

Politecnico di Torino
Torino, Italy



Energy conversion and storage: focus on electric power storage: P2X (P2G and P2P) solutions

Prof. Massimo Santarelli

Energy Department, Politecnico di Torino (IT)

STEPS Group (Synergies of Thermo-Chemical and Electro-Chemical Power Systems)

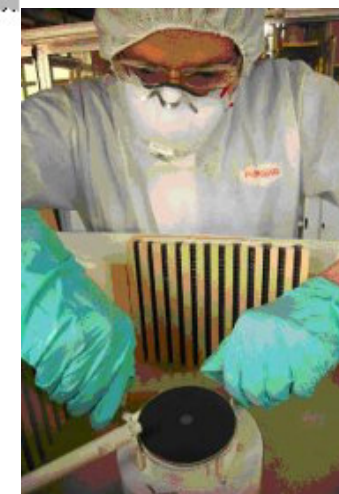
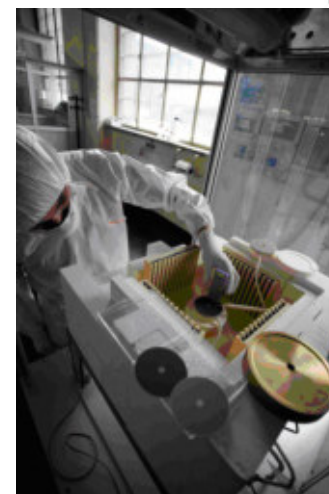
**Joint Workshop for Energy and Environment EMPIR
calls in 2019**

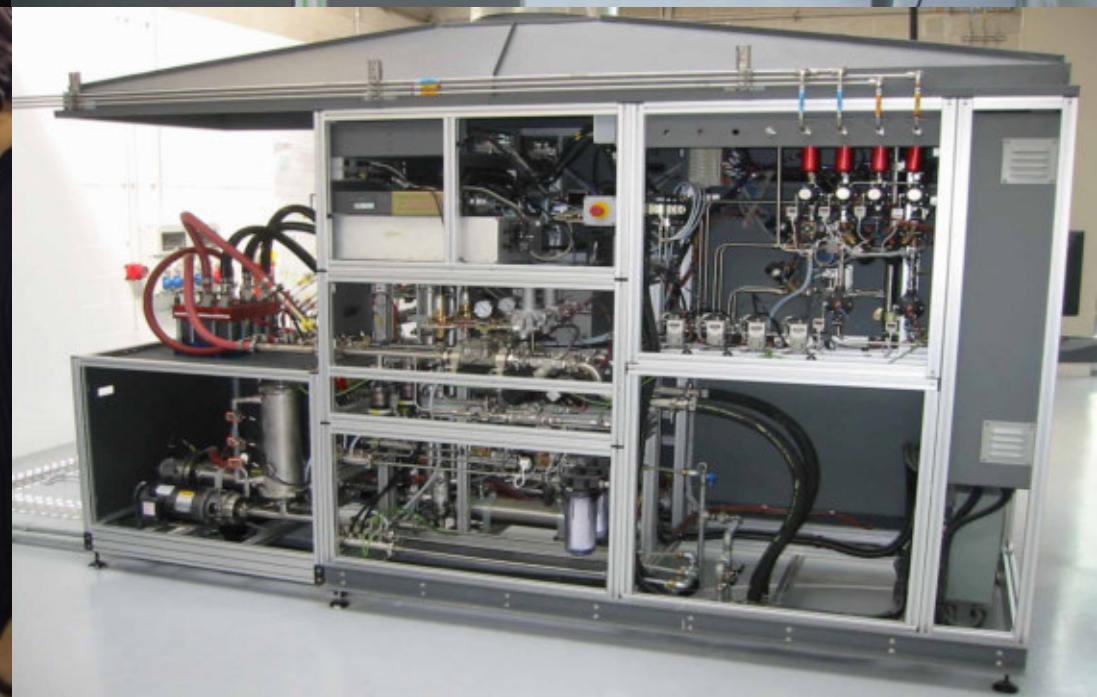
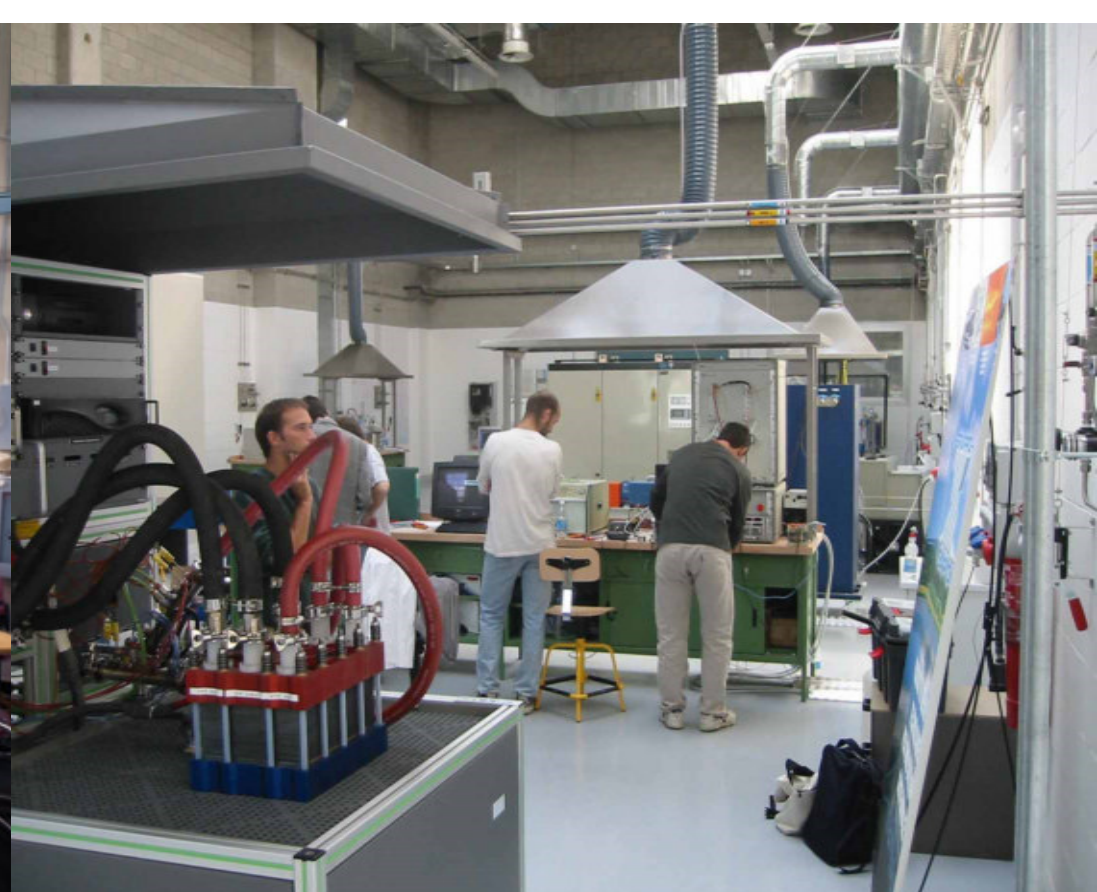
LNE, Paris, October 22, 2018



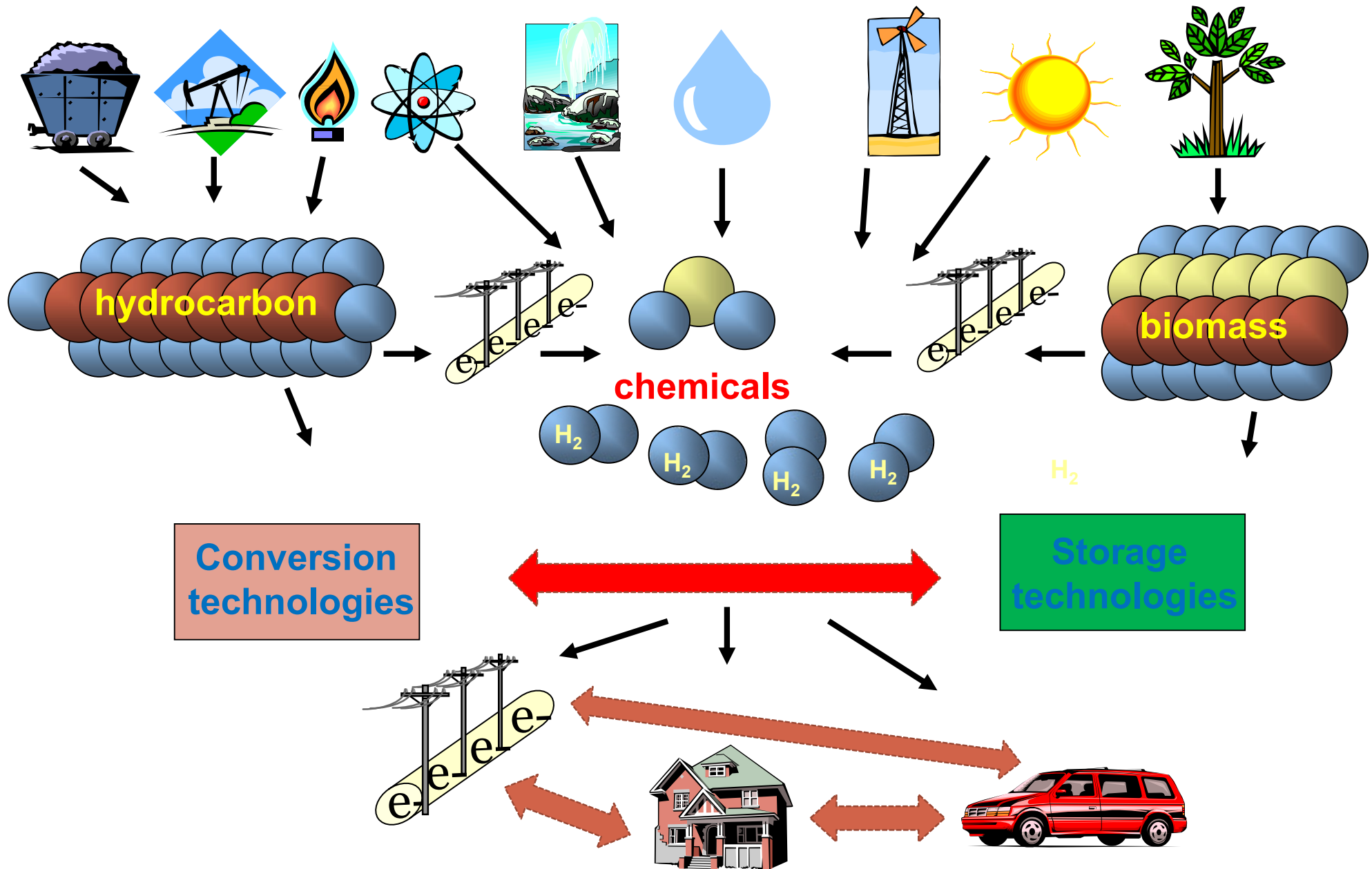
**Synergies of Thermo-
chemical and Electro-
chemical Power Systems
(STEPS)**

**Dept. of Energy
Politecnico di Torino**





Energy conversion: general

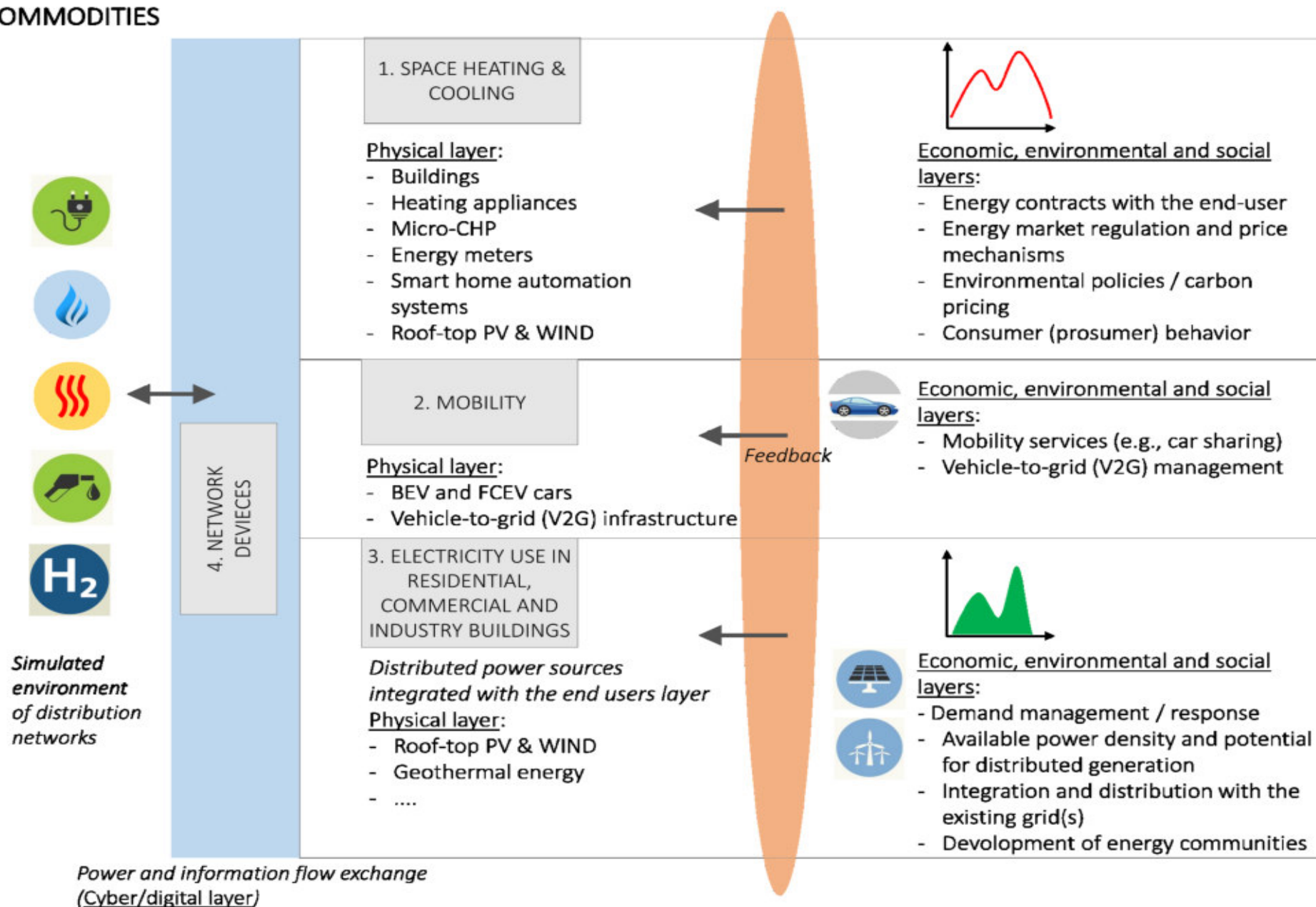


Energy conversion: general

ENERGY NETWORKS / COMMODITIES

END USES

ENERGY DEMAND/AVAILABILITY



EU: 2050 roadmap

Decarbonization → at least 80% reduction of CO₂ emissions

Why (fossil) decarbonization is needed?

