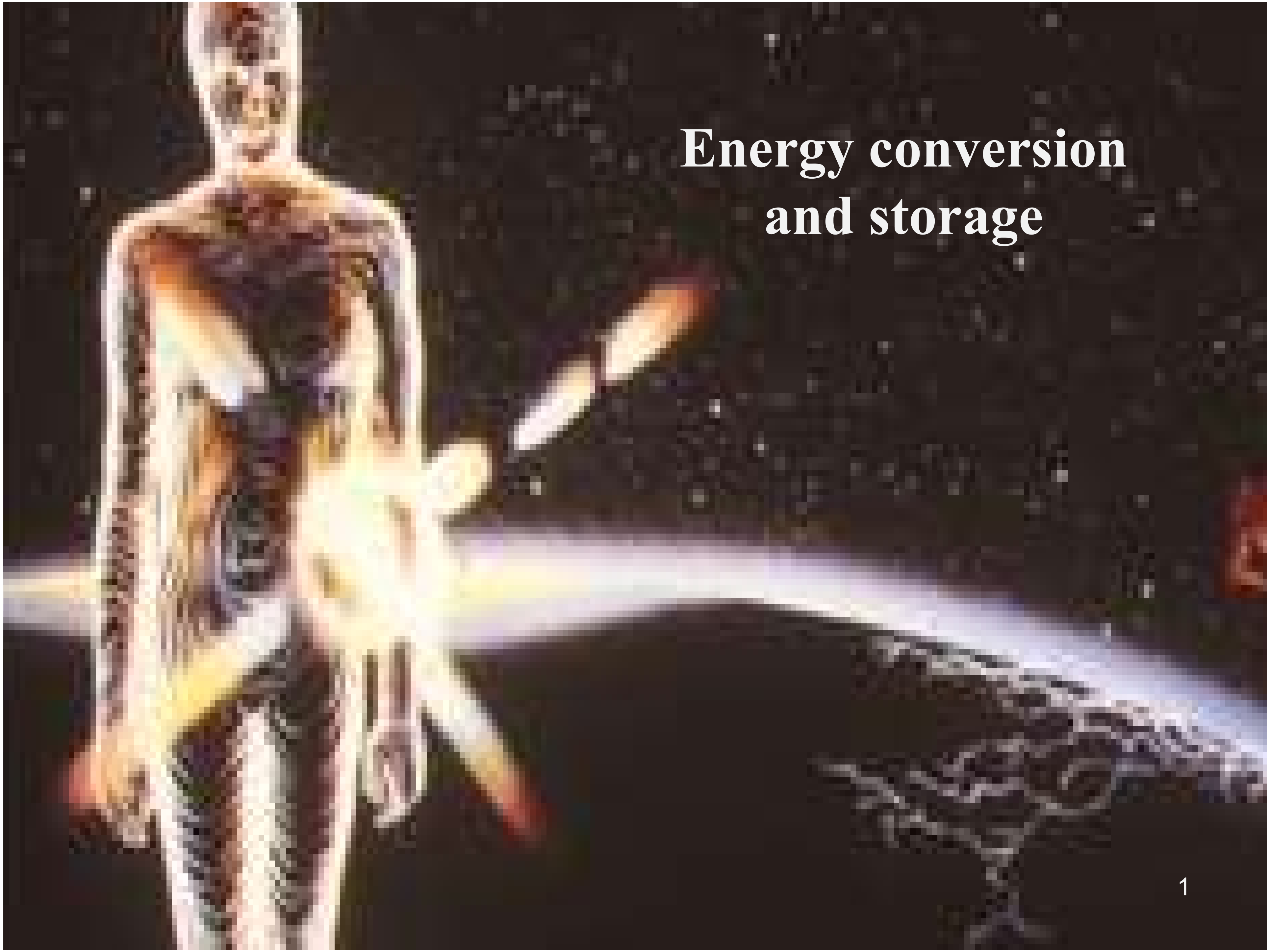


Energy conversion and storage

The problem

- ❑ Some energy sources have in-built storage:
  - fossil fuels;
  - biofuels;
  - hydro power (to some extent).

- ❑ Others are available on demand:
  - geothermal energy;
  - ocean thermal energy.

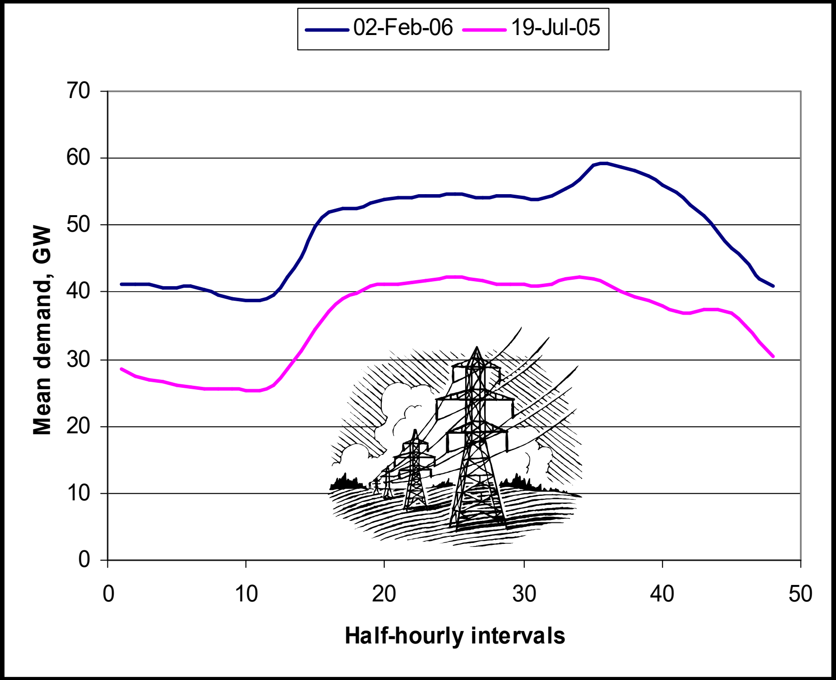
- ❑ Most renewable sources are intermittent, and the times at which they are plentiful will not necessarily coincide with consumer demand.

- ❑ The energy *grade* indicates how easily one form of energy may be converted into another.

- ❑ Electricity is a high grade and heat a low-grade form of energy:
  - electricity to heat efficiency >90%;
  - heat to electricity, or to mechanical energy, is always an inefficient process.

