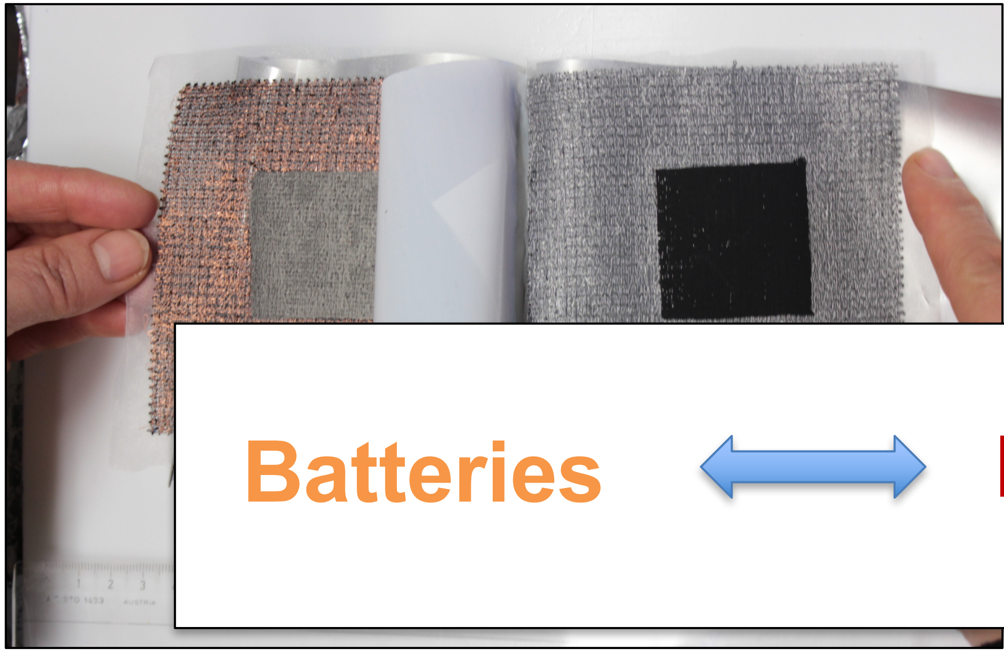
# Textile structures in batteries

- Lithium-ion batteries



- Redox flow batteries

**Batteries ⟷ Energy concerns**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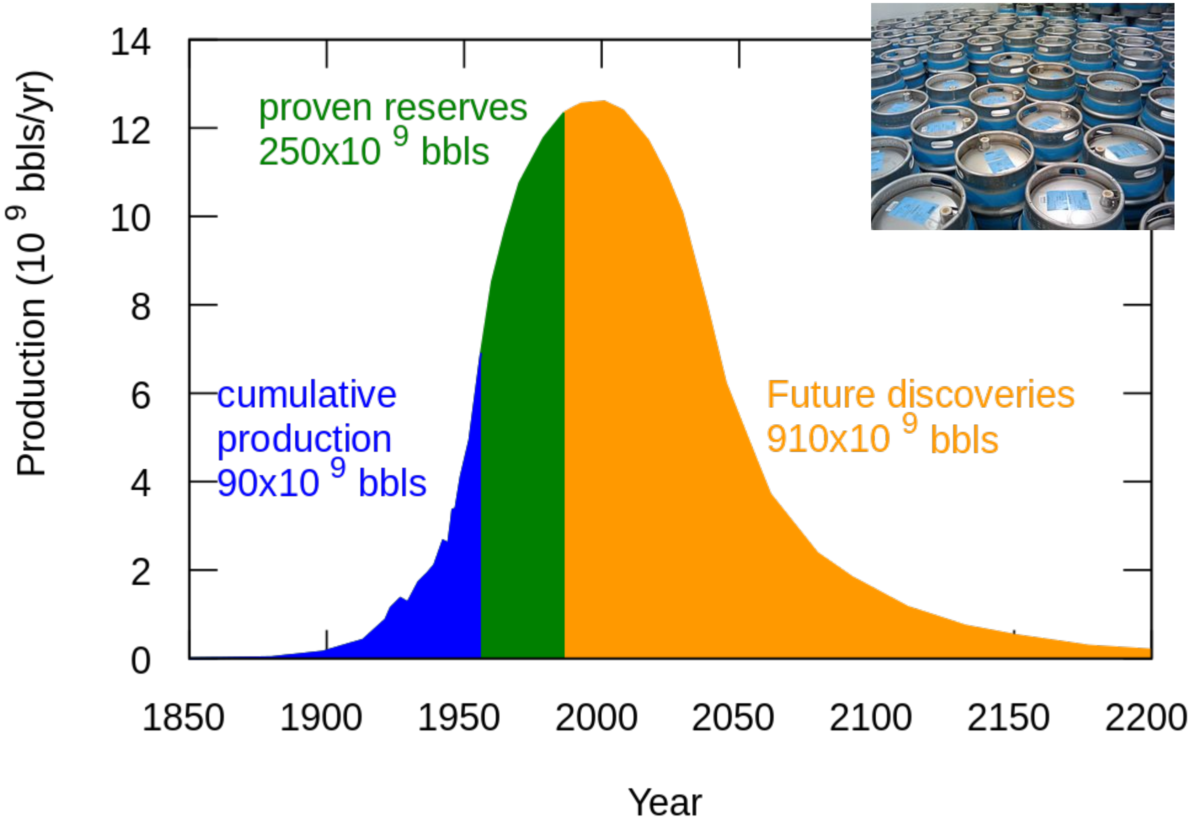
6th May 2019

**1956** M. King Hubbert predicted that oil production in US lower 48 states would peak in the early 1970s




**There is something worse than finishing the supply of fossil fuels….**

**ENVIRONMENTAL IMPACT**
***Umweltbelastung***

**human health and wellbeing**
***menschliche Gesundheit und Wohlbefinden***

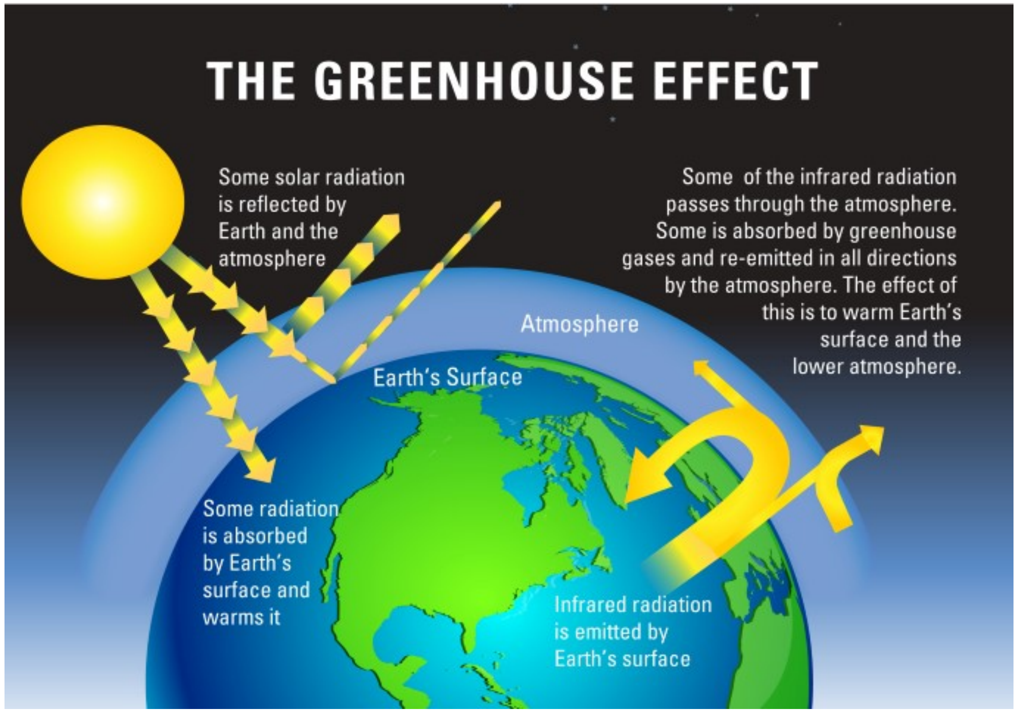
2016, the world's oil production was 29.4 billion barrels per year (80.6 Mbbl/day)

bp

*BP (British Petroleum company) Statistical Review of World Energy 2016*
*50 years of both oil and natural gas remaining, 115 years of coil production*

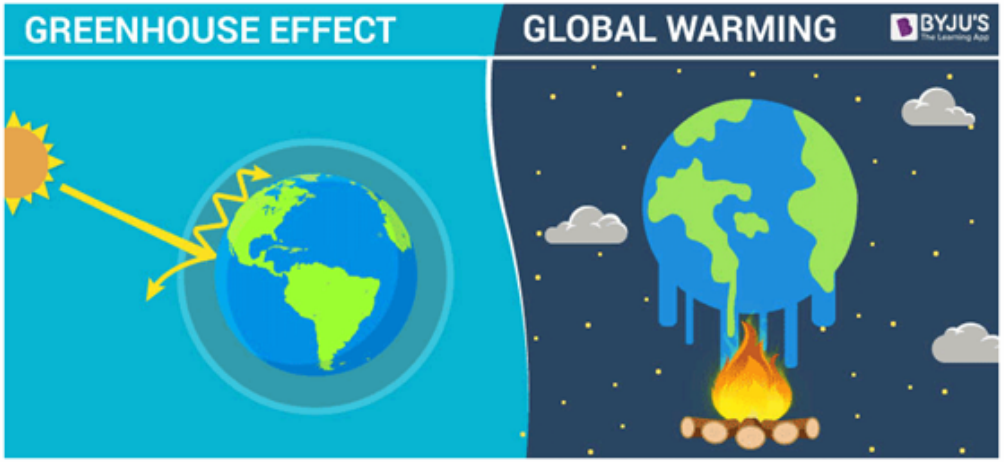
https://en.wikipedia.org/wiki/Peak_oil
https://www.bp.com/en/global/corporate/energy-economics/statistical-review-of-world-energy/downloads.html

## Negative impact of fossil fuels on the environment:




- Air pollution by burning fossil fuels:

- Carbon dioxide $CO_2$, huge contributor to the greenhouse effect, sulfur dioxide and nitrogen oxides emissions contribute to acid rain and formation of harmful particulate matter…




Smog can burn lung tissue and can make people more susceptible to asthma, bronchitis, and other chronic respiratory diseases, premature death due to cancer and respiratory diseases.

# Negative impact of fossil fuels on the environment:

- **Extracting fossil fuels** (e.g. coal mining, fracking...)

  - Surface mining involves removing **overlaying soils devastating local environments**

  - Mines can collapse or gradually subside, **affecting surface and subsurface water flows**

  - Job site accidents, coal mining can lead to **chronic health disorders**. Black lung disease (pneumoconiosis) among coal miners

  - **When oil and gas are extracted, the water** that had been trapped in the geologic formation is brought to the surface. This "produced water" can carry with it naturally-occurring dissolved solids, heavy metals, hydrocarbons, and radioactive materials in concentrations that make it **unsuitable for human consumption and difficult to dispose of safely**

  - The ***full* global warming** impact of natural gas also includes **methane emissions** from drilling wells and pipeline transportation.

https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/hidden-cost-of-fossils

# Negative impact of fossil fuels on the environment:

- **Transporting fuel** can generate its own pollution, and increase the potential for catastrophic accidents.