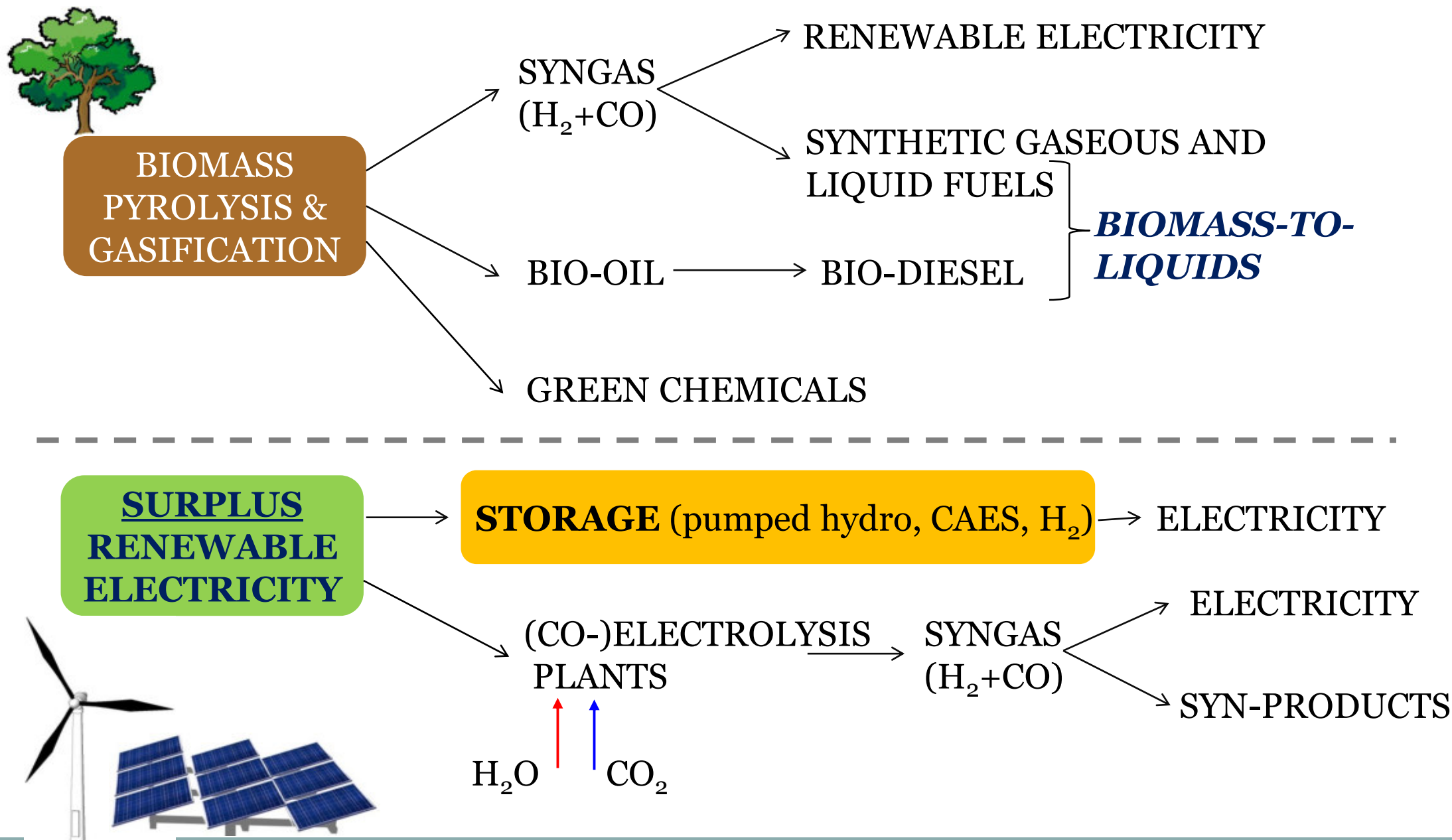
- 1) Rising concern and awareness on climate change related risks with increasing GHG in the atmosphere
- 2) Limited nature of fossil fuels
- 3) Energy security

Which actions are required?

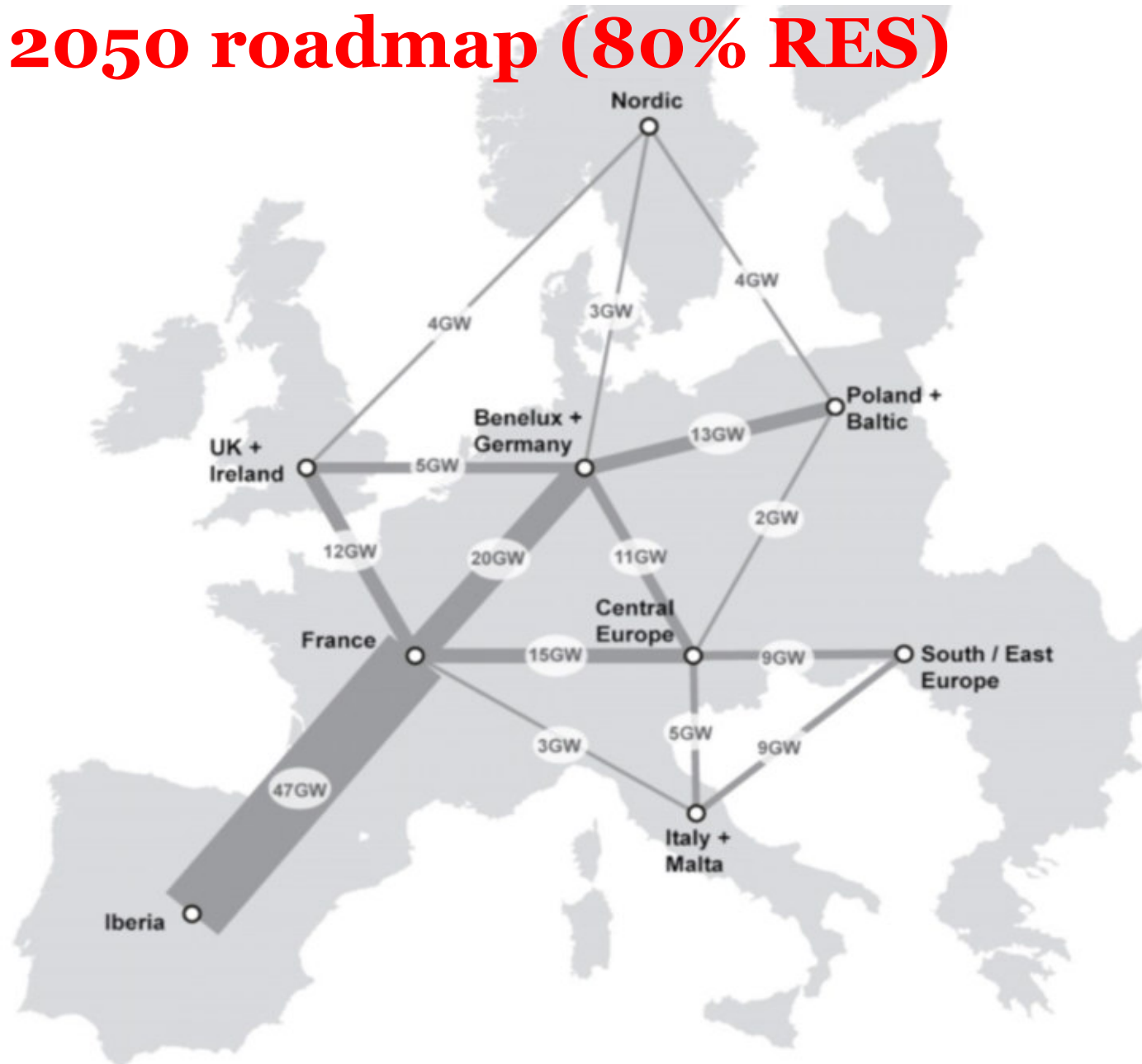
Three main pillars can be identified:

- **Energy efficiency**, in energy transformation (buildings, transport, power sector)
- **Renewable energy sources (RES)**, including biomass as green carbon source
- **Carbon capture and sequestration (CCS)** and/or **utilization (CCUS)**, from industrial emitters and fossil power plants

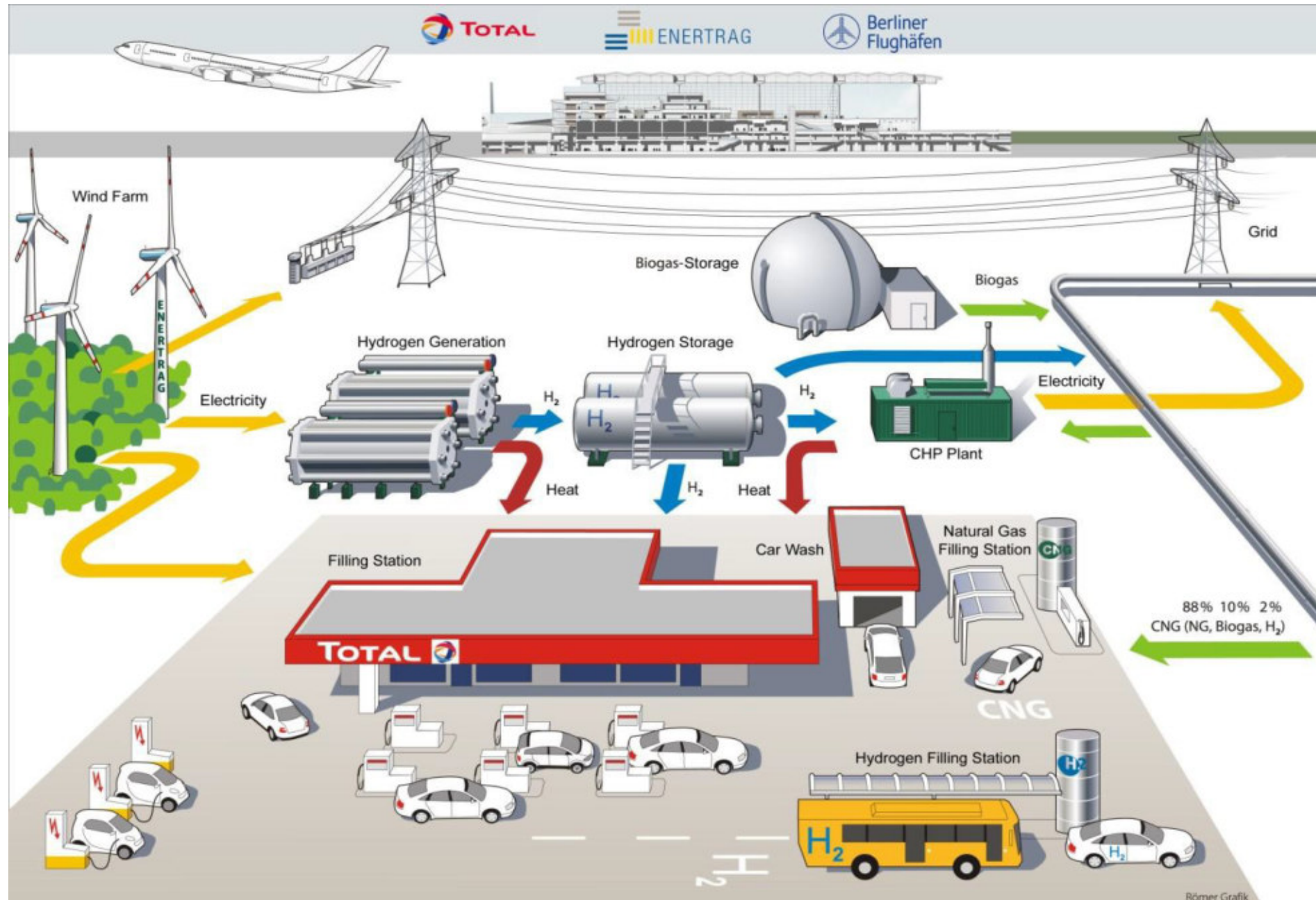
Exaples of possibile new technological pathways with RES



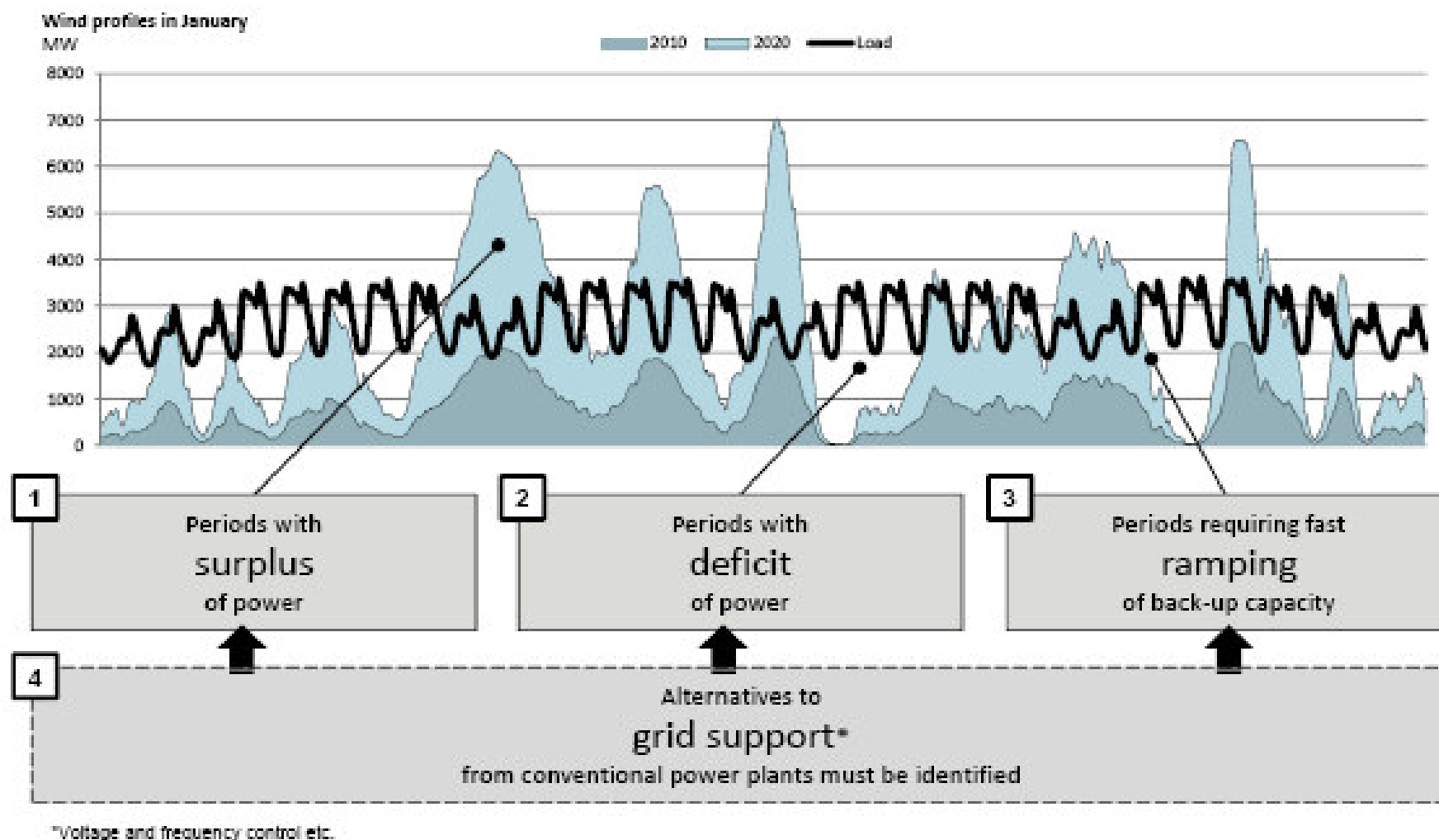
2050 roadmap (80% RES)



