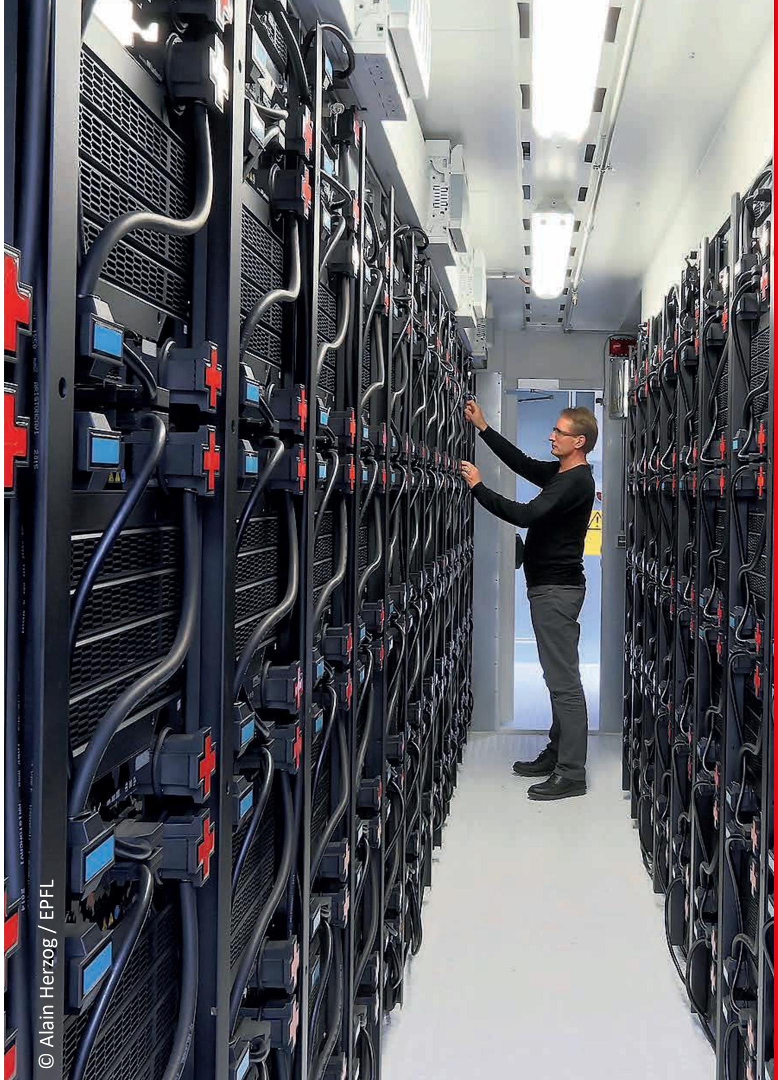
Energy supply, economics and transition

A farmhouse with full solar roof in Switzerland (source: Csem)

Supporting technologies and sustainability

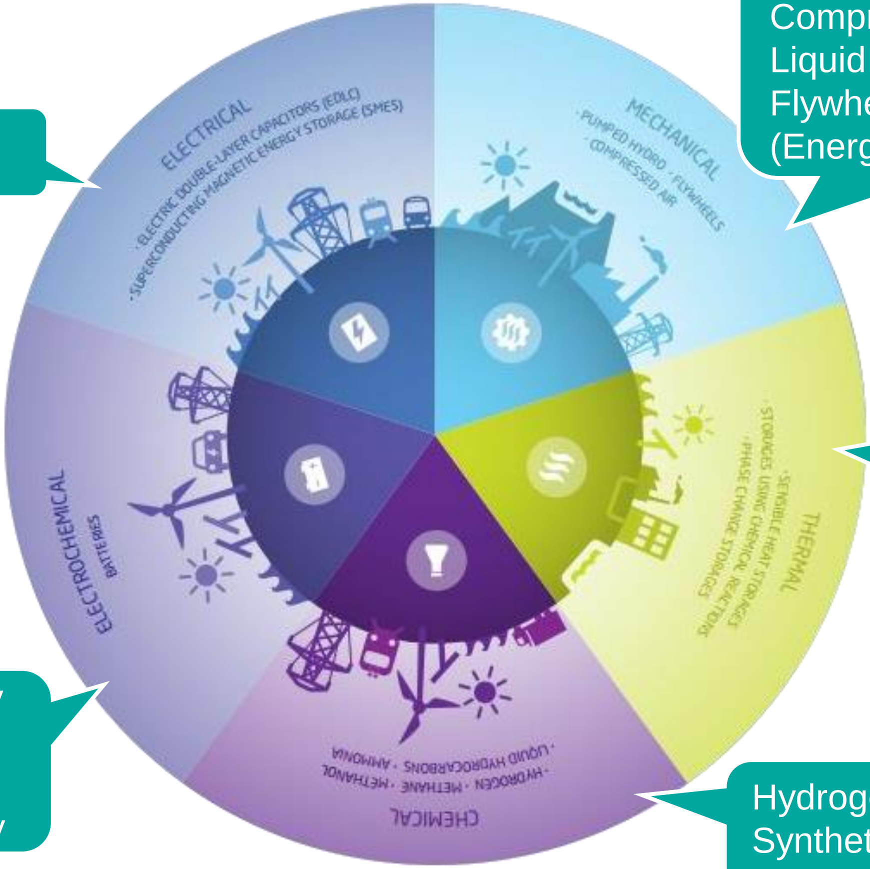
Electricity storage

Christophe Ballif / Philippe Thalmann / Claudia Binder



Electricity storage - technologies

Super capacitors



Pumped hydrostorage
Compressed air
Liquid air storage
Flywheels
(Energy Vault)

Thermo-chemical
Sensible thermal
Latent thermal

Lithium-ion battery
Lead-acid battery
NaS battery
Redox flow battery

Hydrogen storage
Synthetic natural gas
NH3

Christophe Ballif / Philippe Thalmann / Claudia Binder

Electricity storage – pumped hydro storage (PHS)

Principle

Potential energy stored in reservoir above a turbine. Around 160 GW capacity in 2020 * , a few 100 GW planned….****

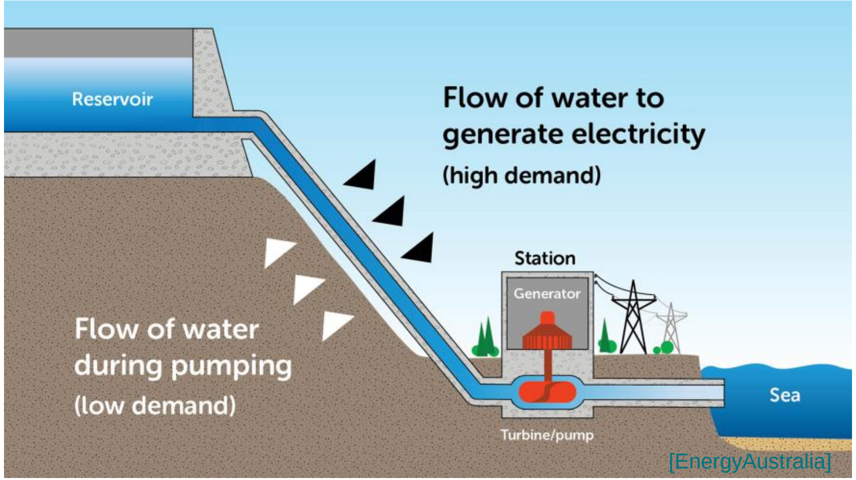
New pumped-storage capacity in China is helping to integrate growing wind and solar power - U.S. Energy Information Administration (EIA)

Pricing (estimates) **

- 1000-2600 $/kW
- 100-300 $/kWh capacity (depends on reservoir size), 70-85% efficiency
- Ultra-long lifetime

Hydro: a key asset in Switzerland (15.5 GW end 2018, > 300 kW). Now 3.9 GW pumped hydro, with >0.9 GW additional soon

Most new PHS will face battery competition !



[EnergyAustralia]

Pumped storage hydropower

Christophe Ballif / Philippe Thalmann / Claudia Binder

Batteries and electrochemical storage: the next big thing

Stimulated by the automotive market, strong growth of the battery market

1. Vehicles, possibly become prosumers
2. At home with «prosumers»
3. Providing services, reserves or «virtual inertia» on the grid**
4. Larges systems coupled to large PV or wind parks

Same learning curve as Wind and PV thanks to mass/volume effect

Potential for low cost storage (but not seasonal) In general underestimated

* Cf for an introduction: Inertia and the Power Grid: A Guide Without the Spin

Prof. Dr. Christophe Ballif

Storage

Several tens of new companies/products are developing storage solutions, mostly based on batteries

Home storage

… MW

… MW

Possible Vehicle to Grid

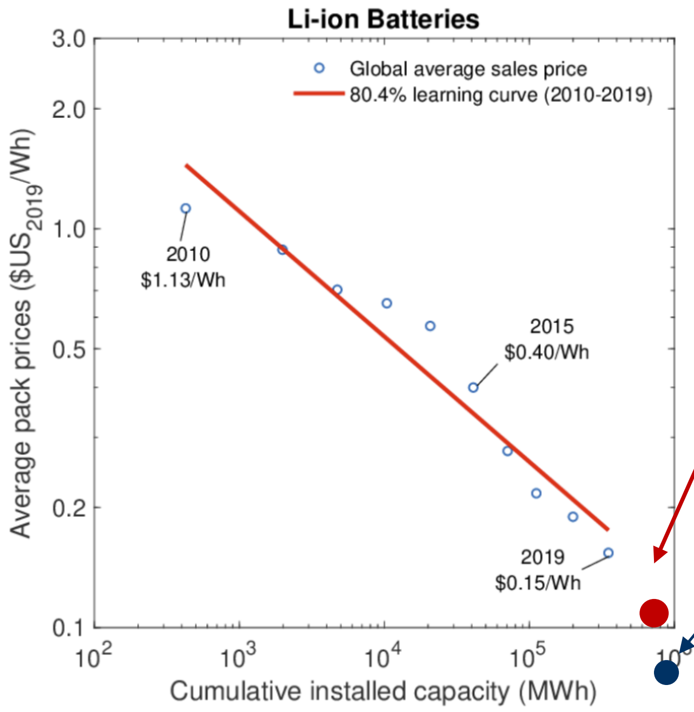
Small storage systems (typ 10 kWh) for home application.
In Germany over 50% home solar with storage !

