3]Y. Yavor, S. Goroshin, J. M. Bergthorson, D. L. Frost, R. Stowe, S. Ringuette, Int. J. Hydrogen Energy 2013, 38, 14992.

Seasonal Storage demand of Italy: 399 TWh

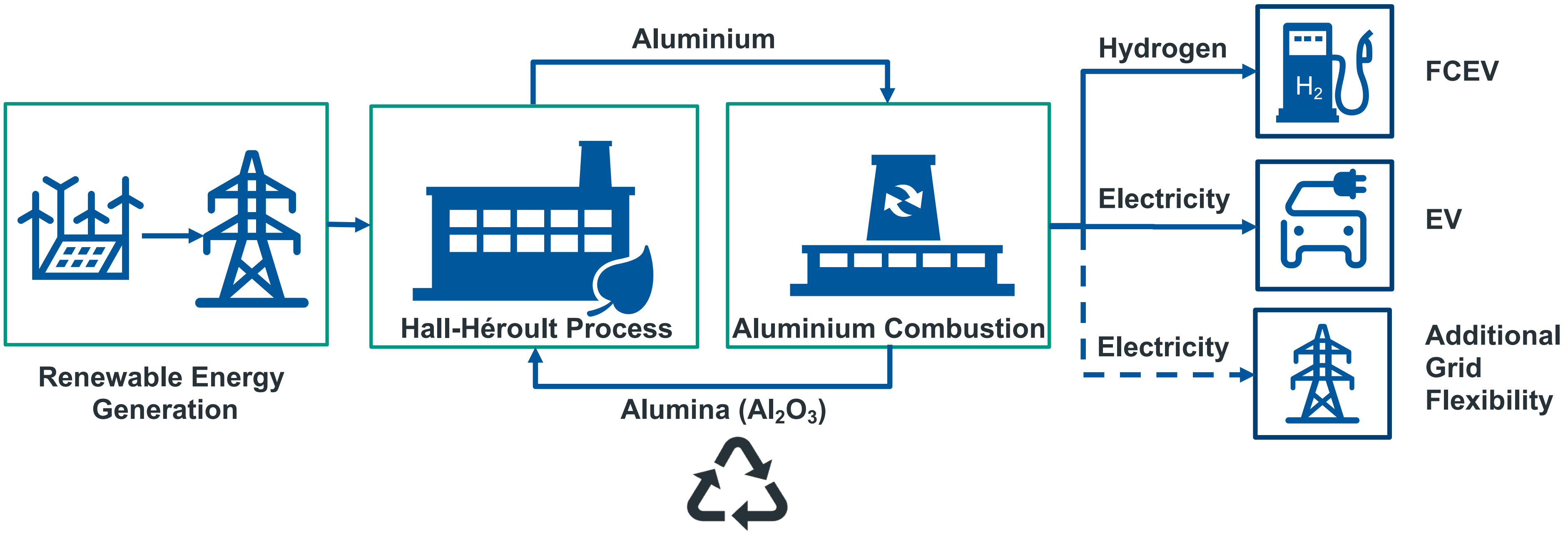


A soccer field covered with 7 metres of aluminium corresponds to 1 TWh (1800 fields for the annual needs of Italy).

One cubic metre of aluminium provides 25 MWh - exceeding the annual needs of a household.

[4] Barelli, L.; et al.. Reactive Metals as Energy Storage and Carrier Media: Use of Aluminum for Power Generation in Fuel Cell-Based Power Energy technology, 8 (9), Art. Nr.: 2000233. doi:10.1002/ente.202000233

Implementation Scenario – Business case: BEV and FCEV charging stations



Full recyclability of the energy carrier

H. Ersoy et al., "Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services" Advanced Materials Technologies, Jan. 2022, doi: 10.1002/admt.202101400

RTE, volumetric energy density of various Power-to-Power technologies employing different energy carriers

Energy Carrier	Conversion Technology	Round Trip Efficiency (RTE)	Energy Density [kWh/L]
Al	Aluminium Wet – Combustion (ST,GT, & SOFC)	35.6 %	23.5
H_2	PEM Electrolyzer – PEM Fuel Cell (PEMFC) Reversible – Solid Oxide Cell	30% (H_2@200 bar) 48% (H_2@70 bar)	0.53 0.2
Methanol / DME	Solid Oxide Electrolizer (SOE) / H_2 to methanol-DME / Solid Oxide Fuel Cell (SOFC)	36% (26.5%*)	5.5
Gasoline	SOE/ H_2 to gasoline/SOFC	27% (20%*)	8.8
LNG	SOE/TSA dehydration, H_2 and CO_2 membrane separation/SOFC	28% (23%*)	5.8

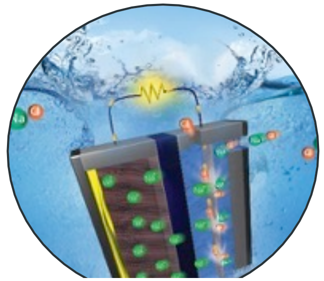
RTE values include the thermal (1750 kWh/tCO_2) ed electric (250 kWh/tCO_2) energy consumption for CO_2 trapping via low temperature absorption technology

Addressing the Global Energy Transformation: Sodium

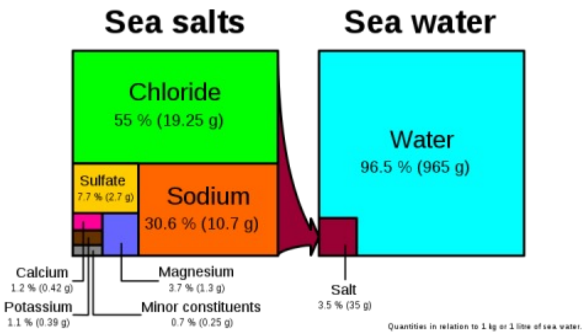
Seawater

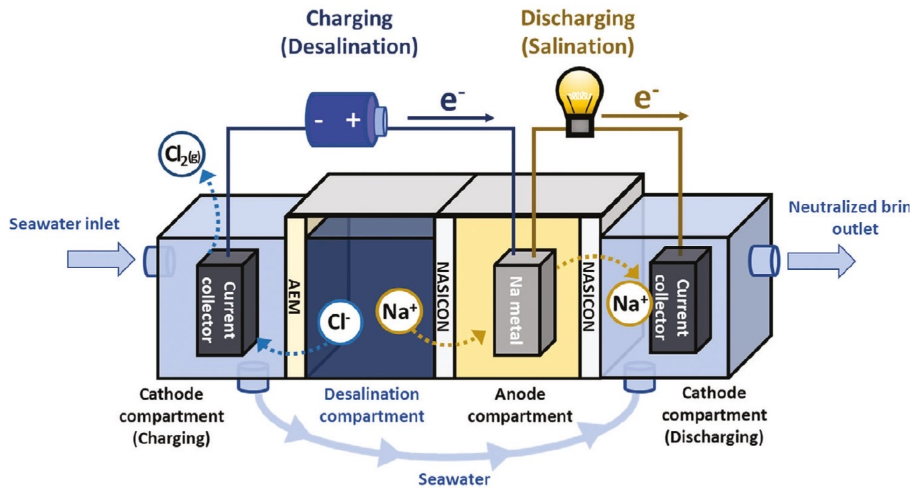

Energy Production

“Seawater battery”