Energy: an integrated system (e.g. renewable H₂ platform for transportation)



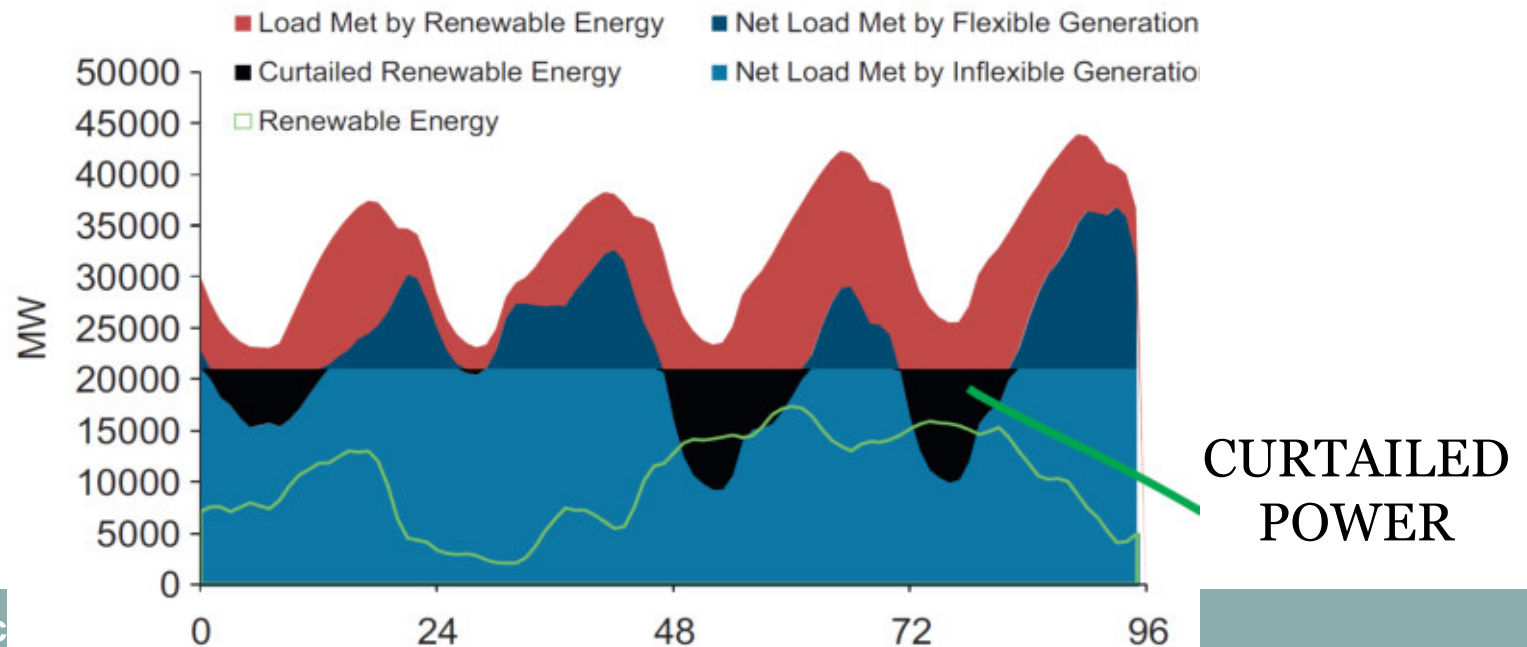
The intermittent nature of wind power challenges the existing electricity system



The electric grid must provide a reliable service at all times.

What happens when the power output from renewables is lower or higher than load demand

1. RES **deficit** → Reserve capacity is activated
2. RES **surplus** → Storage if capacity is available, otherwise curtailment

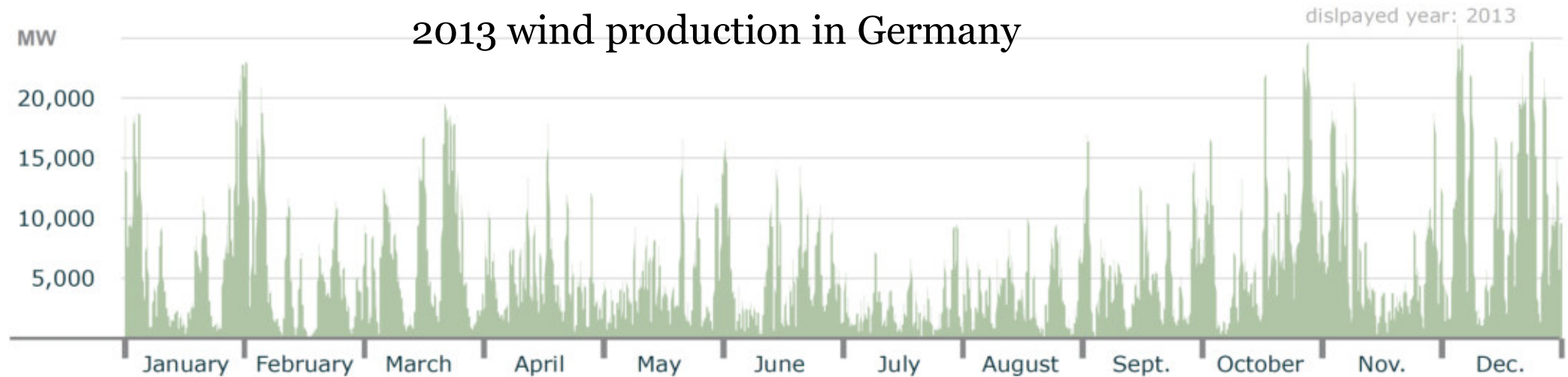


Two types of storage issues:

- short-term storage (for load demands in daily perspective): closed batteries may be enough
- long-term storage (monthly, seasonal,...): which technologies?

Rationale: long-term storage requirement (country-wide example)

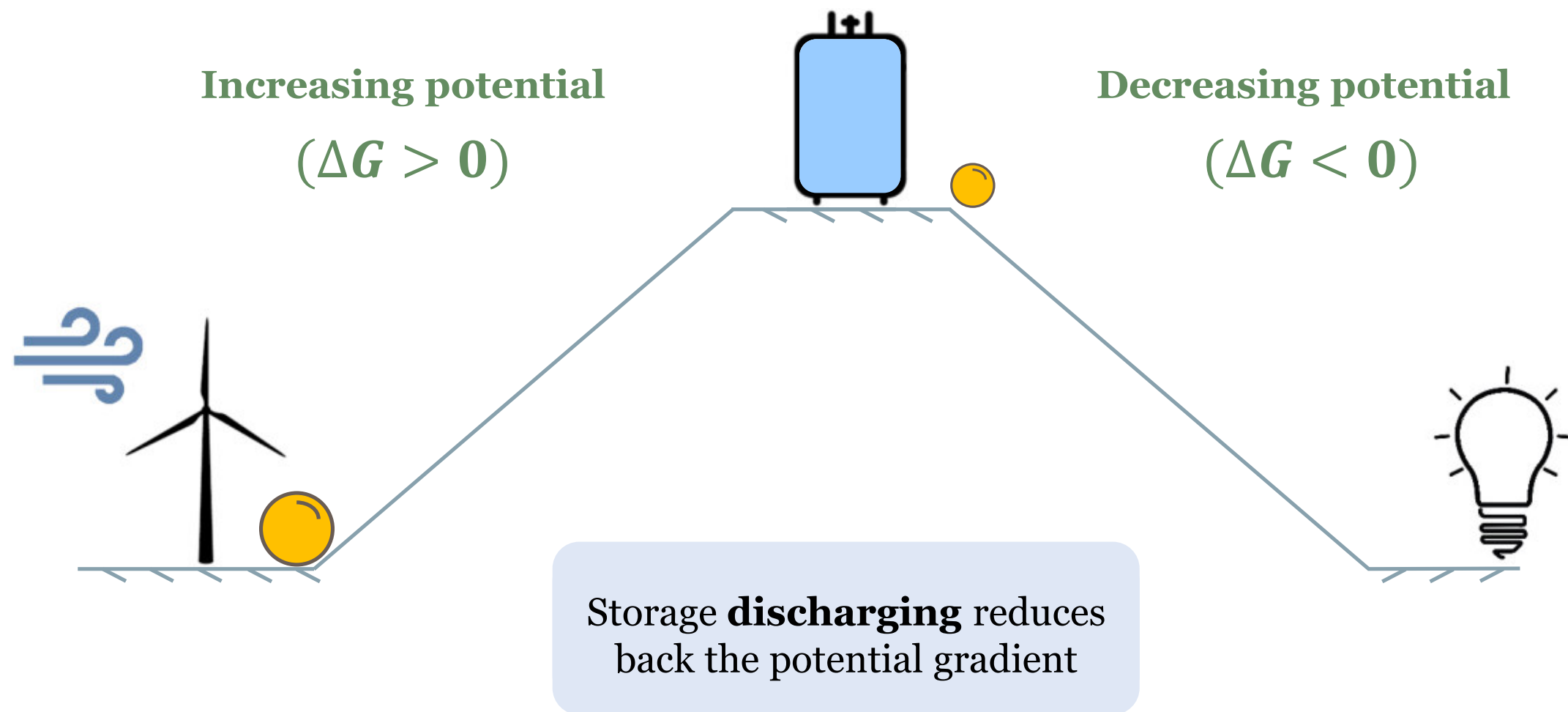
Actual production wind



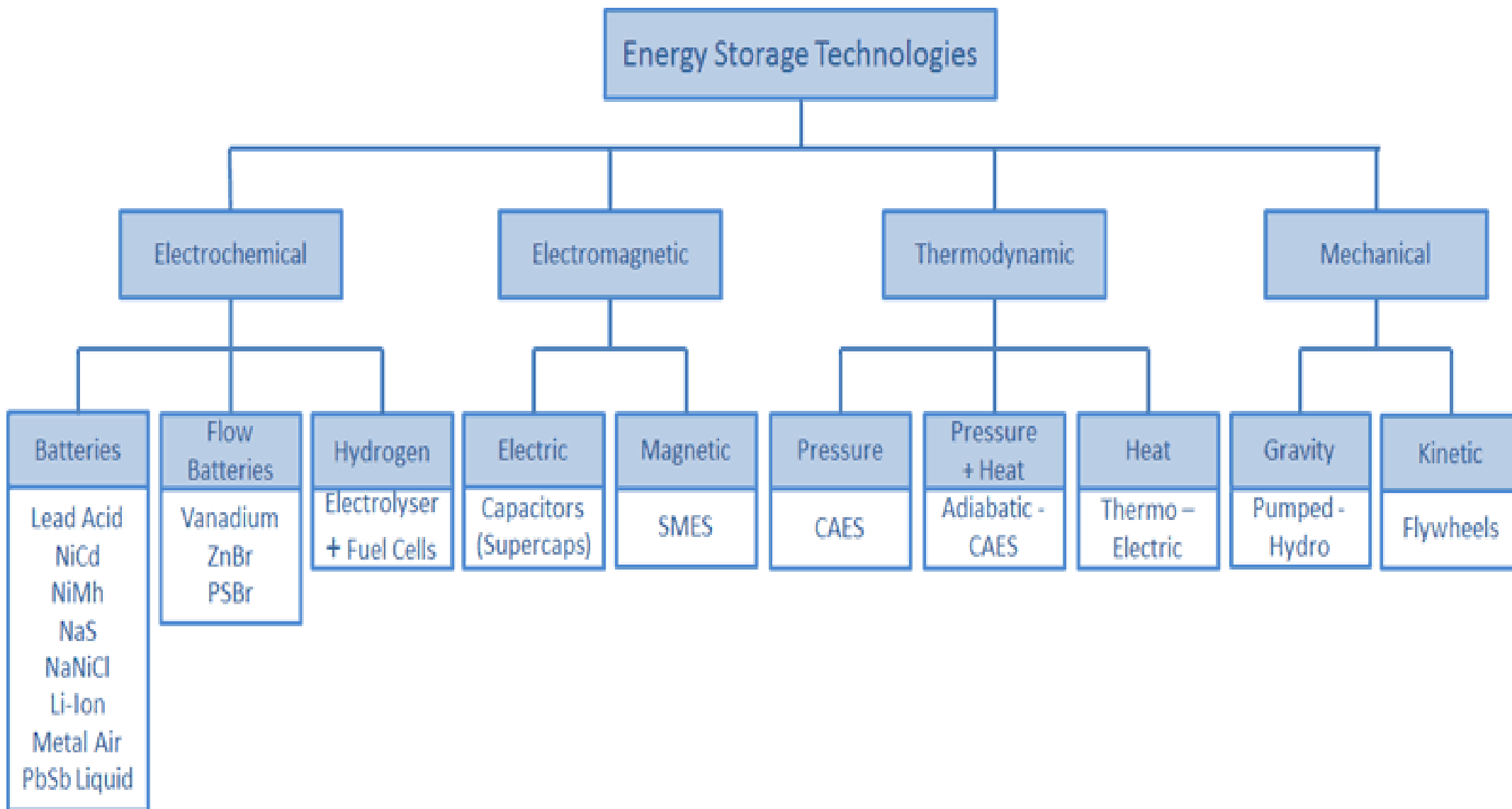
Required storage capacity : (average wind power) \times (low wind period) = 5 GW \times (7 \times 24 h) = **840 GWh**

(The calculation above is just a rough estimate on how much long-term energy storage we would need to fully compensate a period of 1 week with low wind power)