Currently more and more large wind and solar parks installed with 1 to 2 hours storage

Small volumes,
Still expensive (but no reason why it should stay so), needs standards

STORAGE STIMULATED BY THE AUTOMOTIVE MARKET

Automotive Battery learning curve



Today automotive battery pack at 100-120 $ /kWh battery cells **at 50-60 $/kWh**

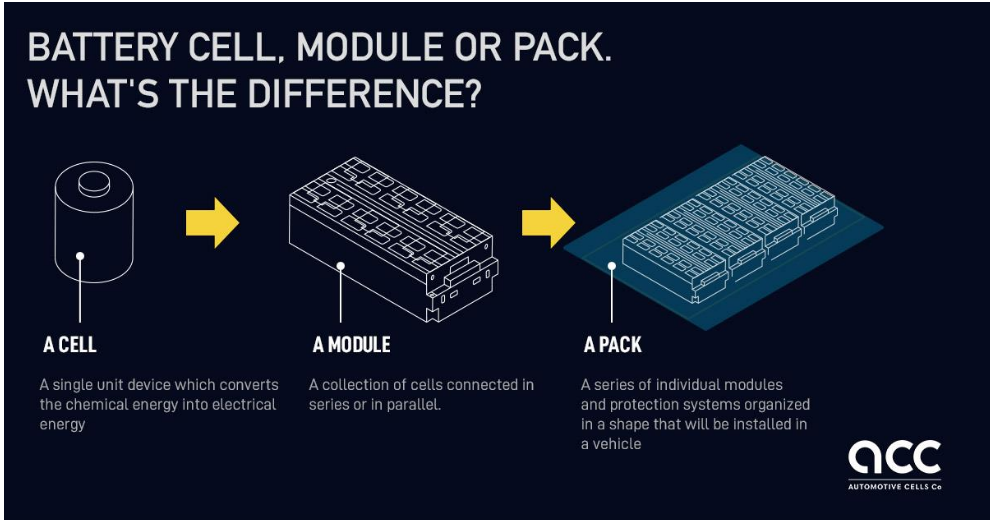
We expect the price of an average battery pack to $62/kWh by 2030

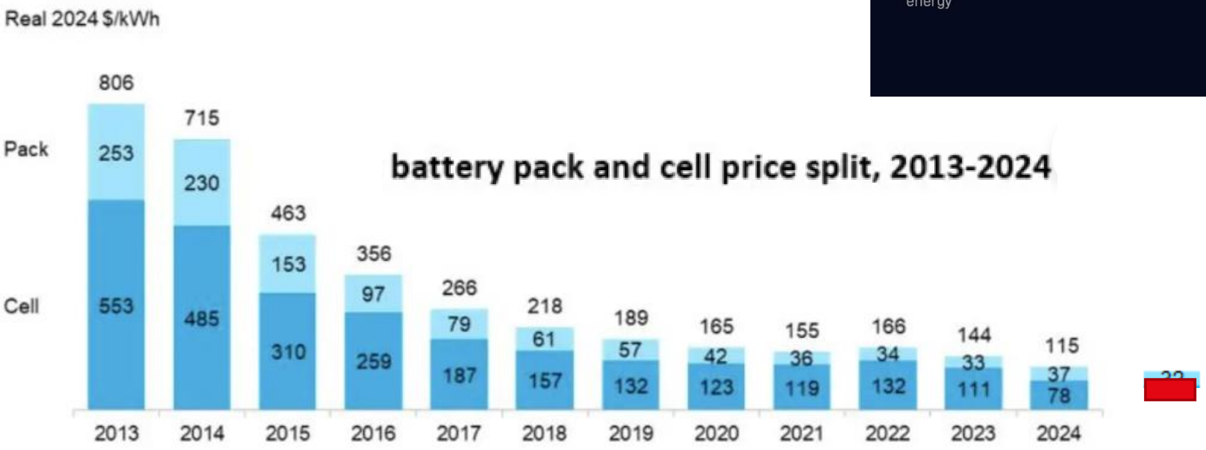
Ultra-fast learning curve, as for PV

Usable for stationnary storage

Cost Dynamics of Clean Energy Technologies, Glenk et al.

Battery





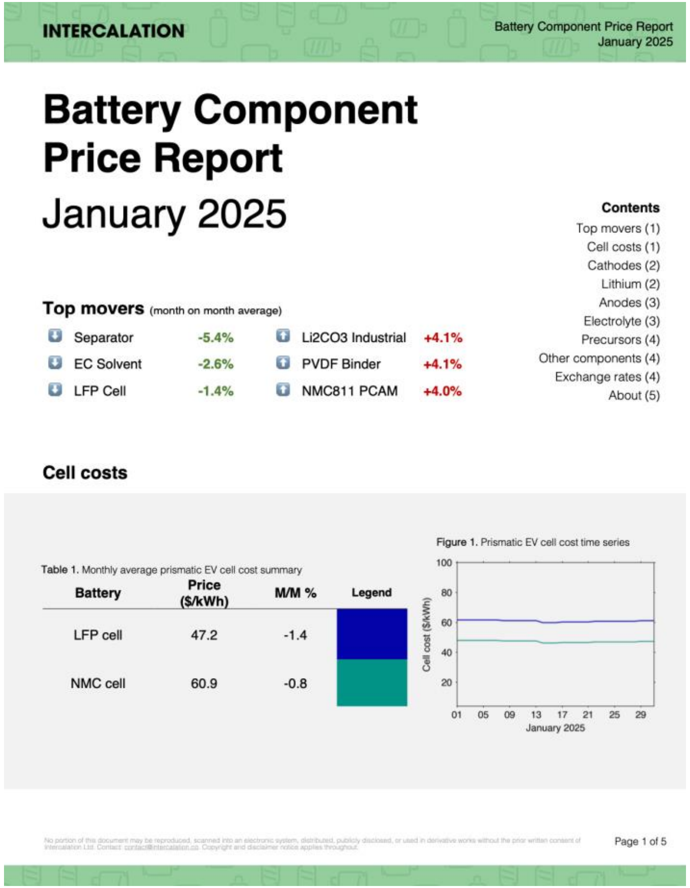
Best 2025

Source: BloombergNEF. Note: Historical prices have been updated to reflect real 2024 dollars. Weighted average survey value includes 343 data points from passenger cars, buses, commercial vehicles and stationary storage.

AS RENEWABLES, BATTERIES MADE IMPRESSIVE COST REDUCTION

LFP Battery cell at 47 $/kWh

NMC at 60$/kWh



INTERCALATION

Battery Component Price Report
January 2025

Battery Component Price Report
January 2025

Contents

Top movers (1)
Cell costs (1)
Cathodes (2)
Lithium (2)
Anodes (3)
Electrolyte (3)
Precursors (4)
Other components (4)
Exchange rates (4)
About (5)

Top movers (month on month average)

Separator	-5.4%	Li2CO3 Industrial	+4.1%
EC Solvent	-2.6%	PVDF Binder	+4.1%
LFP Cell	-1.4%	NMC811 PCAM	+4.0%

Cell costs

Table 1. Monthly average prismatic EV cell cost summary

Battery	Price ($/kWh)	M/M %	Legend
LFP cell	47.2	-1.4	
NMC cell	60.9	-0.8	

Figure 1. Prismatic EV cell cost time series

With 4000-5000 cycles battery cell cost at 1 $cts/kWh stored !
No material limits. A complete revolution

csem

RIDICOUSLY LOW PRICE FOR BATTERY SYSTEMS ANNOUNCED

- Note of caution: likely low margin at 66 $/kWh (cf cell price at 47$/kWh, only 19 for BMS, packaging,container containers)… but the trend is here…

“This procurement covers a comprehensive range of services beyond the delivery of storage equipment, including system design, installation guidance, commissioning, 20-year maintenance, and integrated safety features”

pv magazine
energy storage

[PowerChina receives bids for 16 GWh BESS tender with average price of $66.3/kWh - Energy Storage]

News & Analysis About Us Advertise

Markets Projects & Applications Industry Technologies Products & Services

Tenders Policy Supply chain

TENDERS

PowerChina receives bids for 16 GWh BESS tender with average price of $66.3/kWh

The tender marks the largest energy storage procurement in China’s history.

By Vincent Shaw | Dec 09, 2024

Markets Tenders 1

The Edwards & Sanborn solar-plus-storage project in California is now fully online, with 875MWdc of solar PV and 3,287MWh

Masdar, EWEC announce 5 GW/19 GWh solar-plus-storage project in Abu Dhabi

Masdar and Emirates Water and Electricity Co. (EWEC) plan to build a $6 billion, 5 GW/19 GWh solar-plus-storage project in Abu Dhabi, with operations set to start by 2027.

JANUARY 14, 2025 **BLATHNAID O'DEA**

Cost of Storage

- if 100 $/kWh investment at system level for storage s over 5000 cycles (1 cycle per day)

→2 cts/kWh storage costs (without capital costs and maintenance)

- Combined with Wind and PV:
  generate, store and dispatch at will !

Batteries

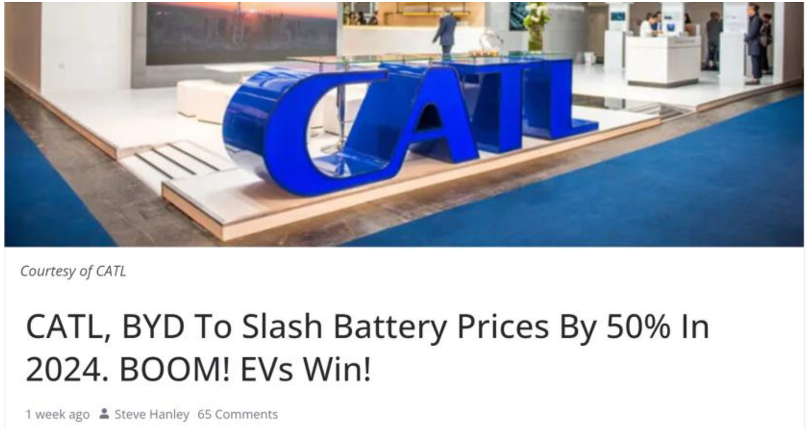
- Due to large increase in investement in China, huge capacity in place
- 4800 GWh by end 2025 of battery manufacturing (enough for e.g. 100 Millions cars battery).

→Price war and lower battery costs

2025: Cells down at <50 $/kWh, packs at < 100$/kWh,

DC storage system at < 100 $/kWh. Still expensive in CH for small systems

Strong effort in Europe in many companies to catch up on manufacturing

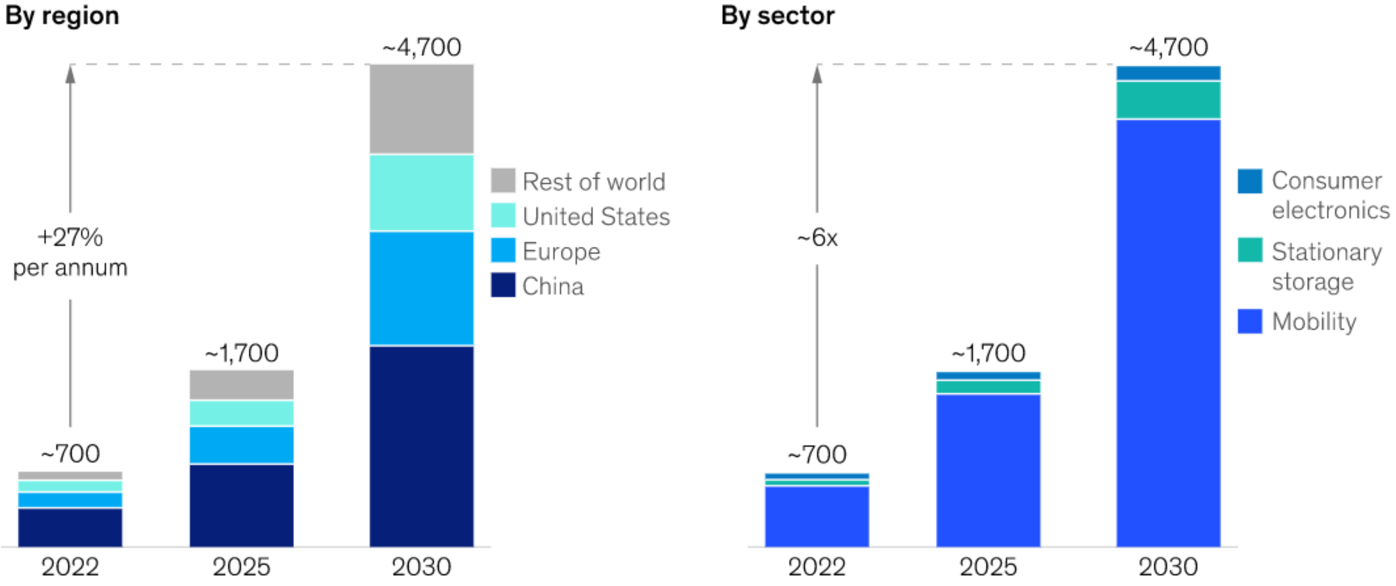


Prof. Dr. Christophe Ballif

Exhibit 1

Li-ion battery demand is expected to grow by about 33 percent annually to reach around 4,700 GWh by 2030.