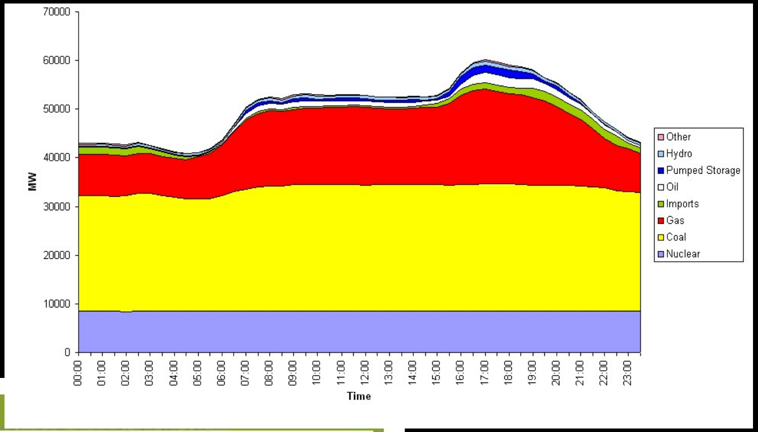
Matching of supply to demand

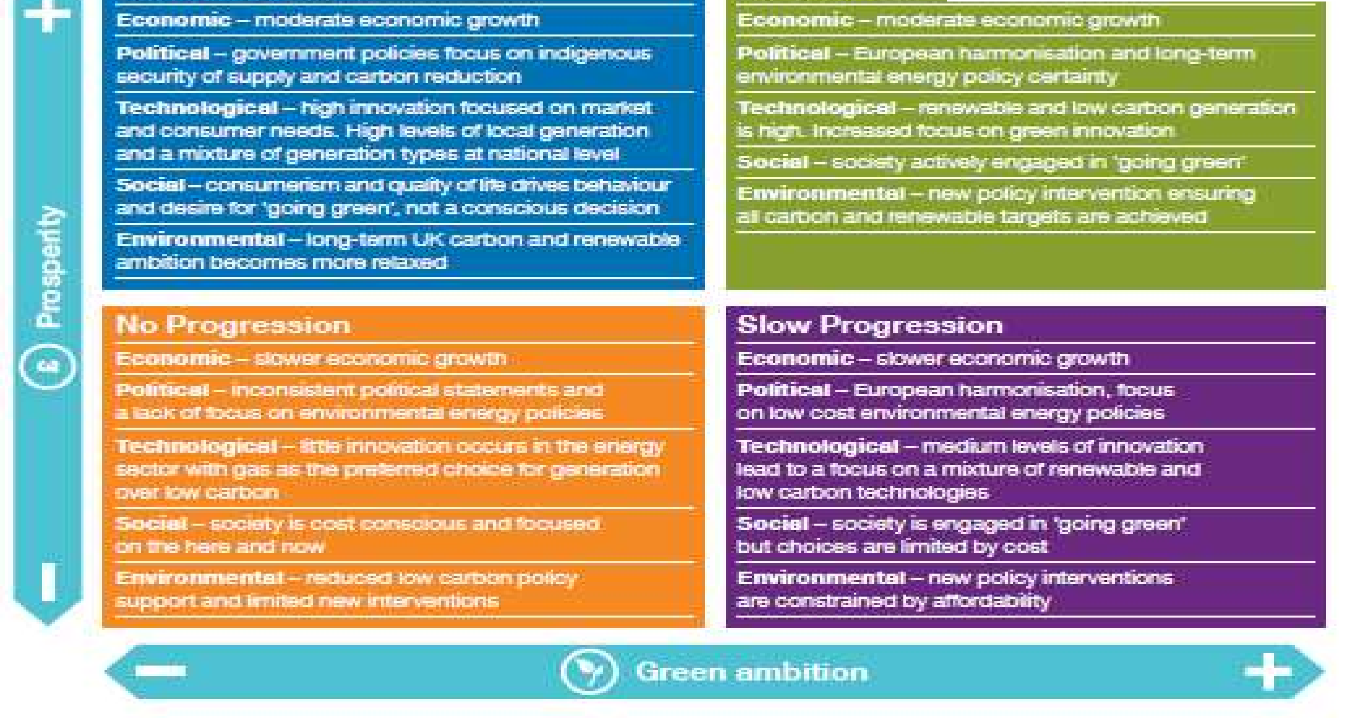
- Electricity demand in the UK varies continually (two 2-weekday periods shown).
- There is a strong seasonal influence on demand.
- The electricity network has no capacity for storing energy. If demand changes, the amount supplied must change almost immediately.
- Power stations output must be brought online/ offline or modulated to follow changes in demand.
- Some types of power station will tolerate this better than others.



- Peak power plants are started when there is a demand spike and stopped when the demand recedes.

Matching of supply to demand





Consumer Power

Economic – moderate economic growth

Political – government policies focus on indigenous security of supply and carbon reduction

Technological – high innovation focused on market and consumer needs. High levels of local generation and a mixture of generation types at national level

Social – consumerism and quality of life drives behaviour and desire for 'going green', not a conscious decision

Environmental – long-term UK carbon and renewable ambition becomes more relaxed

Gone Green

Economic – moderate economic growth

Political – European harmonisation and long-term environmental energy policy certainty

Technological – renewable and low carbon generation is high. Increased focus on green innovation

Social – society actively engaged in 'going green'

Environmental – new policy intervention ensuring all carbon and renewable targets are achieved

No Progression

Economic – slower economic growth

Political – inconsistent political statements and a lack of focus on environmental energy policies

Technological – little innovation occurs in the energy sector with gas as the preferred choice for generation over low carbon

Social – society is cost conscious and focused on the here and now

Environmental – reduced low carbon policy support and limited new interventions

Slow Progression

Economic – slower economic growth

Political – European harmonisation, focus on low cost environmental energy policies

Technological – medium levels of innovation lead to a focus on a mixture of renewable and low carbon technologies