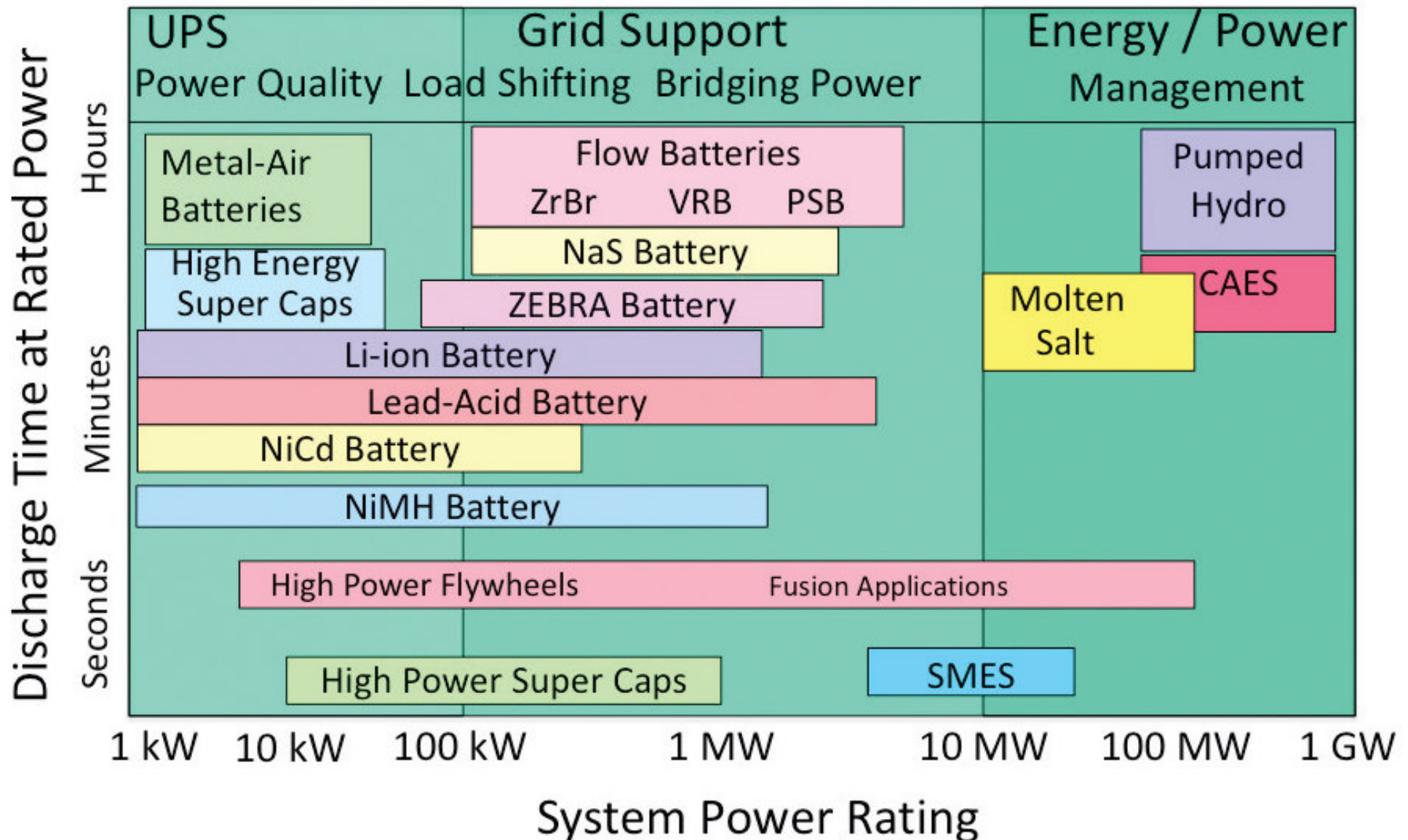
Rationale: energy storage



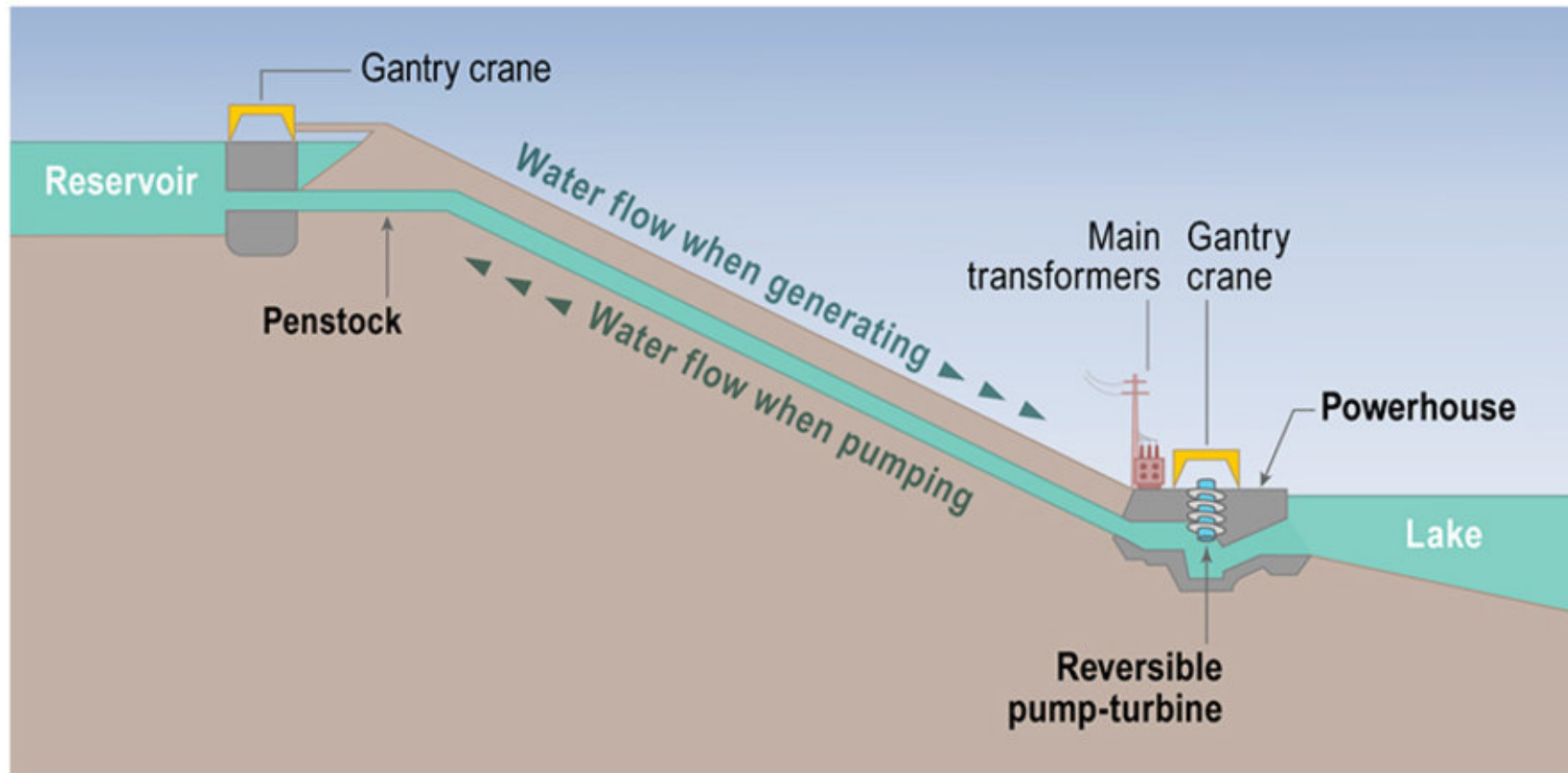
Energy storage: some options



Energy storage: some options

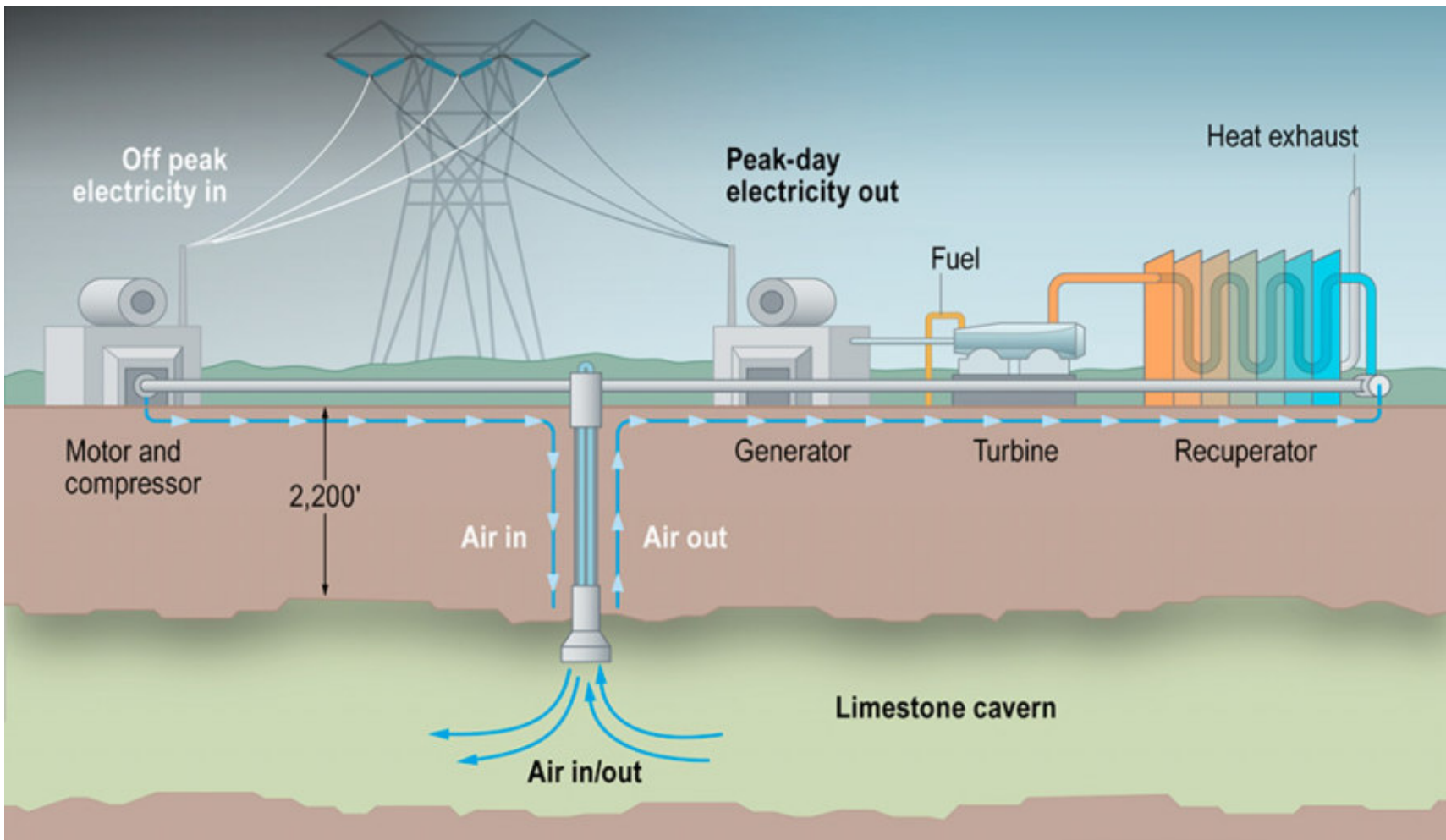


Pumped hydro

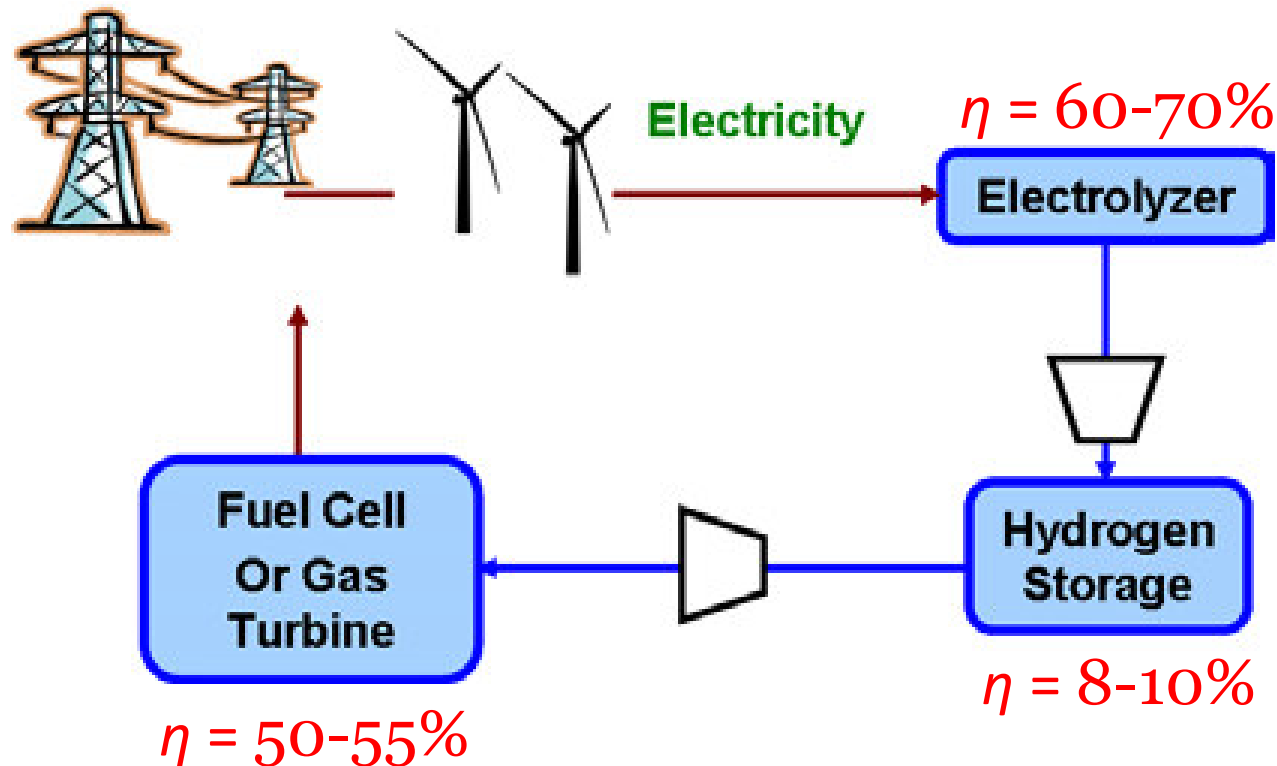


Limited storage in the EU energy system, mainly in mountain areas (Alps, Pyrenees, Scottish Highlands, Ardennes, Carpathians).

