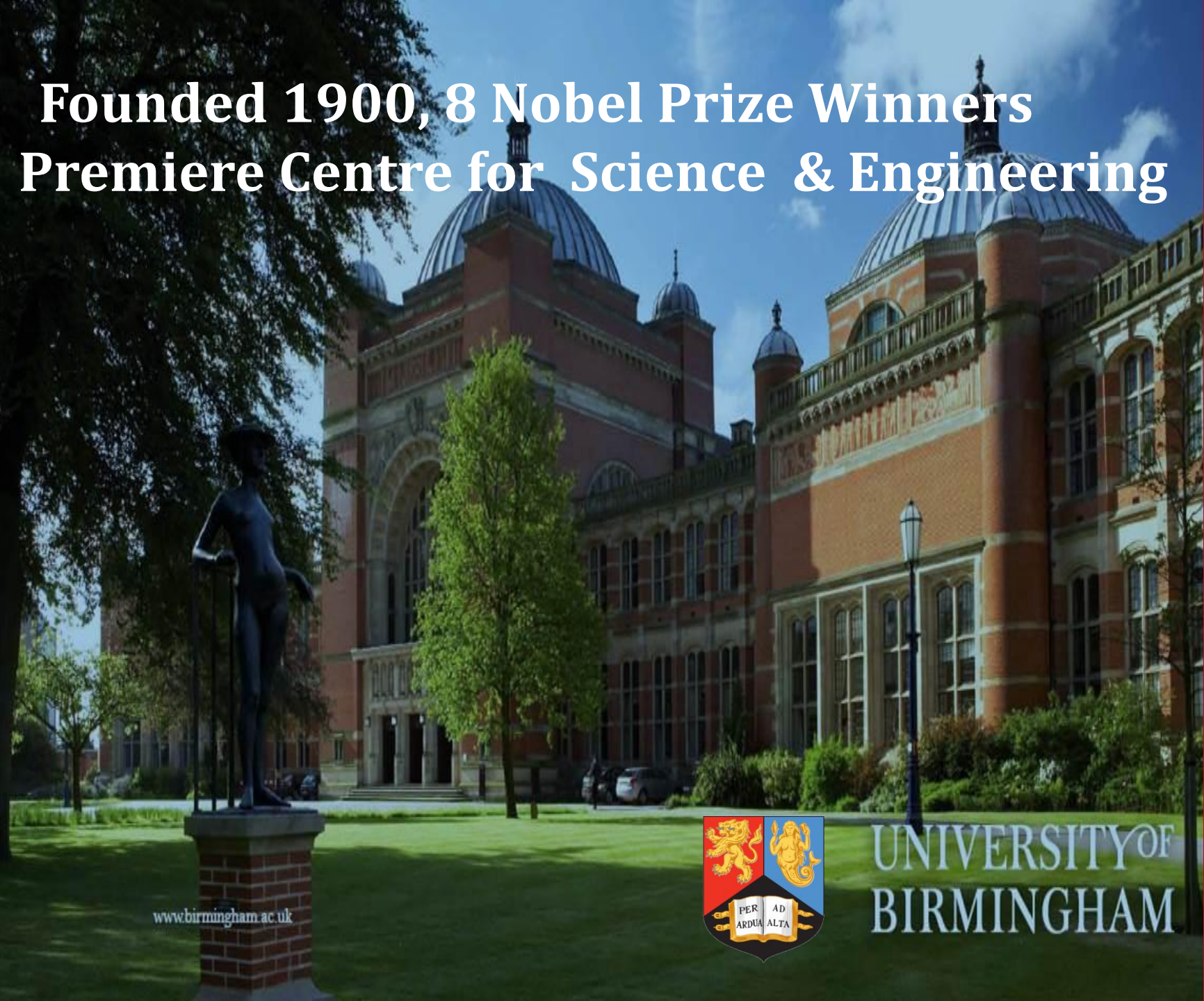
INNOVATION IS GREAT BRITAIN

85 NOBEL PRIZES IN SCIENCE AND TECHNOLOGY ALONE

Touch Bionics
Livingston, Scotland


Founded 1900, 8 Nobel Prize Winners
Premiere Centre for Science & Engineering
www.birmingham.ac.uk
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UNIVERSITY OF BIRMINGHAM

Liquid Air Energy Storage –

a new energy vector and means of large-scale energy storage?

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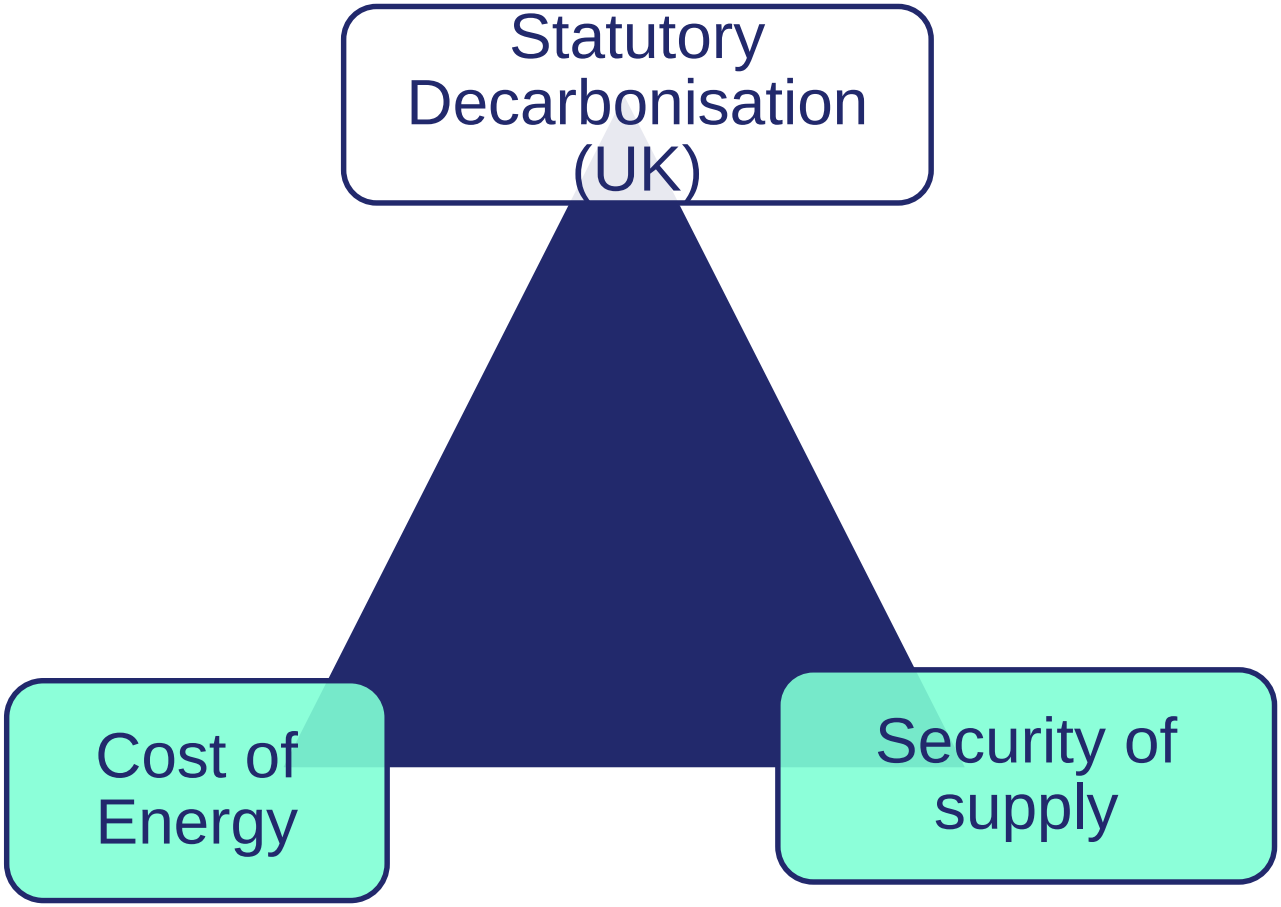
"Energy storage is a necessity for the future not an option"

