Liquid Air in Transport -

Examples of use of Liquid Air in transport

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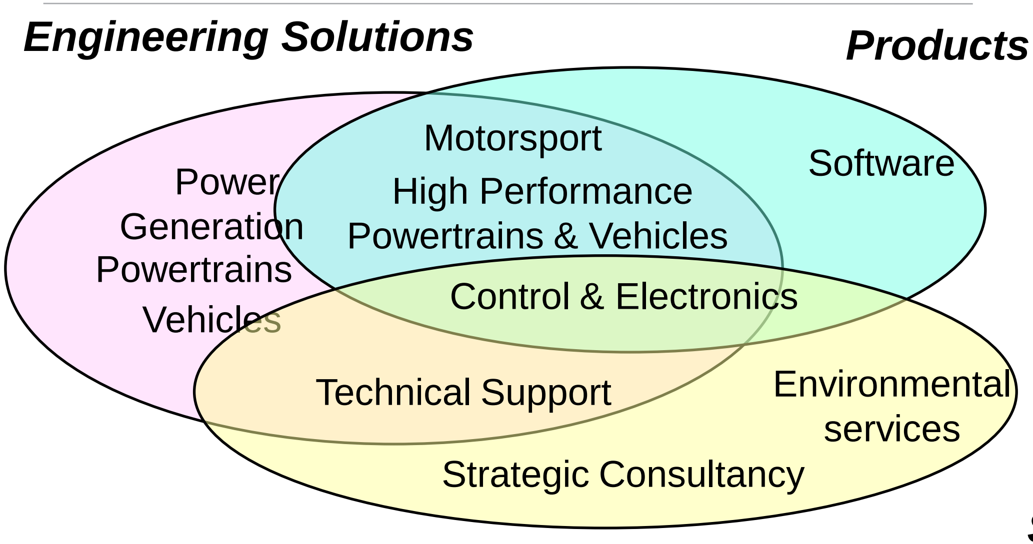
Ricardo delivers world class strategy, engineering & technology to global automotive, transport, defence & energy industries

Company:

- Established in 1915 and independent
- £197.4 million revenue (FY 11/12)
- Additional £39.1 million revenue from AEA Europe (FY 11/12) acquired 2012
- More than 2300 employees - over 2000 technical, scientific & engineering staff
- Significant internal investment in R&D
- Global presence in 21 locations

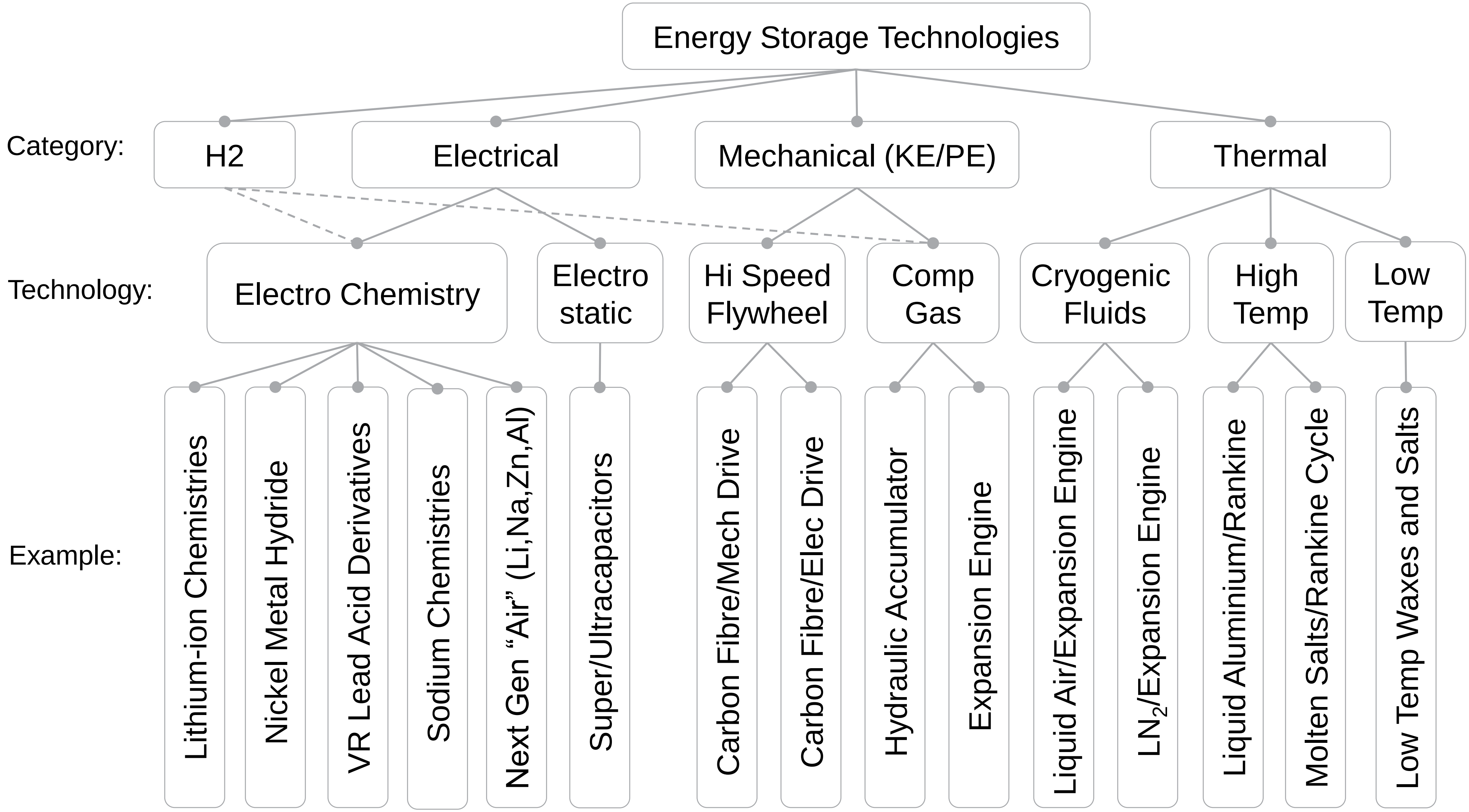
Capabilities:



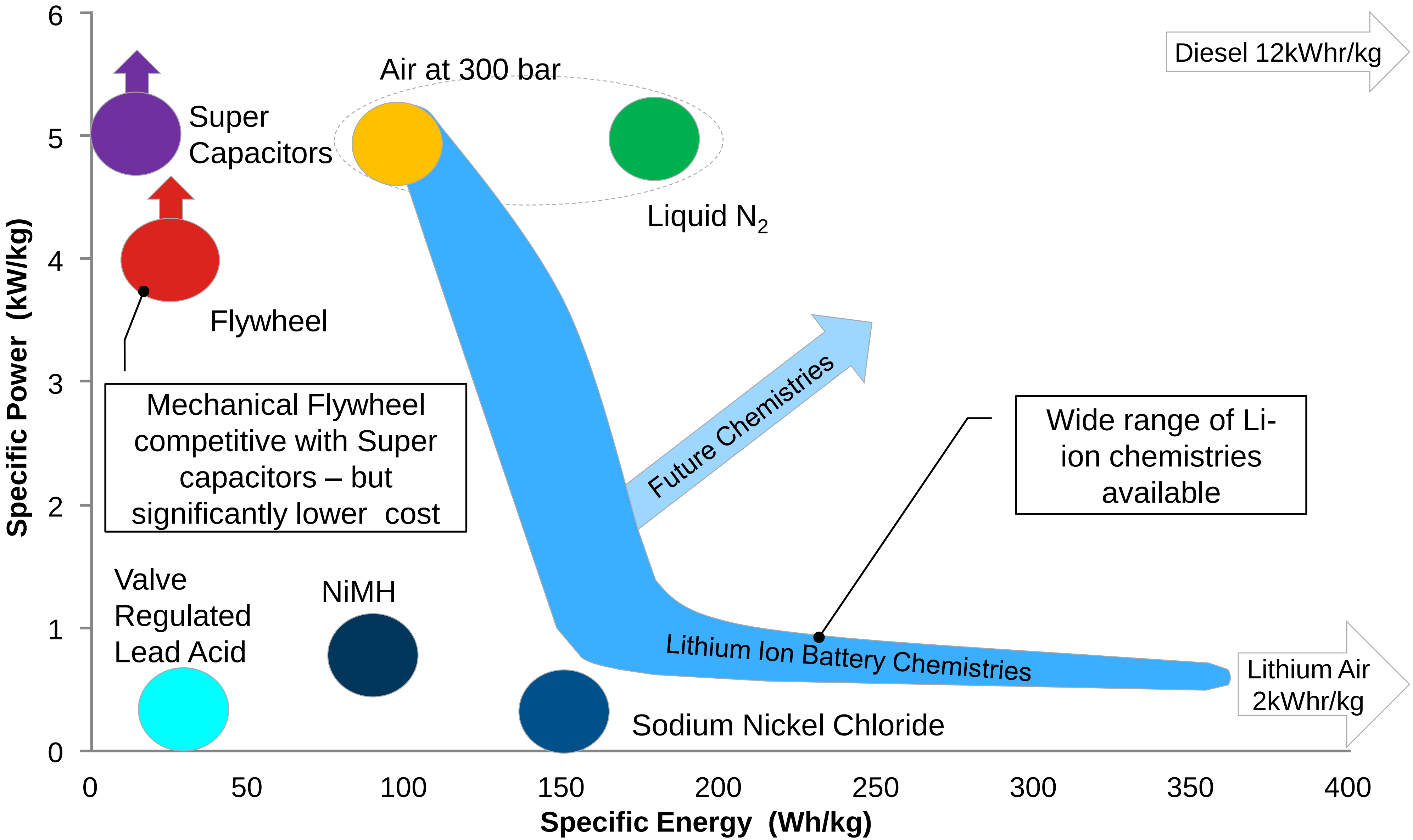
What we do:

- Ricardo provides Research, Design, Development & Strategic Consulting services to the Automotive & related sectors
- Environmental Consulting for public and private sector clients around the world
- Specialist manufacturing and assembly capability for niche product applications
- Global footprint with people/facilities in UK, USA, Germany, China, India & Japan
- Systems engineering approach that considers integrated solutions for the entire product lifecycle
- Extensive experience of introducing production vehicles and major sub-systems

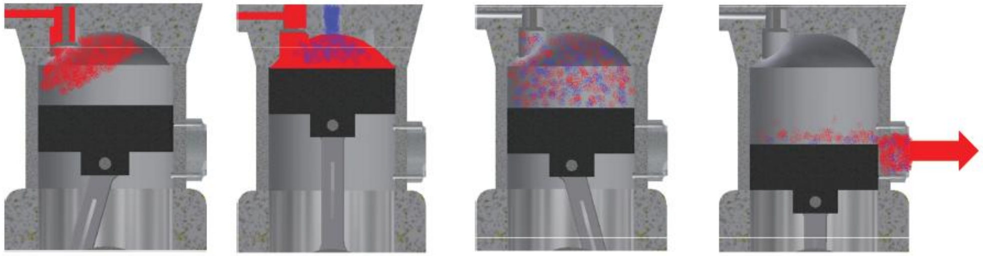
Looking forwards → a range of options are available for Energy Storage in transport - electrical, mechanical & thermal are possible



Air based technologies, being mechanical in its energy delivery have power density advantages over electro-chemical systems



Dearman Engine Company system meets addresses need for rapid boil and isothermal expansion of base engine technology when using liquid air as primary fuel



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

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

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

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

2 stroke engine sequence for internal steam engine

Liquid air injected at pressure in to water creates a very energetic event!

Dearman engine concept

- Critical features
  - Injector technology to deliver cryogenic air and promote mixing for heat transfer
  - Internal ‘steam engine approach’ → Extremely rapid boil gives power density
  - Heat transfer during expansion giving isothermal expansion (estimate 7*range of 300bar air for same volume)

Courtesy: Dearman Engine Company

Base engine technology running from low grade heat could find many applications

Application of technology

Cryogenic engine uses classical engine technology to provide a clean at point of use, light weight (compared to eg batteries), compact engine that works from low grade waste heat.

Liquid air engine

Waste heat recovery

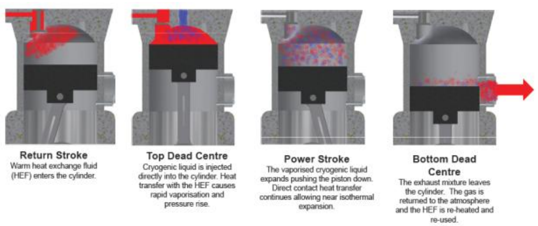
- Use heat from radiator or in tandem with exhaust waste heat devices
- Depending on application used to power auxiliaries when the primary engine is off (eg bus) or peak load support to facilitate down sizing (eg bulldozer)

Refrigeration

- Liquid air currently used for perishable goods transport. Use heat scavenged for work as well.
- The same approach could be used for AC systems → convert AC from net drain on the primary drive to net support