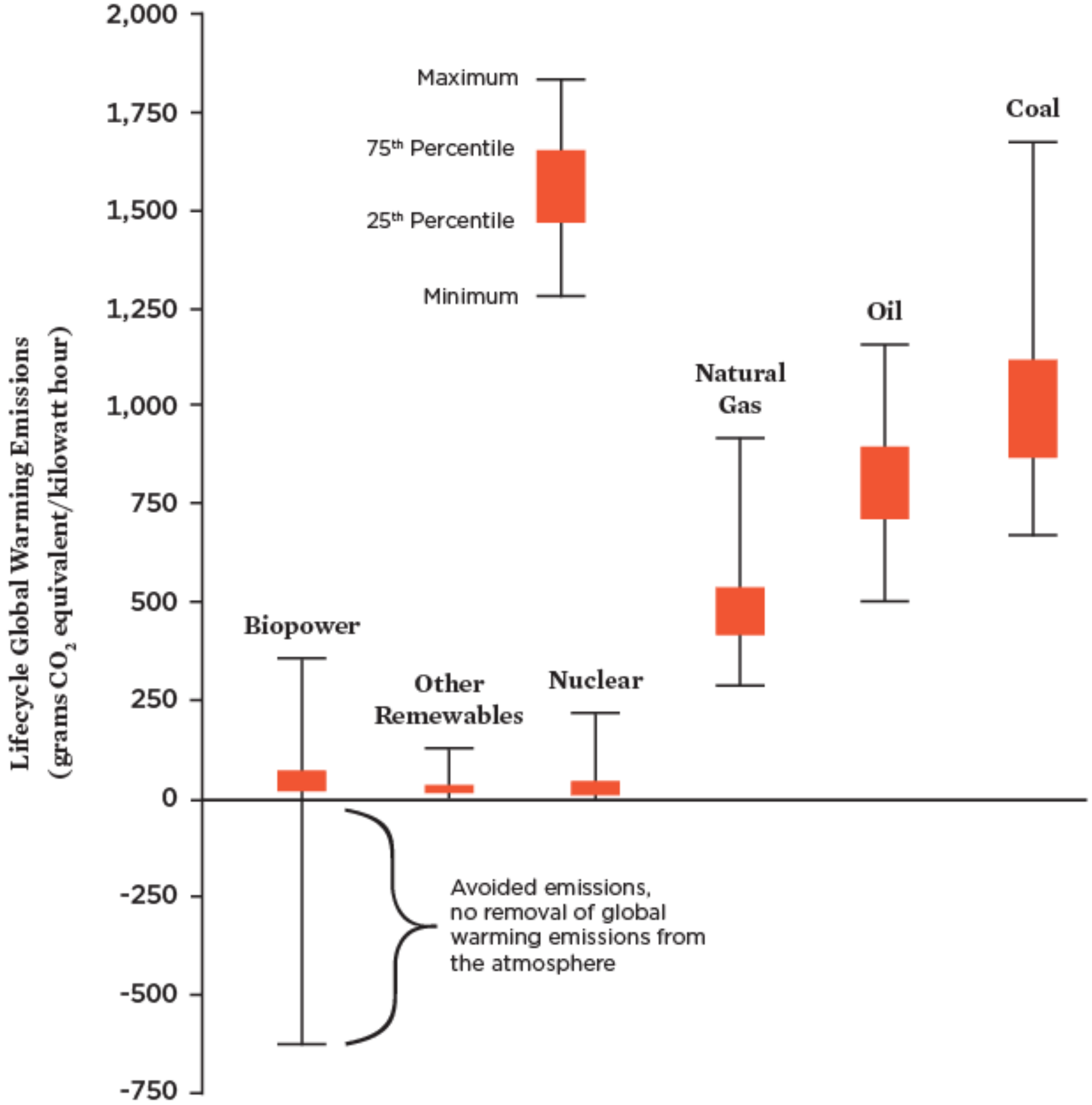
- Transporting coal can also produce **coal dust**, which presents serious **cardiovascular and respiratory risks** for communities near transportation routes

- **Natural gas leaks** from transmission and distribution pipelines are a significant source of **methane emissions**.

https://www.ucsusa.org/clean-energy/coal-and-other-fossil-fuels/hidden-cost-of-fossils

Non-fossil fuel energy generation technologies, like wind, solar, and geothermal, **contributed less than 1 percent of the total energy related global warming emissions.**

Comparing Global Warming Emissions of Energy Sources



## Disadvantages of nuclear power

- **Waste is radioactive** and safe disposal is very difficult and expensive.

The waste from nuclear energy is extremely dangerous and it has to be carefully looked after **for several thousand years** (10'000 years according to United States Environmental Protection Agency standards).

- Despite a generally high security standard, **accidents** can still happen.

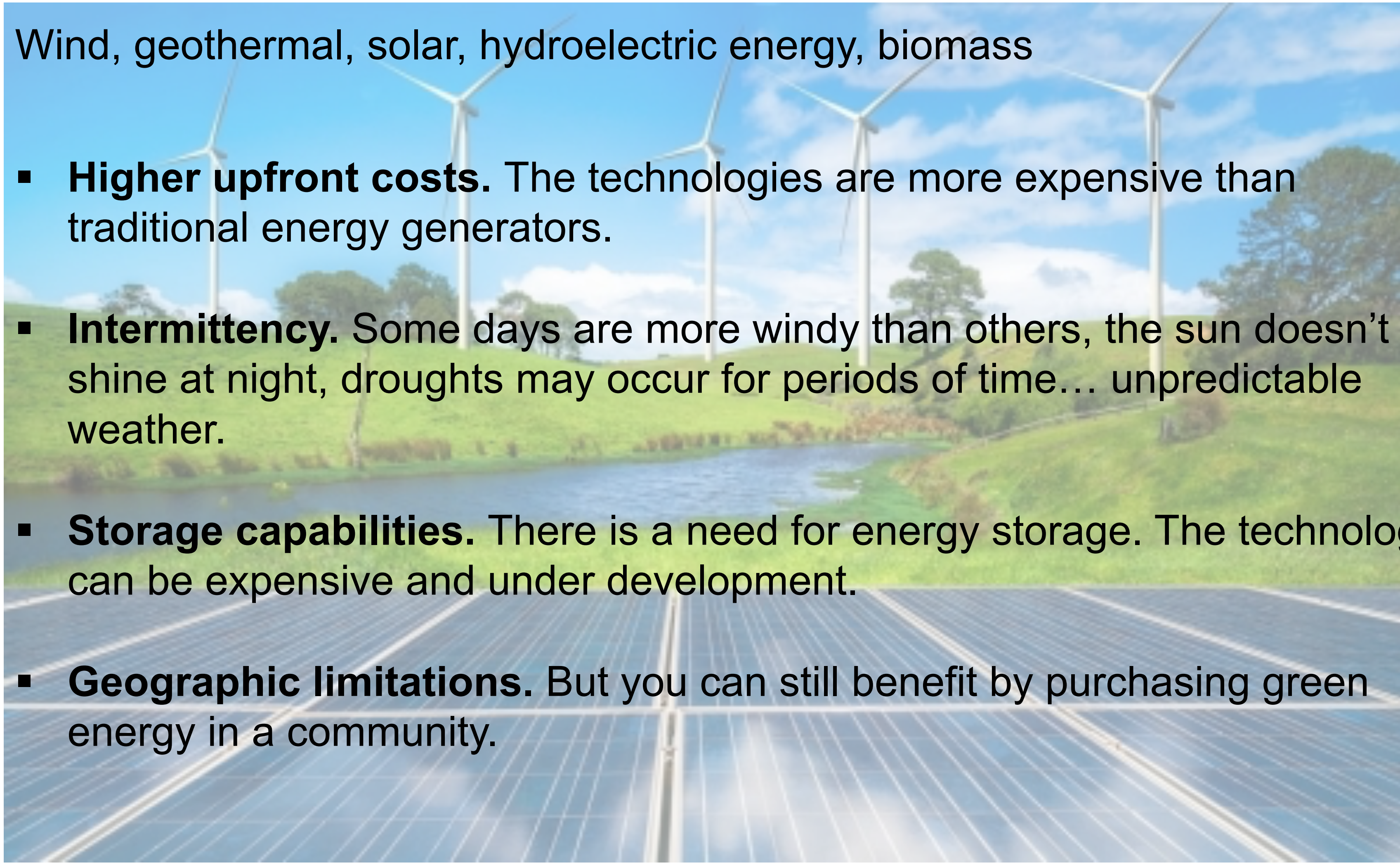
- Nuclear power plants as well as nuclear waste could be preferred **targets for terrorist attacks.**

- The energy source for nuclear energy is **Uranium**. Uranium is a scarce resource, its supply is estimated to last only **for the next 30 to 60 years** depending on the actual demand.

- The time frame needed for formalities, **planning and building of a new nuclear power generation plant is in the range of 20 to 30 years** in the western democracies.

https://timeforchange.org/pros-and-cons-of-nuclear-power-and-sustainability

## General disadvantages of renewable energy

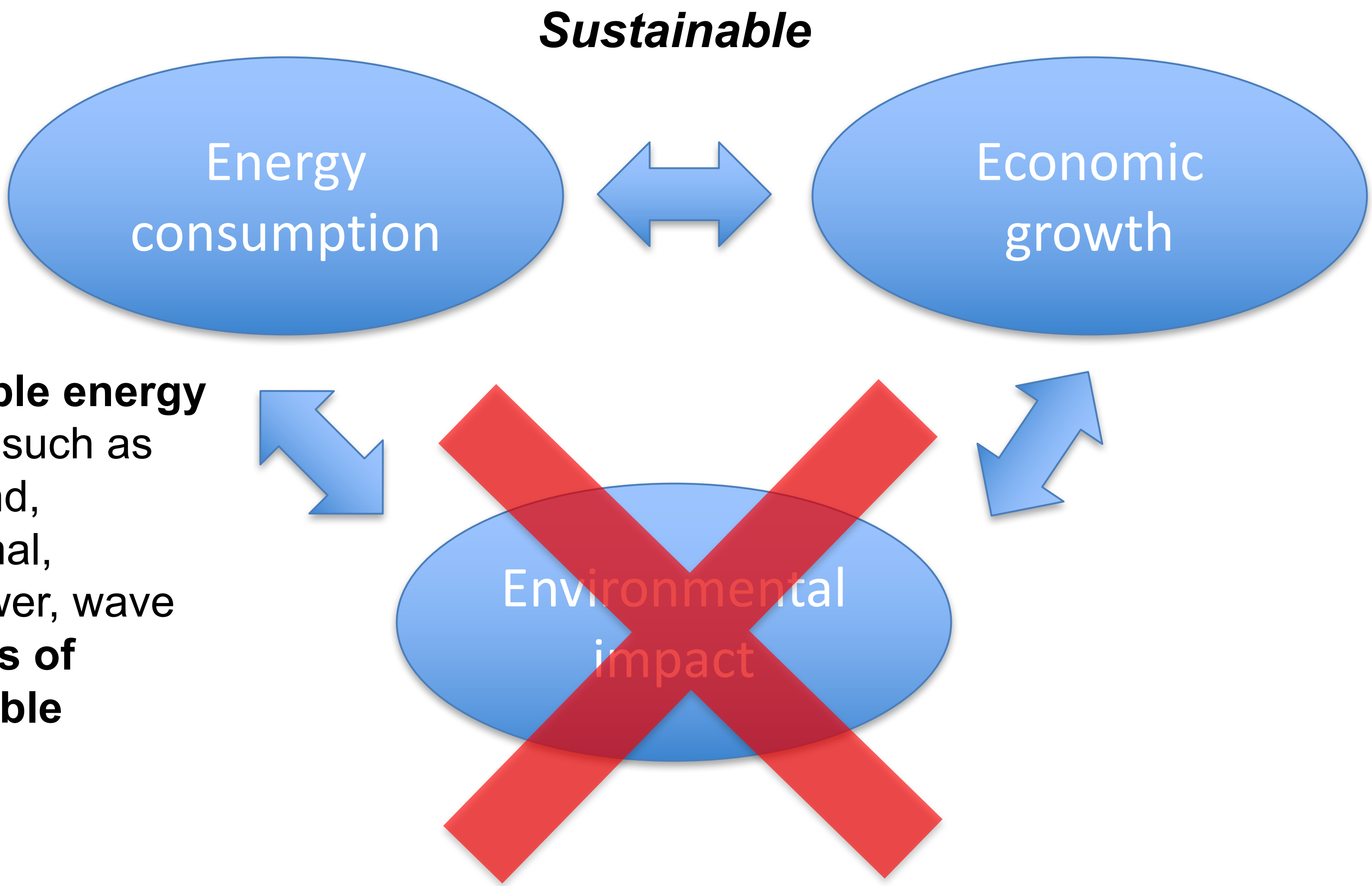


Wind, geothermal, solar, hydroelectric energy, biomass

- **Higher upfront costs.** The technologies are more expensive than traditional energy generators.
- **Intermittency.** Some days are more windy than others, the sun doesn't shine at night, droughts may occur for periods of time… unpredictable weather.
- **Storage capabilities.** There is a need for energy storage. The technology can be expensive and under development.
- **Geographic limitations.** But you can still benefit by purchasing green energy in a community.