Global Li-ion battery cell demand, GWh, Base case



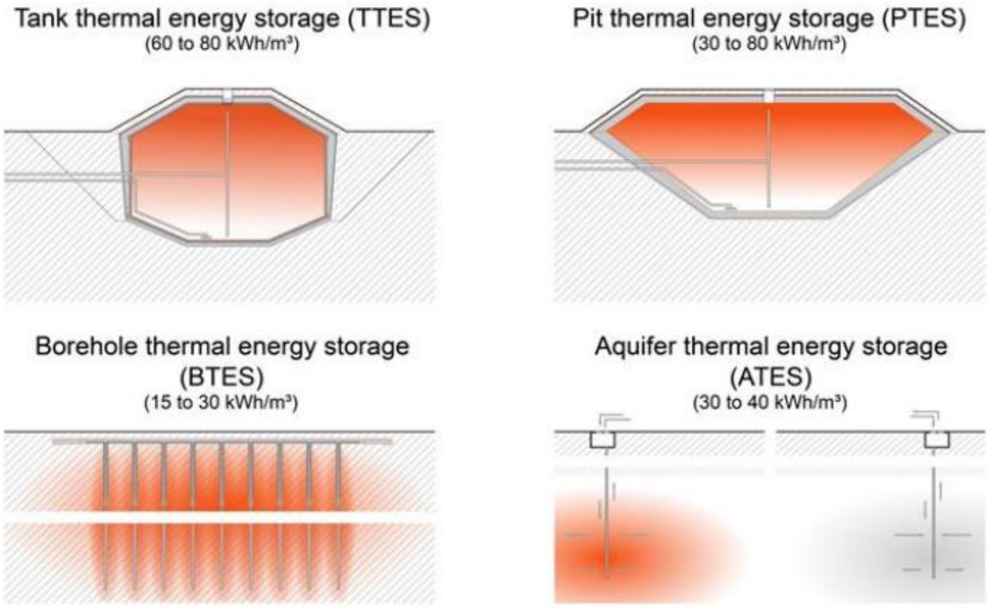
[1]Including passenger cars, commercial vehicles, two-to-three wheelers, off-highway vehicles, and aviation.
Source: McKinsey Battery Insights Demand Model

Indeed… Production capacity Reached in 2025 in large part thanks to china!

Lithium-ion battery demand forecast for 2030 | McKinsey

Thermal storage - TES

Main concepts for seasonal thermal energy storage.
Use heat (solar) or excess electricity in Summertime



Swiss solar tank

Sørensen, P. A., and Thomas Schmidt. "Design and construction of large scale heat storages for district heating in Denmark." *14th International Conference on Energy Storage*. 2018.

Low T Solar thermal heat

In the Danish city of Silkeborg, 44 000 inhabitants, the wolrd's largest solar thermal plant will be installed until the end of the year. The 12 436 large collectors will be mounted on agricultural areas in front of the city's gate. Completed, the plant will have a total area of 156 694 m².

- Heat production and Storage with solar thermal
- Strong potential also with excess summer electricity !
- Heat up at 95°C for winter district heating
- Announced seasonal storage costs **of 4 cts/kWh** thermal !
- (but requires areas)

Christophe Ballif / Philippe Thalmann / Claudia Binder

Power-to-gas

- Electrolysis of hydrogen will likely the most meaningful route, thanks to ultra-low cost renewable and electrolysers, and possibly competitive in the near and medium and long term → realistic target at less tan 1$/kg H_2 (3 cts/kWh chemical)
- Could be a long-term support to decarbonization with storage/winter usage (e.g. H_2 by pipeline to CH), or for industrial process
- Replacing natural gas by Hydrogen in some application could be the route to follow
- Longer term storage and all compression steps, pipeline adaptation, challenging, efficiency losses: challenging
- H2 initiative at EU level, billions are flowing… Many projects announced and delayed

- **Market entrance for alternative route with Ammonia (green chemical). Later transport and use green Amonia. Easier to transport (vs H2) by boat.**
- Entrance for Methane (methane from captured CO2 and H2) not clear, unless a high price on CO_2 tons. Could be pushed by fossil fuel/chemical industry
- **Still better to go all electric whenever possible (as much as you need, but as little as necessary)**

Christophe Ballif / Philippe Thalmann / Claudia Binder

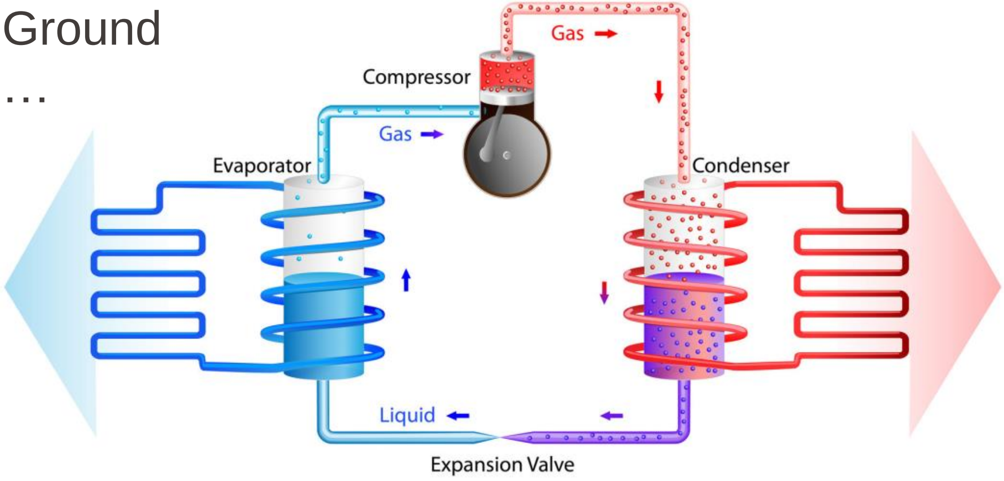
Christophe Ballif / Philippe Thalmann / Claudia Binder

Synthesis storage

- Electricity storage is a cornerstone of the future grid. Or a possibility to work without large grids !
- Worldwide battery storage capacity is quickly increasing due to dropping of the lithium-ion battery price and rising of the e-mobility. For short-term from seconds to hours or a few days batteries will help.
- For seasonal storage only Hydro, thermal energy storage, and possible PtG (power-to-gas), in salt cavern or oil/gas field are possibly cost effective (and of course Bio-mass, wastes).
- In many scenario, over-production and curtailement of production ! (e.g. wind and solar) or on purpose production (e.g. peak with biofuel) might be cheaper than additional long term storage… In CH not easy to store Hydrogen

Support to decarbonization: Heat pump -

Sources
- Air
- Water
- Ground
- …



https://www.airteamltd.com/hvac-knowledge-check-heat-pumps-101/

Coefficient of performance (COP= heat/electricity) up to 3 to 5 or more (depending
On final and temperature difference)

The heat pump absorbs heat from the cold source and releases it to the warmer one.

Components
- Evaporator
- Compressor
- Condenser
- Expension Valve

Can be used with district heating
With CO2 network

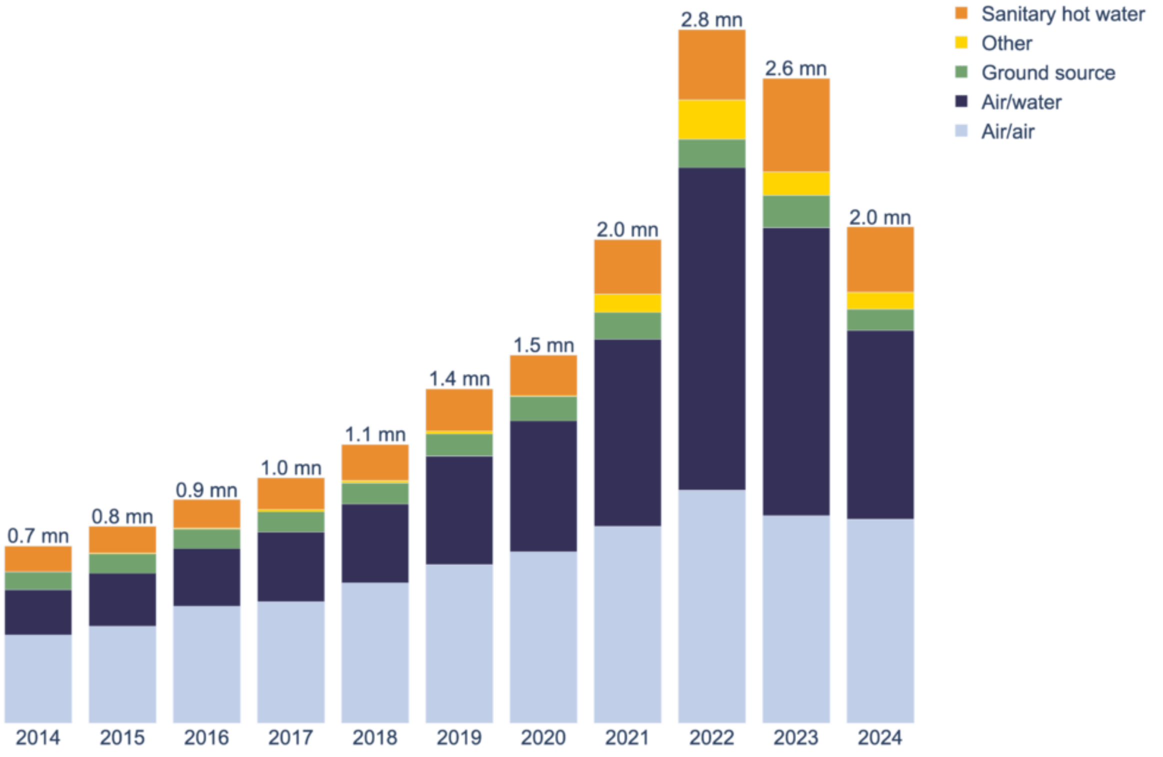
Heat pumps will become an essential Elements of the energy transition. Range from kW to MW