Energy Storage and Delivery

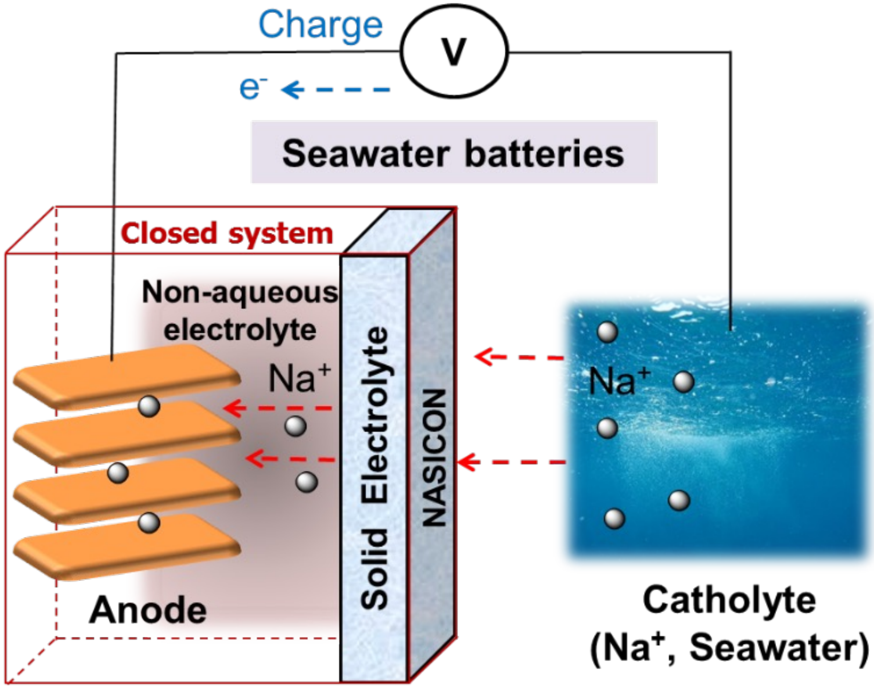




Sustainability and Efficiency:
Rather non critical raw materials and High Round Trip Efficiency (> 70%)

S. Passerini and coll, *J. Mater. Chem. A*, 2016, 4.19: 7202-7213.

Addressing the Global Energy Transformation: Sodium



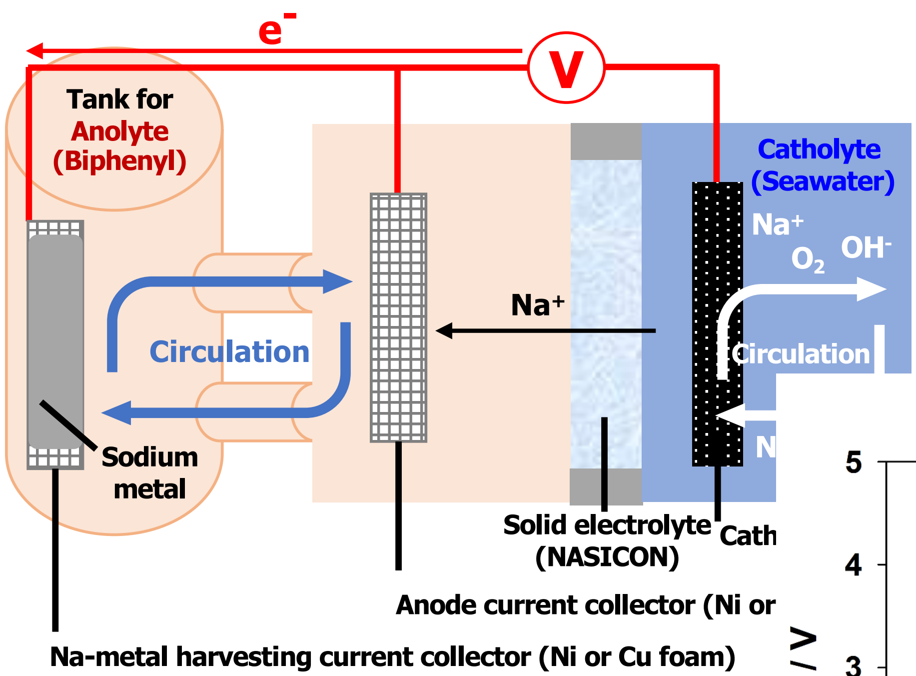
- Multilayer electrolyte system: Catholyte | Solid electrolyte | Anolyte
- No cost for cathode using unlimited natural seawater (0.47 mole of NaCl)

	Negative electrode	Positive electrode
Charge:	$Na^+ + (H) + e^- \rightarrow Na(H)$	$NaCl\ (aq) \rightarrow Na^+ + 1/2Cl_2\ (g) + e^-$ $NaCl\ (aq) + 2OH^-\ (aq) \rightarrow Na^+ + ClO^- + H_2O + 2e^-$ $2OH^-\ (aq) \rightarrow H_2O + 1/2O_2\ (g) + 2e^-$
Discharge:	$Na(H) \rightarrow Na^+ + e$	$2Na^+ + H_2O + 1/2O_2\ (g) + 2e^- \rightarrow 2NaOH\ (aq)$

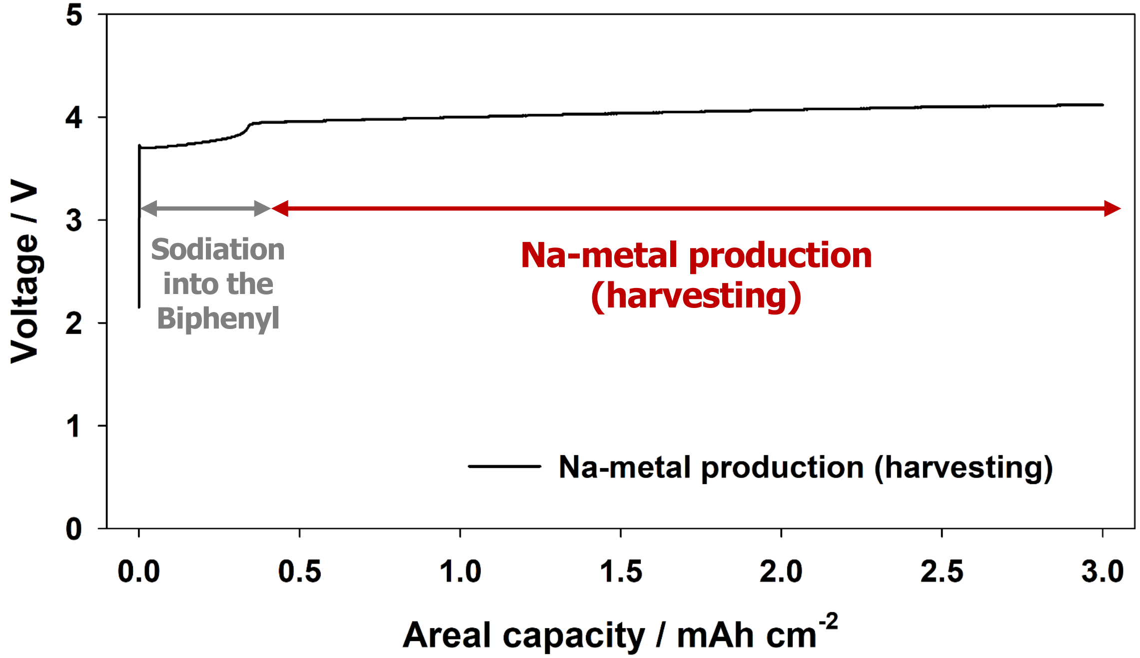
The energy stored is proportional to the amount of Na stored