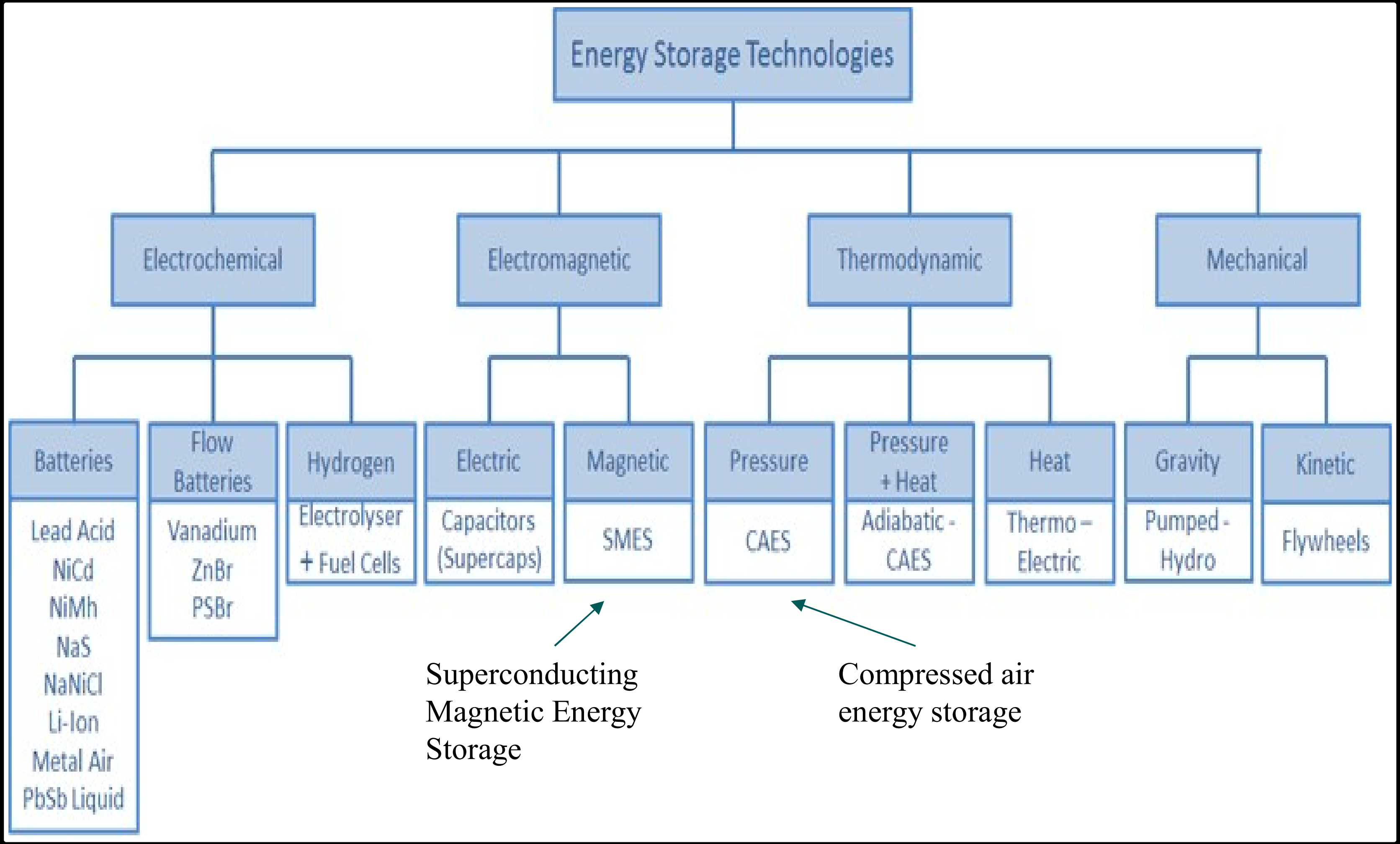
Social – society is engaged in 'going green' but choices are limited by cost

Environmental – new policy interventions are constrained by affordability

National Grid Ten Year Statement (2015), http://www.nationalgrid.com/uk/Electricity/SYS/

Energy storage technologies

Three main types: bulk, distributed and fast.

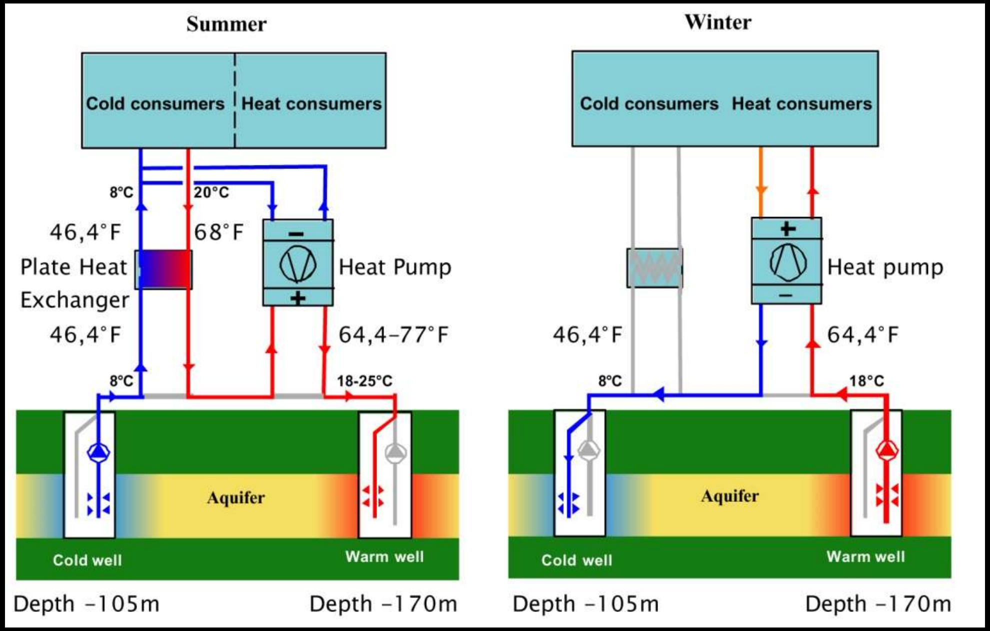


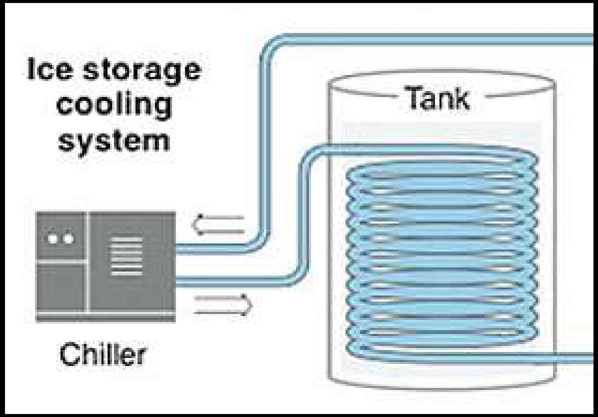
Superconducting Magnetic Energy Storage

Compressed air energy storage

Thermal storage

- Use of aquifers.
- Production and storage of chilled/ hot water, ice, hot oil, molten salts.
- District heating/ cooling schemes.
- Phase change materials for small scale use.