Christophe Ballif / Philippe Thalmann / Claudia Binder

Heat pump installation in Europe

[Market data - European Heat Pump Association (ehpa.org)]

Annual sales of heat pumps in 13 European countries



Source: European Heat Pump Association
Countries: FI, NL, DE, UK, FR, PL, AT, BE, DK, IT, NO, PT, SE

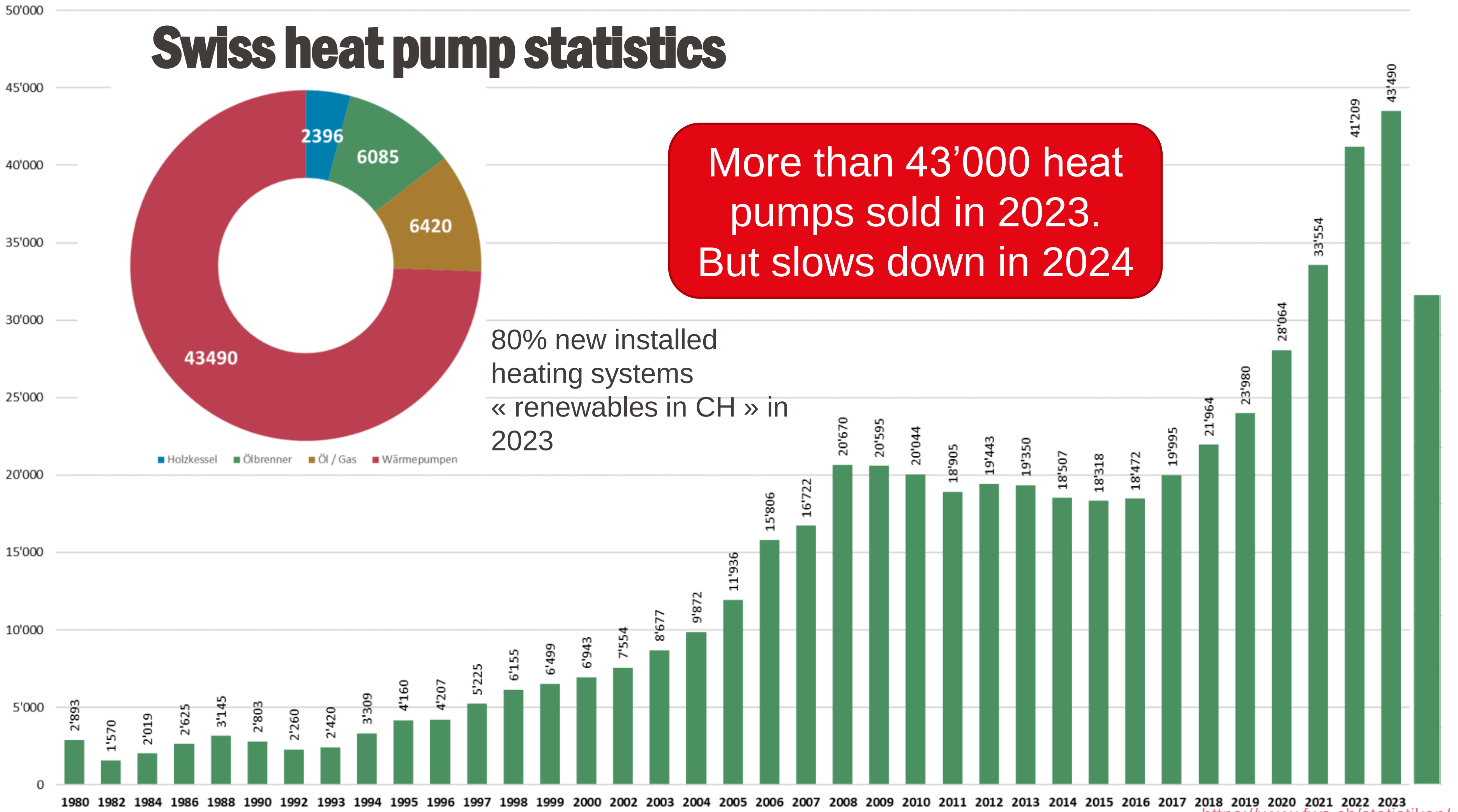
Some support scheme stopped in 2023…

Higher interest rate

Need to reach 60 millions heat pumps by 2030 to reach «repowerEU» with 50% renewable heat

JRC Publications Repository - Clean Energy Technology Observatory: Heat pumps in the European Union - 2023 Status Report on Technology Development, Trends, Value Chains and Markets (europa.eu)

Swiss heat pump statistics



More than 43’000 heat pumps sold in 2023. But slows down in 2024

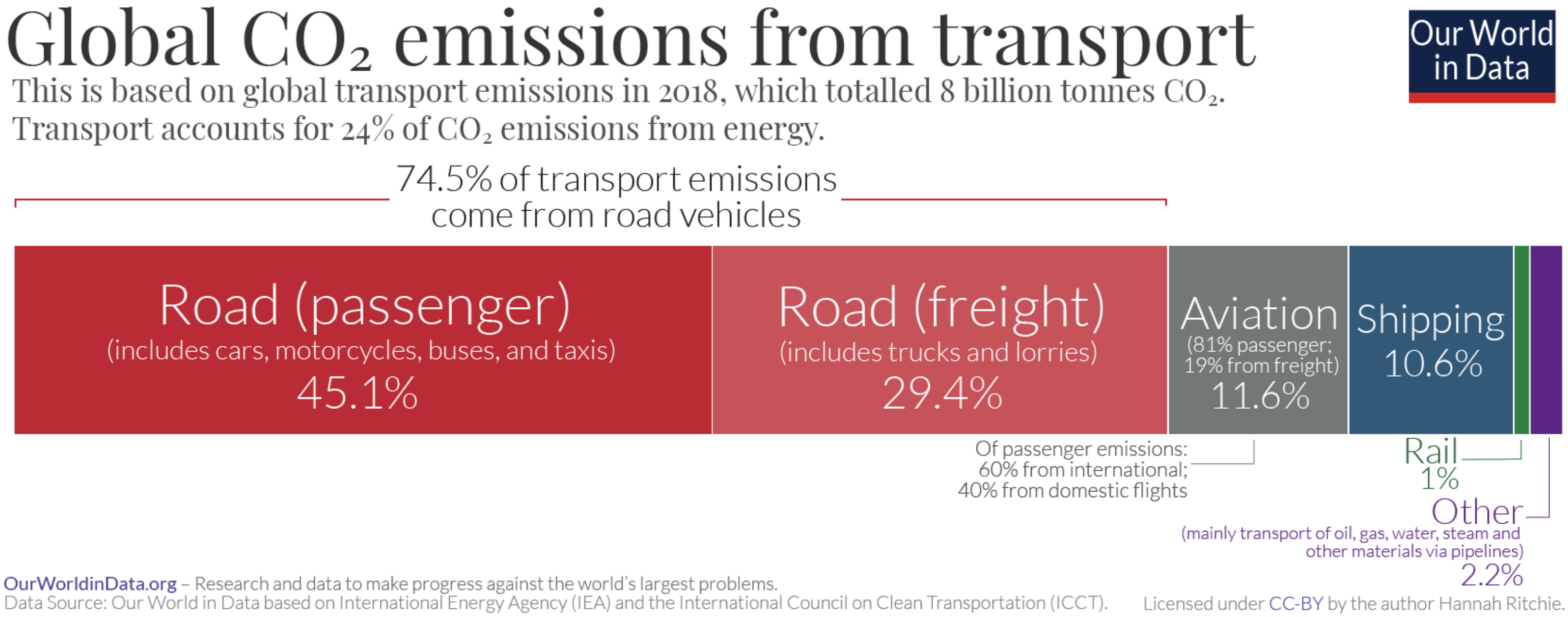
80% new installed heating systems « renewables in CH » in 2023

https://www.fws.ch/statistiken/

Transport

Christophe Ballif / Philippe Thalmann / Claudia Binder

CO2 emission by transport mode



Challenge for aviation and shipping ! → ideally biofuels, or NH3 for boats (do not use biofuels in cars..)
Not much happening

https://ourworldindata.org/co2-emissions-from-transport

Emergence of the electric car

If Battery packs → 60$/kWh (600 to 1000 cycles)

→40 kWh pack → 2400$

→100 kWh pack → 6000$

Car electricity usage: 10 – 20 kWh/100 km

- No more servicing (save ~500 $/year)
- Can use cheap electricity (save 200-1000$/year)
- Saves 700 to 1500$/year and does not need to be more expensive than a regular car !

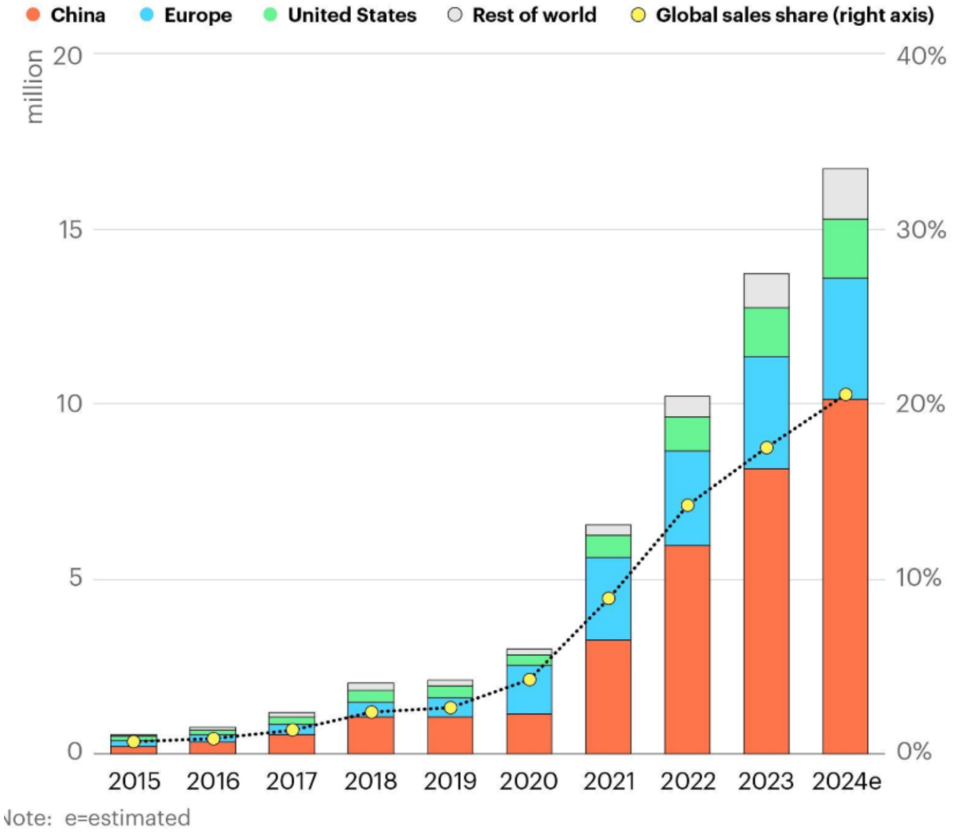
→Electric car will/should replace fuel cars in many markets (ideally small cars…)