Y. Kim, S. Passerini et al., Adv. Funct. Mater. **2020**, 2001249

Addressing the Global Energy Transformation: Sodium

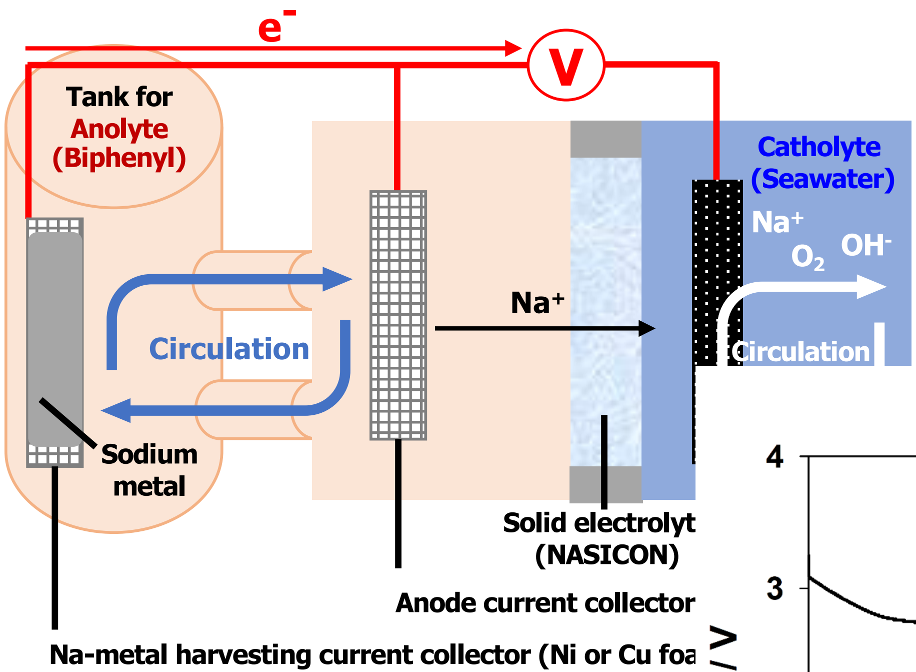


Na^{+} + BP (sol) + e^{-} → Na-BP (sol), followed by Na^{+} + e^{-} → Na (s)

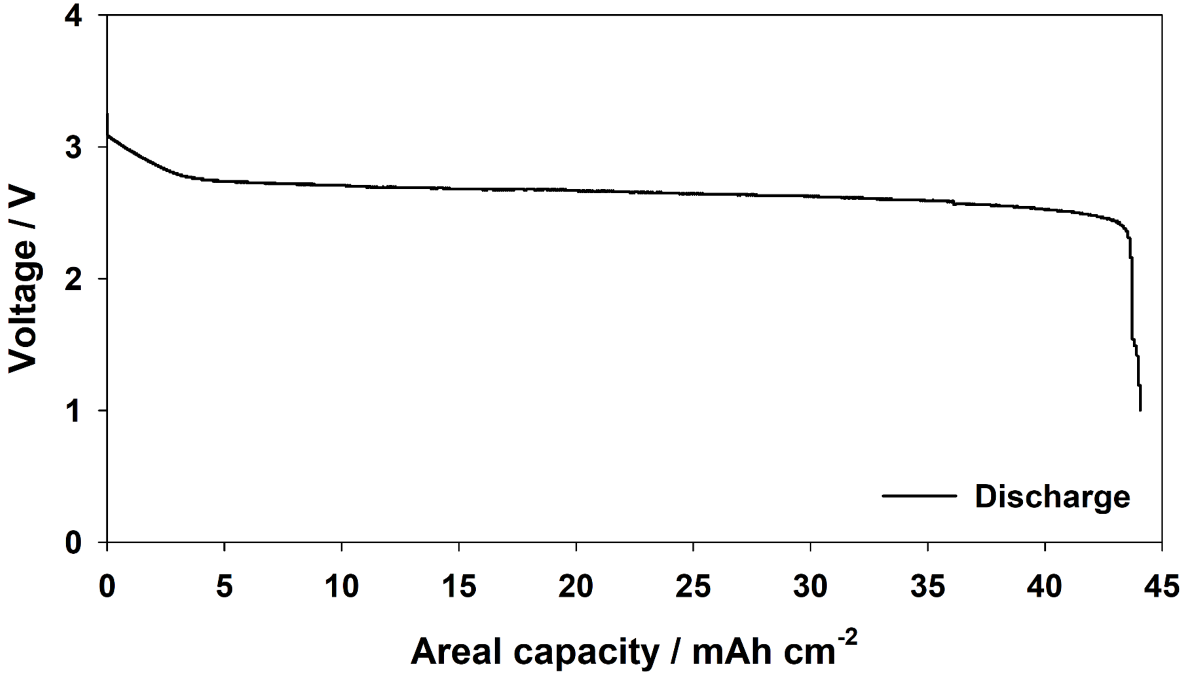


Sodium and Chlorine production and water desalinization

Y. Kim, G-T. Kim, A. Varzi and S. Passerini; DE Patent pending



$$4Na + O_2 + H_2O \rightarrow 4\ NaOH + \text{electricity}$$



Further details in Dr. Y. Kim presentation

Power generation from Sodium and Seawater demonstrated

Applicable for marine transportation, on-shore and off-shore power generation

Y. Kim, G-T. Kim, A. Varzi and S. Passerini; DE Patent pending

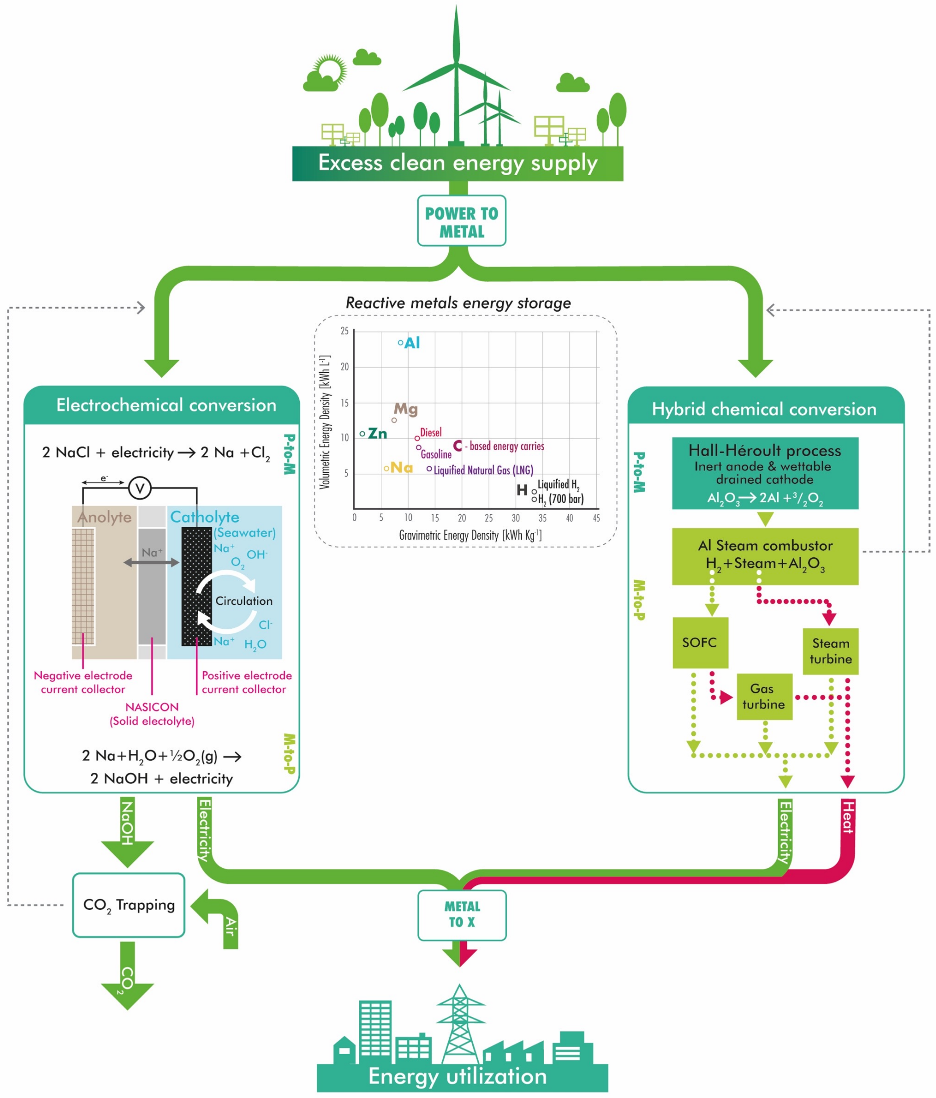
Addressing the Global Energy Transformation: Sodium