- Policy drivers
- Technical drivers
- Storage devices
- Liquid air as a energy vector
- Putting a value on storage
- What next?
- Opportunities for UK-Brazil collaborations

Common Drivers Brazil/UK



Policy Drivers/Mechanisms (UK context)

- Climate Change Act 2008 (80% reduction CO_2 by 2050)
- EU Renewable Energy Directive 2009
- Renewables Obligations Banding Review (15% renewables by 2020)
- Electricity Market Reform (EMR) and Energy Bill (2013)
- Regional country governance & the cities agenda
- National security (supply/cyber)

In UK 25GW by 2020 from wind

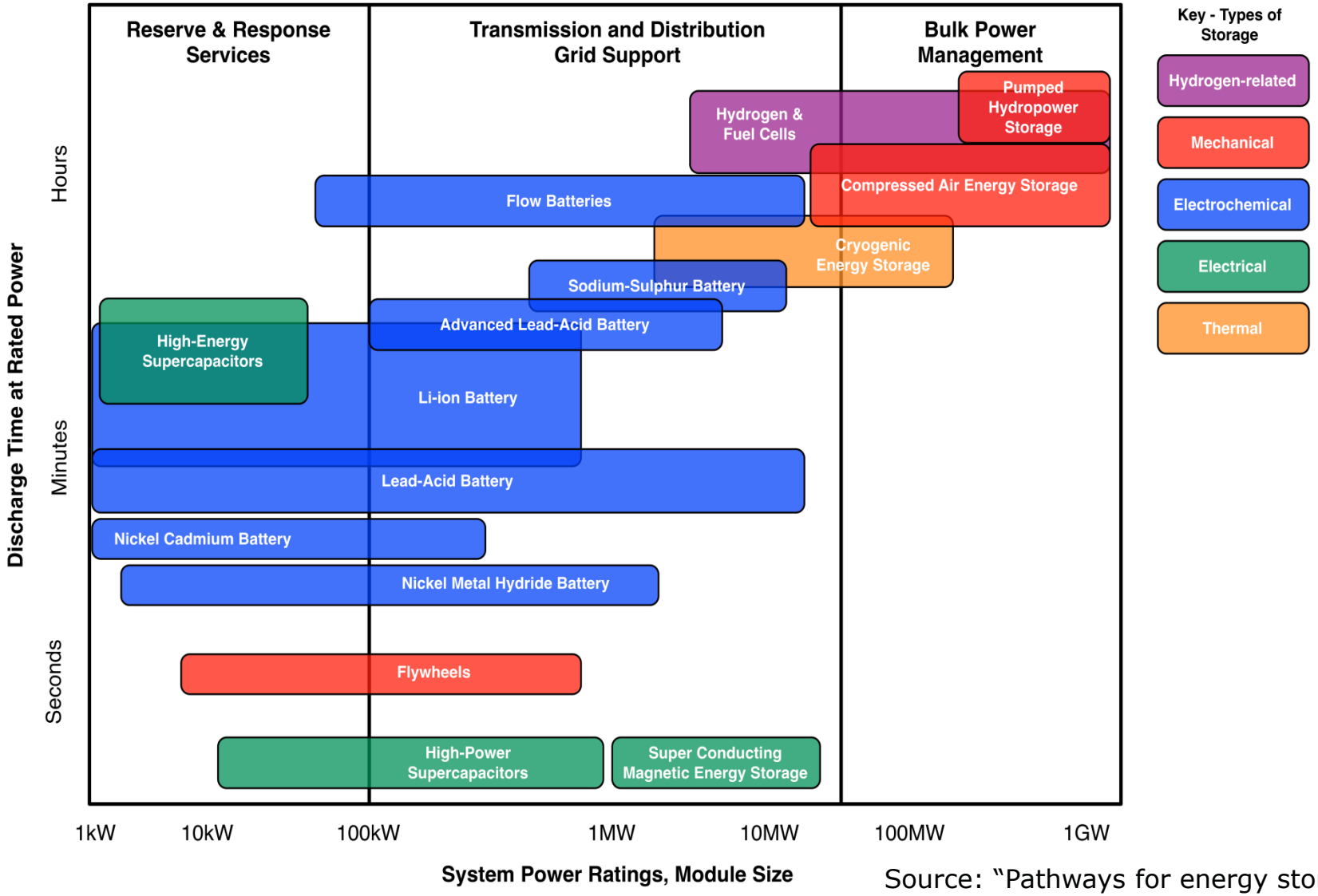
Technical Drivers & Issues

- Shift of energy mix in UK and Europe (coal, nuclear, gas (LNG, fracking), biomass, renewables)
- Uncertainty of pathways ahead
- Large base-load electricity generation (need to sweat assets)
- Wrong ***time*** energy (intermittency) and wrong ***place*** energy (e.g. offshore)

- Storage needed at range of locations associated with generation, interconnection, transmission & distribution.