Rising company: BYD in China, with cars down to 10 kCH$

Christophe Ballif / Philippe Thalmann / Claudia Binder

EPFL

Electricity storage - electric car



International Energy Agency

Electric car deployment has accelerated with news sales in the 20% range of the full parc for around 17 millions cars

The goal is globally less cars, but if a car, better it is electrical
n.b. around 100 millions new cars per year

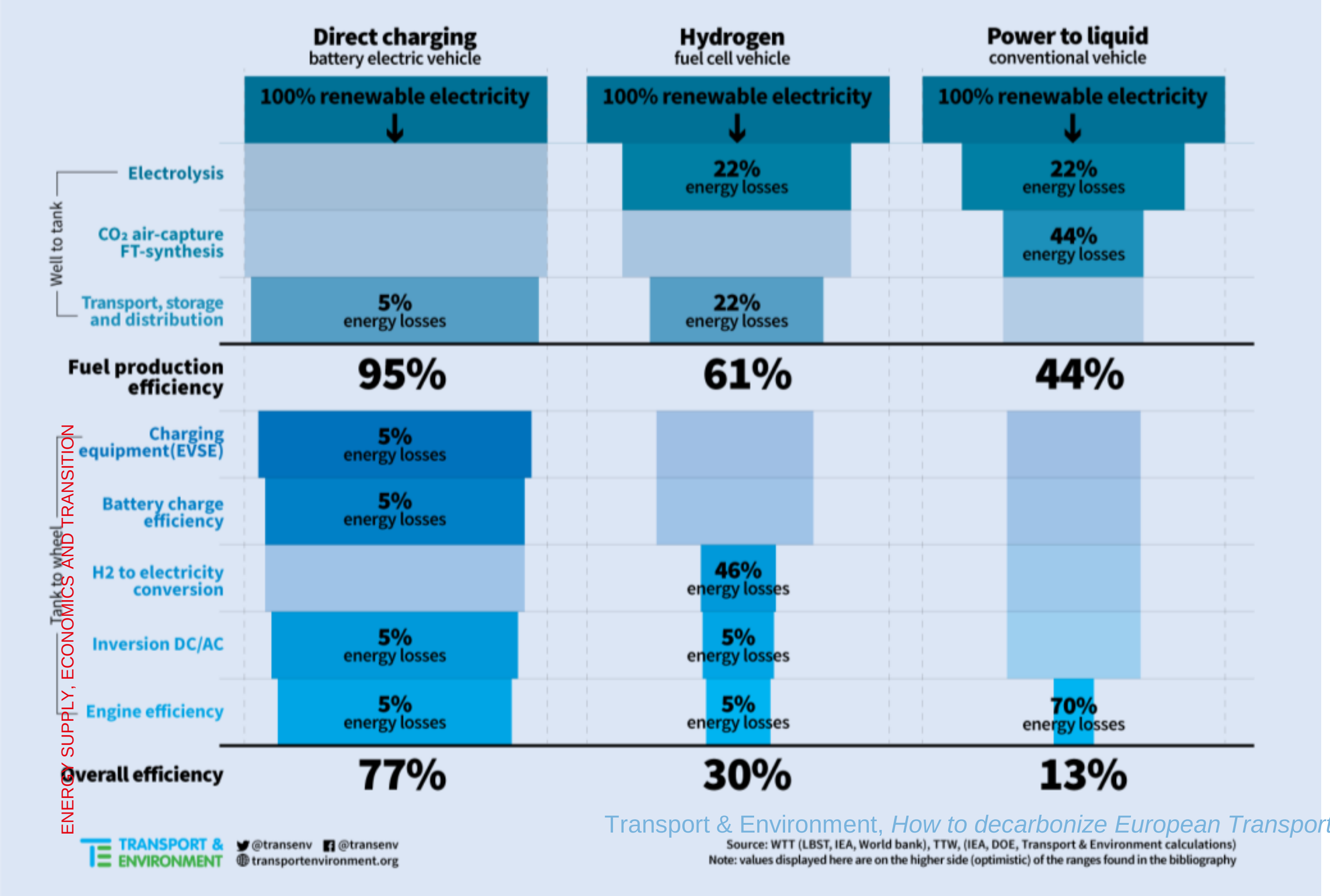
Christophe Ballif / Philippe Thalmann / Claudia Binder

With battery price down and china industrial effort

Many countries worldwide, with no car industry will adopt Chinese e-car.
USA and Europe will try and protect their market !

BYD Seagull at 9500 CHF, with 30 kWh batteries

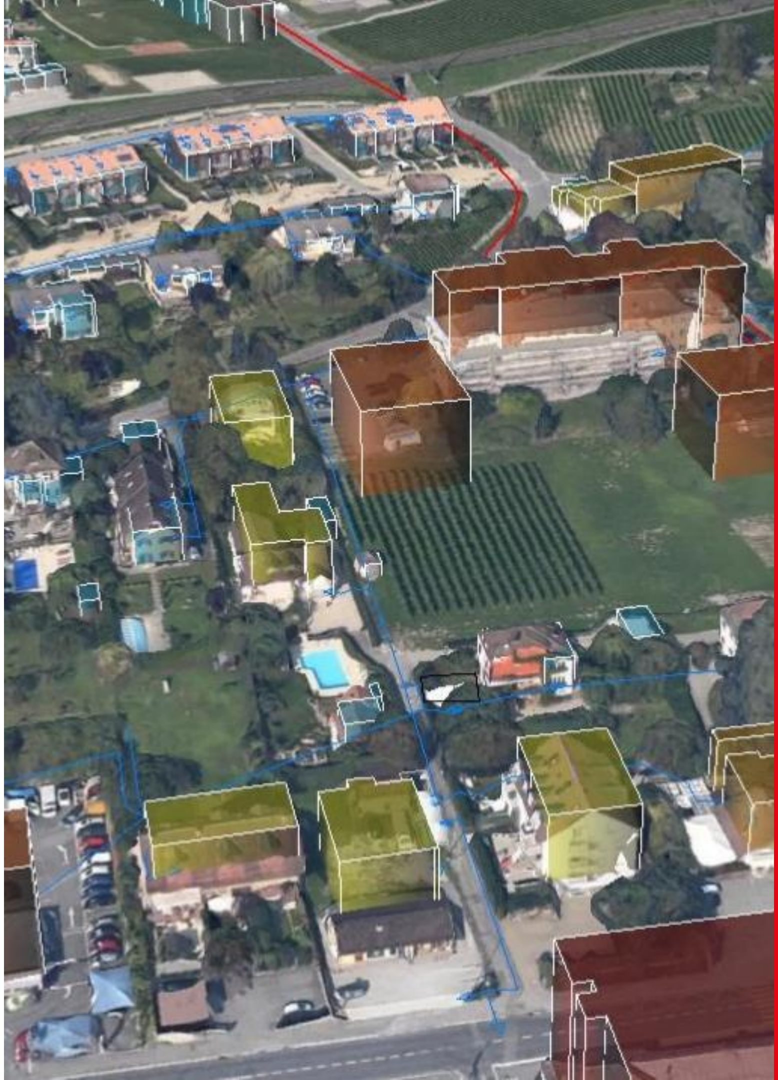
Net zero emission car , battery , hydrogen, syn - fuel



Transport & Environment, *How to decarbonize European Transport by 2050*, 2018

Hydrogen will
not play a role
For private cars.
Possibly for trucks.

Christophe Ballif / Philippe Thalmann / Claudia Binder



Is this sustainable ?

Material availability?

CO2 emission (and others)?

Biodiversity?

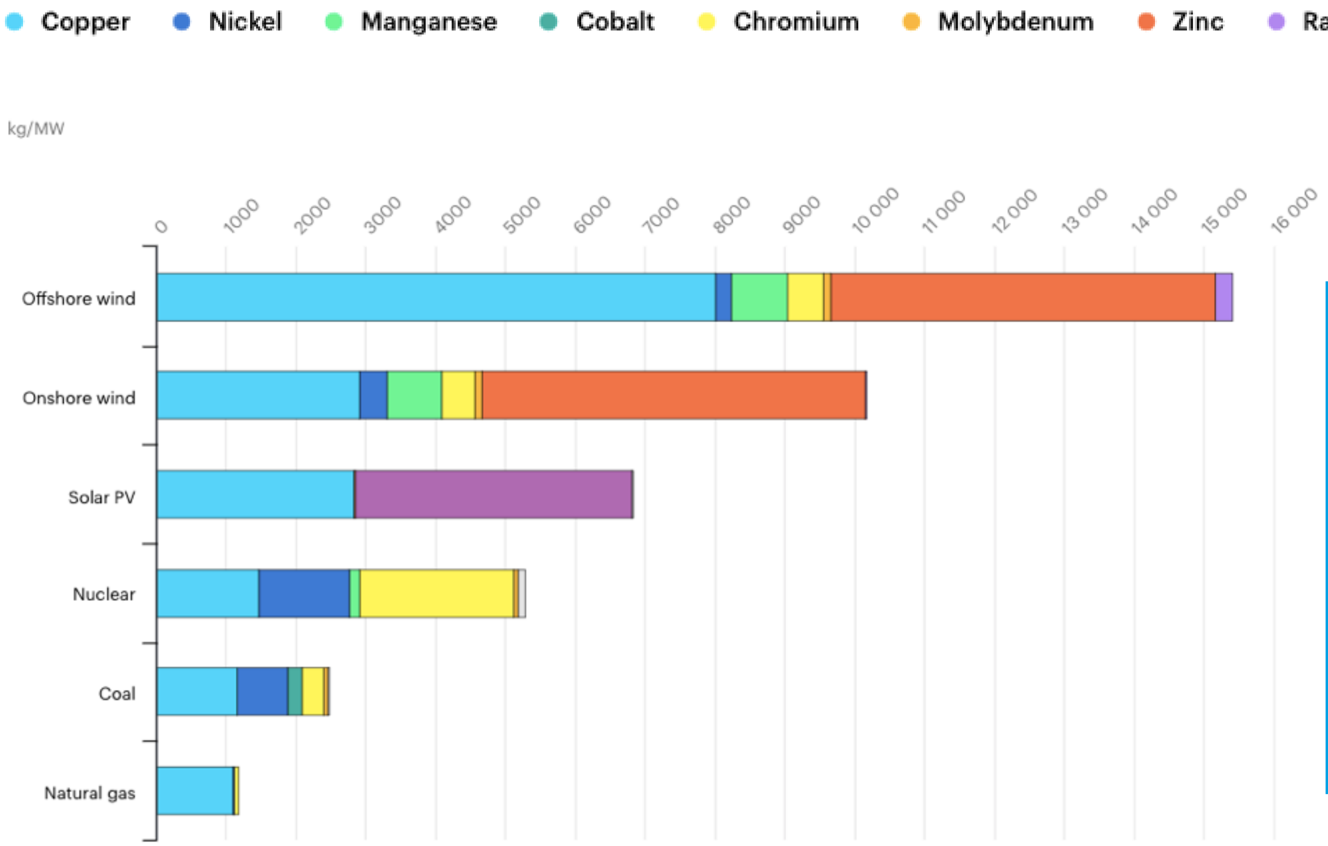
Christophe Ballif / Philippe Thalmann / Claudia Binder

Materials availability

- **At the scale of the energy transition, the limitation in materials is a myth (as is the limitation in fossile fuel availability)**
- Some bottleneck and temporary price increase possible (e.g. on Cu, Ag, Co) quickly solved by market (increased production) or technology adaptations. (Ag, Co, other rare earth for magnets).
- Of course it should not prevent to limit in general material usage (less hardware consumption, less construction, less IT)… But for this, less people seems to

Fossil fuel lobbies would like you to think that materials and mining a major issue associated to renewables and batteries… And many intellectuals, pseudo engineers and economists….