Sodium as energy carrier and storage …

… offers good volumetric energy storage (**3-4 times that of liq. H_2**),[1] but …

… promises substantially higher round trip efficiency (**RTE = 85%**) in laboratory cells.[2]

Additionally, **Chlorine** and **desalinized water** are produced upon charge while the discharge product (NaOH) can be used for **CO_2 trapping.**[2]



1 M. Baumann, S. Passerini et al., *Adv. Energy Materials* (2020) 202001002, DOI: 10.1002/aenm.202001002
2 Y. Kim, S. Passerini et al., *Adv. Functional Materials* (2020) 202001249, DOI: 10.1002/adfm.202001249

Implementation Scenario – Business case: Sardinia

Energy characteristics:

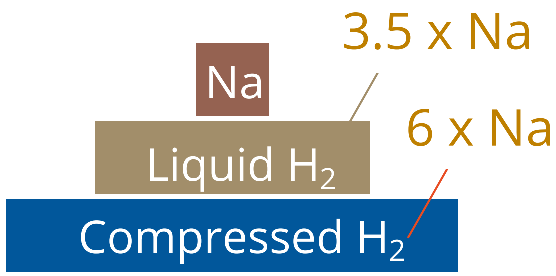
- No natural gas network;
- Old energy infrastructure;
- Great Renewables potential

Primary annual energy needs: 23.5 TWh

Seasonal storage needs: 4.43 TWh

PV (69 km^2) + Seawater Battery

High volumetric energy density
High energy efficiency (>70%)



Confronto volume di accumulo per diverse tecnologie.

Chlorine production

Desalinised water production — **131 mln di m^3 (1.64 mln inhabitants)**

CO_2 trapping — **57,700 tons of CO_2; 36.2 g CO_2 per kWh of stored energy**

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

Na and other abundant metal-based energy systems can help addressing several (and rather different) energy storage issues:

Sustainable Transportation (existing and fast growing market)

Scooters, light-duty and city-transportation vehicles (Na-ion batteries)

Innovative approaches for marine transportation (Na-seawater batteries)

Delocalized power generation for the EV charging infrastructure via reactive metals (Al, Zn, Fe, Na, Ca, Mg, …)

Energy Storage (huge market perspectives)

Stationary storage (Na-ion and Na-seawater batteries)

Seasonal/annual electrochemical and hybrid storage via reactive metals (Al, Zn, Fe, Na, Ca, Mg, …)

StoRIES
Storage Research Infrastructure Eco-System

StoRIES Project

- **Start: 1st November 2021**
- **Duration: 4 years (2021-2025)**
- **Budget: 7 Mio €**
- **Beneficiaries: 47**
- **Research Infrastructures: 64**
- **Coordinator: KIT (DE, Stefano Passerini)**

1ST Transnational Access Call

- **Free access** to **64 world-leading Research Infrastructures** for **Hybrid Energy Storage**
- Travel and accommodation costs **covered by StoRIES**
- **Open** to **all researchers** from academia and industry

- Topic: **Application oriented hybrid and sustainable energy storage solutions**
- Deadline: **31st July 2022**

→ More information & application: www.storiesproject.eu/calls

Contact: eera-jpes@b3.kit.edu

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 101036910

CALL TOPIC: "APPLICATION ORIENTED HYBRID AND SUSTAINABLE ENERGY STORAGE SOLUTIONS"

The call topic foresees **three** different **sources of innovation**: material research, development and testing of a component, device or device cluster and the integration of the innovation in the energy system.

Proposals concentrating on the same innovation source and **investigating** it **from different scientific directions** (proposal cluster) with the aim of fast and successful implementation of the innovation to the market, will receive **additional points** by the proposal evaluation. This approach will support solutions with a clear and predefined path for an uptake to the market.

The proposals should include **sustainability-oriented** assessments regarding e.g. the use of critical raw materials, possible environmental and economic impacts over the entire lifecycle of the storage solution, as well as indications about the potential recyclability of used materials. Beyond that, social implications related to relevant upstream value chains, the use and end of life phase should be considered.

To apply for the call please use the **application form** available at the StoRIES website (storiesproject.eu).

Only proposals submitted by the **31st of July 2022** will be evaluated.

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 101036910

Questions? info@storiesproject.eu
(TNA in the email title)

StoRIES RIs

[Research Infrastructures | StoRIES (storiesproject.eu)]

- 58 physical infrastructures
- 6 virtual infrastructures
- 17 countries all over the Europe
- 5 energy storage technologies:
  - Electrochemical
  - Chemical
  - Thermal
  - Mechanical
  - Superconducting – Magnetic
- Cross-cutting infrastructures
- TRL 1-6