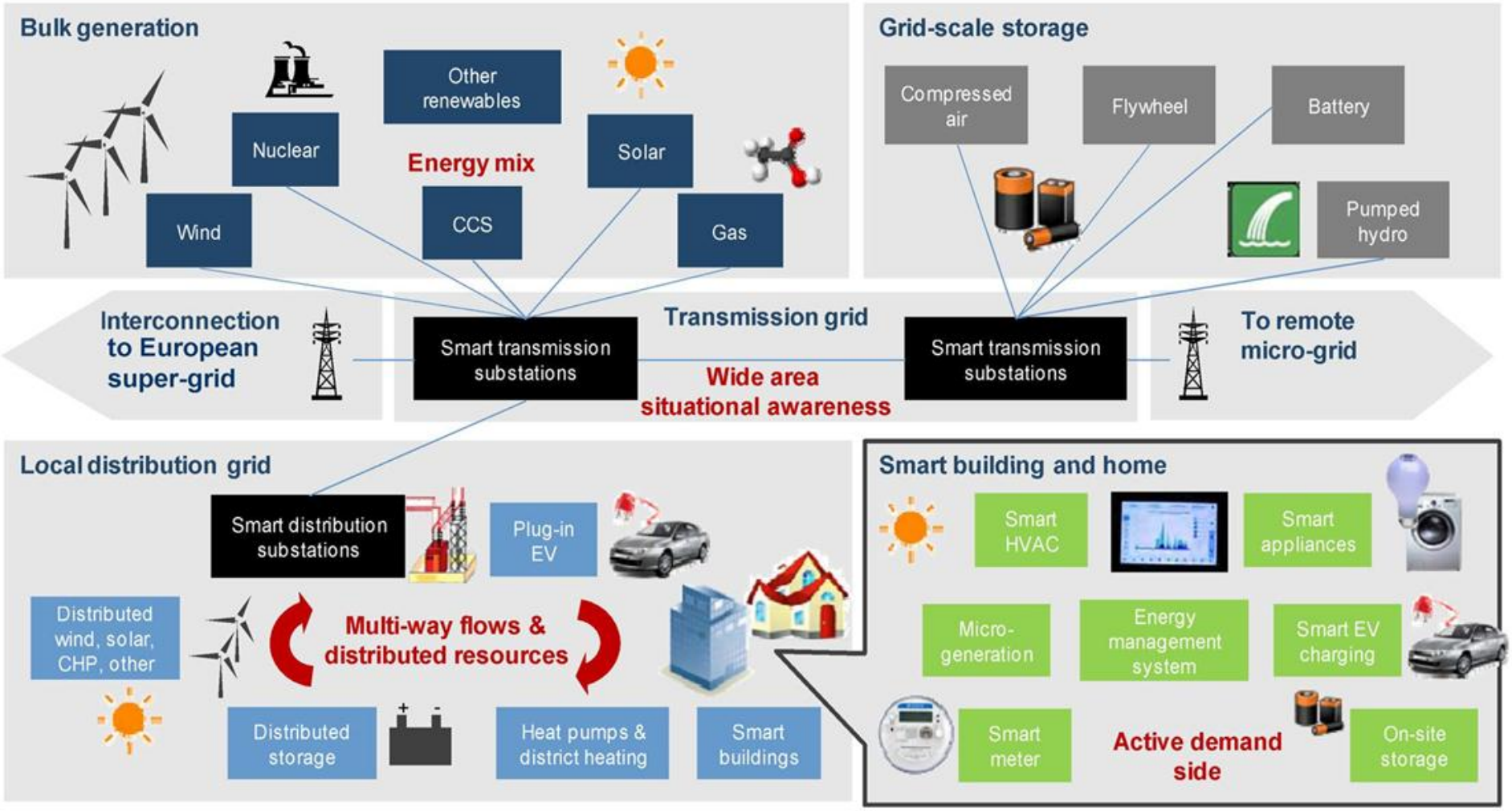
Storage gives flexibility of scale and location, defers investment and lowers systems costs, reduce SMART grid and interconnect risks

Storage Technologies



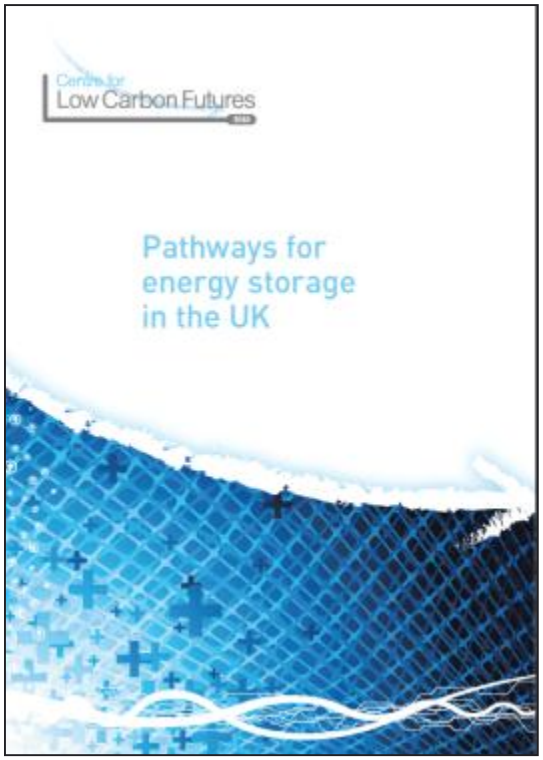
Source: "Pathways for energy storage", Centre for Low Carbon Futures, 2012

Storage Needed Across the Entire Grid System



Recent reports

Energy Research Partnership, June 2011
http://www.energyresearchpartnership.org.uk/energystorage



Centre for Low Carbon Futures, March 2012
http://www.lowcarbonfutures.org/energy-storage

Royal Academy of Engineering/Chinese Academy of Sciences, August 2012

Liquid Air as an Energy Vector?