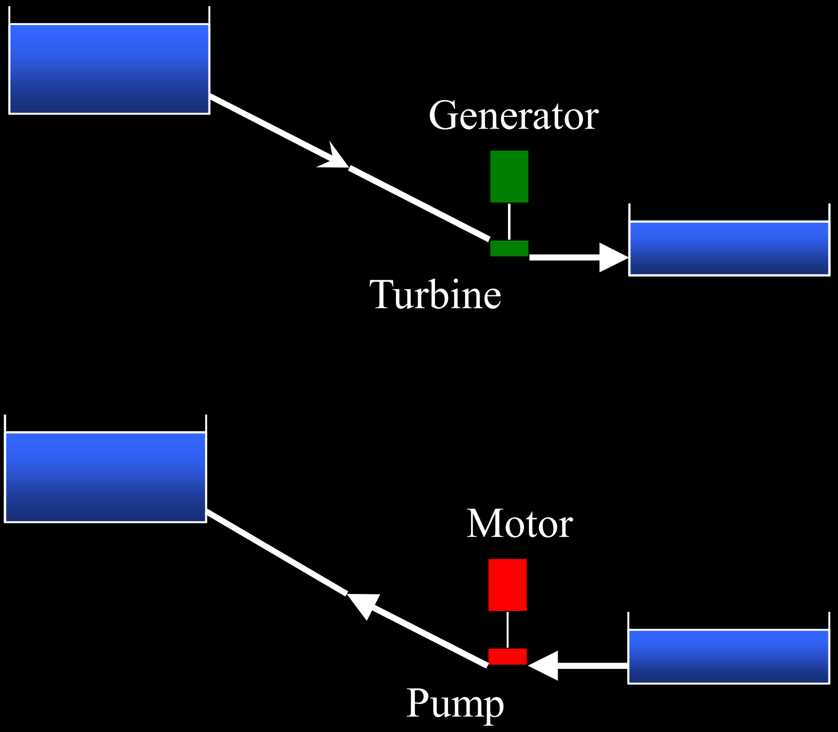




Hydraulic pumped storage

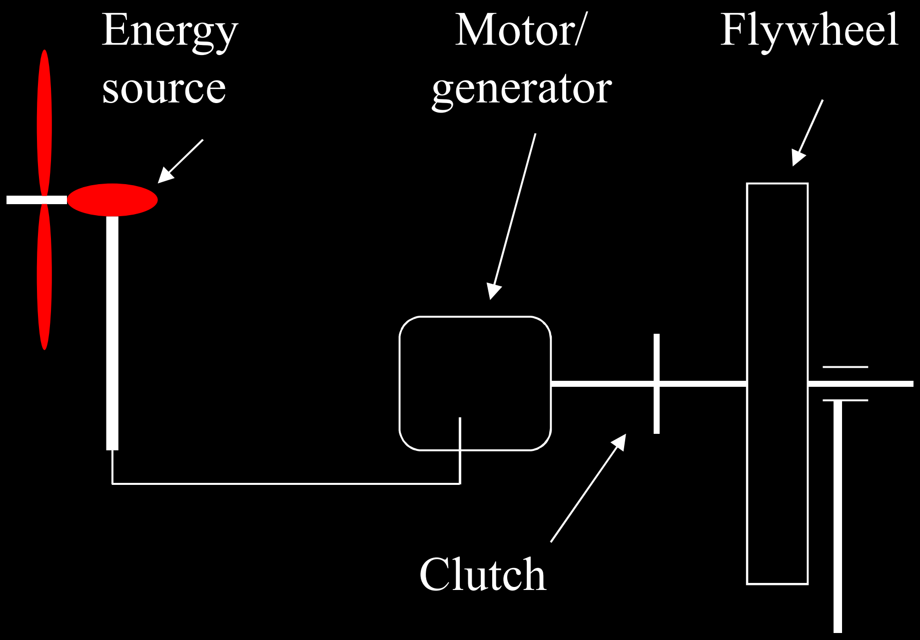
- ☐ In generating mode, the plant operates as a conventional hydro power plant.
- ☐ But the generator can function as a motor, and the turbine as a pump.
- ☐ When demand for electricity is low, power may be taken from the grid to pump water into the upper reservoir, to act as an energy store for future use when demand for electricity is high.

Cruachan pumped storage scheme



Flywheel storage

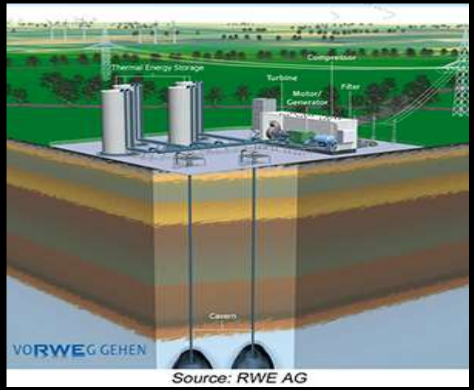
- ☐ Principle: A mass turning at high speed can store a large amount of energy in kinetic form $E_k=0.5I\omega^2$. For a cylinder of mass m and radius r, $I=0.5mr^2$.
- ☐ Storage: Electrical energy from an intermittent source (such as a wind turbine) drives an electric motor to spin up the flywheel. Clutch is disengaged, electric motor stopped, flywheel spins freely. Longevity of storage is affected by friction in bearings; friction can be reduced by magnetic levitation.



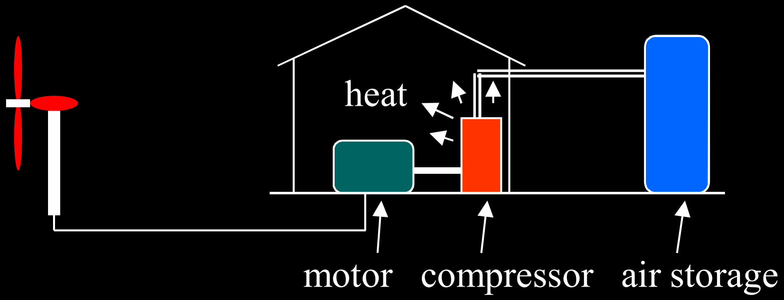
- ☐ Recovery: Clutch is engaged, electrical machine now functions as a generator and supplies energy to meet the demand. Speed of generator will not be constant, so it may be necessary to process its output using an inverter.