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 875126

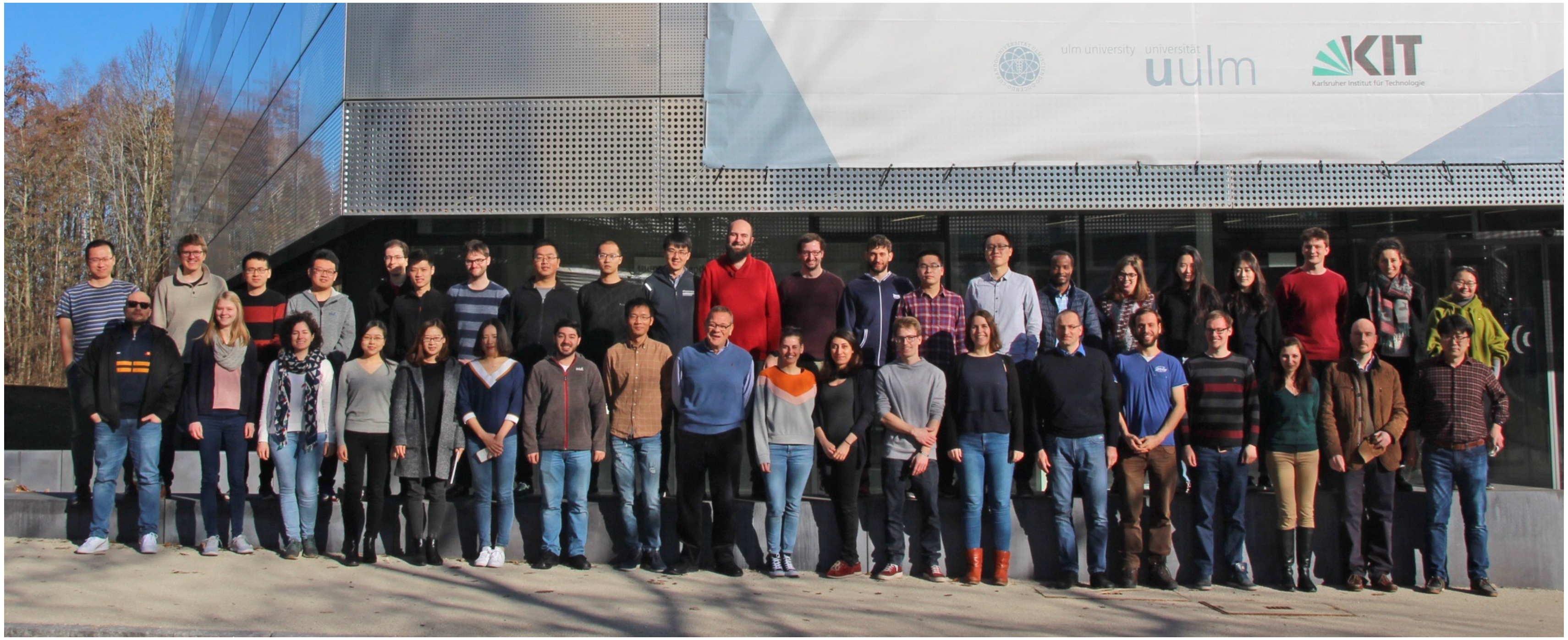
Questions? info@storiesproject.eu
(TNA in the email title)

StoRIES

Acknowledgment

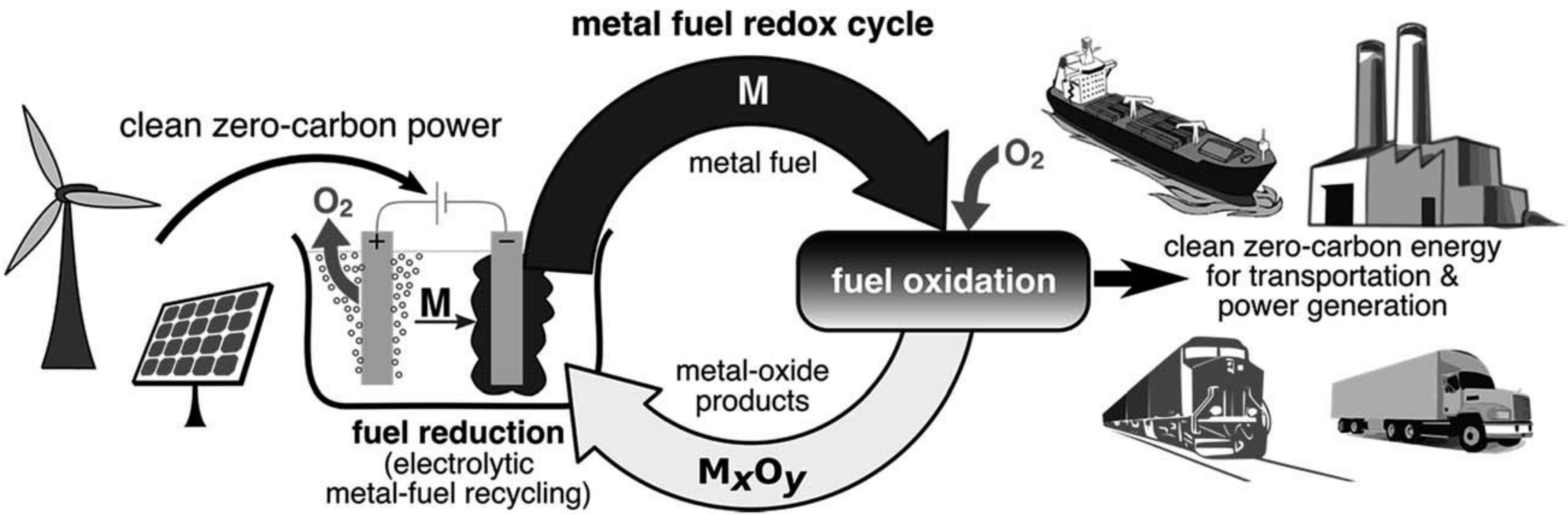
Federal Ministry of Education and Research