MATERIALS EXTRACTION



Yes you'll need a little more material extraction than with the **current status**

Outside fuel extraction not considered here

MATERIAL USAGE: EXEMPLE CUPPER

PV: 1 TW/year at 3 Cu Tons/MW → **3 MT /year**

Windturbines: 500 GW/year at
2 Tons/MW, with Al grid connection) → **1 MT/year**

Electric cars: 80 millions cars at
60 kg Cu, with charging station → **4.8 MT/year**

~ 8-9 MT out of 25 MT /year processed today

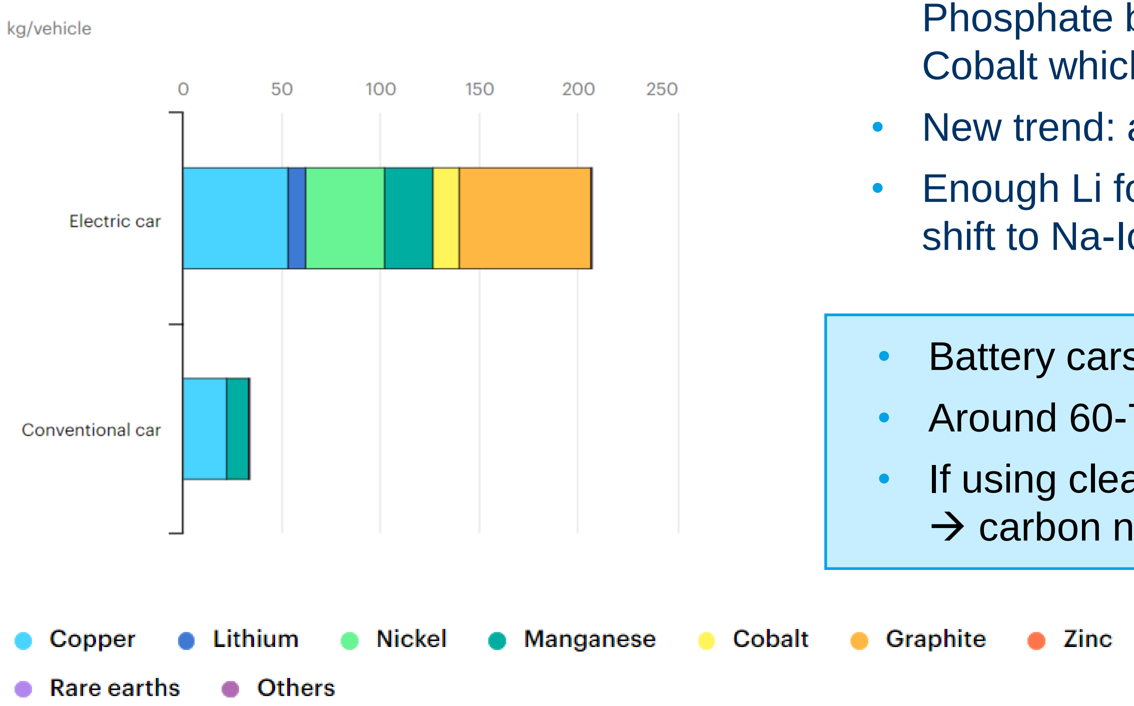
→ market pressure and possible bottlenecks, but not fundamental, and…

- Materials can be saved (improved designs), additional/improved mining and recycling.
- As for other less used materials alternative solutions always exist! e.g. rare earth for magnets of windturbines , Ag for photovoltaics, cobalt for batteries….
- **There is no succesfull product that every stopped being produced because of „not enough“**

Materials and electric cars

- Before electric cars, nobody seem interested where the materials for the car were coming from …..

MATERIAL USAGE FOR ELECTRICAL NICO LITHIUM BATTERIES

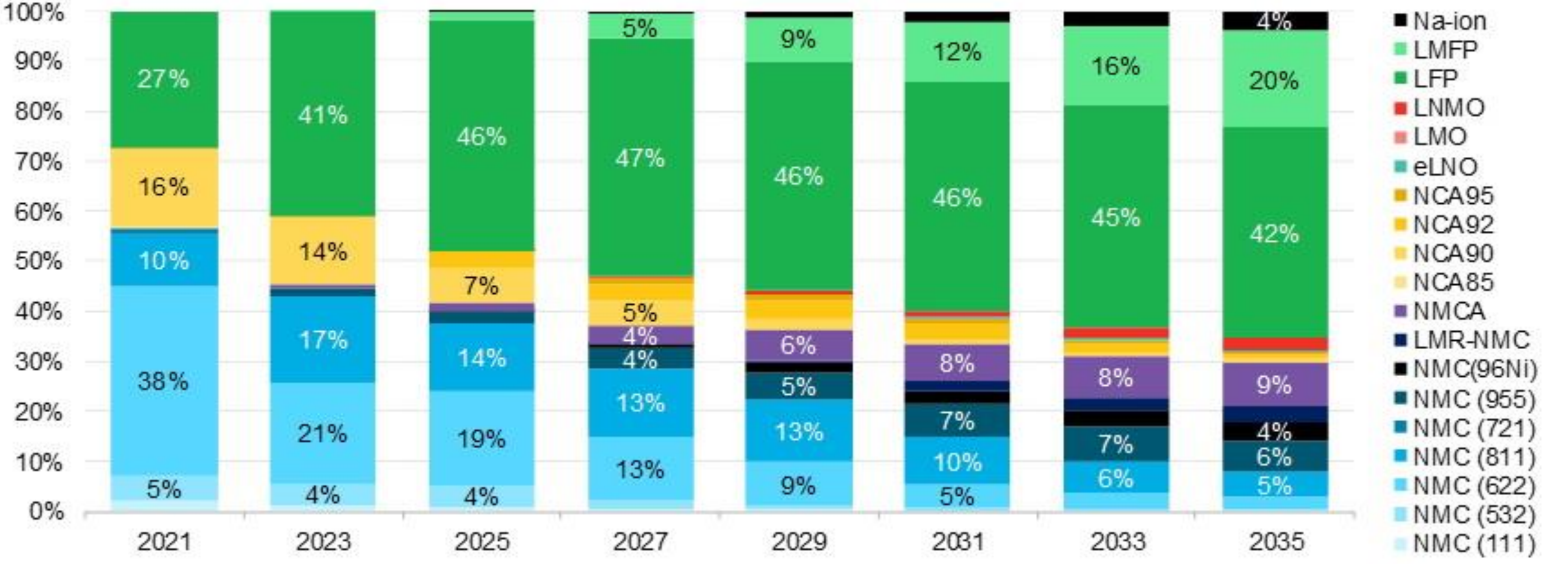


- Car makers can shift to Lithium Iron Phosphate batteries. Heavier but no Ni and Cobalt which are the most critical.
- New trend: add manganese
- Enough Li for > 2 billions cars, and possible shift to Na-Ion

- Battery cars of 70 kWh, CO_2 emission ~ 5 T
- Around 60-70 kg CO2 emission /kWh.
- If using clean electricity in 30’000 km → carbon neutral!

Lithium-iron-phosphate (LFP) is taking over the battery market

Evolution of cathode chemistry mix across all passenger electric vehicle segments



Source: BloombergNEF. Note: Na-ion refers to sodium ion; LMFP is lithium manganese iron phosphate; LFP is lithium iron phosphate; LNMO is lithium nickel manganese oxide; LMO is lithium manganese oxide; LNO is lithium nickel oxide; NCA is nickel cobalt aluminum oxide; NMCA is nickel manganese cobalt aluminum oxide; LMR is lithium- and manganese-rich; NMC is nickel manganese cobalt oxide. See Appendix A for glossary of battery chemistries.

EPFL
PV-lab
IMT NEUCHATEL

Materials: more strategic risks ?

ELSEVIER
Energy Research & Social Science
Volume 82, December 2021, 102311

Perspective

More transitions, less risk: How renewable energy reduces risks from mining, trade and political dependence

Jim Krane, Robert Idel

[More transitions, less risk: How renewable energy reduces risks from mining, trade and political dependence - ScienceDirect]

“an emerging perspective in the US public discourse makes the opposite case, arguing that a buildout of renewable electricity would exacerbate supply risks, mining intensity, and import dependence. This paper’s findings challenge such assertions.”

Joule

CellPress

Volume 7, Issue 11, 15 November 2023, Pages 2408-2413

Commentary

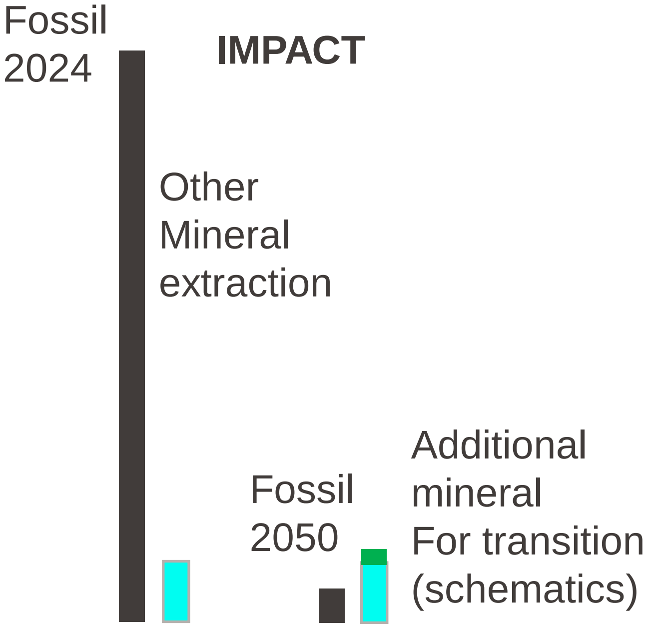
Energy transition will require substantially less mining than the current fossil system

Joey Nijnens [1], Paul Behrens [2], Oscar Kraan [1], Benjamin Sprecher [3], René Kleijn [2]

As for all mining possible local problems, and good practices required!! Use transition to make mining sector better …

Fossil

- 5 trillions per year health costs
- 4-7 millions death
- Climate warming
- (and Putin)



Keeping a small fraction of our emissions for the energy transition

- for decarbonising the world economy
- 40 TW of PV panels at 300 g CO2 /W emission par panel manufactured (Appendix) ?
- 15 GW of Wind at 200 g CO2/W → 3 GT
- 2 billions batteries of 50 kWh at 60 kg CO2/kWh → 6 GT
- Systems, grid update…. → 6 GT