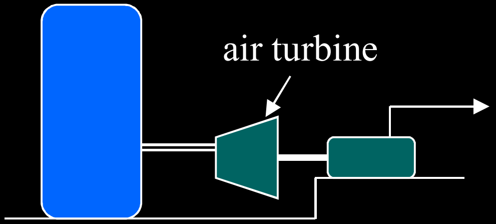
Compressed air energy storage

- Intermittent energy source supplies an electric motor to drive an air compressor.
- In a domestic context, compressor waste heat may be put to use.
- Stored energy recovered as electricity by using an air turbine to drive a generator.
- Potential problems: noise and pressure vessel integrity.
- Industrial scale systems may be constructed around caverns in natural salt or limestone deposits, which then act as the air reservoir.
- Where such systems have been built, the heat produced by the compressor is dissipated so the overall efficiency is low.



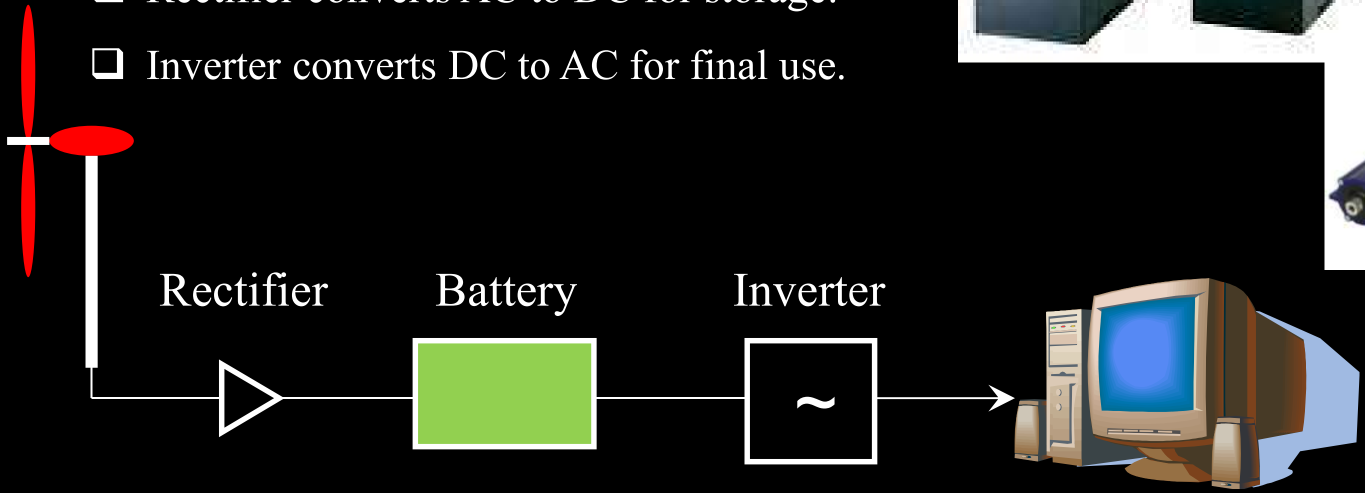
Source: RWE AG





Battery storage

- Chemical processes involved, import/ export efficiency limited as a result.
- Rectifier converts AC to DC for storage.
- Inverter converts DC to AC for final use.


Rectifier

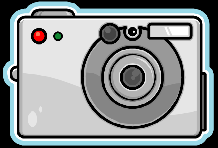
Battery

Inverter

- Super capacitors:
    - energy stored electrostatically, no chemical reactions;
    - long life cycle, high cycle efficiency (95% or more);
    - low impedance;
    - high rate of charge (and discharge if required);
    - cannot overcharge;
    - relatively expensive in terms of cost per watt;
    - low energy density (20-70 MJ/m^3).

Re-chargeable batteries

- ❑ After a long period of inactivity, battery technology has developed rapidly in the last 10-15 years.
- ❑ Import/export efficiency can be as high as 75% for lead acid batteries; over 80% possible for other types. For many small-scale applications it is much lower, between 20% and 50%.
- ❑ Recent research is directed towards use in road vehicles, where high efficiency and energy density are required. Hybrid vehicles presently use NiMH cells, moving towards lithium ion types as they become more reliable.
- ❑ Li-ion
  - advantages – high energy density; low rate of self-discharge; low maintenance.
  - disadvantages – relatively rapid ageing.



	Lead acid (sealed)	Nickel Cadmium	Nickel metal hydride	Lithium Ion
Energy density (Wh/kg)	40	65	90	150
Cycle life	250	1500	400	500+
Charge time (h)	12	1	3	< 1
Introduced	1970	1950	1990	2000

TESLA Powerwall

- Application – home energy storage
- Battery – rechargeable lithium-ion
- Inverter – fully integrated
- Energy – 14 kWh
- Power – 5 kW continuous, 7 kW peak
- Mounting – wall or floor mounted, indoor or outdoor
- Round trip efficiency – 89% for AC, 91.8% for DC
- Cost – $5,500
- Operating temperature range – -20 C to 50 C
- Warranty – unlimited cycles for up to 10 years
- Dimensions – 1150 mm x 755 mm x 155 mm
- Weight – 122 kg

Thermal energy storage requirements

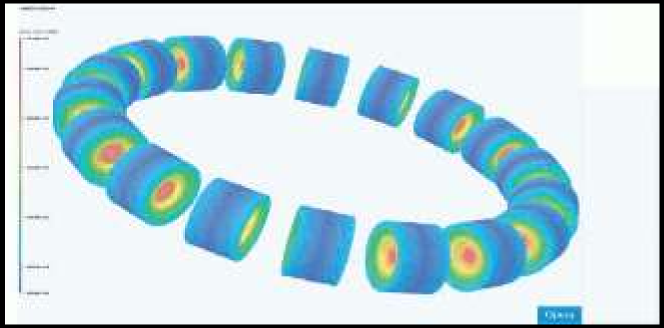
- ☐ Readiness for deployment at scale
- ☐ Speed of charge/ discharge
- ☐ Storage capacity
- ☐ Ability to schedule
- ☐ Life expectancy and reliability
- ☐ Unit capital cost (£/kW and £/kWh)
- ☐ Environmental impact
- ☐ Round-trip energy efficiency
- ☐ Ease of installation (size/ weight)