HELMHOLTZ ASSOCIATION



www.hiu-batteries.de

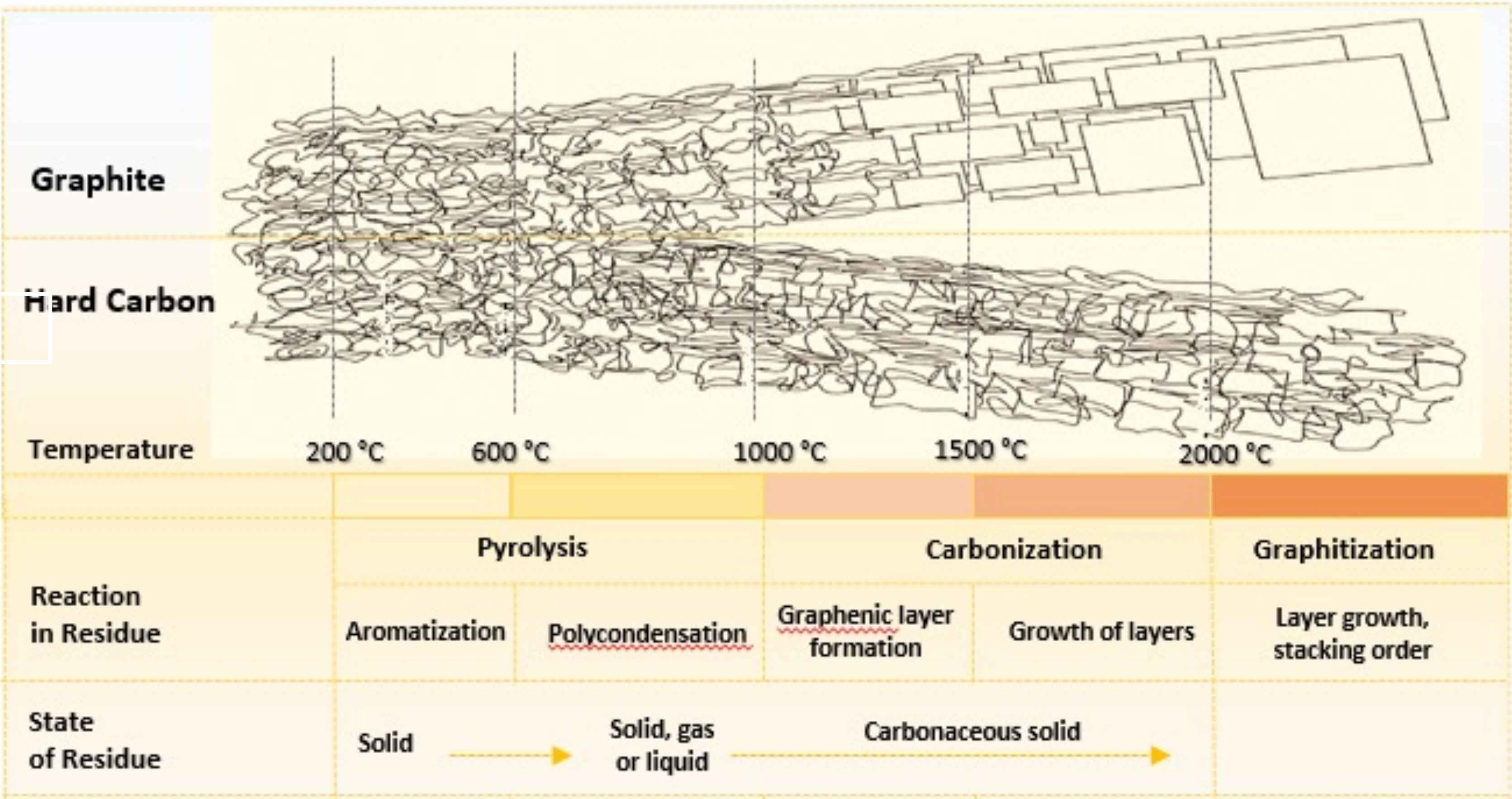
Back up



Reactive metals (Al, Mg, Ca, Si Na, …) can store large amounts of energy

P. Julien, J. M. Bergthorson, *Sustainable Energy Fuels* (2017) 1, 615.
D. J. Durbin and C. Malardier-Jugroot, *Int. J. Hydrogen Energy* (2013) 38, 14595–14617.

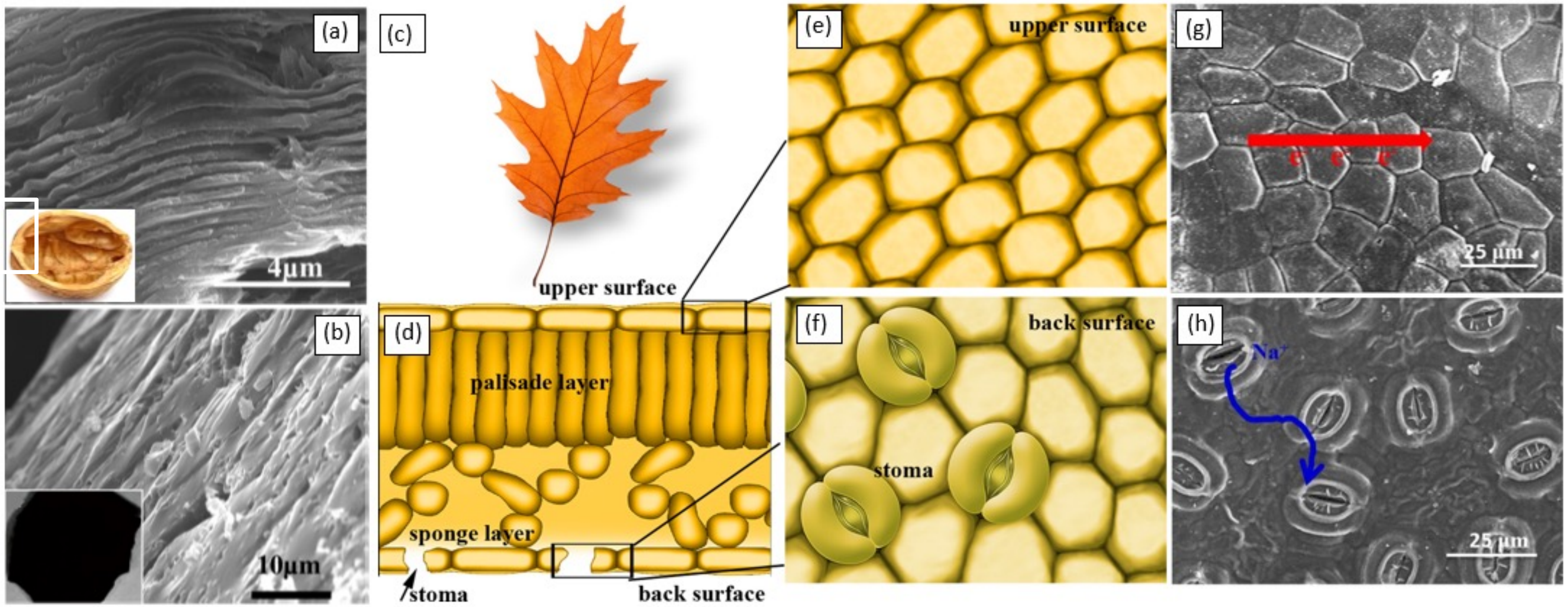
Graphite and Hard-carbon formation



Not all carbon-containing materials form graphite upon thermal treatment

X. Dou, I. Hasa, D. Saurel, C. Vaalma, L. Wu, D. Buchholz, D. Bresser, S. Komaba, S. Passerini, Materials Today, 2019, doi.org/10.1016/j.mattod.2018.12.040

Bio-precursors and hard carbons



Some precursors, mainly biological materials with polymeric structures, carbonize retaining a non-graphitic structure.

X. Dou, I. Hasa, D. Saurel, C. Vaalma, L. Wu, D. Buchholz, D. Bresser, S. Komaba, S. Passerini, Materials Today, 2019, doi.org/10.1016/j.mattod.2018.12.040

Press release | 8 July 2020 | Brussels

Powering a climate-neutral economy: Commission sets out plans for the energy system of the future and clean hydrogen

However:

Hydrogen Economy was first proposed by John Bockris in 1970 during a talk at GM Technical Center.

After 50 years of R&D&I, still no complete solution!!!

National Hydrogen Association (*hydrogenassociation.org*) United States Department of Energy.

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

Case study: Multiservice Case for Electric Mobility and Energy Storage Services

Partial load of the SOFC

0.275 kg/s of Aluminum

CAPEX: 4200–6200 €/kW

SOFC Partial Loads	P_{el} production	H_2 production	$\eta_{Power\text{-}to\text{-}X}$
100%	~4 MW	-	35.6%
80%	3.1 MW	28 kg/h	38.8%
65%	2.6 MW	46.8 kg/h	40.7%

H. Ersoy et al., "Hybrid Energy Storage and Hydrogen Supply Based on Aluminum—a Multiservice Case for Electric Mobility and Energy Storage Services"
Advanced Materials Technologies, Jan. 2022, doi: 10.1002/admt.202101400