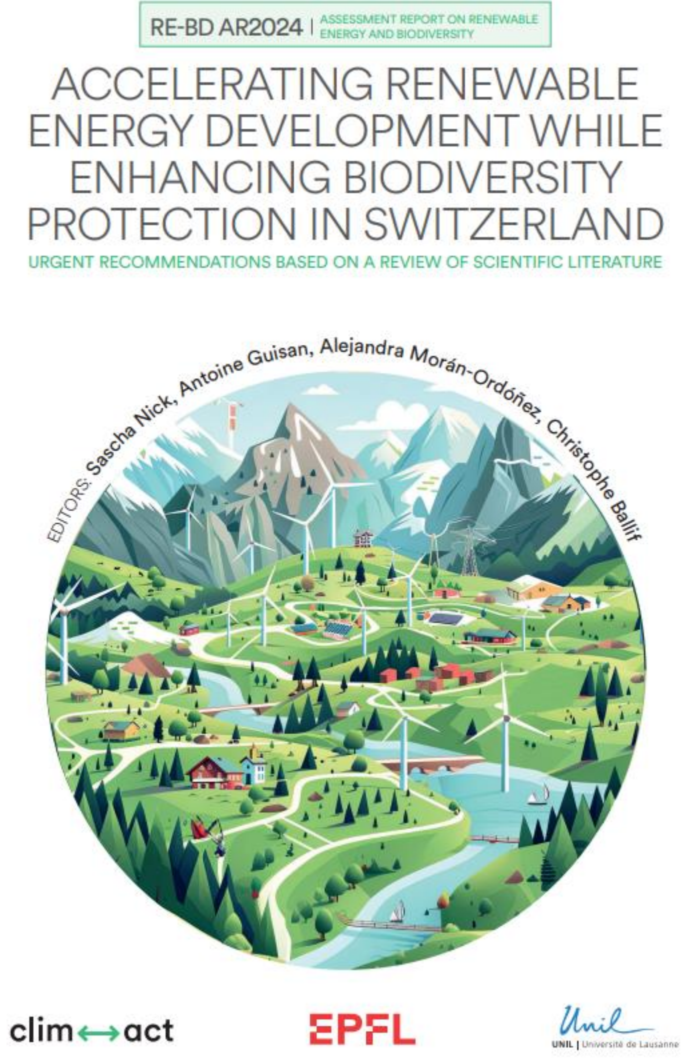
Estimated total (with current good practice) → 27 GT To compare with the current ~ 50 GT billions tons CO_2 eq produced every year, and the remaining 1000 GT remaining for a +2°C scenario

Using around 3 % percent of our remaining carbon budget to make the object and infrastructure that will save on CO2 emission is the «less worse» use case for CO2
And again, the more you decarbonise, the better the CO2 contents of all components

Biodiversity

Be-smart and beware !
Doesn't need to be in opposition

[RE-BD AR2024. Assessment Report on Renewable Energy and Biodiversity]



EPFL
PV-lab
IMT NEUCHATEL

Batteries, solar, wind, electrolysers

SENS eRecycling

- For metals, mining, good practice required (as for any other product)
- Same for industrial production (as for any other product)
- Renewables: **chance to put more pressure on mining industry**
- Recycling possible and necessary (Batteries, PV, …) = materials will be here for ever
- To make products cheap, you need to save on resources and energy !!! This forces the material and energy learning curve !

- Green transition has a minimum impact
- In all cases, a minor problem compared to global warming
- Think of reducing non-essential things and try globally to «reduce» the mining sector, don't put the blame on renewables

Or

Conclusions first part

Christophe Ballif / Philippe Thalmann / Claudia Binder

Conclusion first part in 14 points

- With >50 Gt CO_2 , including 38 Gt direct CO_2 annually, we are dramatically changing the world, 19 years left for 2° scenario…
- Primary energy usage (in the substitution method) will still grow, because of countries developing their economy. **All oil/gas producers want to exploit as much as they can their reserves.** If no decarbonized sources of energy**, fossile fuel will further increase because there is no energy crisis and plenty of fossil…**
- **ONLY realistic scenarios to decarbonize the world are based** on a strong increase of electrification, and massive deployment of wind and solar (and partly biomass). Improved electricity management, with strong flexibility (forecast, storage, on-demand usage or reduction) and reserve capacity are essential.
- All other energy and electricity sources will help (geothermal, nuclear fission, solar heat)
- Increased efficiency (in particular in buildings), tracking losses are a must to speed up
- **Sufficiency and less absurd consumption** will help make transition more quickly
- **Green economy works**, but requires massive efforts of industrialization, with mostly China bringing manufacturing to the scale required. If you do not push renewable (or nuclear) it will be made by fossile….

EPFL

Conclusion first part in 14 points

- Agriculture needs to reduce emission, lands and forest can contribute through CO_2 capture
- Instead of pushing consumptions of «futile» products (including Bitcoin, huge cars, 6G, AI ?), green deals should animate economy with clear goals and targets
- A few individual, companies, countries have to loose from the energy transition and will fight against it, by ignoring reality, by denying facts, truth or by being cynical (from a car mechanic, to a local oil reseller, to oil traders, to coal company, to fossil fuel exporting countries, to president of countries authorizing new oil fields).
- Most people, societies, and the planet ecosystem have to gain from transition
- Some countries are going actively for net zero emission, including CH…(to a large extent) current (unsufficient) pledges and actions, as well as plans for fossil fuel extraction plans will not help…. What will likely happen is a mixed scenario with partial decarbonisation, a 2.5-3° temperature increase dramatic overshoots, followed by stronger actions…..
- If you **make clean-tech ultra-low cost**, you have a chance to subvert even the "energy-climate idiots", and possibly even to restore to 2° and 1.5° when you start recapture….

Christophe Bsallif / Philippe Thalmann / Claudia Binder

Christophe Ballif / Philippe Thalmann / Claudia Binder

What should happen ?
What will happen?
How can you contribute?
What about the topics below ?

Innovation

ZEROe

Towards the world's first zero-emission commercial aircraft

H2 airplanes ? Biofuel ?

Methanol ? NH3 ?

Thanks for your attention

Next steps

- Energy economics and policy (how do you favor the transition ?)
- How do you get people to change…..`?

Appendix (n.b. not for the exam)

Christophe Ballif / Philippe Thalmann / Claudia Binder

Electricity storage – Energy vault

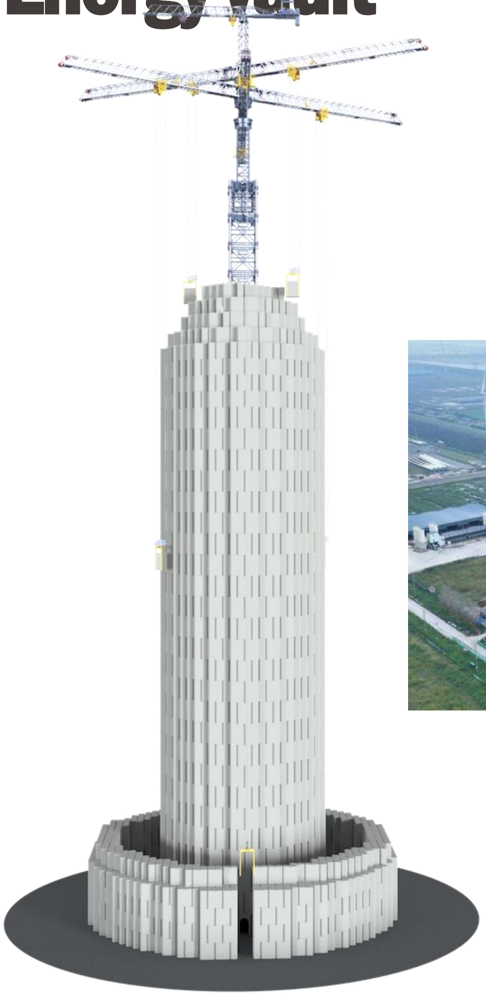
Principle

Store gravitational energy with 35t composite bricks

- 20 to 80 MWh storage
- 4 to 8 MW continuous power

Raised >> 100 millions from Softbank, and stock market

Try an make the cost calculation with concrete blocks ! It is is doubtful that this kind of technology will fly



https://energyvault.com/

Material usage : critical ?

Exemple of Copper:

Photovoltaics (at 1000 GW/year with 3 tons of Cu per MW).
→ **3 millions Tons** per year
Windturbines (at 500 GW per year with 2 Tons/MW)
→ **1 million Tons**
Electric cars (80 **millions** cars at 60 kg Cu, including charging station)
→ **4.8 millions Tons**

~ **8-9 millions** tons on components → market pressure
Out of ~ 25 millions tons/year … Currently increase in mining at 2.5% year

What can/will happen

- pressure for additional/improved mining and recycling will grow…. Energy transition is part of the pressure. Al and other metals can substiute in many cases (Cu used a lot for roofs in CH…)
- Industry has already reacted, Cu will be «hot» but will happen, lithium likely easier….
- For less used materials (e.g. rare earth for wind turbines, Co for batteries), mitigation solutions always exist !

A important note on sustainability of batteries

- Enough lithium for > 2 billion cars (taking a 120 g lithium by kWh of battery). 17 MT reserve and 80 MT ressources.

(with 70 kWh x 0.12x 1 billions= 8.4 millions tonnes)

- Alternative chemistry will appear if huge market !

Mineral Commodity Summaries 2019" (PDF). U.S. Geological Survey. 2019.

As for all mining possible local problems, and good practice required !!

Adapted per kg of batteries from : Kim et al. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis Environ. Sci. Technol. 2016, 50, 14, 7715-7722
Lithium-Ion Vehicle Battery Production – status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling

Christophe Ballif / Philippe Thalmann / Claudia Binder

CO2 emission of battery production
Realistic numbers today at ~60 kg CO2/kWh

- Énorme éventail selon la source : GHG **40 .. 250 $kgCO_2eq/kWh$** !

« *Étude suédoise* »:

Mia Romare, Lisbeth Dahllöf (2017); The Life Cycle Energy Consumption and Greenhouse Gas Emissions from Lithium-Ion Batteries; IVL Swedish Environmental Research Institute

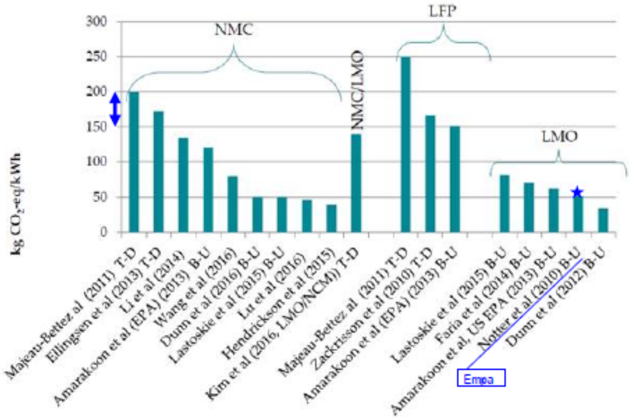


Figure 3: Calculated greenhouse gas emissions for different LCA studies of lithium-ion batteries for light vehicles for the chemistries NMC, NMC/LMO, LFP and LMO. T-D=Top-down approach for manufacturing and B-U is Bottom-Up approach.

a) How large are the energy use and greenhouse emissions related to the production of lithium-ion batteries?

The results from different assessments vary due to a number of factors including battery design, inventory data, modelling and manufacturing. Based on our review greenhouse gas emissions of 150-200 kg CO_2-eq/kWh battery looks to correspond to the greenhouse gas burden of current battery production. Energy use for battery manufacturing with current technology is about 350 – 650 MJ/kWh battery.