TES evaluation example

Attribute	Ice	Chilled water	Low temp. fluid
Volume	good	poor	fair
Footprint	good	fair	good
Modularity	excellent	poor	good
Economy of scale	poor	excellent	good
Efficiency	fair	excellent	good
Low temp. capability	good	poor	excellent
Ease of retrofit	fair	excellent	good
Rapid charge/discharge	fair	good	good
Reliability	fair	excellent	good
Remote siting from chillers	poor	excellent	excellent
Dual-use as fire protection	poor	excellent	poor

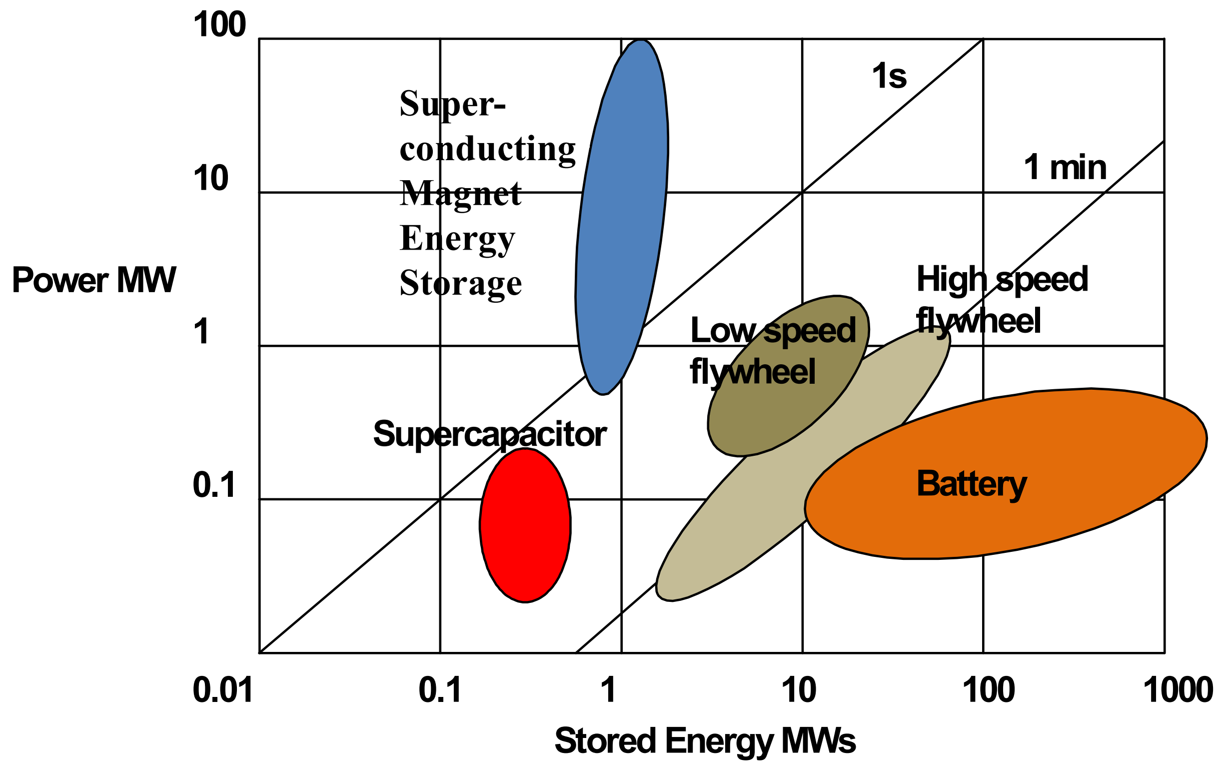
Superconducting Magnetic Energy Storage (SMES)

- Stores electricity within the magnetic field of a coil of superconducting wire with near-zero loss of energy.
- Can store and discharge large quantities of power almost instantaneously.
- Requires a power conditioning system.
- Enables brief bursts of power to maintain grid reliability with high penetration of stochastic RES.
- Benefits:
  - improved power quality for critical loads;
  - provides carryover energy during momentary voltage sags and power outages;
  - improves load levelling between RES and the transmission/ distribution network;
  - environmentally beneficial compared to batteries; no chemical reactions and no toxins produced;
  - enhances transmission line capacity and performance – has a high dynamic range, an almost infinite cycling capability, and an energy recovery rate close to 100%;
  - enables long-term storage in a compact device with cost advantages in system costs.