https://news.energysage.com/advantages-and-disadvantages-of-renewable-energy/

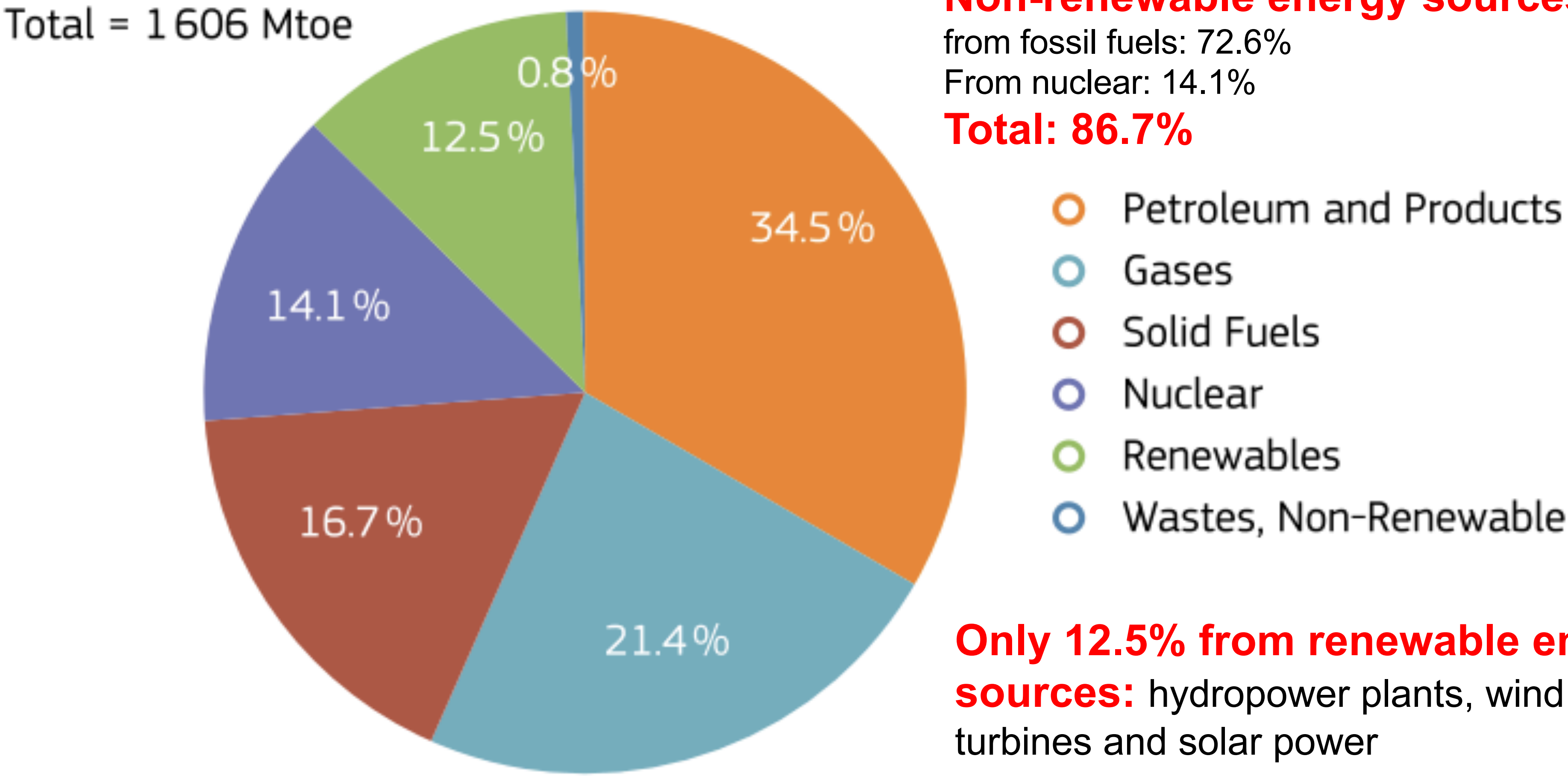
**Dilemma:**




**Renewable energy sources** such as solar, wind, geothermal, hydropower, wave **are forms of sustainable energy**

*Sustainable development* is *development* that meets the needs of the present without compromising the ability of future generations to meet their own needs universität innsbruck

# GROSS INLAND CONSUMPTION – BY FUEL – EU-28 – 2014 (% TOTAL)



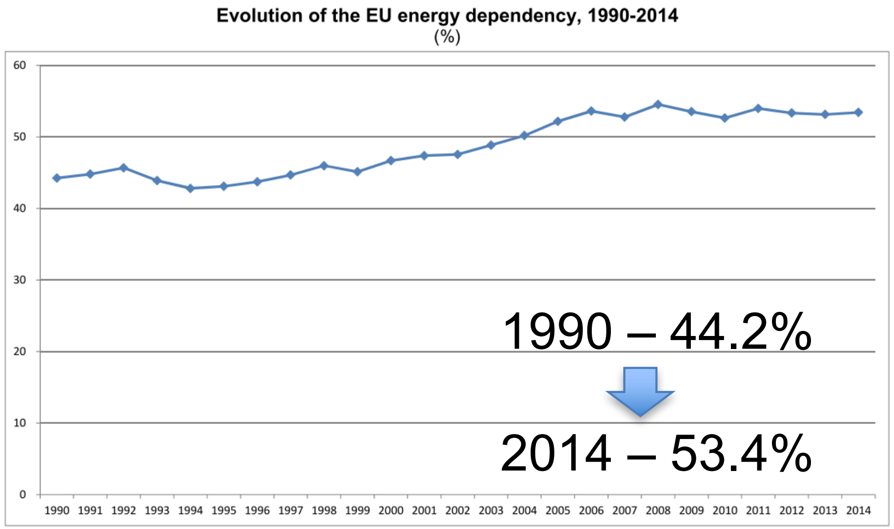

**Non-renewable energy sources...**
from fossil fuels: 72.6%
From nuclear: 14.1%
**Total: 86.7%**

**Only 12.5% from renewable energy sources:** hydropower plants, wind turbines and solar power

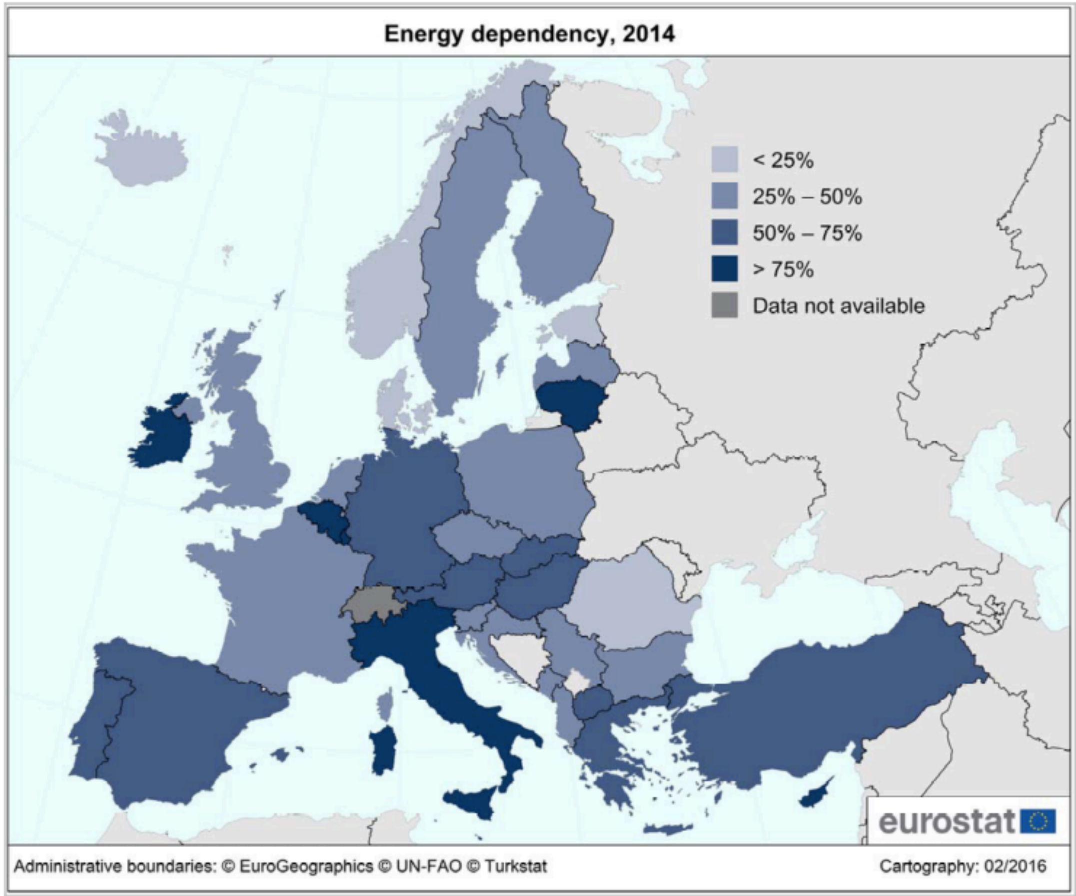
Mtoe: millions of tones of oil equivalent, energy released by burning one tonne of crude oil, ~ 42 Gigajoules

European Commission, EU energy in figures. Statistical pocketbook., 2016. doi:10.2832/91509.

✓ The energy dependency of the European Union (EU) stood **in 2014 at 53.4%**. EU needed to **import half of the energy it consumed** in 2014!




**The EU imports:**
90% of its crude oil
66% of its natural gas
42% of its coal and other solid fuels
40% of its uranium and other nuclear fuels.




**Austria: 65.4 %**
Germany 61.4%, France: 46.1%, Italy: 75.9%
Estonia: 8.9%, Denmark: 12.8%, Romania: 17%

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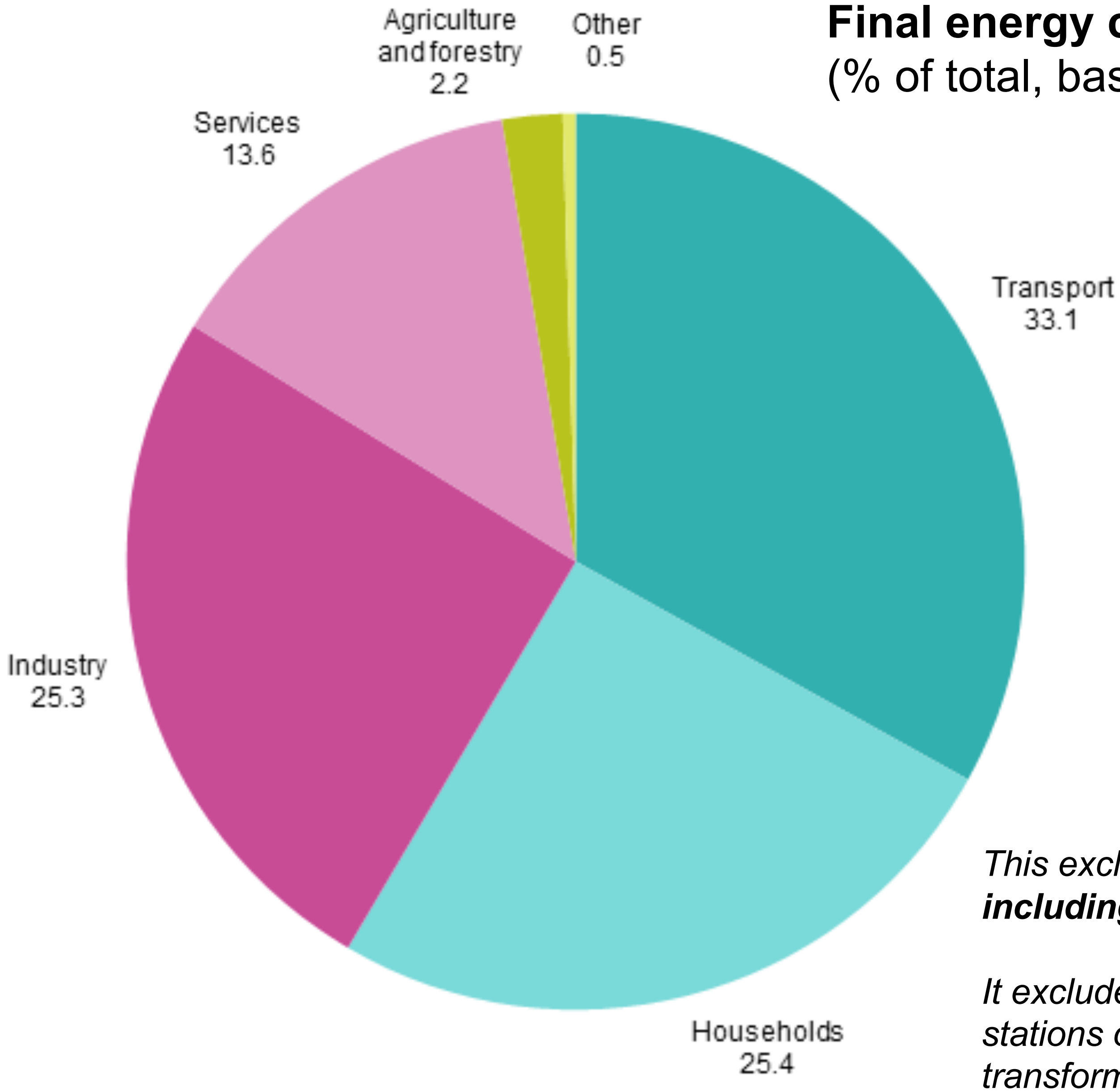
Eurostat Press Office, The EU was dependent on energy imports for slightly over half of its consumption in 2014, Eurostat. (2016) 1–4.