- Seulement **8 études sur 113** reposent sur la saisie et l'évaluation de données propres (Peters et al. 2019) [1]
- De nombreux auteurs reprennent les propos d'autres auteurs et se citent réciproquement. Les données les plus citées sont les données norvégiennes [2] de 150 à 200 kg CO2eq/kWh
  -> Les valeurs élevées souvent citées semblent « vraies »

Actualisations :

- Travail complet de Chine/USA (GREET, Yin et al. 2019) [3]: 43 - 58 $kgCO_2eq/kWh$ (prod. USA), 80 -110 $kgCO_2eq/kWh$ (prod. Chine)
- Travail complet des USA (Dai et al. 2019) [4]: 72.9 $kgCO_2eq/kWh$
- Fin 2019, les auteurs de « l'étude suédoise» ont sensiblement corrigé les anciennes valeurs à la baisse qui sont maintenant de 61 - 106 $kgCO_2eq/kWh$ [5]
- Suisse : Ecoinvent v3.6 (2019): 7.88 $kgCO_2eq/kg$ 69 $kgCO_2eq/kWh$ CH
  Les révisions en cours (Empa, PSI) affichent pour le niveau actuel de la technique (part d'électricité d'origine fossile rel. élevée) à des valeurs d'env. 70 $kgCO_2eq/kWh$.

[1] *The environmental impact of Li-Ion batteries and the role of key parameters – A review; Peters, Baumann, Zimmermann, Braun, Weil; HIU Helmholtz-Institute, KIT Karlsruhe Institute for Technology; Renewable and Sustainable Energy Reviews 67 (2017) 491–506; http://dx.doi.org/10.1016/j.rser.2016.08.039*

[2] *Linda Ager-Wick Ellingsen, Christine Roxanne Hung, Anders Hammer Strømman 2017; Identifying key assumptions and differences in life cycle assessment studies of lithium-ion traction batteries with focus on greenhouse gas emissions; Transportation Research Part D 55 (2017) 82–90 http://dx.doi.org/10.1016/j.trd.2017.06.028*

[3] *Life cycle inventories of the commonly used materials for lithium-ion batteries in China; Renshu Yin, Shuhan Hu, Yang Yang Journal of Cleaner Production 227 (2019) 960e971 https://doi.org/10.1016/j.jclepro.2019.04.186*

[4] *Life Cycle Analysis of Lithium-Ion Batteries for Automotive Applications; Qiang Dai, Jarod C. Kelly, Linda Gaines and Michael Wang; Systems Assessment Group, Energy Systems Division, Argonne National Laboratory; Batteries 2019, 5, 48; doi:10.3390/batteries5020048*

[5] *Erik Emilsson, Lisbeth Dahllöf (2019); Lithium-Ion Vehicle Battery Production Status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling; IVL Swedish Environmental Research Institute; https://www.ivl.se/download/18.14d7b12e16e3c5c36271070/1574923989017/C444.pdf*

Notes on sustainability of batteries: not perfect but ok*

Christophe Ballif / Philippe Thalmann / Claudia Binder

* Train better than a car

Current good practice CO_2 emission for battery !
~ 65 kg/kWh (with optimised assembly lines).
→ 4.5 Tonnes CO_2 additional for the car. **Compensated after 30'000** km (at 130 gCO2/km) **if using clean** electricity
→ 6-8 x better than a fuel car going 280'000 km

- When you decarbonise the grid and the mining , 65 kWh/kg → down to 0 (will happen with decarbonation of the grid)

- Will improve quickly with progress in manufacturing
- You can recycle even Li-Ion battery or give them a second life (stationnary storage)

Adapted per kg of batteries from : Kim et al. Cradle-to-Gate Emissions from a Commercial Electric Vehicle Li-Ion Battery: A Comparative Analysis Environ. Sci. Technol. 2016, 50, 14, 7715-7722
Lithium-Ion Vehicle Battery Production – status 2019 on Energy Use, CO2 Emissions, Use of Metals, Products Environmental Footprint, and Recycling

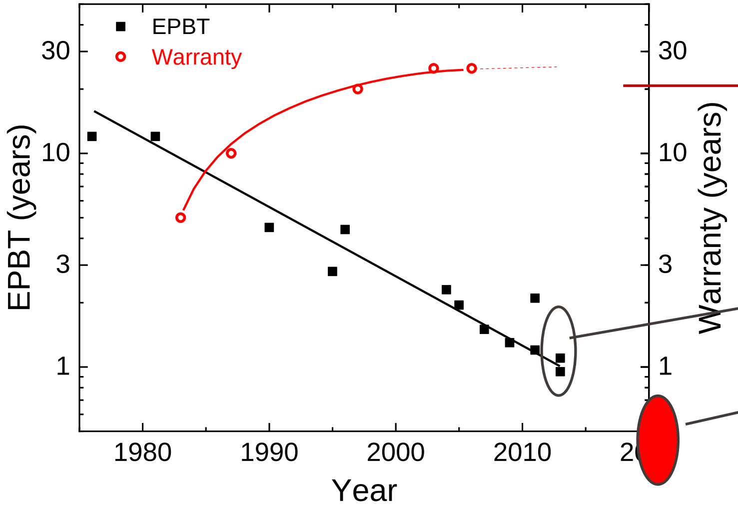
EPFL
PV-lab IMT NEUCHATEL

Energy pay-back time: permanently improved

Prof. Christophe Ballif

Exemple with Energy pay-back time (EPBT) of PV systems

Continuous decrease driven by leaner processing and increasing efficiencies



25 y warranty is today's industry standard

closer look on next page

Today EPBT, 6 months to 1 year

Windturbine EPT 2-6 months

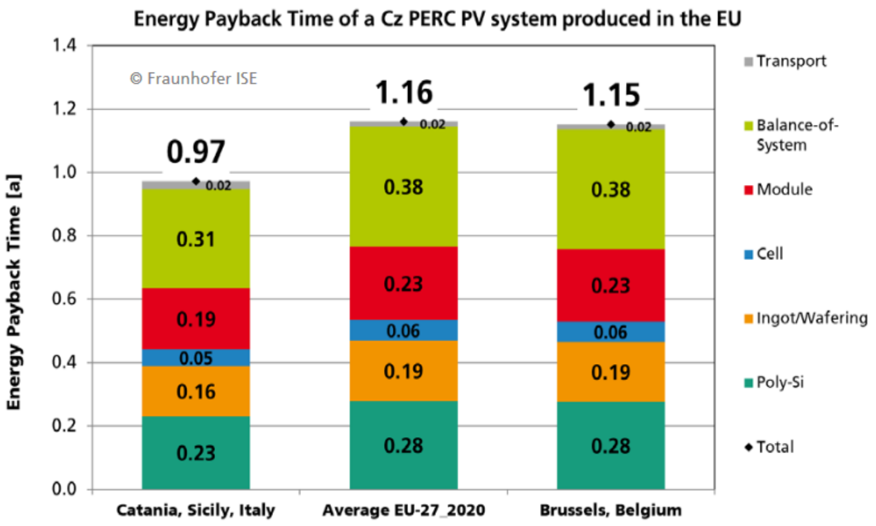
Long living myth: EPBT > module lifetime

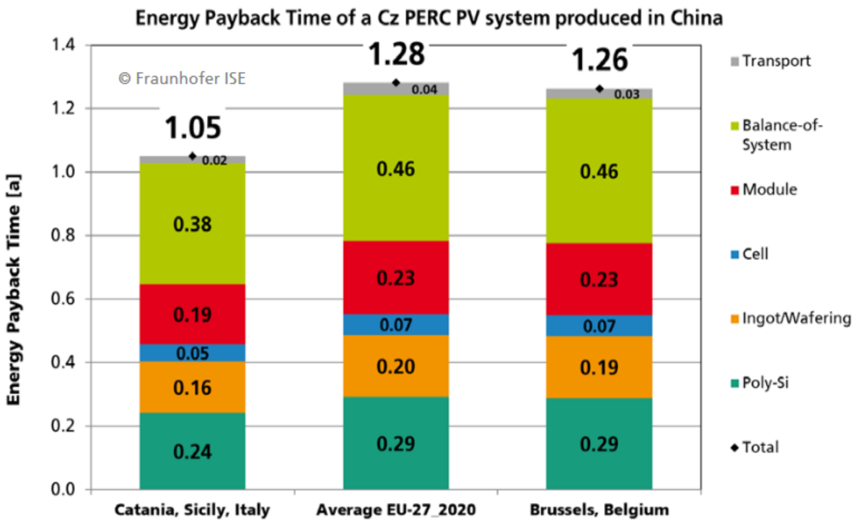
- was true in 1985 for warranty, NOT lifetime
- lifetime usually much longer than warranty

Wetzel, Prog. in PV (2014) Gallaher, Public Investments in Energy Technologies (2012)

Energy Pay-Back Time (EPBT) of Silicon PV Rooftop Systems

Source: Fraunhofer report 2021…. Improved since them





A typical PV system in Central EU will give back the energy required for **fabrication in 1 year.** Module around 60-65% of the total (n.b. Wind around 6 months EPBT)

Full module (from sand to product) : currently around **0.5-0.6 kWh/Wp** electricity required (5-6 cts/W at 10 cts/kWh local electricity).

- Even if electricity prices increase by 5 cts/kWh impact on LCOE of solar electricity minimum (+2.7 cts CAPEX → 0.15 cts/kWh over 25 years at 3% cost of capital).

EPFL

PV-lab IMT NEUCHATEL

Module CO_2 footprint

If EU electricity mix: 350 g/W of modules
With Chinese electricity mix 700g/W

25 years of lifetime → 25 kWh

→ modern processes of module fabrication → 10-20gCO_2/ kWh of solar electricity produced

Full System level typical emission (including inverter, installation…): 20-40 g CO_2/kWh

In summary: even with mono c-Si modules, system energy payback time ~ 1 year and CO_2 emission is acceptable (20 – 40g CO_2/kWh)

A comparative life cycle assessment of silicon PV modules: Impact of module design, manufacturing location and inventory – ScienceDirect 2021

And the more you decarbonize your electricity system, the better it becomes

Reminder:

- Gas power plant 400g CO2 /kWh
- Coal power plant 900g CO2 /kWh

powered by Q.ANTUM DUO

Q CELLS modules earn further low-carbon certification for French tenders

Hanwha Q CELLS GmbH, the German subsidiary of one of the largest solar cell and module manufacturers in the world, Hanwha Q CELLS Co., Ltd, has received on March 14 a Certisolis carbon footprint (CFP) certification of 300 kgeq/CO²/kWc in France for its high-efficiency Q.PEAK DUO module series.

APRIL 1, 2019 Q CELLS

However, these projects must be built using components that are certified as low-carbon during their production. The official certification from CRE module series has a carbon footprint of 300 kg-eq/CO²/kWc, attained through a 25% recycled poly SI methodology.

Sustained and sustainable solar growth thanks to France continues to enjoy encouraging growth as the country aims to reach its government-mandated solar capacity target of between 18.2 GW and 20.2 GW by 2030. Currently, cumulative solar capacity in France stands at just above 8 GW (as of the end of 2018), according to official Environment Ministry of France data.