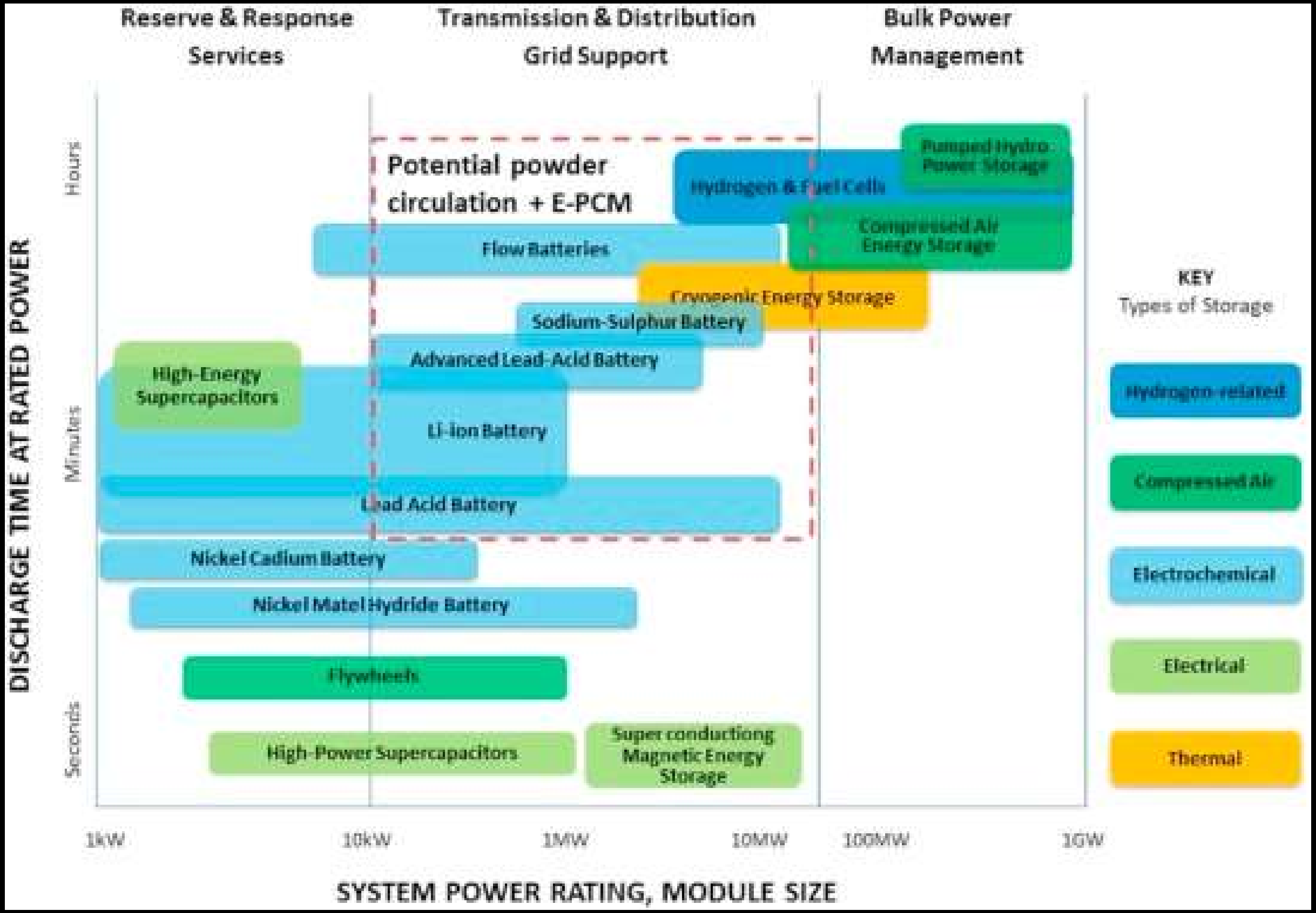


http://www.superpower-inc.com/content/superconducting-magnetic-energy-storage-smes#acp