Cryogens are already safely transported on our roads

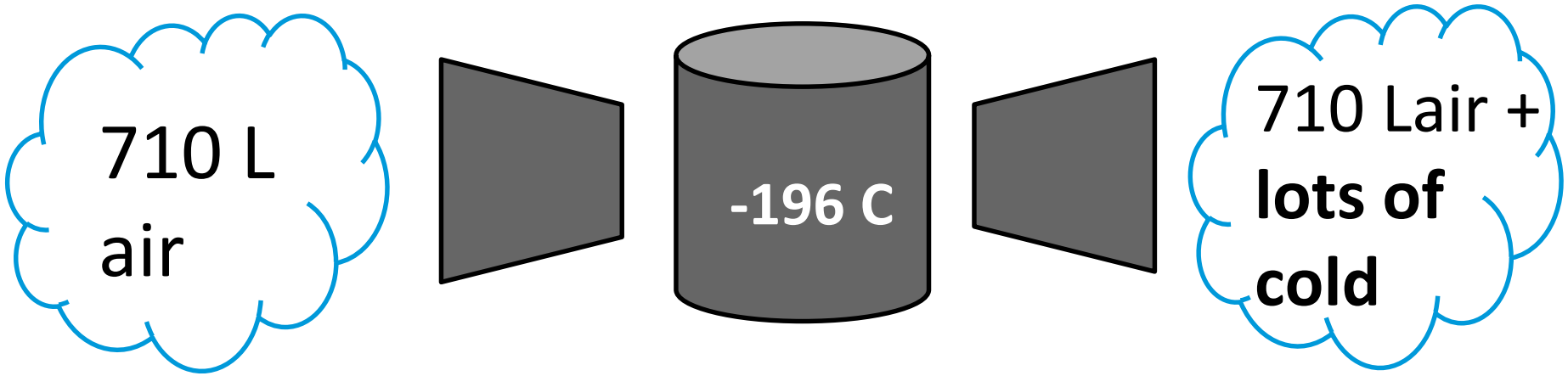
	Energy density, KJ/litre
Liquid Nitrogen at ambient pressure	620
Compressed hydrogen gas at 200 bar	1918
Compressed air at 200 bar (CAES)	143
Water with 100m head (pumped hydro)	1

"*The birth of the nitrogen economy*", Gas World, 89, October 2012. "*Future of Energy Storage: technologies and policy*," RAEng/CAS, London, Aug. 2012, ISBN 1-903496-91-8.

Storage of cryogens is in low pressure containers

Liquid Air: the basic principle

1 L air stored at
atmospheric pressure



Waste / off-peak electricity

Power on-demand and harness low grade waste heat

The basic principle

Liquid Air Energy Network

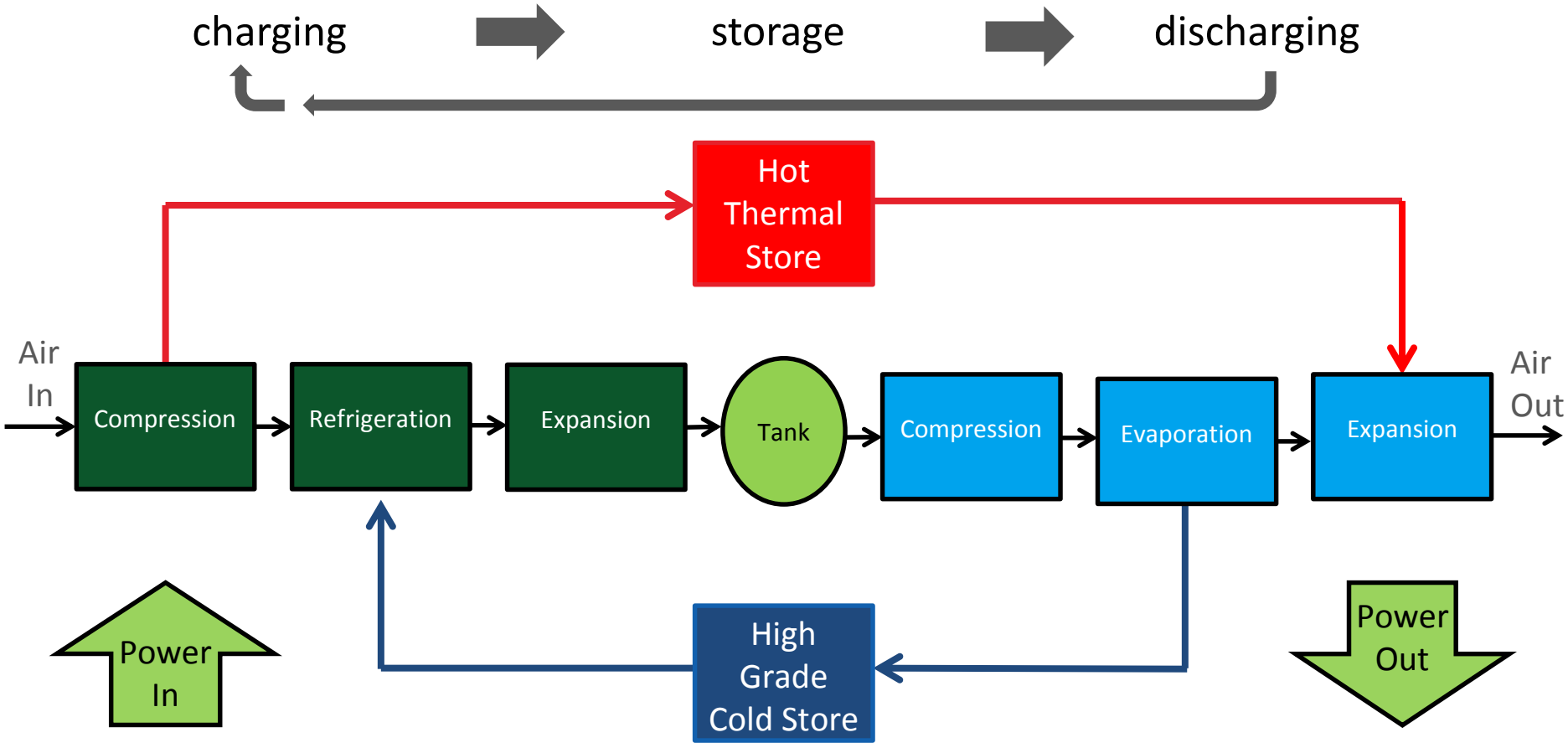
Handling Liquid Cryogens

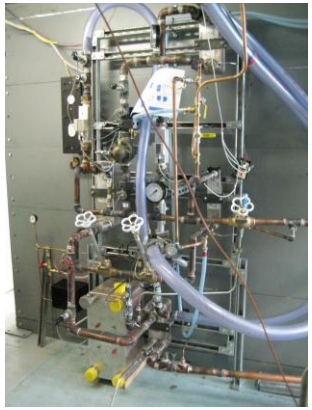
- Cryogens are widely and safely transported on roads