# Final energy consumption, EU-28, 2015
(% of total, based on tonnes of oil equivalent)




Note: figures do not sum to 100.0 % due to rounding.
*Source:* Eurostat (online data code: nrg_100a)

Transport 33.1%

Households 25.4 %

Industry 25.3 %

Services 13.6 %

Agriculture and forestry 2.2 %

Other 0.5 %

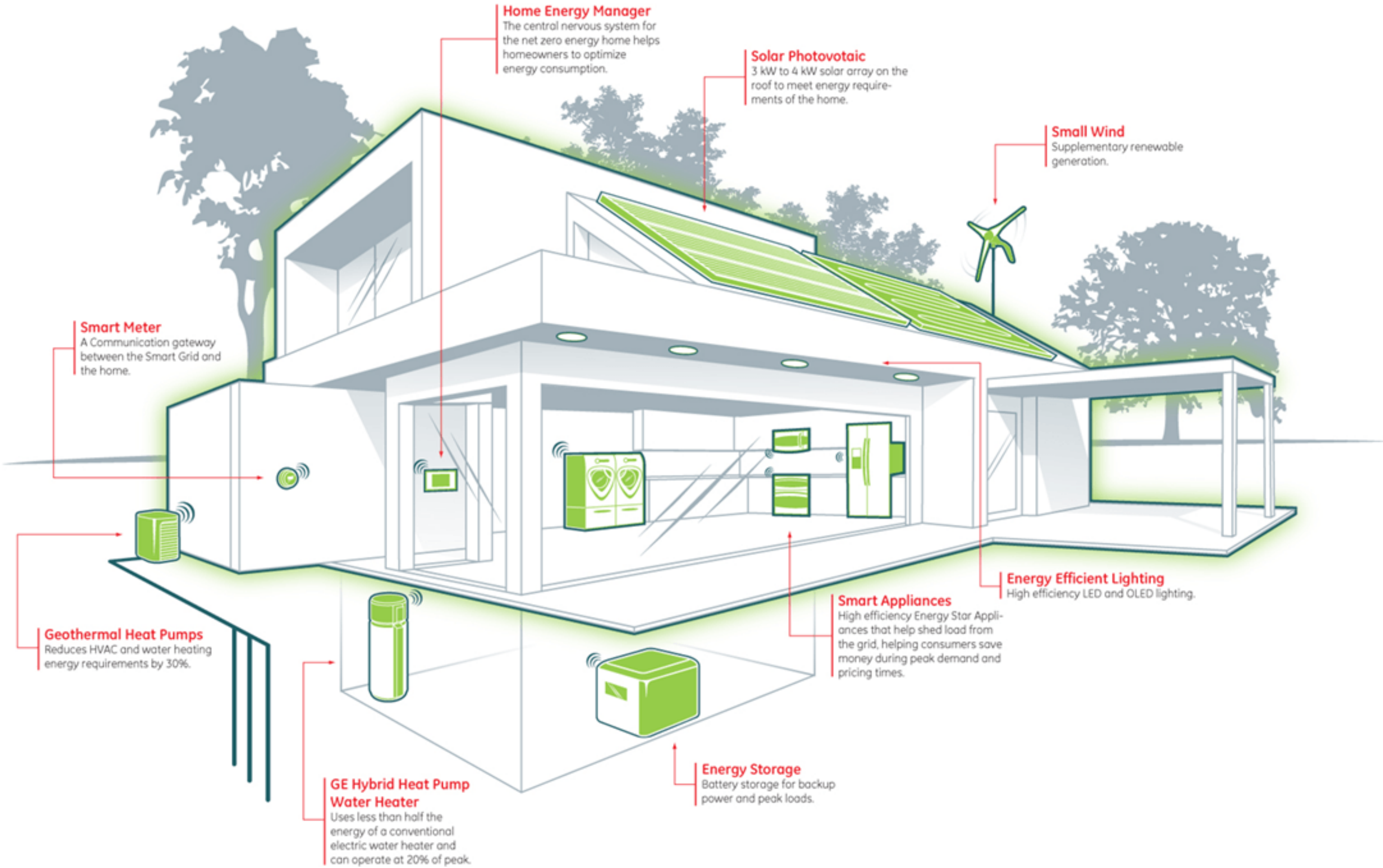
*This excludes energy used by **the energy sector, including for deliveries, and transformation.***

*It excludes fuel transformed in the electrical power stations of industrial auto-producers and coke transformed into blast-furnace gas where this is not part of overall industrial consumption but of the transformation sector.*

# Electric cars

- EU commission: $CO_2$ emissions from new cars should be cut by 30% by 2030.
- Expensive
- They require charging stations
- Recharging batteries takes about 3 hours
- Autonomy on traveling long distances (200 km on average)
- Lack of power (behind gas powered vehicles in their ability to accelerate)
- Safety concerns (thermal runaway casing fire and explosion depending on the material used).

# Zero net energy buildings




The Energy Performance of Buildings Directive requires all new buildings in the EU to be nearly zero-energy by the end of 2020. All new public buildings must be nearly zero-energy by 2018. https://ec.europa.eu/energy/en/topics/energy-efficiency/energy-performance-of-buildings/nearly-zero-energy-buildings https://www.lgc.org/newsletter/zero-net-energy-hub/

**There is only one solution….**

# To reduce the energy consumption!

- The EU has pledged to cut its energy consumption by **20%** (compared with projected levels) by 2020
- The level of EU-28 energy consumption in 2015 was 11.6 % lower than its previous peak of 1 840 Mtoe recorded in 2006, equivalent to an average reduction of 1.4 % per annum
- The number of inhabitants living in the EU-28 increased by 33.3 million persons.