Characterisation of performance



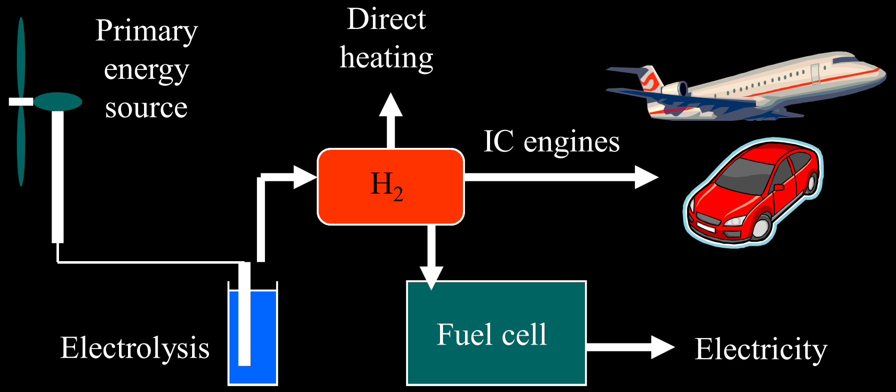
Power versus energy

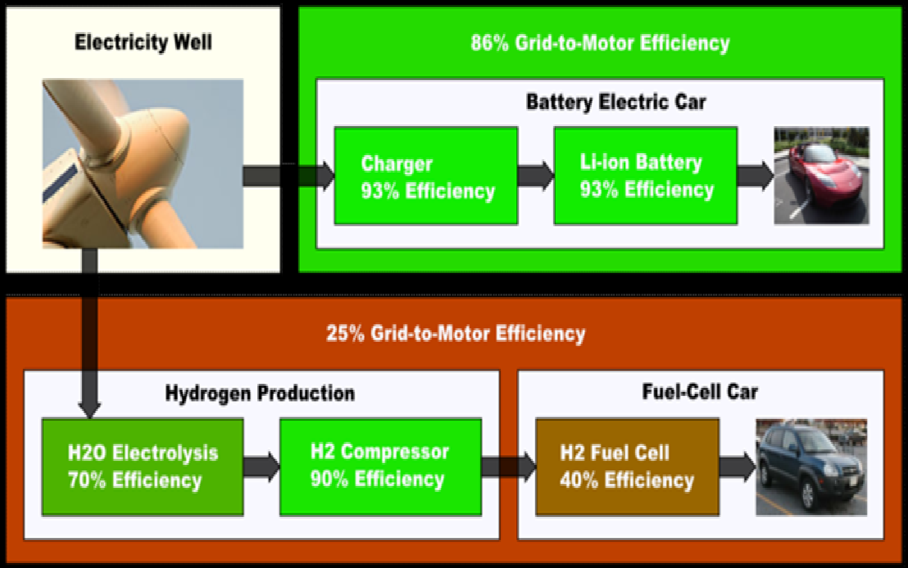


http://www.sciencedirect.com/science/article/pii/S0360128515300149

Hydrogen economy

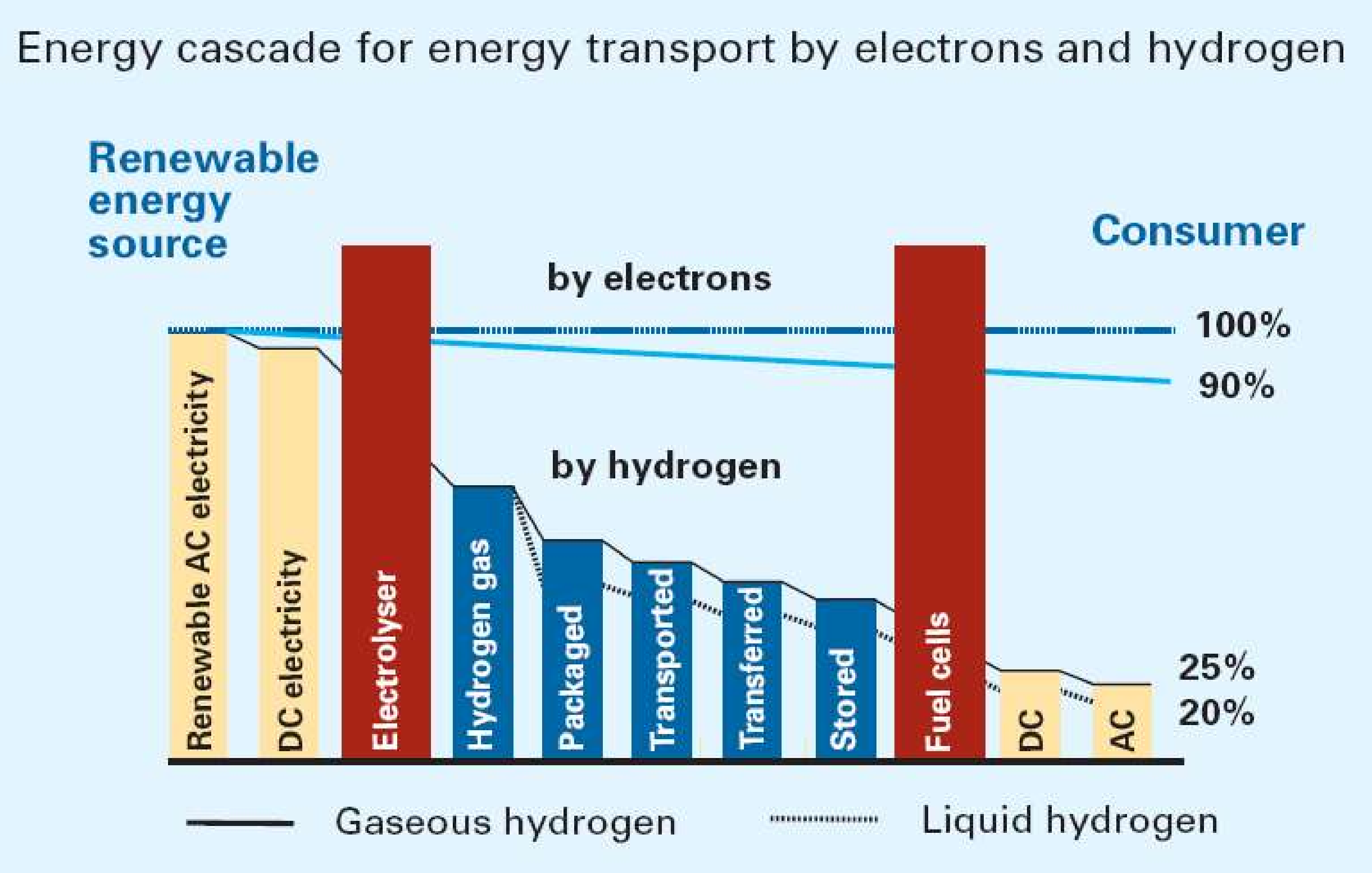
- Could hydrogen replace fossil fuel, acting as an energy store to serve all demands?
- The electrolysis process has an efficiency of ~70% (will improve with research).
- Commercial fuel cells are presently less than 60% efficient.
- Hydrogen must be either compressed or liquefied to have an acceptable energy density – both processes require significant energy inputs.
- Hydrogen gas is volatile – long-term storage and transportation is problematic and costly to resolve.



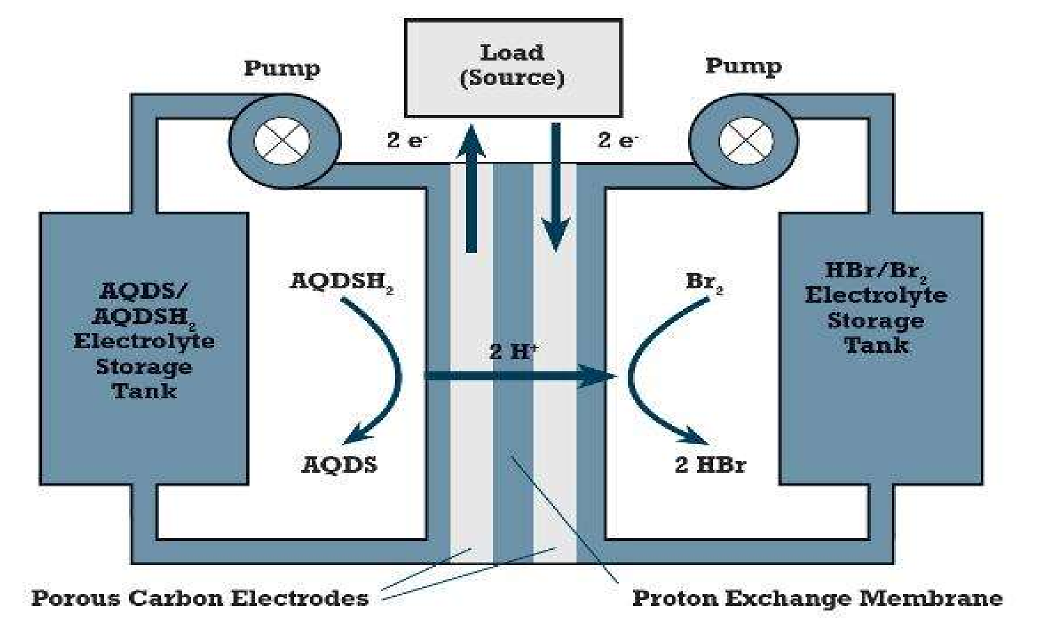


Alternative routes to electric road vehicle propulsion.

Hydrogen round-trip efficiency



Aqueous flow batteries



Electrolyte tanks separated by a membrane across which electrons and protons can transfer, reversibly storing and generating electricity (arrows show discharge).

- ❑ Conventional electrolyte: vanadium redox.
- ❑ Future electrolyte: 9,10-anthraquinone-2,7-disulphonic acid (AQDS) as found in rhubarb.
  - From Huskinson B *et al,* ‘A metal-free organic-inorganic aqueous flow battery’, **Nature**, 505, pp195-198 , 2014: AQDS on the -ve side and a bromine-based redox couple on the +ve side yields a peak galvanic power density exceeding 0.6 W/cm^2 at 1.3 A/cm^2 and a better than 99% storage capacity retention per cycle.
- ❑ Advantages – highly scalable; rapid charging/ discharging; low charge loss.
- ❑ Disadvantages – low power density; relatively large and complex

Conclusions

- ☐ The production of increased amounts of renewable-generated electricity brings problems of matching supply to demand.
- ☐ It therefore becomes relevant to study methods of converting and storing large amounts of energy.
- ☐ A number of well-established methods are available, but all have significant drawbacks.
- ☐ Major research is being directed towards improving existing methods of energy storage and conversion, and developing new approaches such as flow batteries.
- ☐ It seems inevitable that there will always be some trade-off between energy security and cost.
- ☐ Need gives rise to new ideas: e.g. peak power plant.