- Driver operated LN2 systems are in routine use for refrigeration

- LN2/LA can be filled at 100 L/min

A cryogenic energy storage system





Research begins with the University of Leeds

Power recovery cycle demonstrated in lab-scale tests

Installation of complete pilot CryoEnergy Storage plant

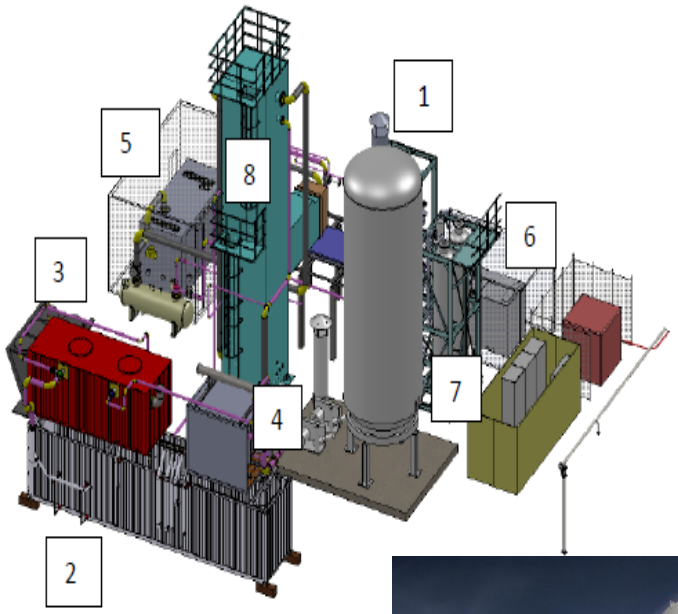
2005 2006 2007 2008 2009 2010 2011 2012 2013

Cold recovery cycle proved viable in lab experiments

Installation of power recovery cycle in pilot plant

Commercial design and build

Liquid Air Energy Storage



1. Cryogen storage
2. Power recovery (40 ft container)
3. High grade cold store
4. Cold circulation compressor
5. Recycle compressor
6. Main compressor
7. Air purification unit
8. Main cold box

- University of Leeds patent 2005, lab demo 2008, licensed to Highview Power Systems.
- £10M on grid demo 2010/1 with SSE, Slough
- 330kW turbine output
- 30 t/day liquifier, having 2.5MWhrs storage
- UK's only on grid storage demonstration project

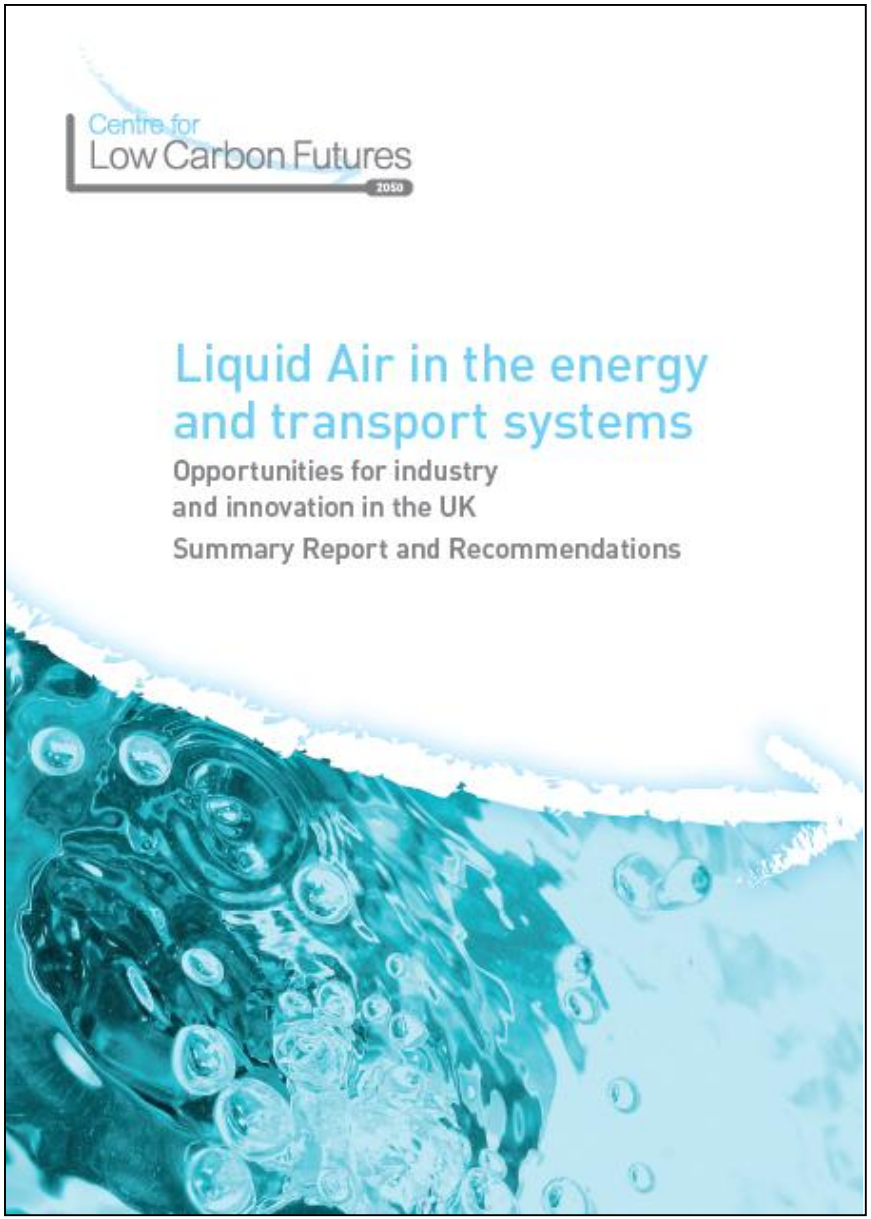
Cryogenic Energy Plant, grid connected, Slough UK