**Gross Inland energy consumption**: the quantity of energy necessary to satisfy inland consumption (2015)

**Germany 19.6%**
**France 15.5%**
**UK 11.7%**
**Italy 10.7%**

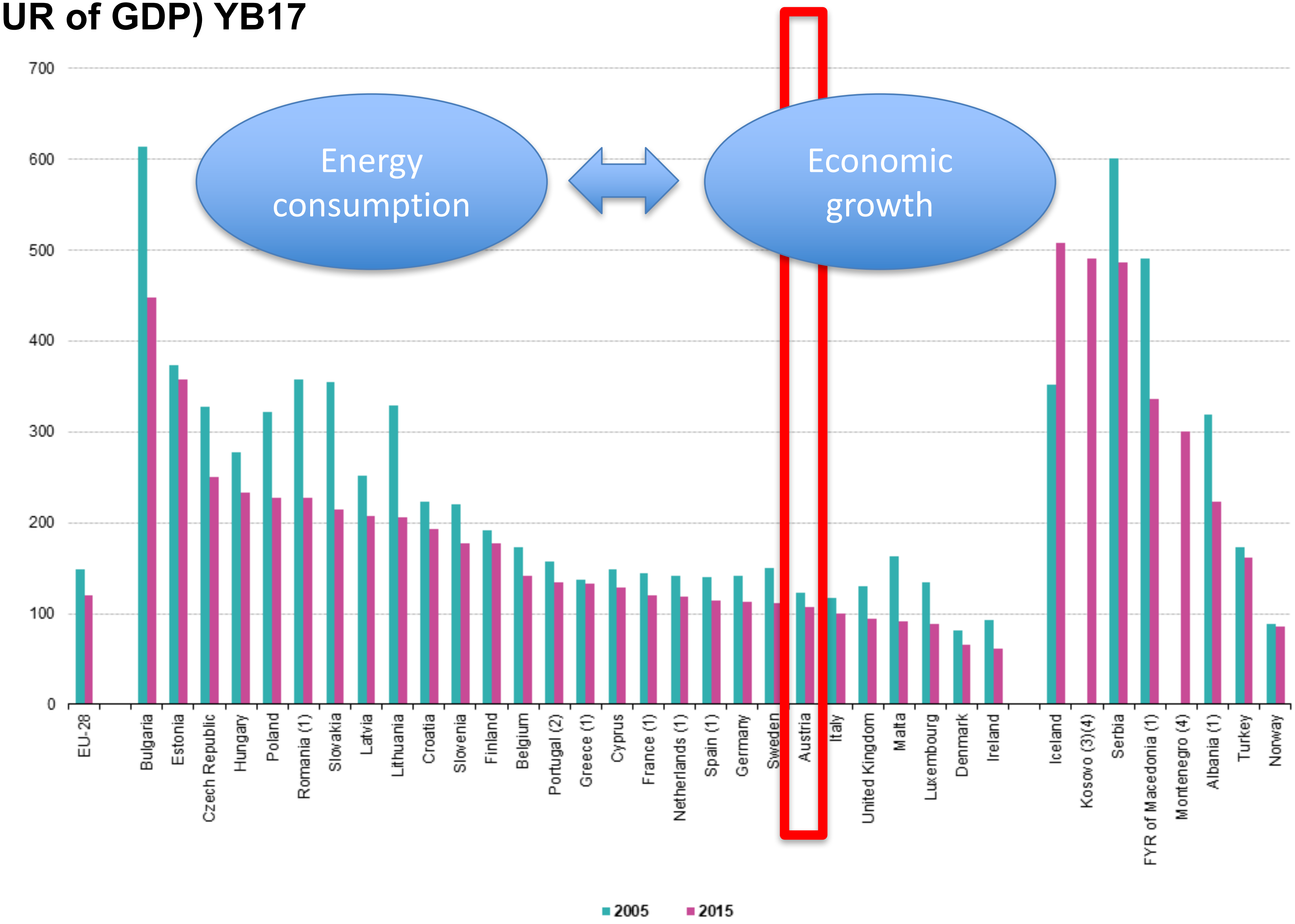
**Austria 2.5%**

| | 1990 | 1995 | 2000 | 2005 | 2010 | 2011 | 2012 | 2013 | 2014 | 2015 | Share in EU-28, 2015 (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| EU-28 | 1 085.0 | 1 082.8 | 1 132.9 | 1 192.3 | 1 164.5 | 1 107.2 | 1 108.0 | 1 107.6 | 1 061.7 | 1 084.0 | 100.0 |
| Belgium | 31.5 | 34.3 | 37.5 | 36.6 | 37.6 | 35.0 | 35.1 | 36.4 | 34.2 | 35.8 | 3.3 |
| Bulgaria | 16.4 | 11.4 | 9.1 | 10.2 | 8.8 | 9.3 | 9.2 | 8.8 | 9.0 | 9.5 | 0.9 |
| Czech Republic | 32.7 | 26.3 | 25.1 | 26.3 | 25.4 | 24.6 | 24.5 | 24.3 | 23.6 | 24.2 | 2.2 |
| Denmark | 13.5 | 14.8 | 14.7 | 15.5 | 15.5 | 14.8 | 14.2 | 14.1 | 13.5 | 13.9 | 1.3 |
| Germany | 228.9 | 221.6 | 220.0 | 218.5 | 219.7 | 208.8 | 212.1 | 217.7 | 208.9 | 212.1 | 19.6 |
| Estonia | 5.7 | 2.6 | 2.4 | 2.9 | 2.9 | 2.8 | 2.9 | 2.9 | 2.8 | 2.8 | 0.3 |
| Ireland | 7.3 | 8.0 | 10.8 | 12.6 | 12.0 | 10.9 | 10.6 | 10.7 | 10.8 | 11.2 | 1.0 |
| Greece | 14.7 | 15.8 | 18.7 | 21.0 | 19.0 | 18.9 | 17.0 | 15.3 | 15.5 | 16.5 | 1.5 |
| Spain | 57.1 | 64.0 | 79.9 | 97.8 | 89.1 | 86.7 | 83.2 | 80.8 | 79.2 | 80.5 | 7.4 |
| France | 136.2 | 143.5 | 155.3 | 160.8 | 155.3 | 143.8 | 148.5 | 151.2 | 140.3 | 144.1 | 13.3 |
| Croatia | 6.5 | 5.3 | 6.0 | 7.2 | 7.2 | 7.0 | 6.7 | 6.6 | 6.2 | 6.6 | 0.6 |
| Italy | 107.7 | 114.6 | 124.7 | 137.2 | 128.5 | 123.1 | 121.8 | 118.5 | 113.3 | 116.4 | 10.7 |
| Cyprus | 1.1 | 1.4 | 1.6 | 1.8 | 1.9 | 1.9 | 1.8 | 1.6 | 1.6 | 1.7 | 0.2 |
| Latvia | 6.4 | 3.8 | 3.3 | 4.0 | 4.1 | 3.9 | 4.0 | 3.9 | 3.9 | 3.8 | 0.3 |
| Lithuania | 9.7 | 4.6 | 3.8 | 4.7 | 4.8 | 4.8 | 4.9 | 4.8 | 4.9 | 4.9 | 0.4 |
| Luxembourg | 3.3 | 3.1 | 3.5 | 4.5 | 4.3 | 4.3 | 4.2 | 4.1 | 4.0 | 4.0 | 0.4 |
| Hungary | 19.9 | 16.2 | 16.1 | 18.2 | 17.4 | 17.5 | 16.5 | 16.6 | 16.2 | 17.3 | 1.6 |
| Malta | 0.3 | 0.5 | 0.4 | 0.4 | 0.5 | 0.5 | 0.5 | 0.5 | 0.5 | 0.6 | 0.1 |
| Netherlands | 45.5 | 51.0 | 52.3 | 54.2 | 55.1 | 51.6 | 51.5 | 51.6 | 47.3 | 48.5 | 4.5 |
| Austria | 19.3 | 21.4 | 23.7 | 27.8 | 28.2 | 27.2 | 27.1 | 28.0 | 26.7 | 27.4 | 2.5 |
| Poland | 59.9 | 62.9 | 55.2 | 58.5 | 66.3 | 64.7 | 64.4 | 63.3 | 61.6 | 62.3 | 5.7 |
| Portugal | 11.9 | 13.9 | 17.9 | 19.0 | 18.1 | 17.3 | 16.0 | 15.9 | 15.8 | 16.0 | 1.5 |
| Romania | 40.8 | 27.0 | 22.8 | 24.7 | 22.6 | 22.8 | 22.8 | 21.8 | 21.7 | 21.9 | 2.0 |
| Slovenia | 3.7 | 4.1 | 4.5 | 4.9 | 5.0 | 5.0 | 4.9 | 4.8 | 4.6 | 4.7 | 0.4 |
| Slovakia | 15.2 | 11.0 | 11.0 | 11.6 | 11.5 | 10.8 | 10.3 | 10.6 | 10.0 | 10.1 | 0.9 |
| Finland | 21.7 | 22.0 | 24.3 | 25.2 | 26.2 | 25.0 | 25.2 | 24.7 | 24.5 | 24.2 | 2.2 |
| Sweden | 31.2 | 35.1 | 35.0 | 33.7 | 34.1 | 32.4 | 32.4 | 31.6 | 31.2 | 31.8 | 2.9 |
| United Kingdom | 136.9 | 142.7 | 153.2 | 152.8 | 143.2 | 132.0 | 135.9 | 136.7 | 129.6 | 131.4 | 12.1 |
| Iceland | 1.4 | 1.5 | 1.9 | 2.0 | 2.6 | 2.7 | 2.7 | 2.9 | 2.9 | 3.1 | – |
| Norway | 16.1 | 16.9 | 18.1 | 18.6 | 19.6 | 18.7 | 18.8 | 19.0 | 18.5 | 18.7 | – |
| Montenegro | – | – | – | 0.8 | 0.7 | 0.7 | 0.7 | 0.7 | 0.6 | 0.7 | – |
| FYR of Macedonia | 1.4 | 1.5 | 1.6 | 1.7 | 1.8 | 1.9 | 1.9 | 1.8 | 1.8 | 1.9 | – |
| Albania | 1.9 | 0.9 | 1.5 | 1.9 | 1.9 | 2.0 | 1.9 | 2.0 | 2.1 | 2.0 | – |
| Serbia | 11.8 | 6.1 | 6.9 | 9.6 | 9.0 | 9.2 | 8.5 | 8.3 | 7.8 | 8.2 | – |
| Turkey | 38.7 | 45.2 | 56.2 | 63.5 | 74.1 | 78.8 | 84.2 | 82.0 | 85.9 | 93.2 | – |
| Bosnia and Herzegovina | *3.3* | *0.8* | *1.2* | *1.5* | *1.9* | *2.0* | *2.0* | *1.9* | *4.5* | : | – |
| Kosovo (¹) | – | – | 0.8 | 1.0 | 1.2 | 1.3 | 1.2 | 1.2 | 1.2 | 1.3 | – |

https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Archive:Consumption_of_energy

dependence.

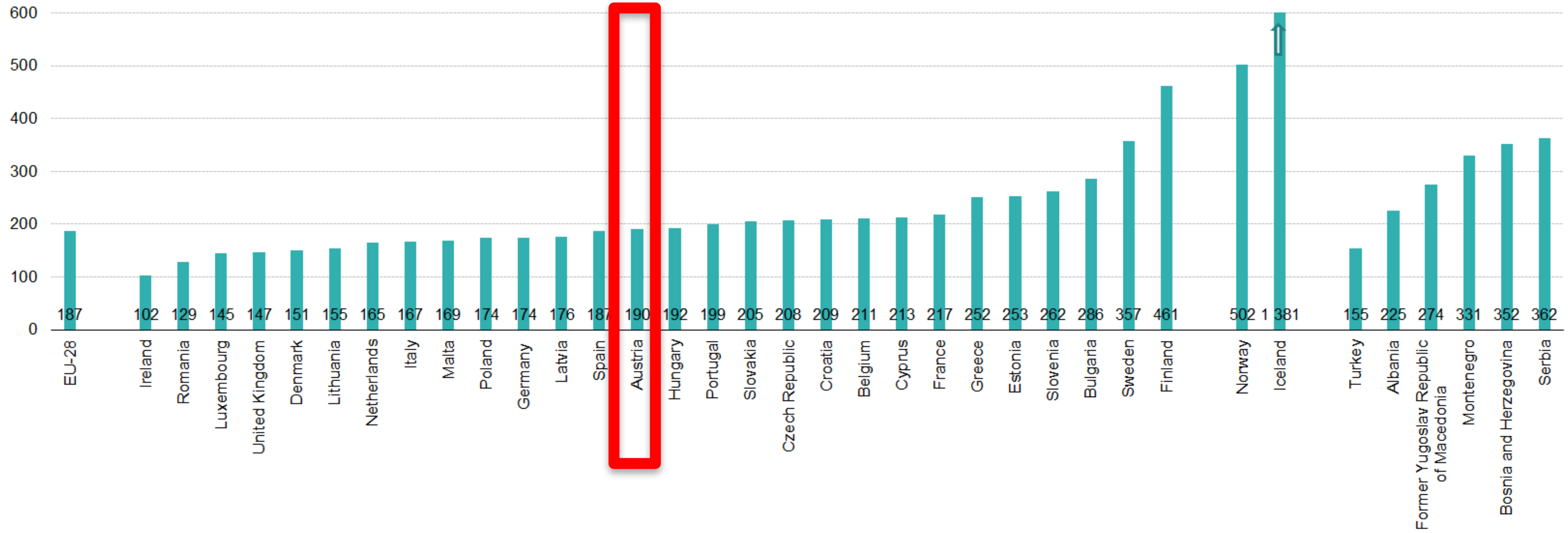
# Energy intensity of the economy, 2005 and 2015 (kg of oil equivalent per 1 000 EUR of GDP) YB17



# Energy consumption per capita

Electricity consumption per unit of GDP (Gross Domestic Product, using Purchasing Power Standards) in the **EU-28 in 2016 was 186.8 kWh per 1000 EUR** (Figure 7). The amount of electricity consumed per unit of GDP depends on many factors, starting from the general standard of living, the economy and weather conditions as well as energy efficiency of buildings and appliances. Using GDP in Purchasing Power Standards allows for better comparison across countries in one year.

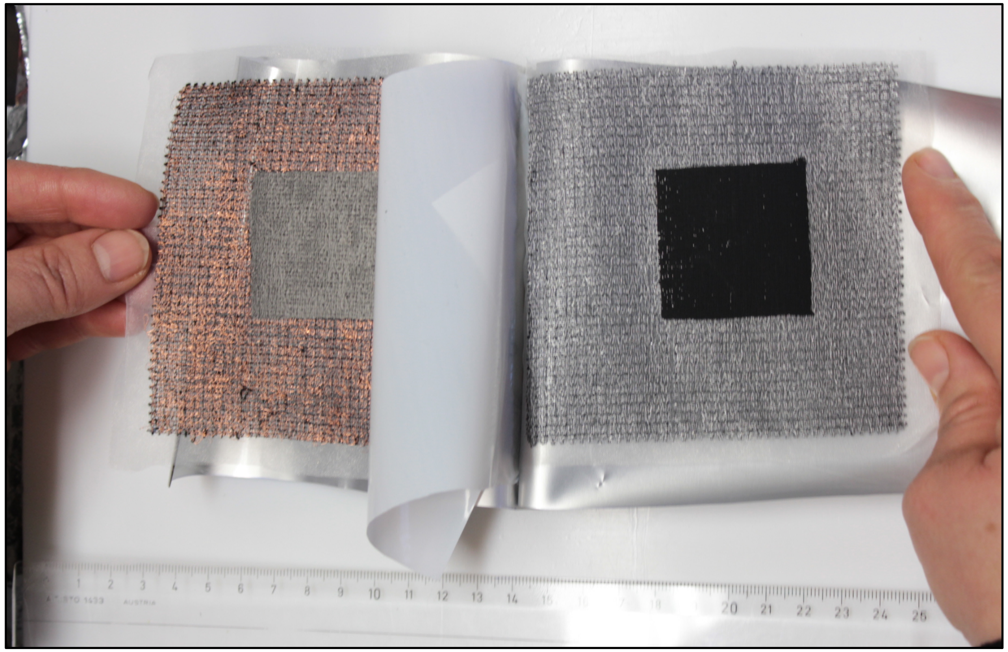
**Final consumption of electricity per GDP (PPS), kWh per 1000 EUR (PPS), 2016**



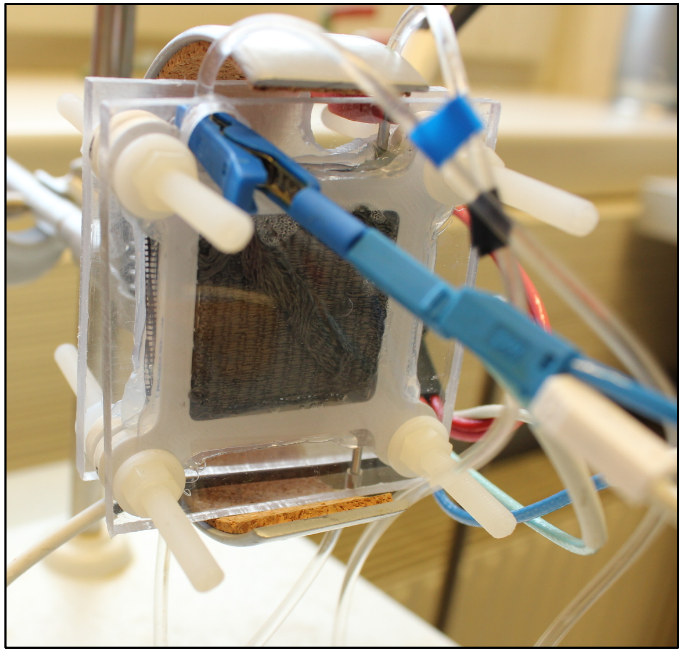

*Source:* Eurostat (online data code: nrg_105a, nama_10_gdp) universität innsbruck