HIU HELMHOLTZ INSTITUTE ULM Electrochemical Energy Storage

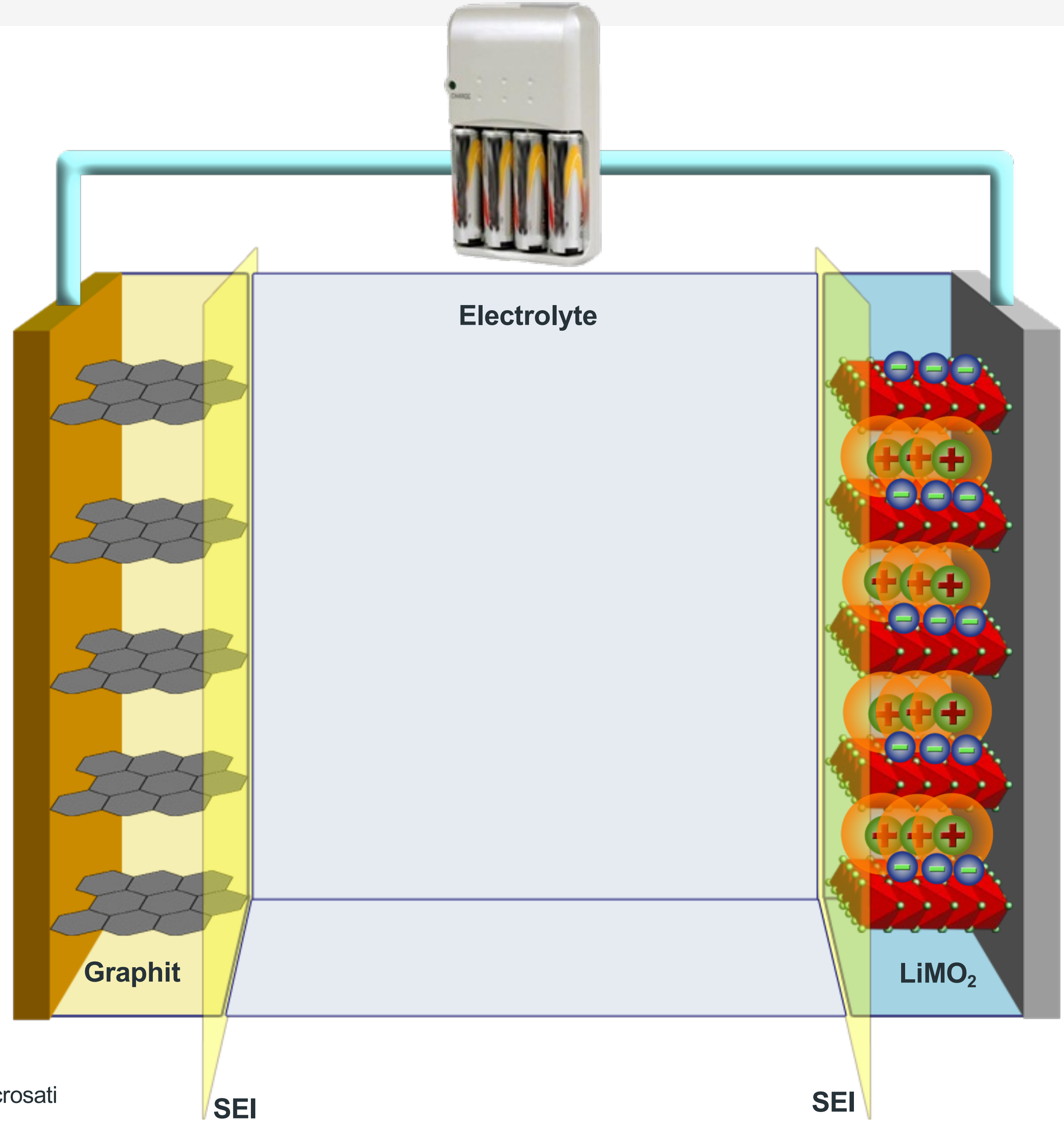
Hydrogen: After 50 years of R&D&I, still

- Storage is still an issue (large volume or high costs)
- Technical hurdles for Electrolysers and Fuel Cells
- Hydrogen embrittlement (direct combustion)
- Overall low RTE
- Safety

https://commons.wikimedia.org/w/index.php?curid=1207497

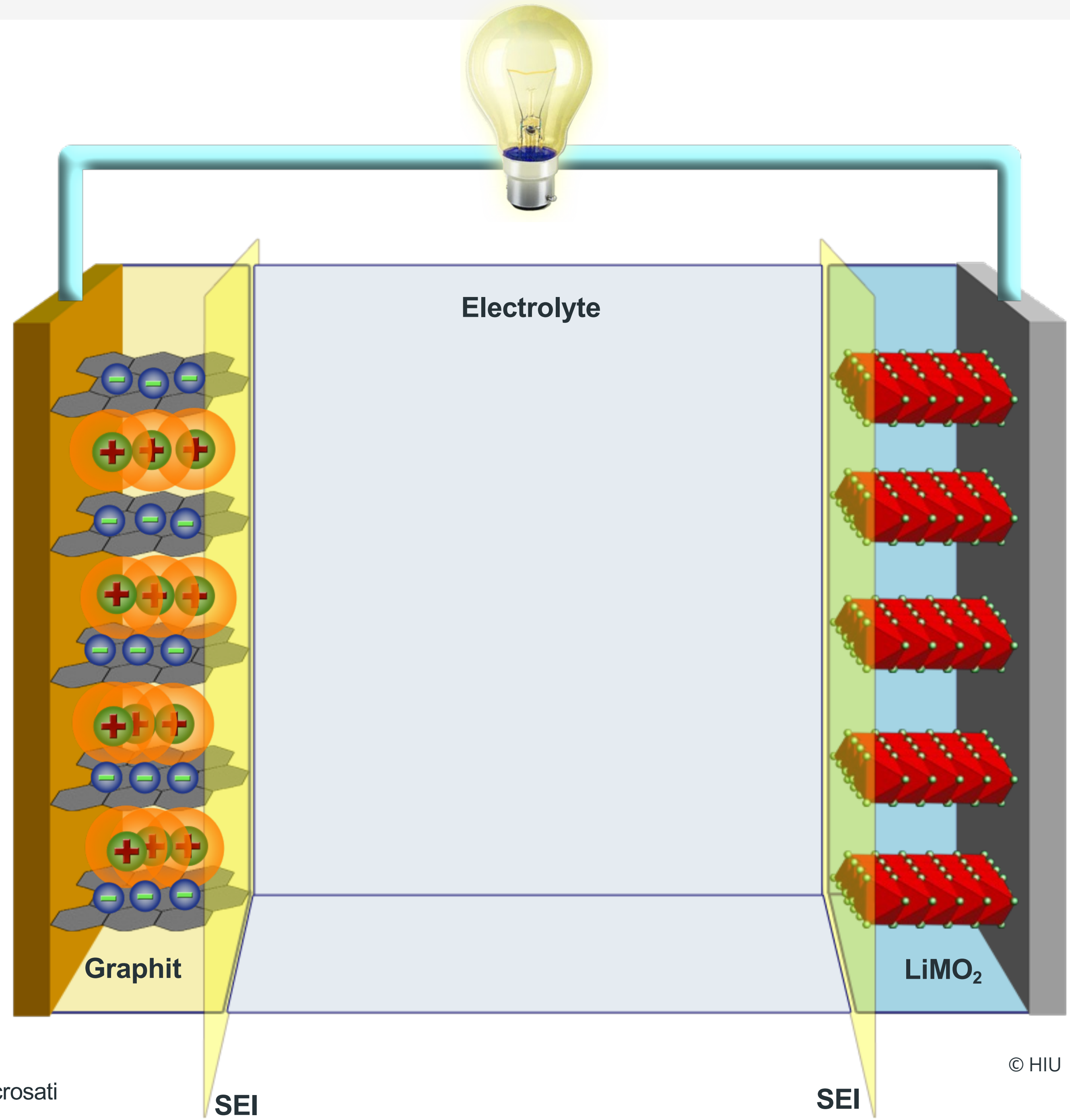
Can hybrid storage including batteries enable seasonal storage while maintaining the high energy efficiency (>75%)?