HIGHVIEW POWER STORAGE

Liquid Air Energy Storage

some emerging comparative data

Technology	Size Range (MW)	Capital Cost ($/kW)	Capital Cost ($/kWh)	Efficiency (% round trip)	Geographical requirements	Use of advanced chemicals
Pumped Hydro	280-530	2,500-4,300	420-430	76-85	Requires mountains	No
CAES (with gas firing)	180	960-1,150	60-120	46-48	Requires caverns	No
NaS Battery	<50	3,100 - 3,300	520-550	68	None	Yes
Flow batteries	<50	1,450 - 1,750	290 - 350	60	None	Yes
Highview Cryo Energy System	10-200	900 -1900 (depending on cycling)	260-530 (depending on cycling)	50-80+	None	No



Cryogenic energy storage

Report launched 9 May 2013 at Conference at Royal Academy of Engineering

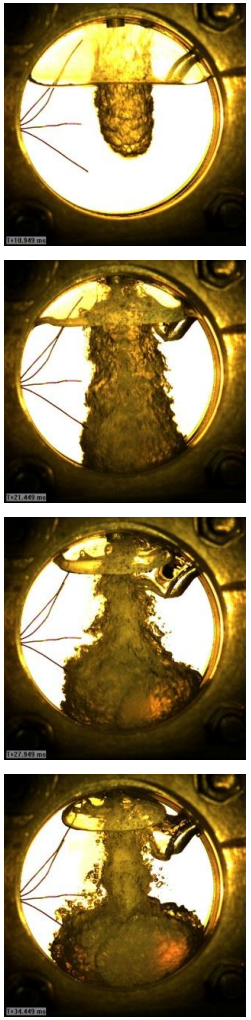
Looking at the potential of ‘liquid air’ as a storage medium and novel energy vector.

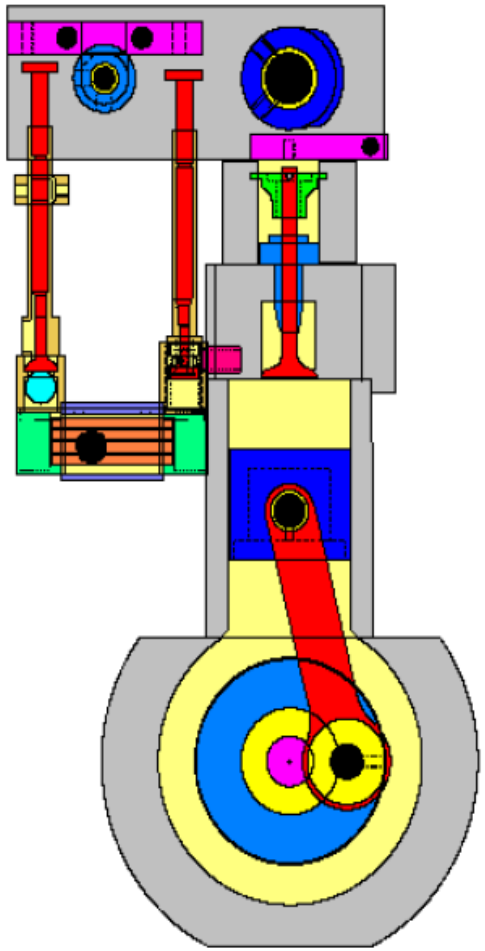
www.liquidair.org.uk

A national cryogenic R&D facility will be developed at University of Birmingham as part of the Centre for Low Carbon Futures (CLCF) programme funded as Great British Technology

Vehicles that runs on air

Example: Cryogenic engine





- Boiling takes place *inside* cylinder through direct contact heat exchange with a heat exchange fluid

- Target for power output: 30kW/litre

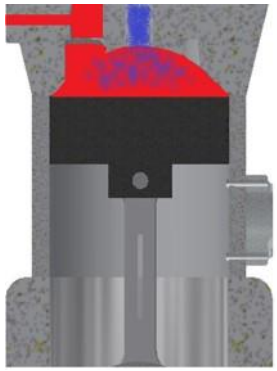
- Clean and cool!

www.dearmanengine.com

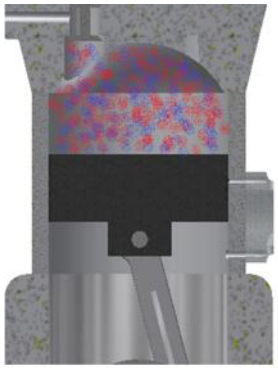
Dearman Engine - technology

1. 

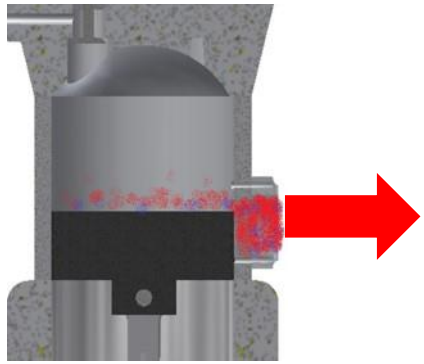
Return Stroke
Warm heat exchange fluid (HEF) enters the cylinder.

2. 

Top Dead Centre
Cryogenic liquid is injected directly into the cylinder. **Heat transfer with the HEF causes rapid vaporisation and pressure rise**.

3. 

Power Stroke
The vaporised cryogenic liquid expands pushing the piston down. Direct contact heat transfer continues allowing near isothermal expansion.

4. 