Compressed air energy storage (CAES)



Power-to-X, example with X=gas (chemical storage): example H₂

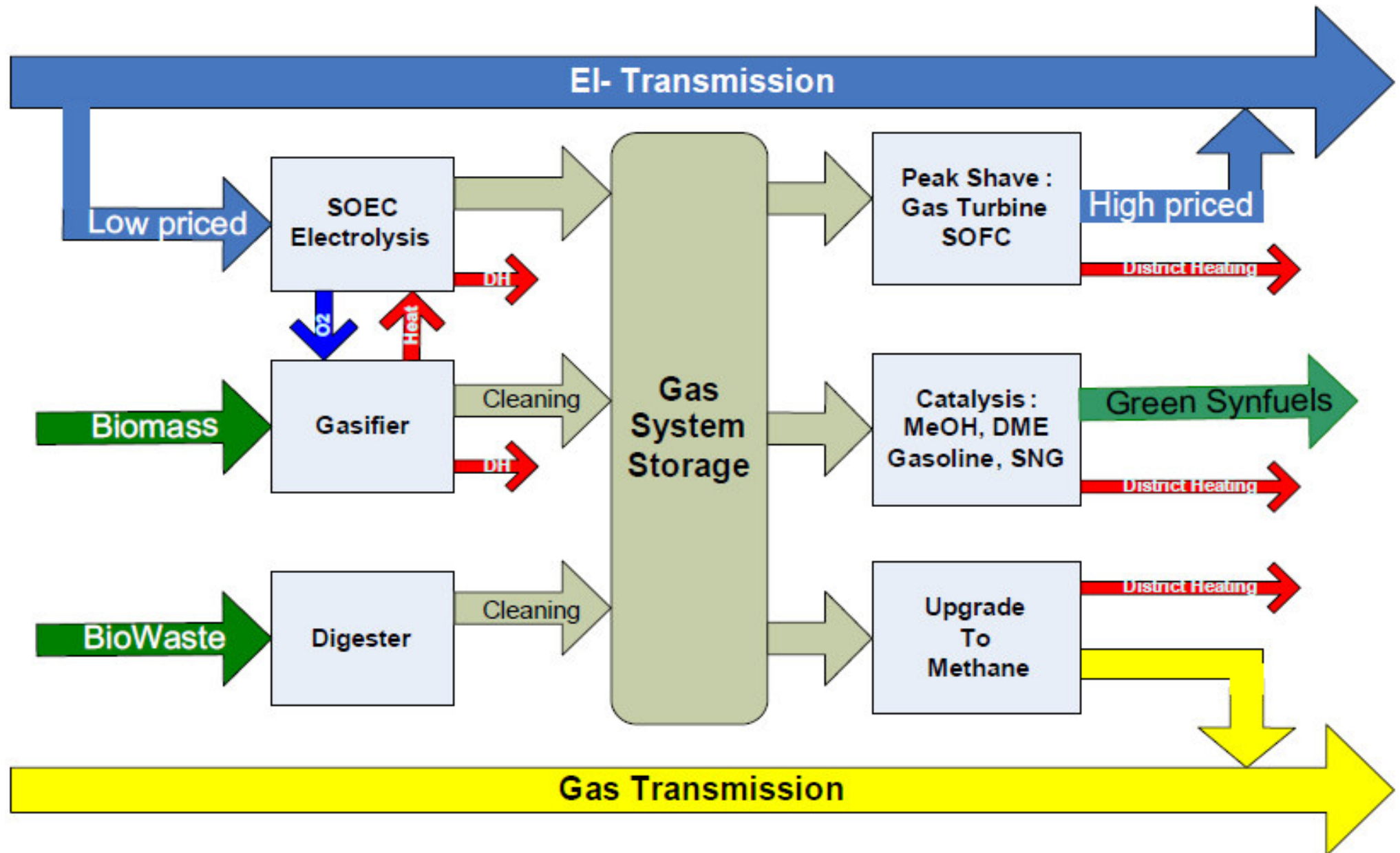


Round-trip efficiency: 30-40%

Performance of large-scale storage systems

Technology	Round-trip efficiency (%)	Volumetric energy density (kWh/m ³)
PHS	70-85	1
CAES	30 - 45	5
H ₂ STORAGE (36 bar)	25-38	100

Rationale: Power-to-X, X=Gas (P2G): CH₄ or other



Technologies and processes for large-scale energy storage (Power-to-Gas)

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Technologies for electrolysis

PEM :

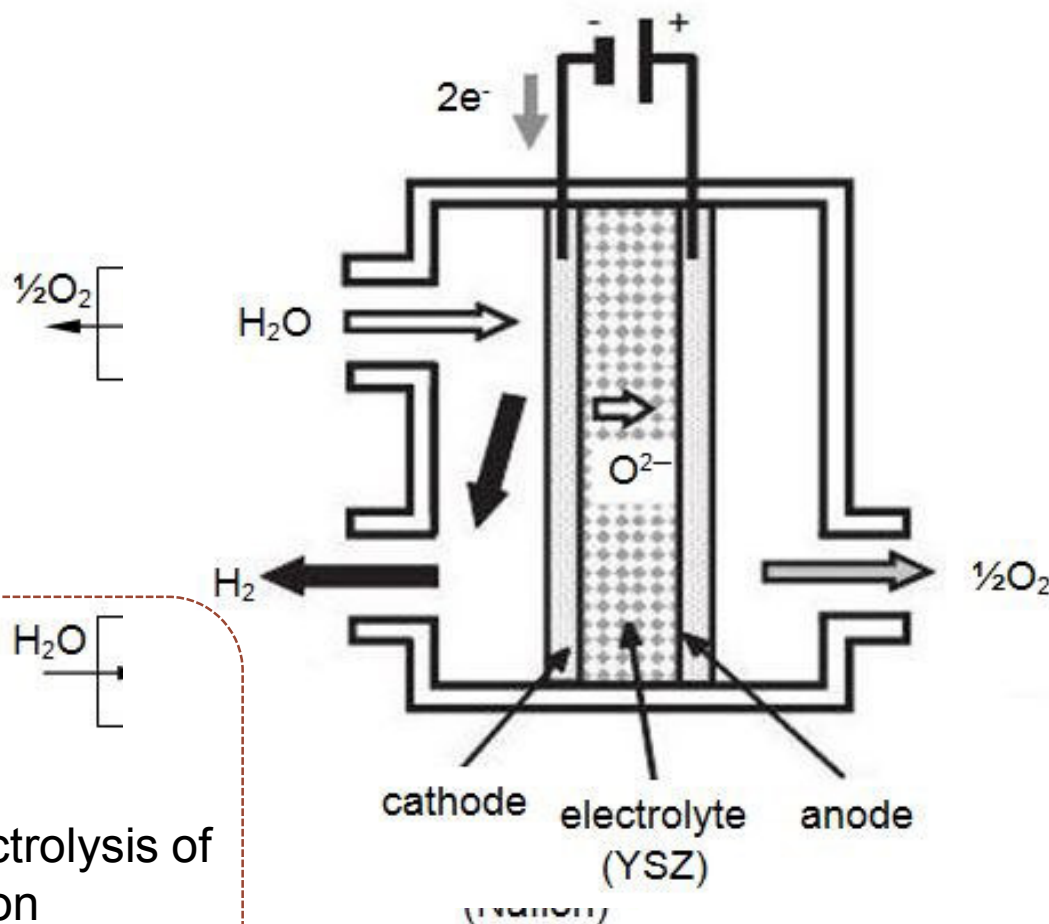
- Low T (40°C - 80°C)
- Solid electrolyte (Nafion)
- Possible H₂ at high pressure
- Commercial level, kWe to MWe

Alkaline (AWE):

- Low T (60°C - 90°C)
- Solid electrolyte (KOH)
- Commercial level, kWe to 100+ MWe

Solid Oxide Electrolytic Cells (SOECs):

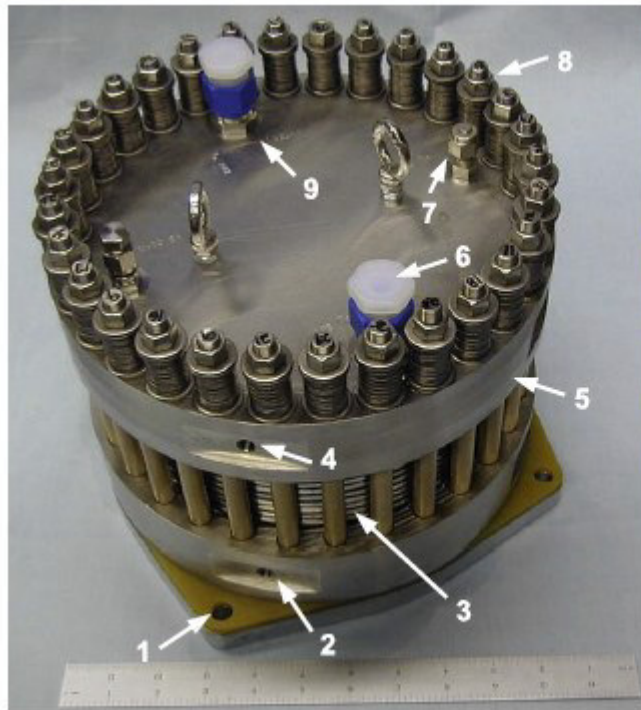
- High T (650°C - 900°C)
- Solid electrolyte (Yttria-stabilized Zirconia)
- Suitable for electrolysis of CO₂ and co-electrolysis of CO₂ and H₂O to syngas (H₂ + CO) production
- R&D level, some commercial, stack 150 kWe max at present



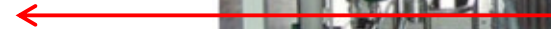
Low-temperature PEM electrolysis

Experimental high-pressure test-bench in PoliTO

H₂ delivered at 70 bar max.



1. Tie down holes (for installation).
2. Anode electrical connection.
3. Cells.
4. Cathode electrical connection.
5. End plate
6. Anode out: water and oxygen outlet flows.
7. Cathode out: high pressure hydrogen outlet flow.
8. Tie bolts and Belleville washers to seal.
9. Anode in: water inlet flow.

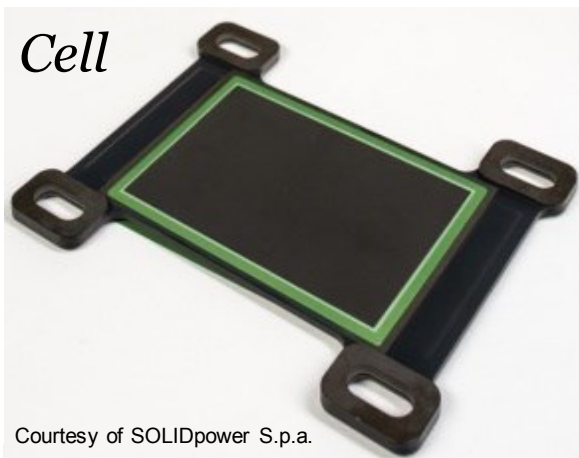


High-temperature SOEC electrolysis

SOEC: cell, stack and module.

H₂ produced with > 80 %_{LHV} efficiency*

Cell



Courtesy of SOLIDpower S.p.a.

Stack

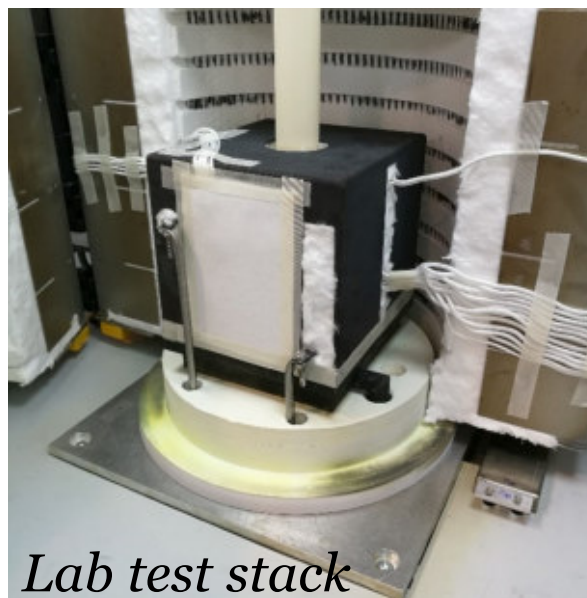


Courtesy of SOLIDpower S.p.a.

SOEC 150 kW



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Lab test stack

* GrInHy project:
overall electrical
efficiency for 150 kW_{AC}
module integrated in a
steel manufacturing
plant.

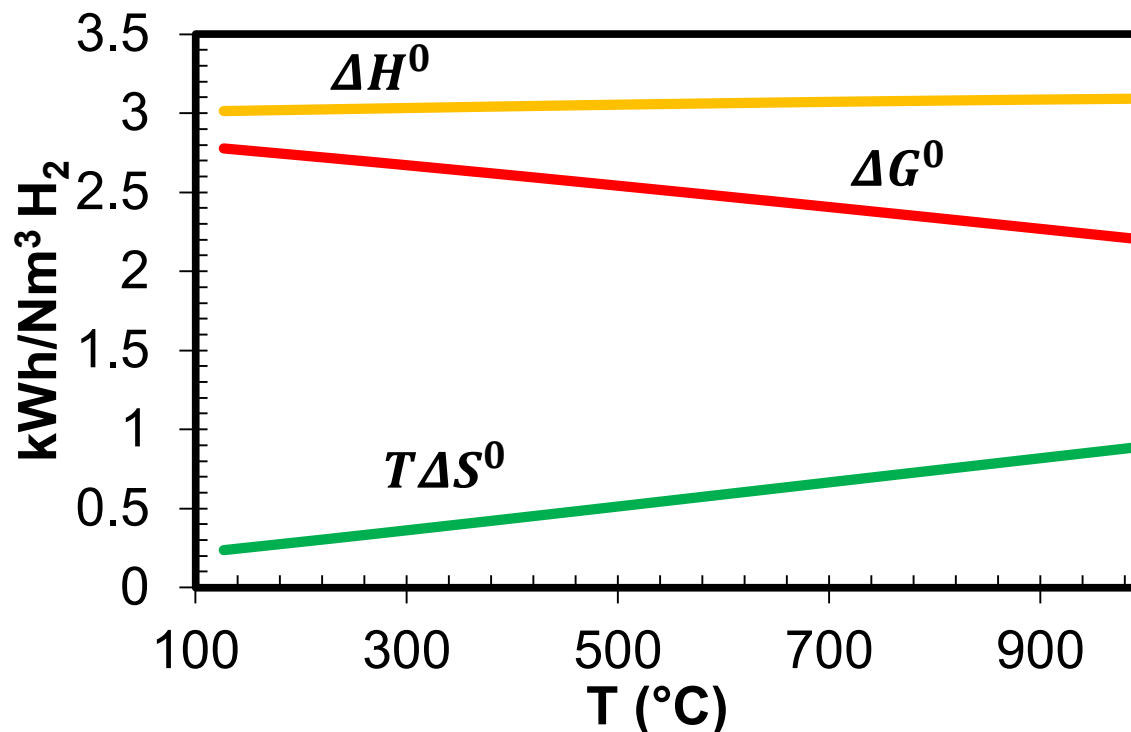
GrInHy
Green Industrial Hydrogen



This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking under grant agreement No. 700300. This Joint Undertaking receives support from the European Union's Horizon 2020 research and innovation programme and Hydrogen Europe and N.ERGHY.

Electrolysis: basic thermodynamics

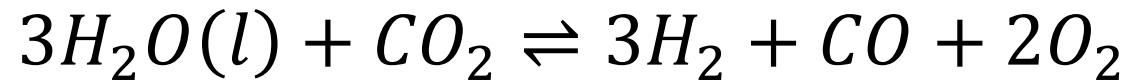
Steam electrolysis



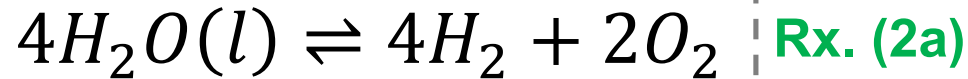
From the thermodynamic perspective, the electrical work required for electrolysis decreases with temperature, and a larger fraction of the total energy or electrolysis, ΔH° , can be supplied in the form of heat, represented by the $T\Delta S^\circ$ term.