Lithium-ion Batteries – operating principle



Courtesy of Prof. Bruno Scrosati

Lithium-ion Batteries – operating principle



Courtesy of Prof. Bruno Scrosati

There are basically 3 approaches:

Aqueous cathode fabrication using bio-derived binders

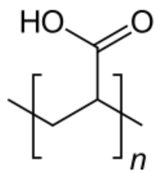
Development of Co-free cathodes

Recycling electrode materials not metals

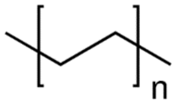
Water/ethanol processable

TRD 202A (Fluoro acrylic polymer)*

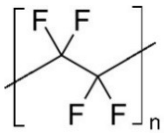
Polyacrylates
Polyacrylic acid (PAA)
Polymethyl acrylate (PMA)
Polybutyl acrylate (PBA)
Polyvinyl acetate (PVA)
Polyacrylonitrile (PAN)



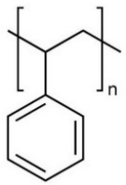
Aliphatic Polymers
Polyethylene (PE)
Polyisoprene
Polyvinyl pyrrolidone (PVP)
Polyvinyl butyral (PVB)



Poly tetra-fluorethylene (PTFE)



Aromatic Polymers
Polystyrene (PS)
Polyurethane (PU)
Styrene-butadiene rubber (SBR)



Oligo- and Poly-saccharides:
Carboxymethyl cellulose (CMC) Chitosan, Alginate, Pectine, Amylose, Starch, Gums (Xanthan, Arabic,

Sustainability

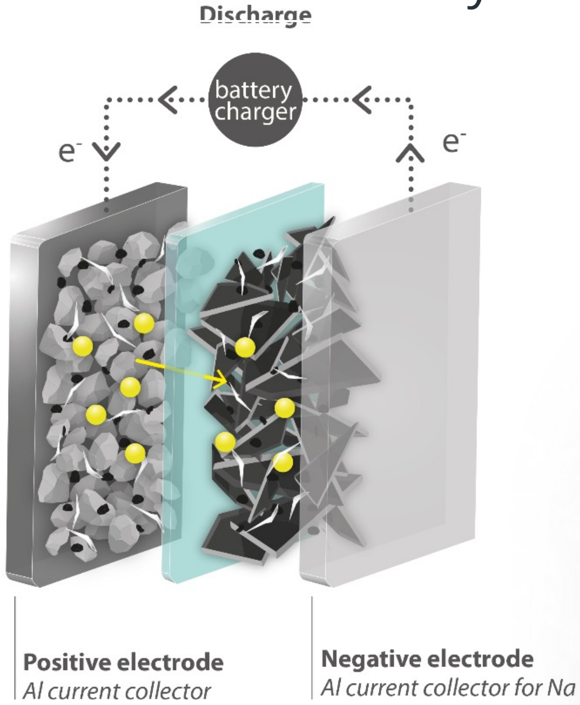
R=CH_2CO_2H

Proteins
Gelatine
Caseinate

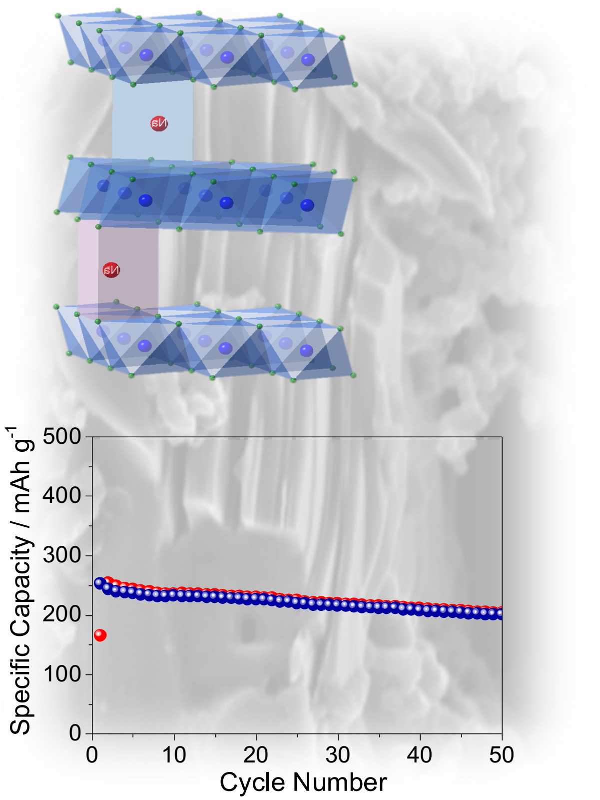
Bio-polymers and derivatives

A. Varzi, A. Moretti, D. Bresser, D. Buchholz, S. Passerini, Energy and Environmental Science 2018 (11) 3096.

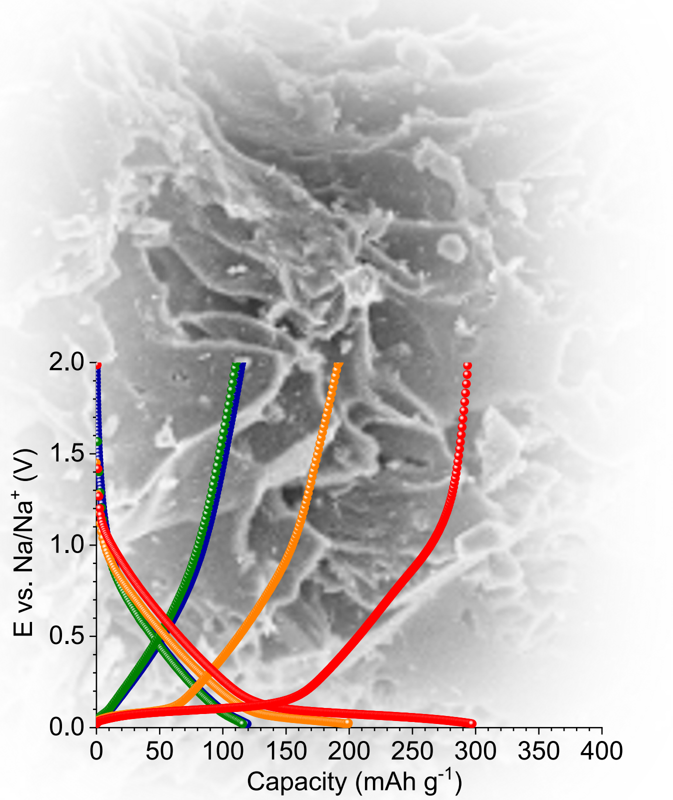
Sodium-ion Battery



Sodium Layered Cathodes



Hard Carbon Anodes



Life cycle assessment for the production of a Na-Ion Battery

18650 cell, 128 Wh/kg

Layered $Na_{1.1}[Ni_{0.3}Mn_{0.5}Mg_{0.05}Ti_{0.05}]O_2$ – Hard Carbon (derived from sugar)

Three impact categories:

GWP = global warming potential — **Cathode production**

FDP = fossil depletion potential
MEP = marine eutrophication potential — **Anode production**

GWP: Emission of greenhouse gases like CO_2, CH_4, N_2O (measured in kg of CO_2 equivalents)

FDP: Depletion of fossil energy sources (measured in kg of oil equivalents)

MEP: Deposition of macronutrients in water (measured in kg of N- equivalents)

Peters, J.; Buchholz, D.; Passerini, S.; Weil, M. Energy Environ. Science, 2016, 9, 1744-1751.

Relative environmental impact per kWh over energy stored over lifetime

Lifetime based on existing LCA studies for better comparability

	GWP (in kg CO_2 eq.)		MEP (in kg N eq.)		FDP (in kg oil eq.)		
LFP-Graphite (3k)	48%		23%		38%		high
LFP-LTO (14k)	13%		5%		13%		
LMO-Graphite (1k)	73%		44%		83%		
NCA-Graphite (2.2k)	38%		20%		39%		
Na-Ion (2k | 5k)	50%	20%	50%	20%	50%	20%	
							low

Battery lifetime is fundamental for environmental impact (also for cost (€/kWh))
Use of bio-waste is a promising way to enhance sustainability and lower the environmental impact

Peters, J.; Buchholz, D.; Passerini, S.; Weil, M. Energy Environ. Science, 2016, 9, 1744-1751.