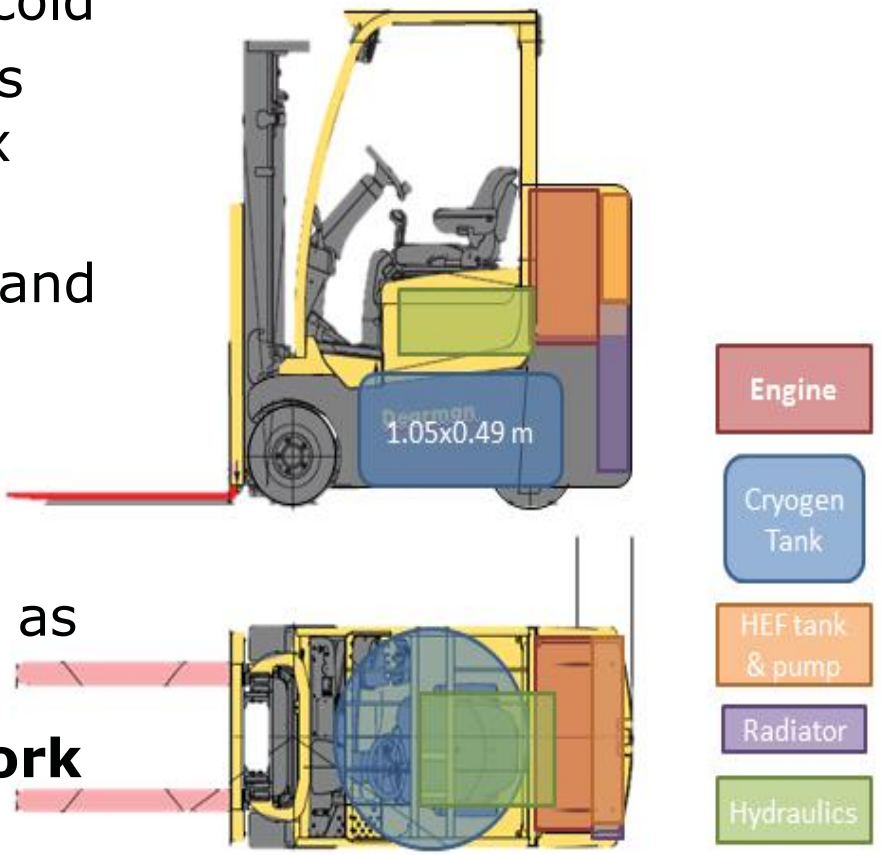
Bottom Dead Centre
Exhaust mixture leaves the cylinder; gas is returned to the atmosphere; HEF is re-heated and re-used.

The Dearman Engine COMPANY
www.dearmanengine.com

Vehicles that runs on air!

Application: Consequences

- New class of renewable system
- Utilise low grade heat and cold
- Displacement for fossil fuels (political, economic and tax issues)
- Displacement for batteries and fuel cells (based on cost, resource)
- Will drive renewable routes (solar/wind) for gas compression and liquid gas as an energy storage medium
- Early ZEV applications **in fork lift truck**, **tuk-tuks and mining operations** likely.

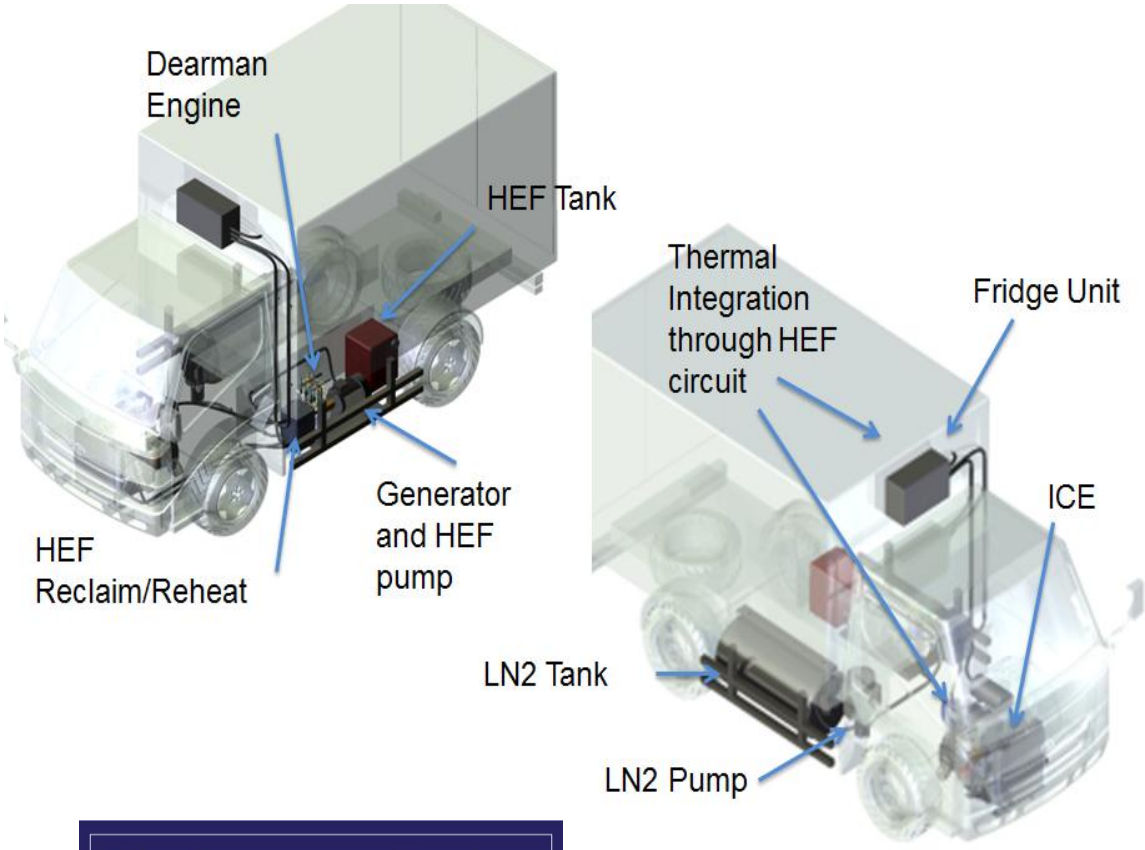


"Pathways for energy storage in the UK", Centre for Low Carbon Futures, York, March 2012.
www.bbc.co.uk/news/science-environment-19785689 .

Vehicles that runs on air!