Involved reactions in SOEC are:

Rx. (1a)



$$\Delta H^0 = 1140.5 \text{ kJ/mol}$$



Rx. (2a)

$$\Delta H^0 = 1143.3 \text{ kJ/mol}$$

Involved reactions in methanation are:



Rx. (1b)

$$\Delta H^0 = -206.1 \text{ kJ/mol}$$

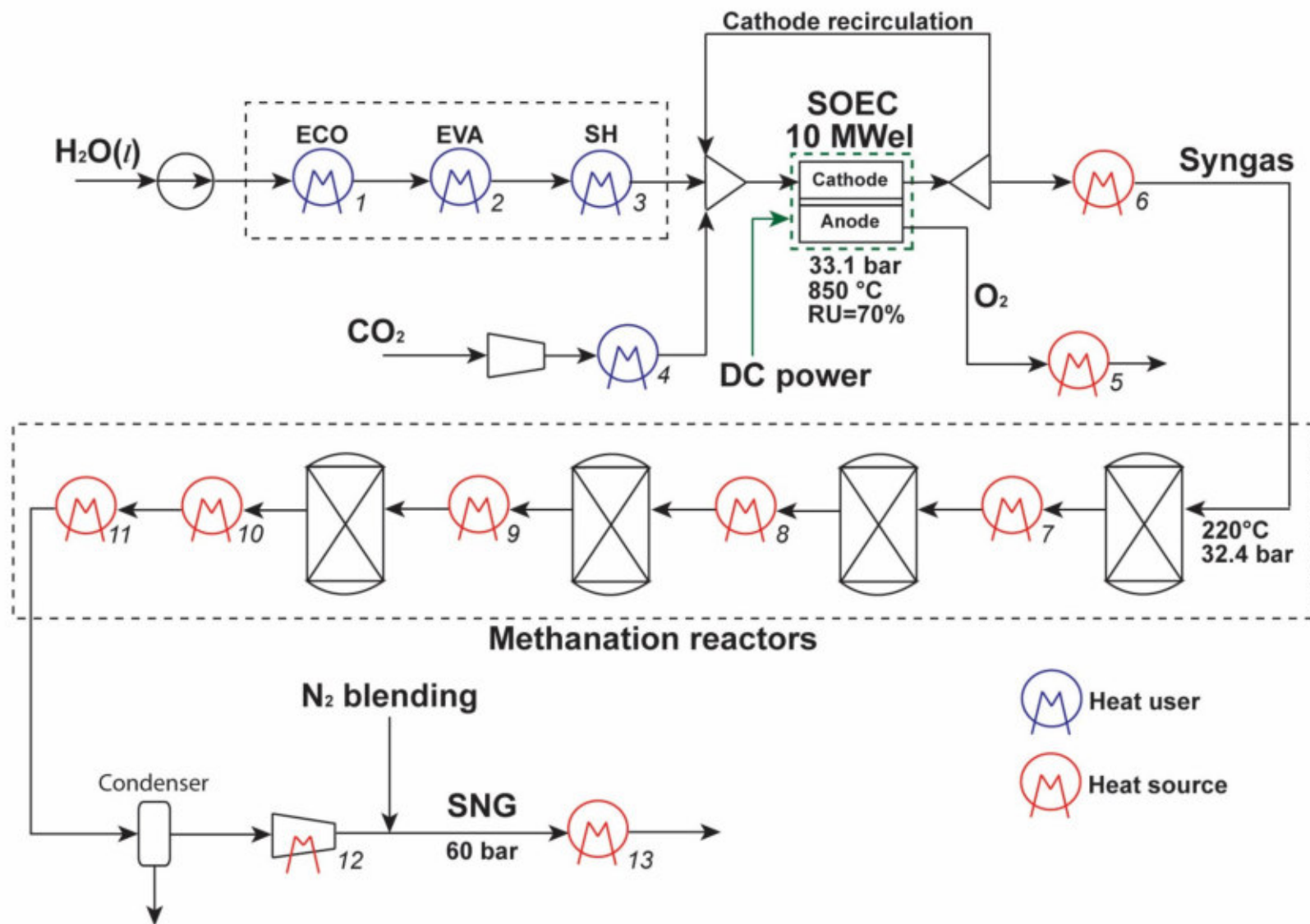


Rx. (2b)

$$\Delta H^0 = -165.0 \text{ kJ/mol}$$

$$\eta_{teor} = \frac{LHV_{CH_4}}{\Delta H_{tot}^0} \begin{cases} \frac{802.3}{934.3} = 85.9\% & \text{Rx. 1 H}_2\text{O}+\text{CO}_2 \text{ electrolysis} \\ \frac{802.3}{978.4} = 82.0\% & \text{Rx. 2 H}_2\text{O electrolysis} \end{cases}$$

P2G layout: co-electrolysis (CoE) + methanation



SNG: technical specifications

Before pumping the obtained SNG into the transport infrastructure, some technical specifications must be verified (e.g. in Italy by “SNAM Rete Gas”) for pumping natural gas into pipelines.

The main constraints regard three parameters :

- Gas Gravity
- Wobbe Index
- Higher Heating Value of produced SNG

Gas Gravity is the ratio between densities of produced SNG and air, both calculated at standard conditions, i.e. 101325 Pa and 288.15 K.

$$GG = \frac{\rho_{SNG}}{\rho_{air}}$$

ρ_{air} set to a value of 1.22 kg/Sm³ assuming a mole mass equal to 28.84 kg/kmol .

Wobbe Index is expressed by:

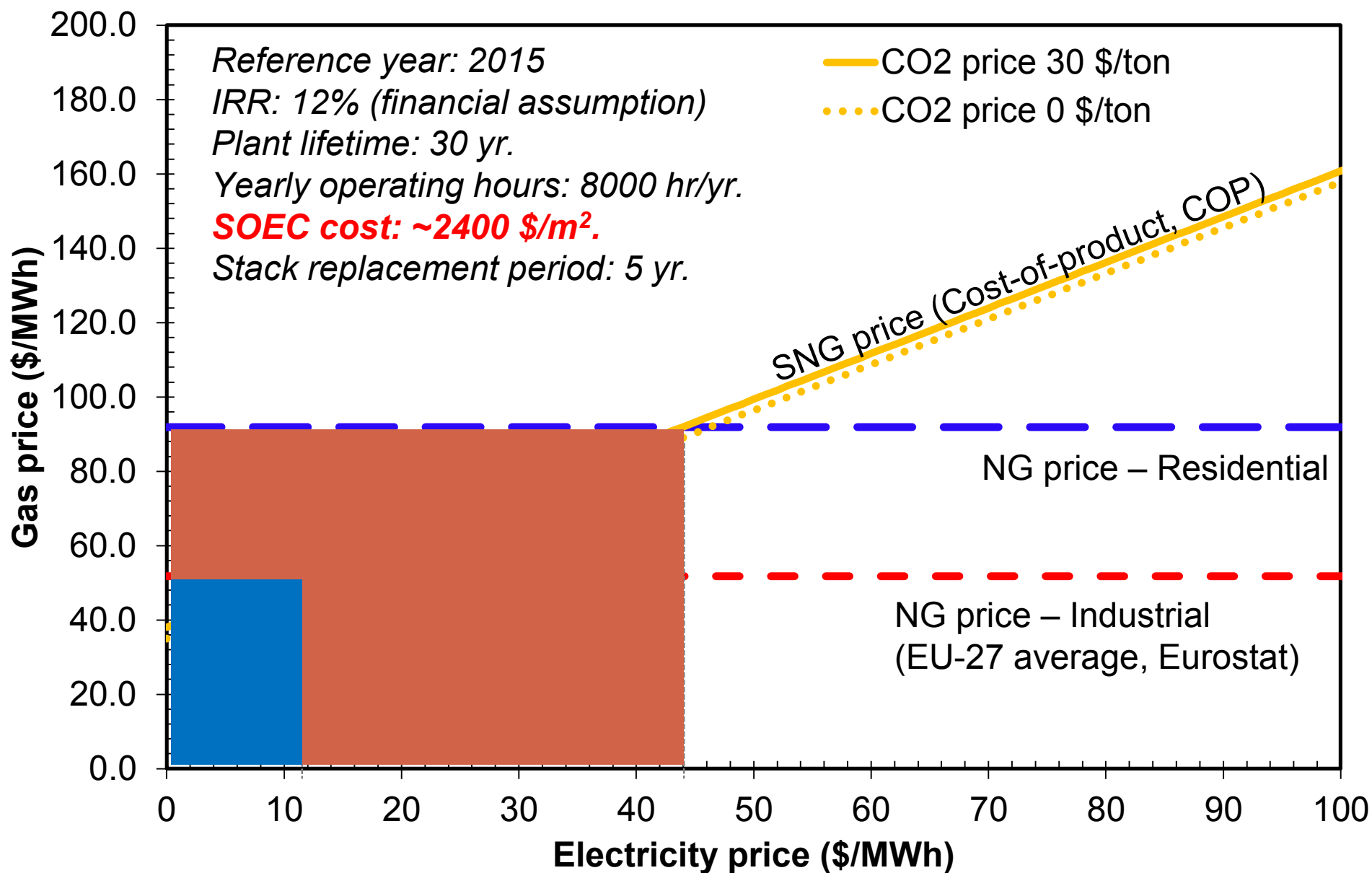
$$WI = \frac{HHV}{\sqrt{GG}}$$

HHV is the Higher Heating Value of SNG.

Boundaries accepted by the SNAM grid for these parameters are summarized in the Table.

HHV [MJ/Sm³]	34.95 - 45.28
Wobbe Index [MJ/Sm³]	47.31 - 52.33
Gas Gravity	0.5548 - 0.800

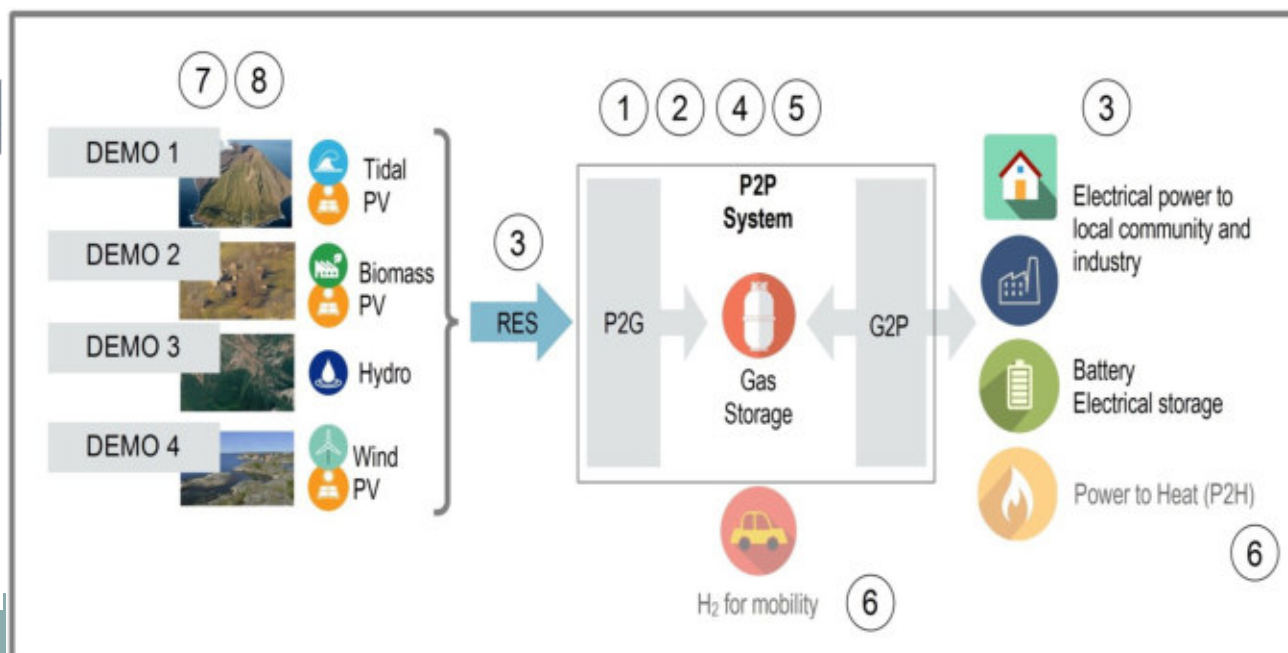
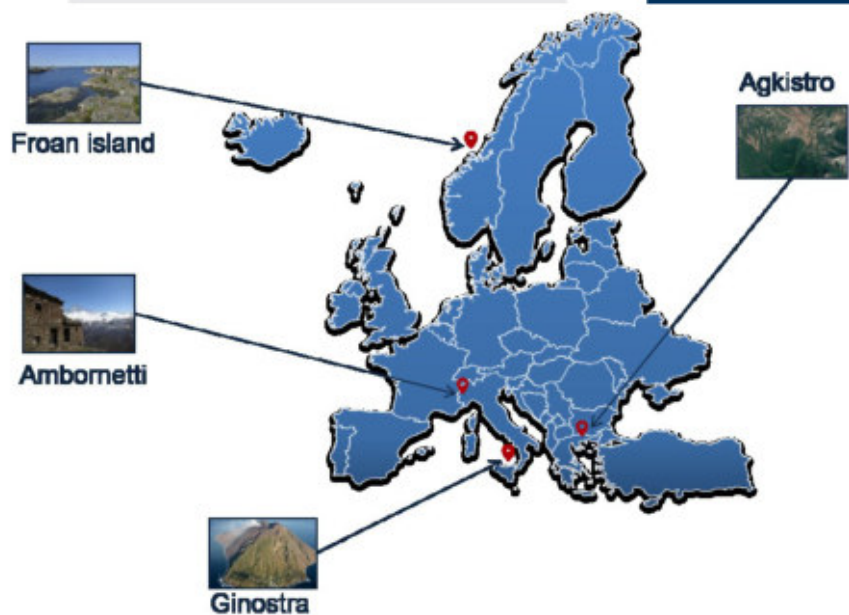
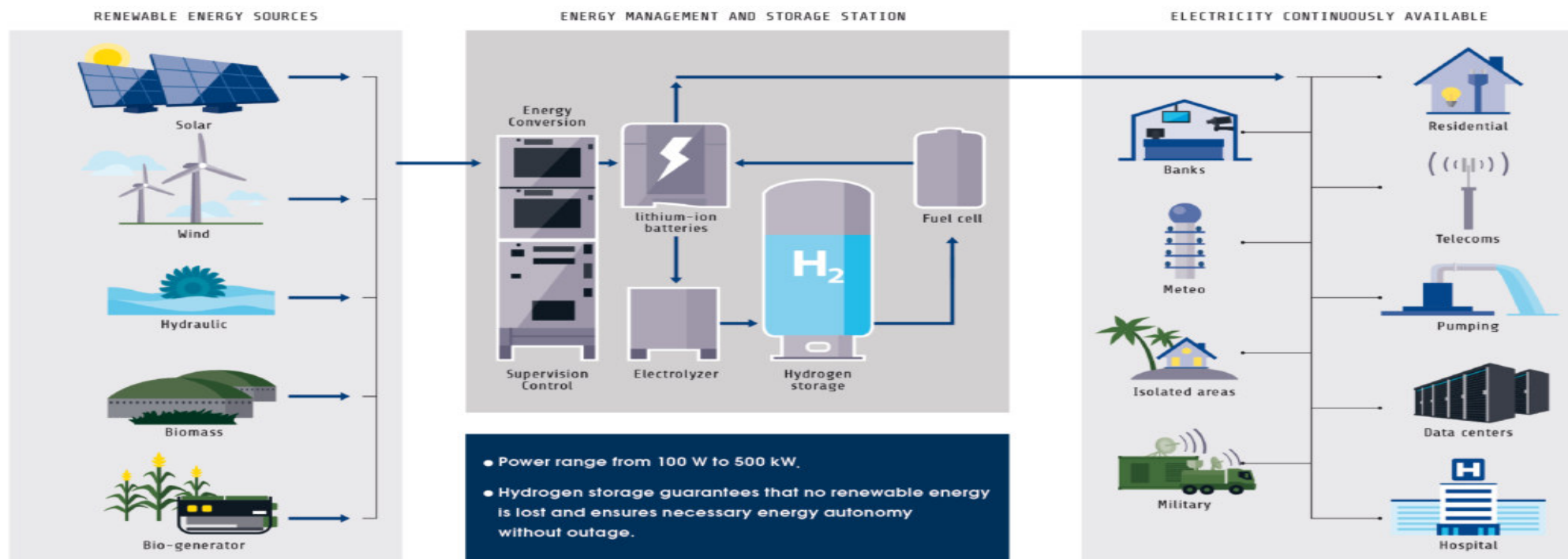
Economic results (EU scenario) – CoE case