# Textile structures in batteries

- Lithium-ion batteries



- Redox flow batteries



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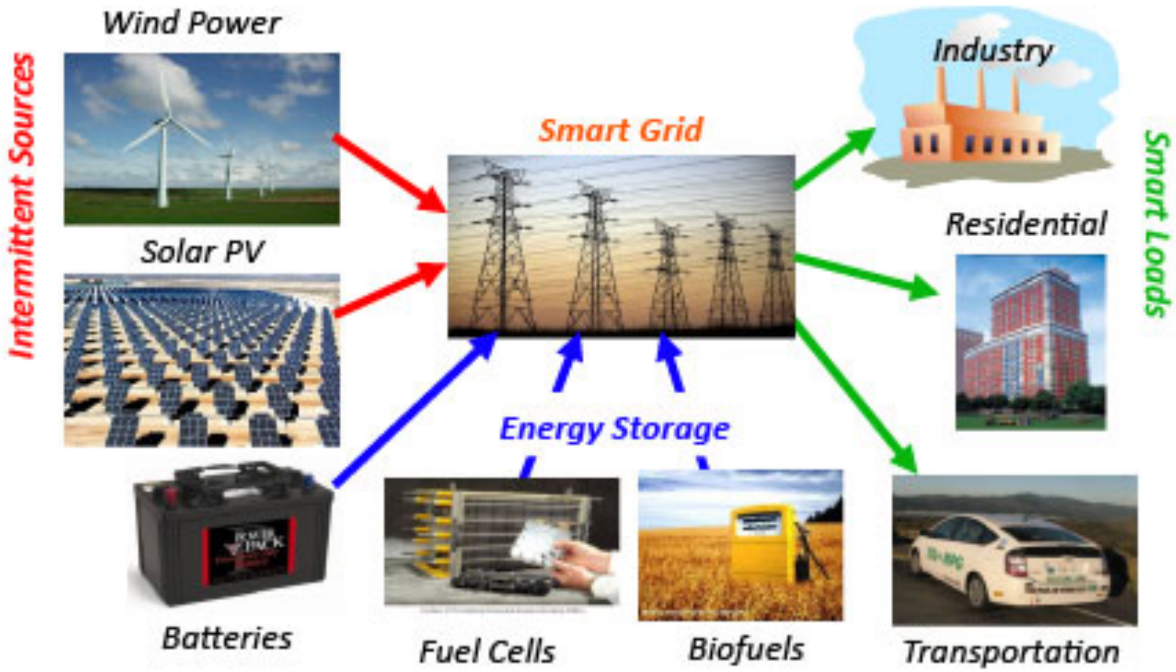
6th May 2019

➢ Replacing fossil-fuel electricity
➢ Storage systems supporting intermittent renewable energy sources

✓ **Different types depending on applications:** Electrochemical energy storage systems



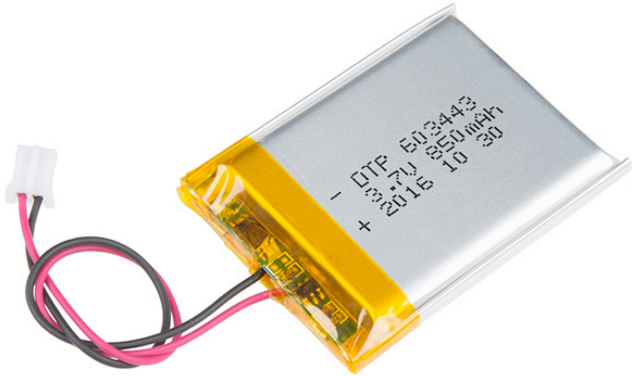

- automotive,
- stationary applications,
- portable electronic devices,

Depending on energy and power requirements…

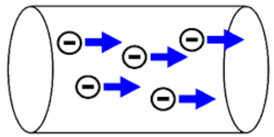
http://www.ntnu.edu/ima/research/electrochemistry/electrochemical-energy

# Electrochemical energy storage systems

e.g. Li-ion batteries




Chemical energy ⟷ Electrical energy



**How?**

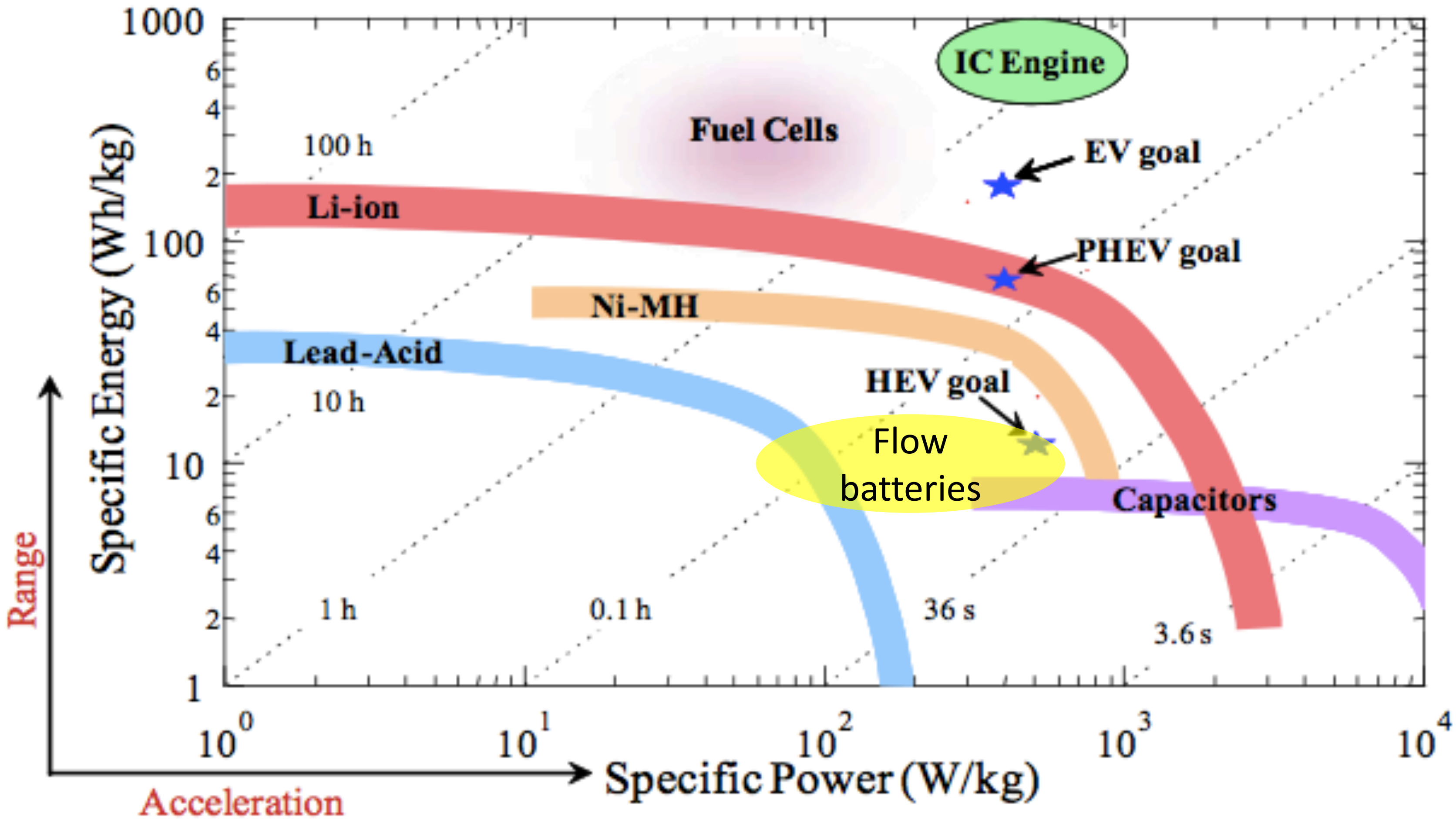
Chemical reactions where electrons are transferred into molecules/atoms the so-called reduction-oxidation reactions (redox reactions).

Oxidation: $Zn\ (s) \rightarrow Zn^{2+}(aq) + 2\ e^-$ ***loss of electrons***

Reduction: $Cu^{2+}\ (aq) + 2e^- \rightarrow Cu\ (s)$ ***gain of electrons***

# Electrochemical energy storage systems

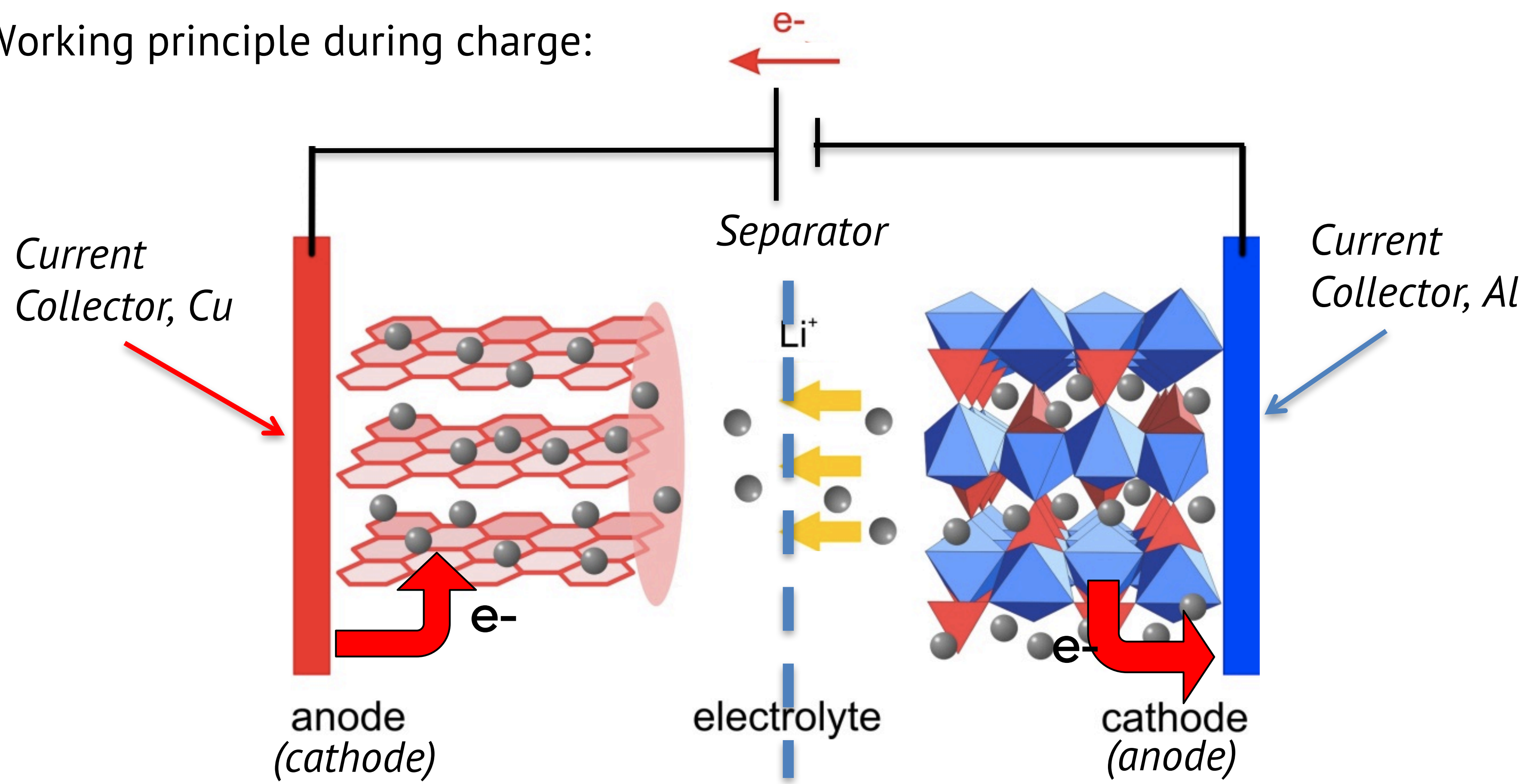
- Different types:




E.D. Wachsman, C. a Marlowe, K.T. Lee, Role of solid oxide fuel cells in a balanced energy strategy, Energy Environ. Sci. 5 (2012) 5498–5509

# Li-ion batteries: Background

Working principle during charge:




Reduction:

$6C + xLi^{+} + xe^{-} \rightarrow Li_{x}C_{6}$

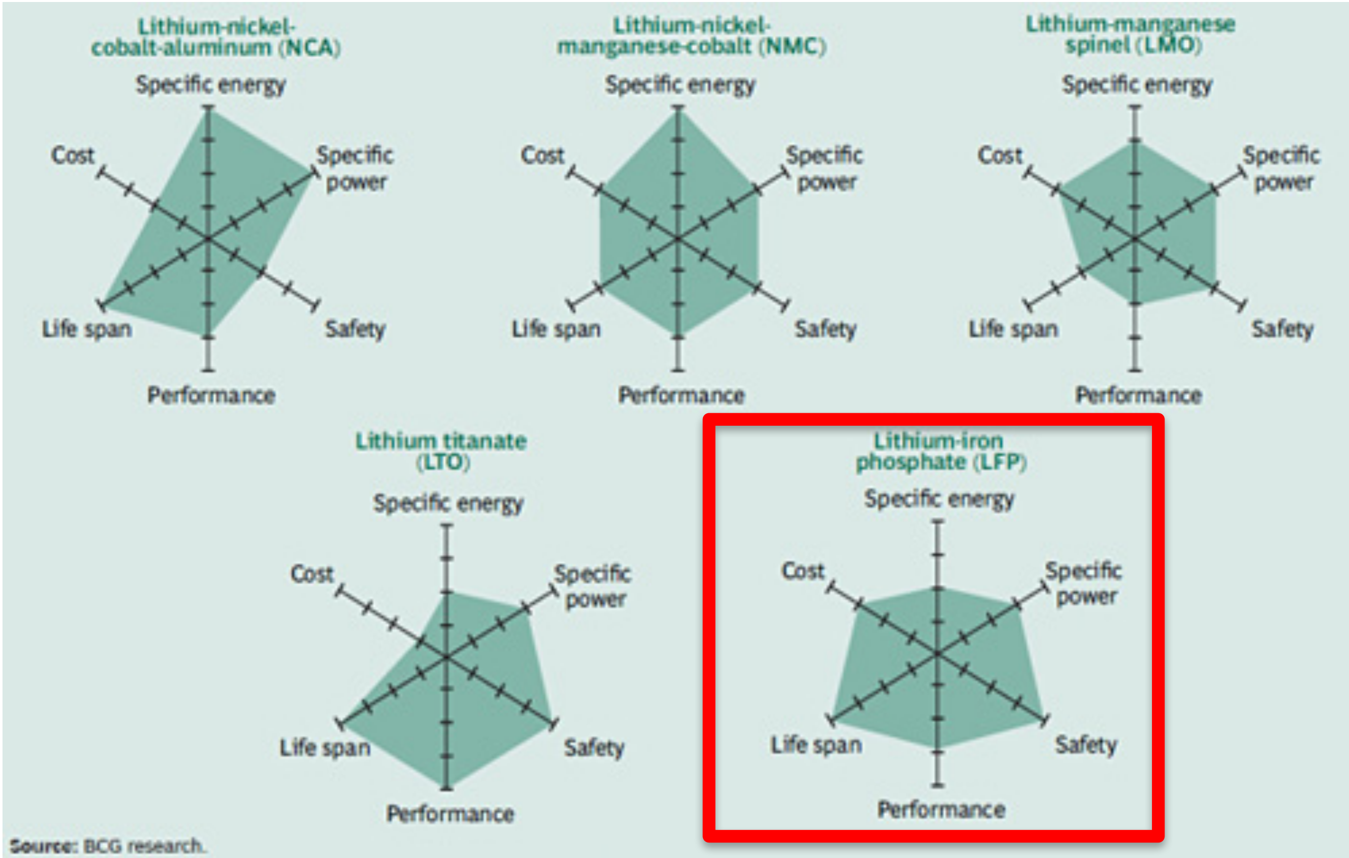
Oxidation: $Fe^{2+} \rightarrow Fe^{3+} + e^{-}$

$LiFePO_4 \rightarrow Li_{(1-x)}FePO_4 + xe^{-} + xLi^{+}$

# Li-ion batteries: Background

e.g. different types of lithium-ion batteries:

**Specific energy**
**Specific power**
Cost
Life span
Life cycles
Performance
Safety
Environmental impact
Technical maturity



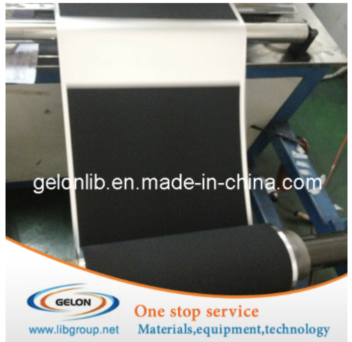

http://batteryuniversity.com/learn/archive/is_li_ion_the_solution_for_the_electric_vehicle

# Li-ion batteries: Two main problems

## 1) The trade-off between energy density and power density

- Poor electronic conductivity
- Poor mechanical stability

→ Thin layers of electrode material ~ 20-50 µm 2-7 mg $cm^{-2}$




## 2) High costs

130 Wh/kg, 247 Wh/L → In 2020: 235 Wh/kg, 500 Wh/L for battery EVs cost competitive

How to reduce costs?

- Improving battery performance
- Reducing material costs

→ Water-based solutions, also more environmentally-friendly!

224 €/kWh → < 150 €/kWh

- Electroactive material
- Conductive additive
- Binder
- Solvent

The typical binder and solvent:

- Binder: Poly(vinylidene fluoride) (PVDF)
- Solvent: N-methyl-2-pyrrolidone (NMP)

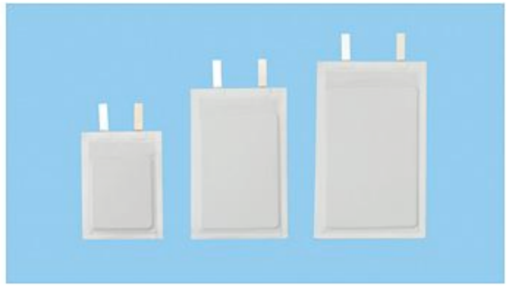
→ toxic and expensive!

# Li-ion batteries: Other problems

## Too rigid structure

130 Wh/kg
295 Wh/L

Flexible Lithium-ion Battery (CG-064065)



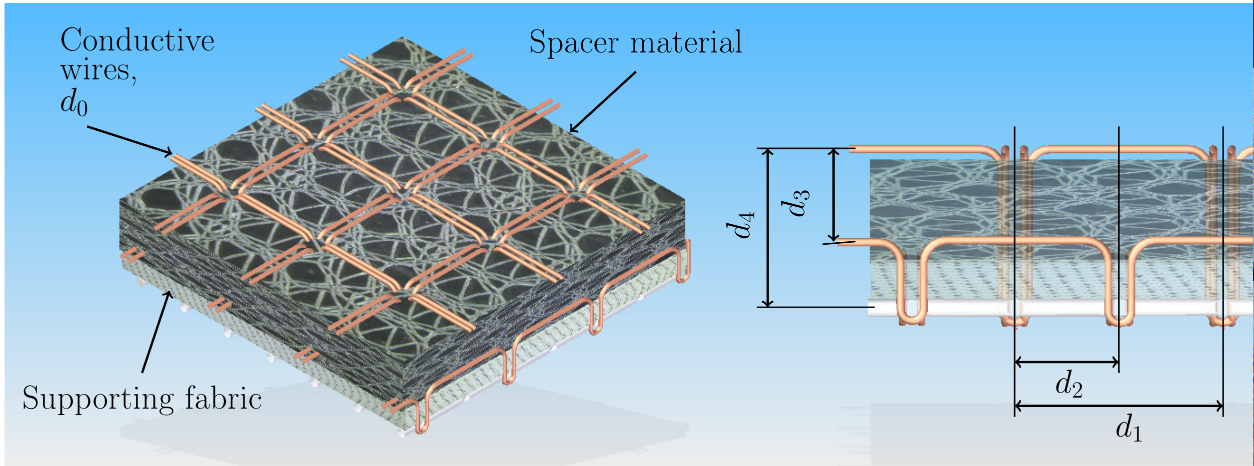
Flexible Lithium-ion Battery
(From the left, CG-062939, CG-063555, CG-064065)

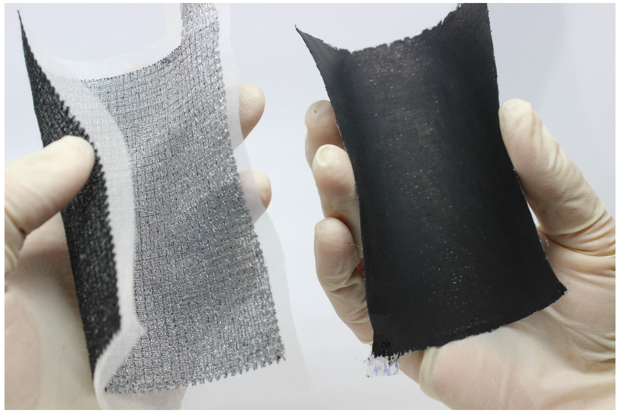
Nominal Capacity: 40 mAh
Weight: 1.4 g
Nominal voltage: 3.8 V
Thickness: 0.55 mm
Size: 35.0 mm x 55.0 mm

40 mAh * 3.8 V / 1.4 g = 109 Wh/kg
40 mAh*3.8 V / (0.05*3.5*5.5 $cm^3$) = 157 Wh/L

# Li-ion batteries: Our proposal

## 1) Embroidered current collectors → Thick electrodes

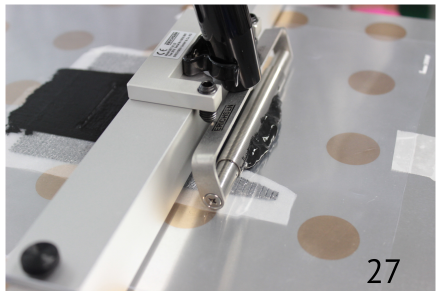


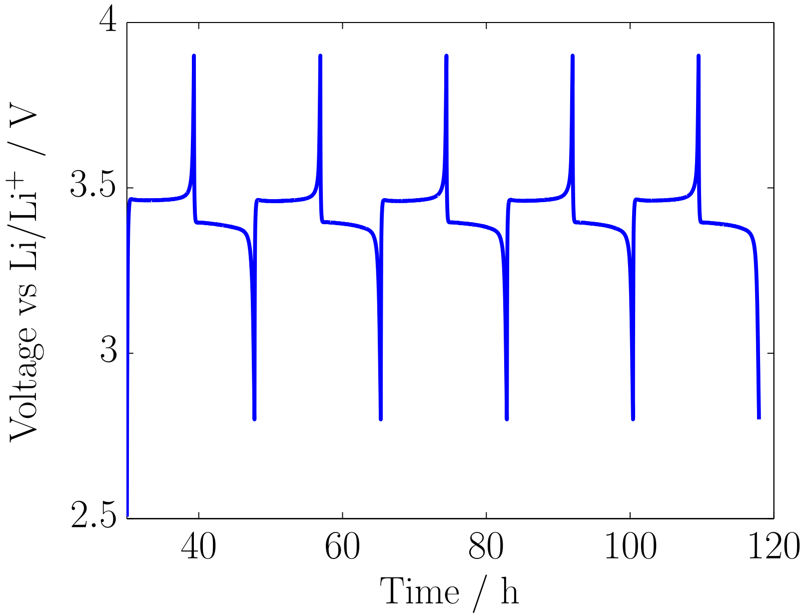



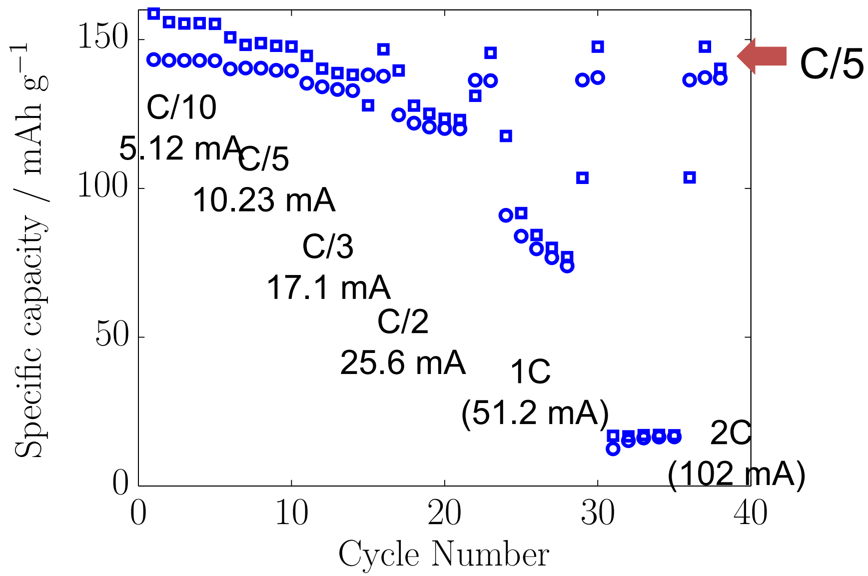
Open possibilities for:

- ✓ Better mechanical stability → larger amounts of electrode materials
- ✓ Improvement of the electrical and ionic conductivity → ease of electron transfer, ease ionic transport open macroporosity