Application: Hybrids will be first applications

- **A cost-effective and zero-emission combined power and cooling solution** applicable to mobile refrigeration and buses – a multi-billion $ global market
- **A very high yield *low- grade* heat energy recovery system**; to be integrated with an internal combustion engine (or fuel cell) or as an APU with air conditioning/cooling



Power and transport integrated

Cold from LNG (Optional)

Cold storage

Cooling / Refrigeration

Surplus / 'waste' electricity

Liquefaction

Liquid Air Energy Storage

Tank

Power Recovery

Peak/security of supply electricity

Liquid air transported onsite

Waste heat (convert to additional power)

Cooling

Peak shaving or remote back-up pov

Power Recovery

Tank

On and off highway

Co-generation or industrial processes

Waste heat (convert to additional power)

Zero emissions remote back-up power

Putting a Value on Storage

Value is complex to calculate due to:

- Generation, transmission, interconnection, distribution responsibilities
- Scales of modelling (micro/macro) and into the future
- Distribution mixes for each city/nation dissimilar
- Need to consider holistic system (water, waste, vehicle electrification, thermal management(district heating/cooling).

Value clearly lies in:

Delay/optimisation of planned investment in transmission
Security of capacity of renewables at point of generation
Partitioning the risk profile to suit city/region characteristics
Provides basis for off-grid generation
New business and economic benefits e.g. provision of **cold**

What Next?

UK Collaboration for Research and Commercialisation

- University of Birmingham is a National Centre for Hydrogen Research and runs many EV and H2 cars from our own filling station. In future we look forward to development of **liquid air energy storage** and associated hybrid transport applications for **cars, trains** and **boats.**

- An **industry facing network** has also been formed: ***liquidair.org.uk***

Liquid Air Energy Network

UNIVERSITY OF BIRMINGHAM

PER ARDUA AD ALTA

What Next?

UK Collaboration for Research and Commercialisation

To recognise: collaboration likely to be valuable due to different energy mix and pathways against a governmental drive of radical decarbonisation.

- Research into energy storage technologies

- Modelling of energy storage options and technical utilisation applications

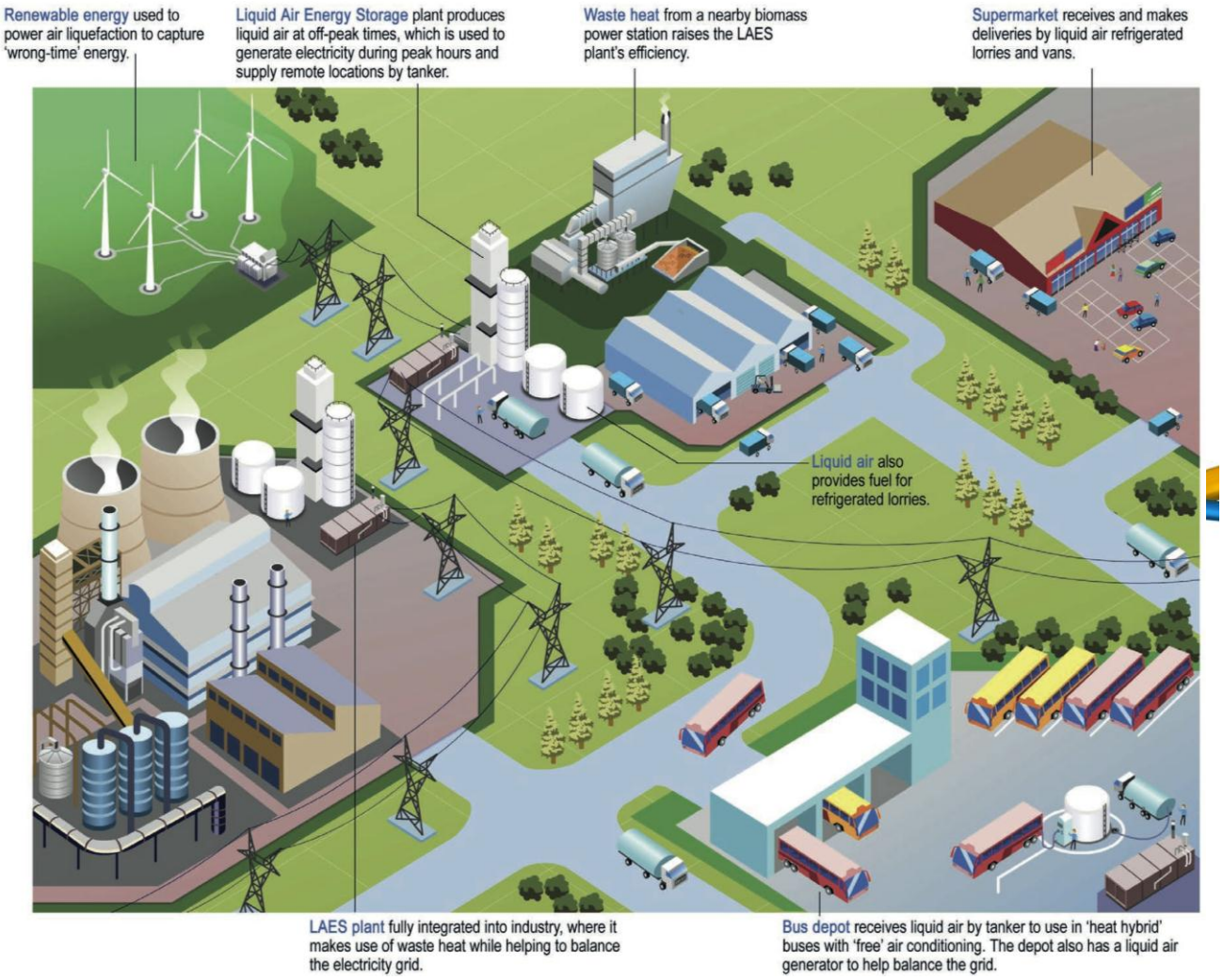
- Simulating grid response

- Business evaluation of storage scenarios and value created for a 'cold' economy

- Demonstration of technologies and integrated (industrial) applications in Brazil?

Delivering a regional green economy in Brazil?

The Liquid Air Economy



In a liquid air economy, many different energy services could be provided from a single 'tank of cold'.

The environmental and economic benefits could be great.