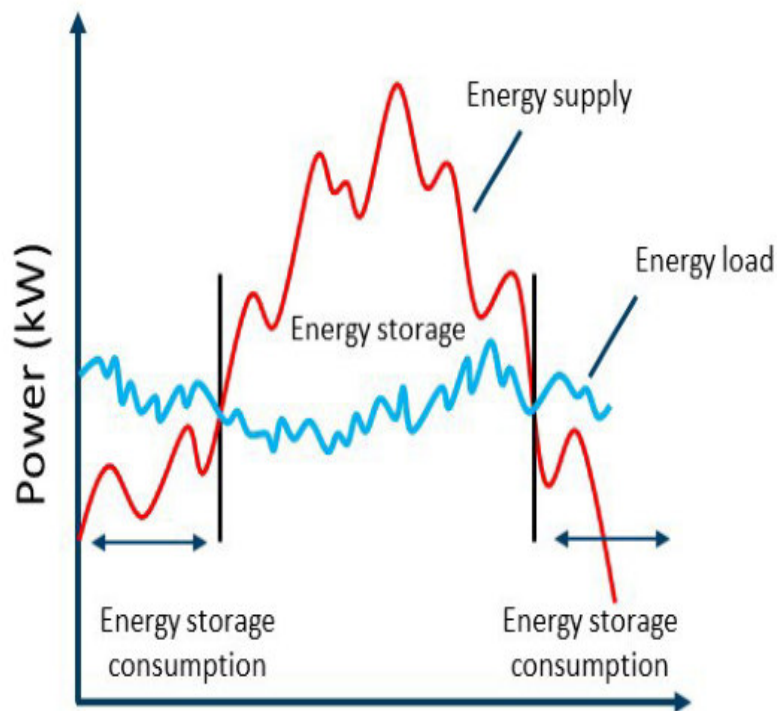
Power-to-Power hybrid systems based on Li-ion and H2 systems

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Power-to-Power (P2P)

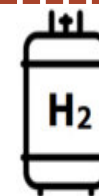


P2P: Remote areas and importance of energy storage



**Energy
storage**

Long term

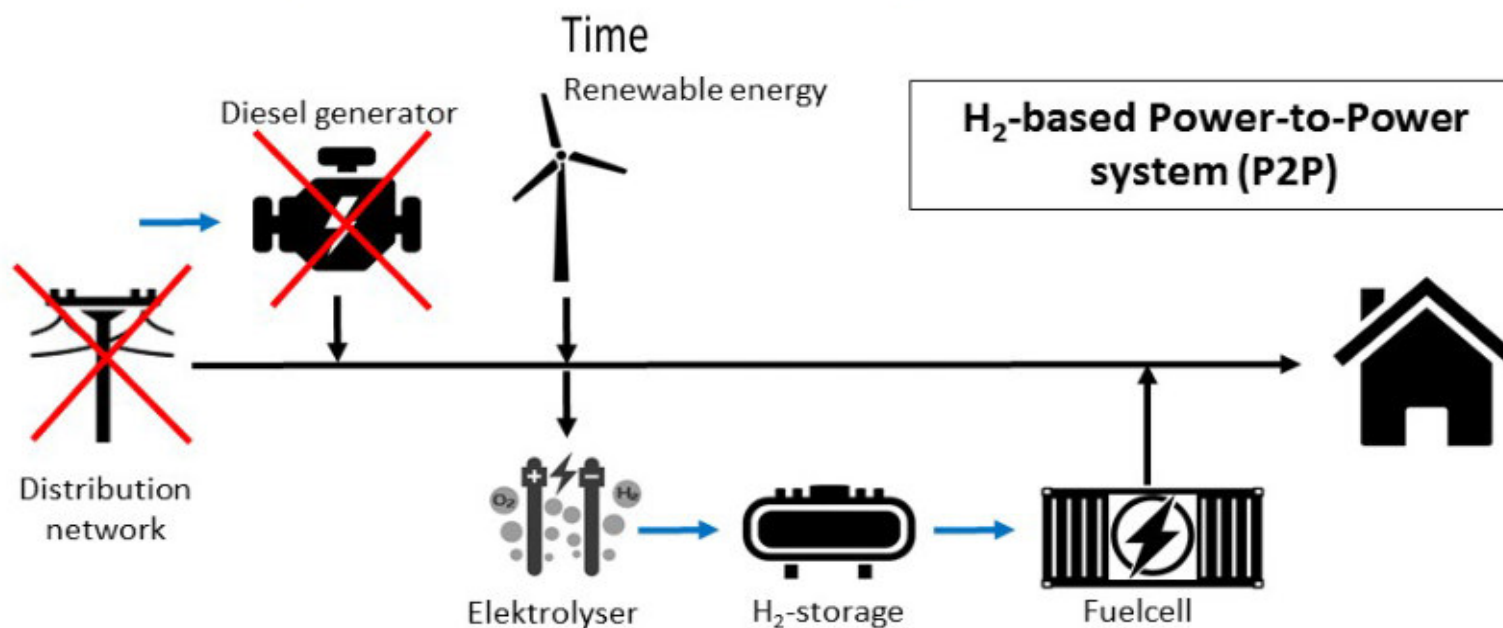


Hydrogen

Short term



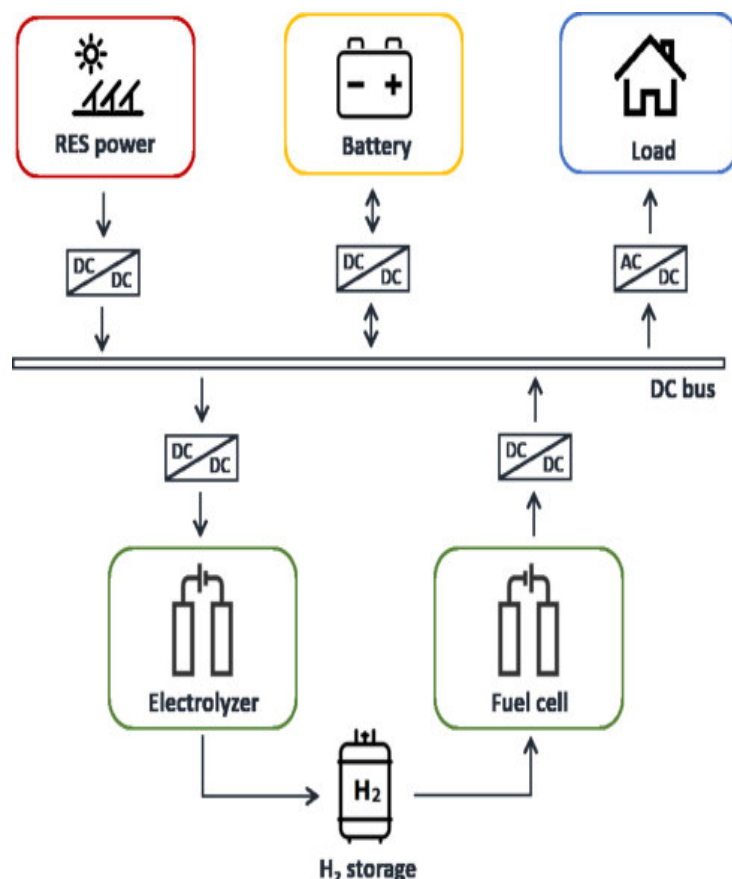
Battery



P2P concept: why and how

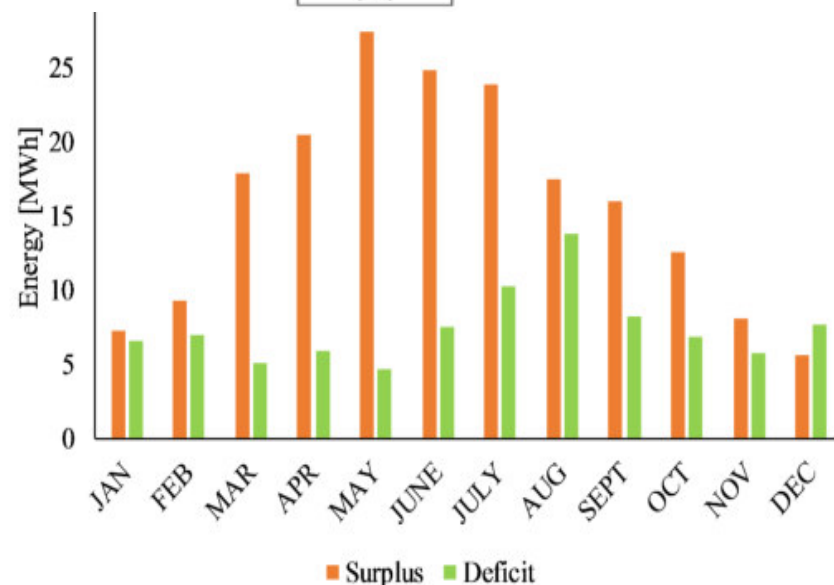
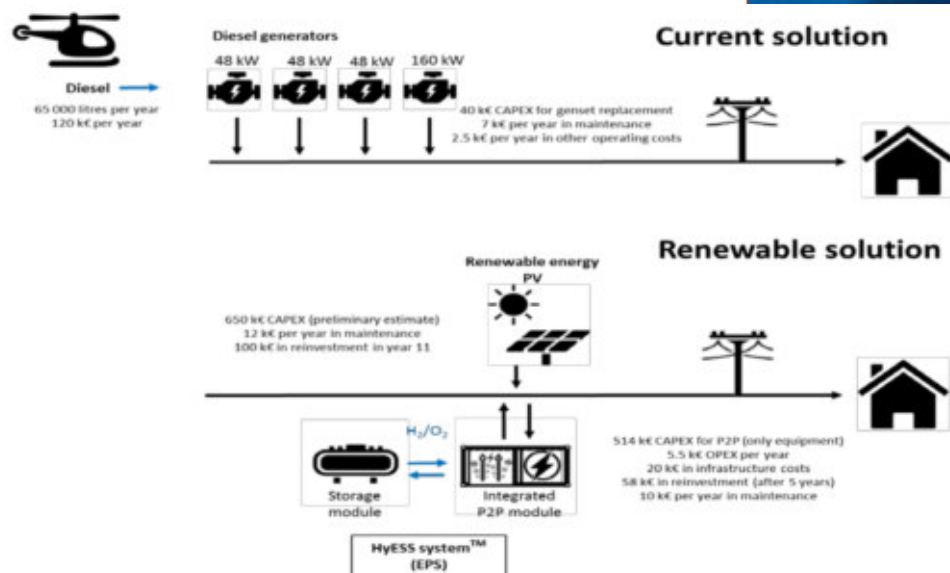
- **Environmental:** reduce fossil consumption to **decrease local pollution**
- **Economic:** reduce fossil consumption to **lower the cost of electricity** (transportation and logistic issues of fossil fuels due to the remoteness of the location)
- **Energy security:** increase and optimize the exploitation of **local renewable energy sources**
- **Reliability:** reliability of the local electricity service

General configuration of a hybrid stand-alone P2P system:



- **Electrolyzer:** converting the excess of RES power into H₂
- **Fuel cell:** re-converting the stored H₂ into electricity when a RES power deficit occurs
- **Battery:** support for the system operation and daily energy buffer
- **Power electronics (converters):** to allow the different sub-systems to exchange the correct amount of energy

P2P: Case study Ginostra (South EU)



RES and load data on yearly basis

Total load: 171.5 MWh

RES production: 273.2 MWh

Direct RES consumption: 82.4 MWh

RES surplus: 190.8 MWh

Deficit: 89.2 MWh

- Deficit more than half of the total load
- RES surplus around two thirds of the total RES
- High surplus in spring and increased deficit in the summer (**seasonal effect**)






Necessity of **energy storage**

Operation of the stand-alone power system

- Optimize energy/economic balances (roundtrip efficiency)
- Avoid operation outside safe working ranges (reduce plant degradation and replacement)




Discharging

1. Battery 
2. Fuel cell 
3. External source 

Constraints:

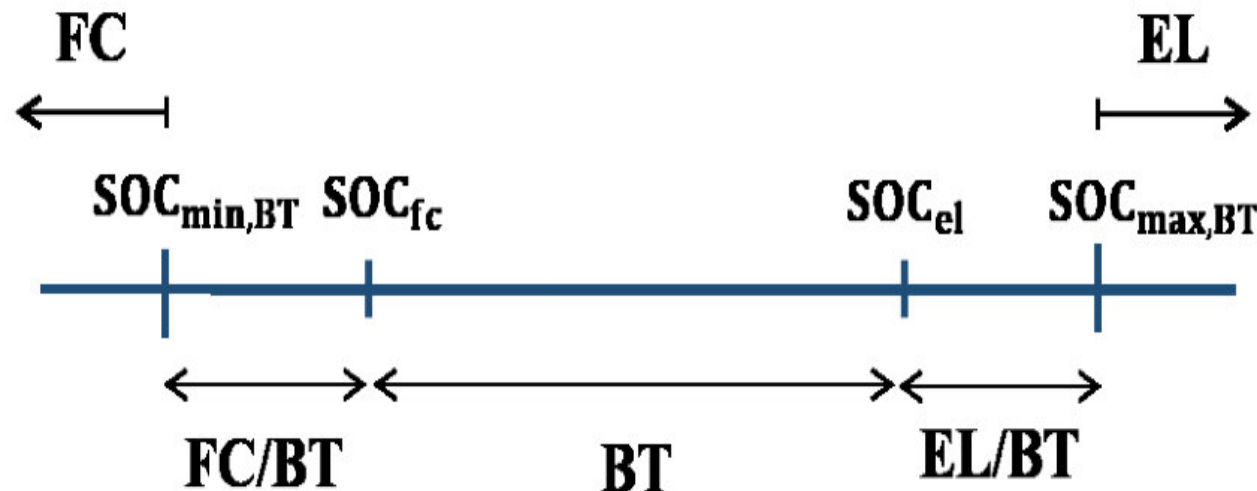
$SOC_{min,bt}$, SOC_{min,H_2} , FC modulation range

Charging

1. Battery 
2. Electrolyzer 
3. Curtailment 

Constraints:

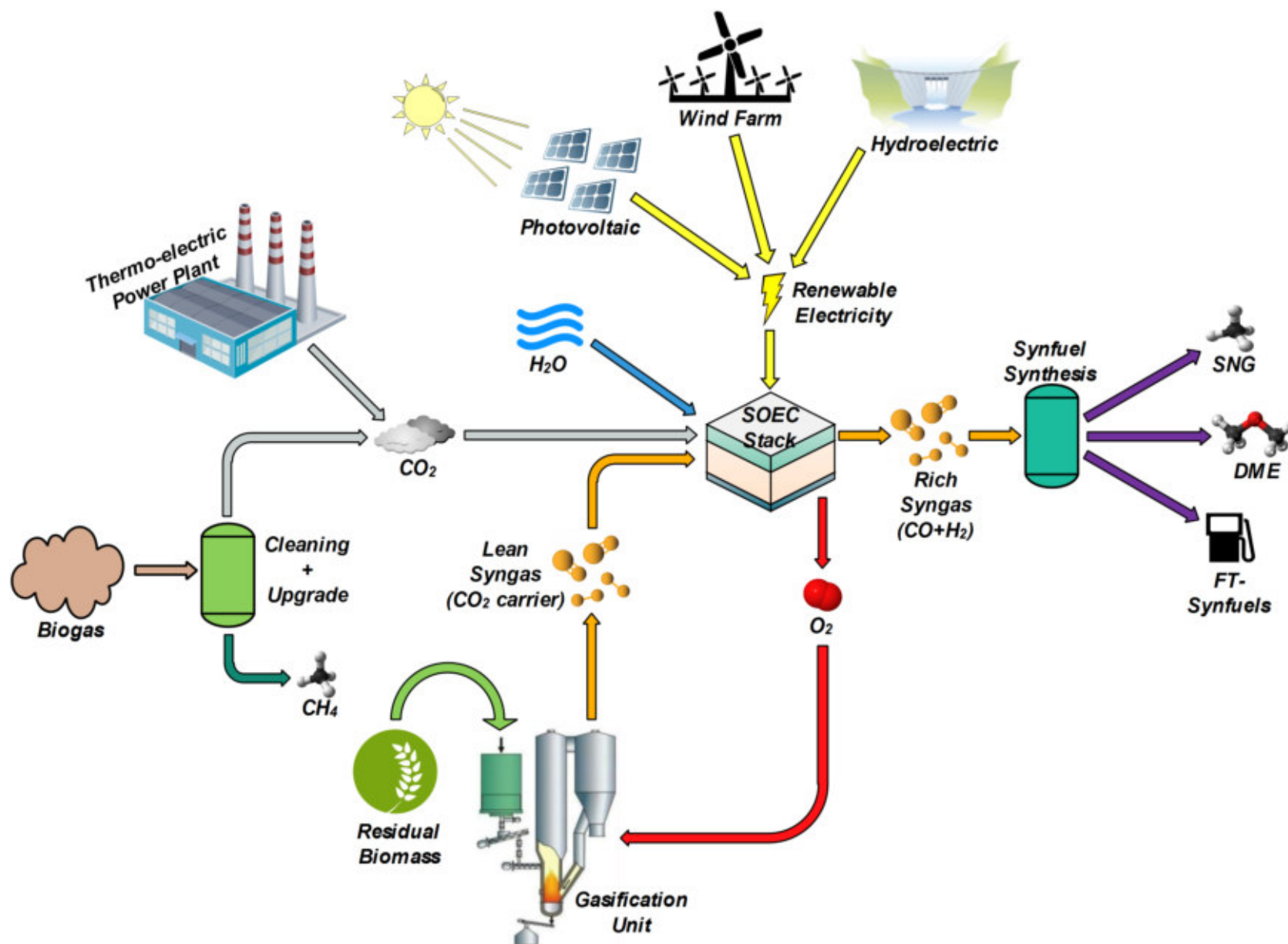
$SOC_{max,bt}$, SOC_{max,H_2} , EL modulation range



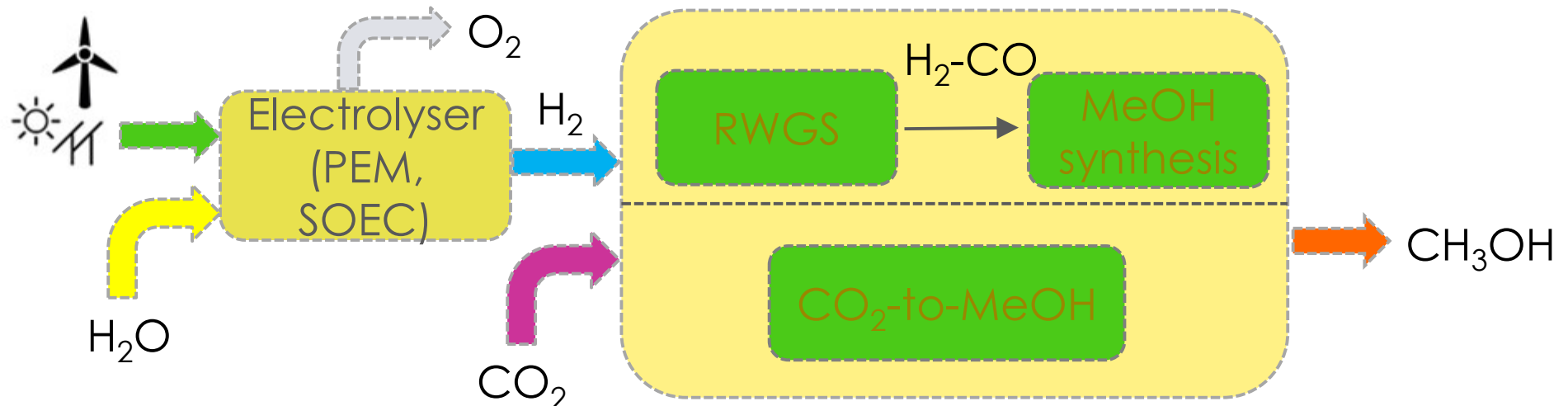
A few about Power-to-Liquid (P2L)

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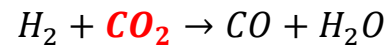
Power-to-Liquids (P2L): general concept



P2L: CO₂ + H₂O to CH₃OH (or CH₃OCH₃)

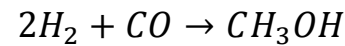


RWGS:
mol



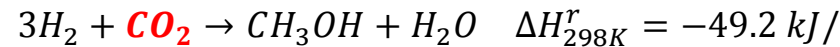
$$\Delta H_{298K}^r = +41.2 \text{ kJ/}$$

MeOH synthesis:



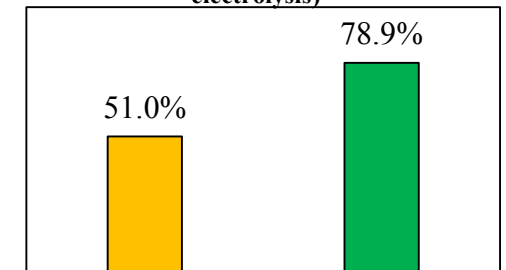
$$\Delta H_{298K}^r = -90.4 \frac{\text{kJ}}{\text{mol}}$$

CO₂-to-MeOH:
mol

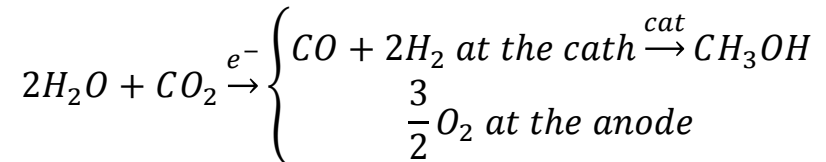
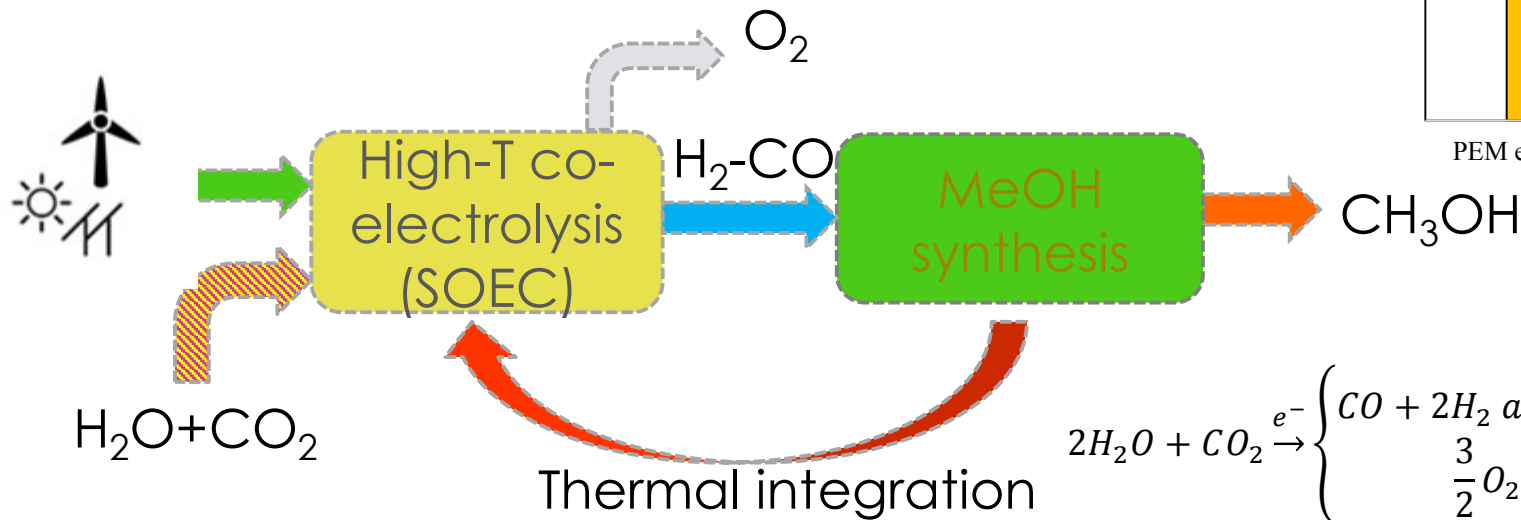


$$\Delta H_{298K}^r = -49.2 \text{ kJ/}$$

H₂ (PEM) vs. H₂-CO (SOEC co-electrolysis)



PEM electrolysis SOEC co-electrolysis



P2L: DME general process

The **CO₂ source** is gasified biomass (i.e., biosyngas)

Biomass-to-liquid
efficiency: ~70%*

(*it includes the electricity
supply to the electrolyser)

Specific productivity:

0.86 kg_{DME}/kg_{dry biomass}



Enhanced biomass-to-liquid (BTL) conversion process through high temperature co-electrolysis in a solid oxide electrolysis cell (SOEC)

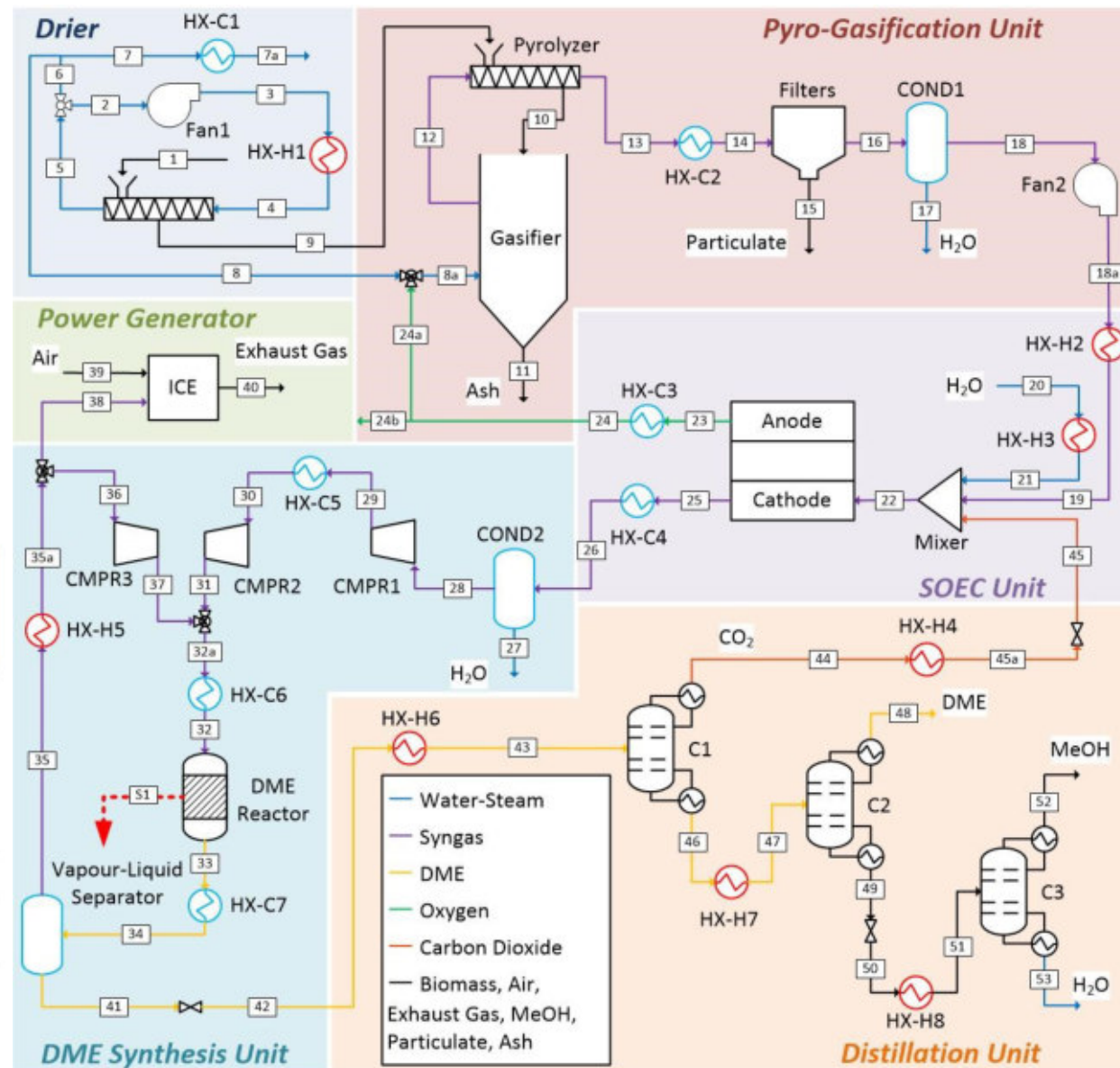
Matteo Pozzo*, Andrea Lanzini, Massimo Santarelli

Department of Energy (ENERG), Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

HIGHLIGHTS

- We modelled a BTL plant combining gasification and co-electrolysis.
- A high integration level between plant units was achieved.
- The process converts RES power into an eco-friendly fuel (DME).

Source: M. Pozzo, A. Lanzini, M. Santarelli
/ Fuel 145 (2015) 39–49



Energy systems: more integrated (production, storage, different end-uses) and complex (mix of thermo-chemical, electrochemical, biological processes, and residual thermal machines) in the future scenarios.

Most probably: higher electrification

Electrical storage: cornerpoint of complex energy systems based mostly on RES.

Electrical storage: for large-scale and long-terms, mostly electrochemical and chemical

In electrical storage, **measurement needs** mostly on **electrical variables** and variables related to **streams of fluids** (gas and liquid) (thermodynamic variables, composition, contaminant in traces, ...) with increasing frequency of the data for **fast control/regulation strategies**

Thanks!

You can find me at:
massimo.santarelli@polito.it