**2) Water-based solutions:** optimization of water-based formulations for thick electrodes





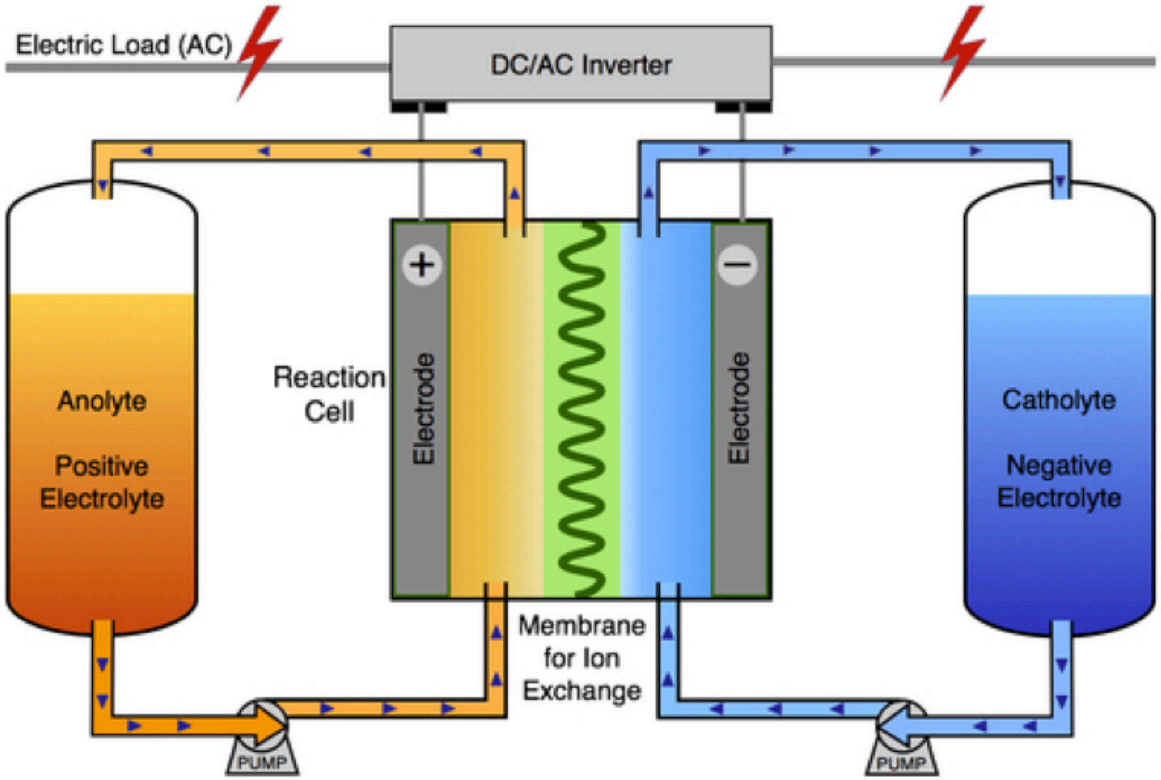




**Comparison of relevant technical parameters and specifications with systems on the market:**

| **Embroidered LFP electrodes** | **Conventional LFP electrodes** |
|---|---|
| Areal active mass loading: 20 mg/cm$^2$ | 5 mg/cm$^2$ |
| Active/total weight (em+cc): 55% **(1.5 times)** | 36% |
| Thickness: 360 μm (em+cc) | 30 μm (em) + 20 μm (cc) = 50 μm |
| Areal capacity: 3.4 mAh/cm2 (~4 times) | 0.85 mAh/cm$^2$ |
| Grav. capacity/energ.: 91 mAhg$^{-1}$/ **290 Whkg$^{-1}$** **(1.5 times)** | 60 mAhg$^{-1}$ / **192 Whkg$^{-1}$** (only electrode) |
| Vol. capacity/energ.: 94 mAhL$^{-1}$/ **302 WhL$^{-1}$** | 170 mAh/L / **544 WhL$^{-1}$** (only electrode) **(1.8 times)** |
| Water-based LFP slurries 150€/kwh | NMP-based LFP slurries 300-500€/kwh |
| Possibility to flexible high-energy batteries | Flexibility achieved by reducing energy densities |

# Redox flow batteries

- Principle:




- External tanks containing the electroactive material dissolved in a solution
- Independence of the energy capacity with power capability.
- Leading candidate for stationary energy storage.

https://www.solarchoice.net.au/blog/news/an-introduction-to-flow-batteries-030315

# Embroidered current collectors in redox flow batteries

Embroidered electrodes ⟷ carbon paper/carbon felt

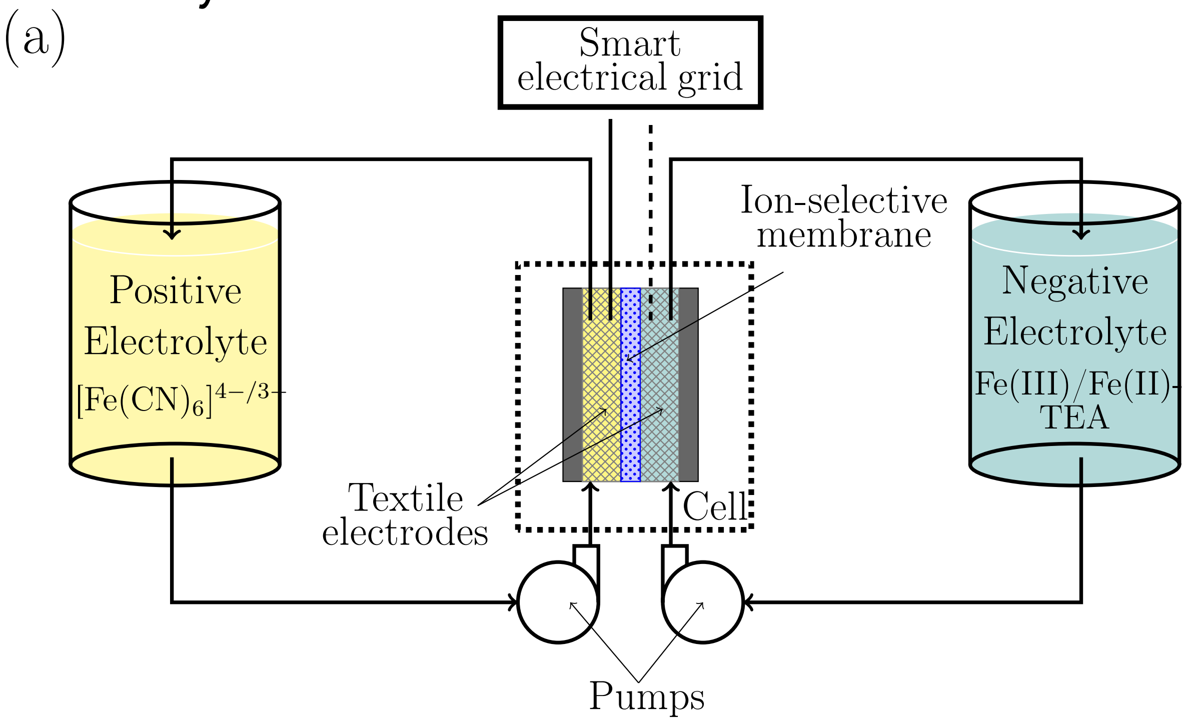
- High flexibility in selection of conductive materials.
- Controlled degree in porosity, real surface area of electrodes.
- Integration of non-conductive spacers to modulate flow dynamics.
- Electrode is also the current collector.

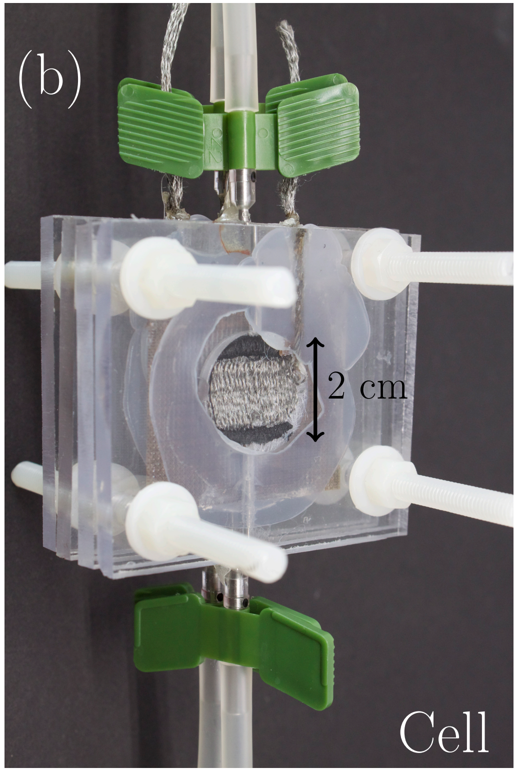
Froeis, T.; Lenninger, M.; Bechtold, T.; Grabher, G.; Hofer, J.; Riedmann, M. Electrode for a galvanic cell. WO2014028958 A1, February 27, 2014.

http://fuelcellstore.com
http://www.avcarb.com

# Embroidered current collectors in redox flow batteries

- Our system:




*During charge:*
$[Fe(CN)_6]^{4-} \rightarrow [Fe(CN)_6]^{3-} + e^-$

*During discharge:*
$[Fe(CN)_6]^{3-} + e^- \rightarrow [Fe(CN)_6]^{4-}$

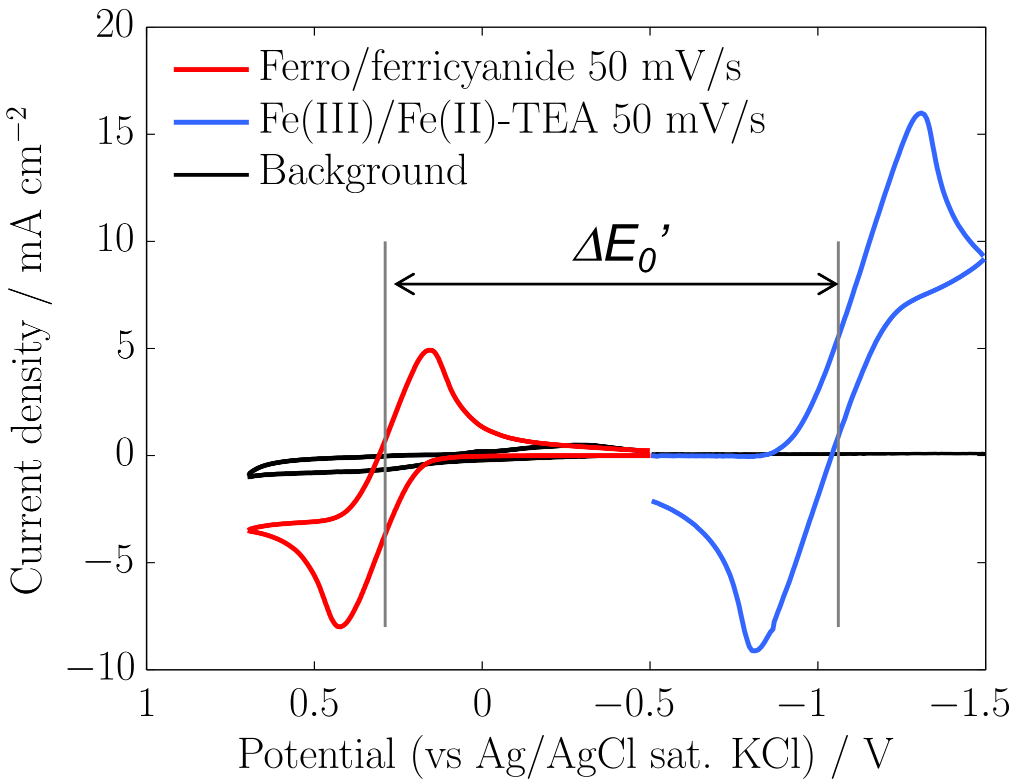
*During charge:*
$Fe(III)\text{-}TEA + e^- \rightarrow Fe(II)\text{-}TEA$

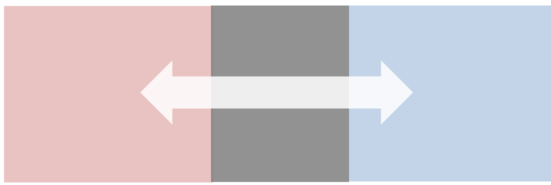
*During discharge:*
$Fe(II)\text{-}TEA \rightarrow Fe(III)\text{-}TEA + e^-$

FWF Hertha-Firnberg FWF project https://www.uibk.ac.at/textilchemie/embelred/news/

Der Wissenschaftsfonds.

# Embroidered current collectors in redox flow batteries




- ✓ Why $Fe^{2+}/Fe^{3+}$ system? **non-toxic**, reaction involves **colour change (monitoring state-of-charge).**
- ✓ **High potential** in desirable potential window, $\Delta E_0'$=1350 mV.
- ✓ Further electrolytes will be investigated → **Fe rich in family of complexes.**
- ✓ In redox flow batteries dynamic situation: similar pH is required, equilibrium, heterogeneous rate constants are pH, C dependent → worthy to be investigated

Thank you for your attention!!

Questions?