Primary drive

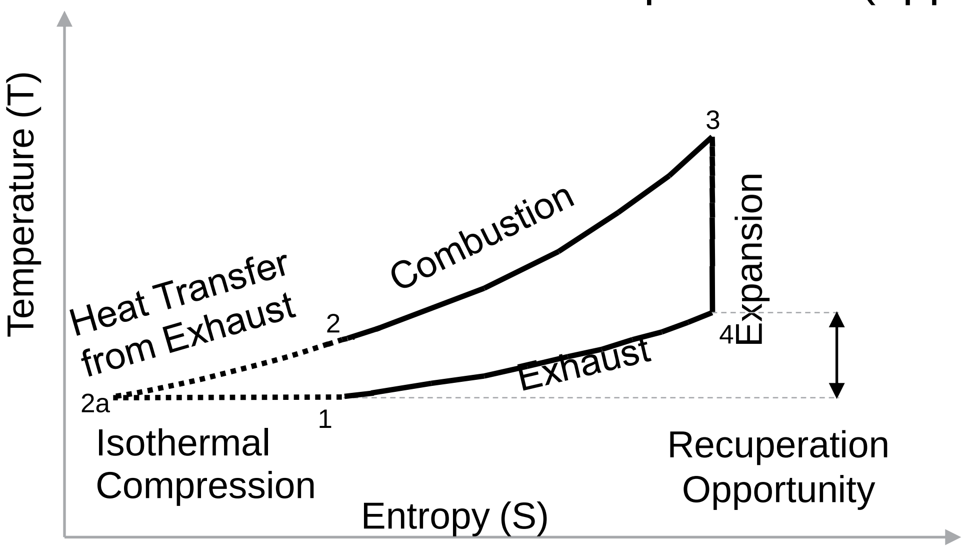
- Light weight, short range (<30miles) personal mobility
- Outboard and marine engines on in-land waterways
- Short hop ferries – eg Portsmouth harbour – where short recharge makes low energy density less important



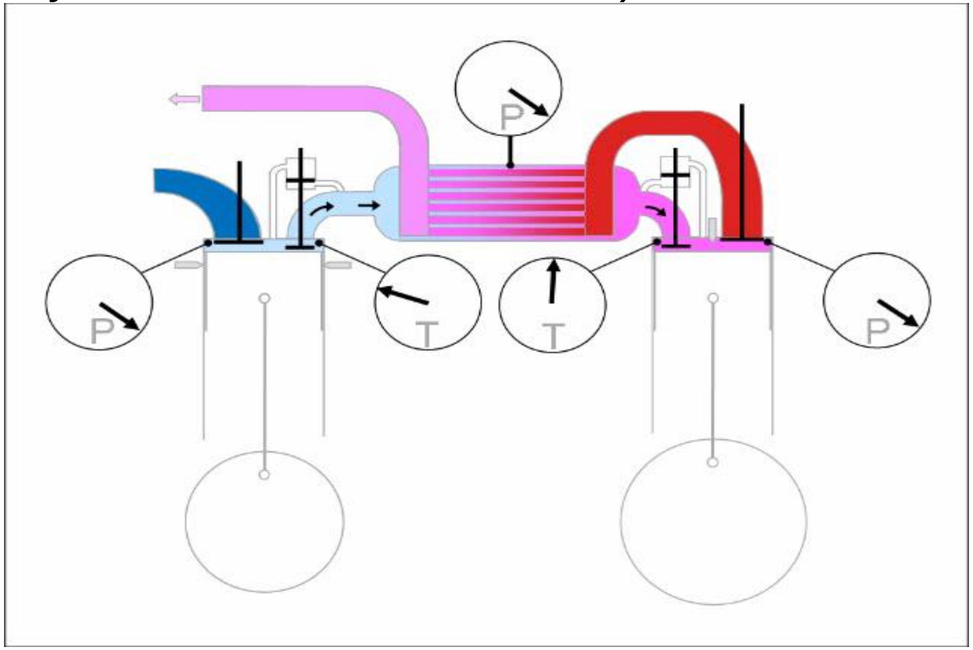
Ricardo CoolR recuperated split-cycle uses liquid air to support isothermal compression and recuperation to potentially increase heavy duty core engine efficiency to > 60%η_e

- ***'Marries the natural recuperation of Combined Cycle Gas turbine with the high CR of a ICE'***
  - 2002 - Ricardo successfully demonstrated 3MW split-cycle isothermal compression engine using water. (BORE: 385 Stroke: 400 mm)

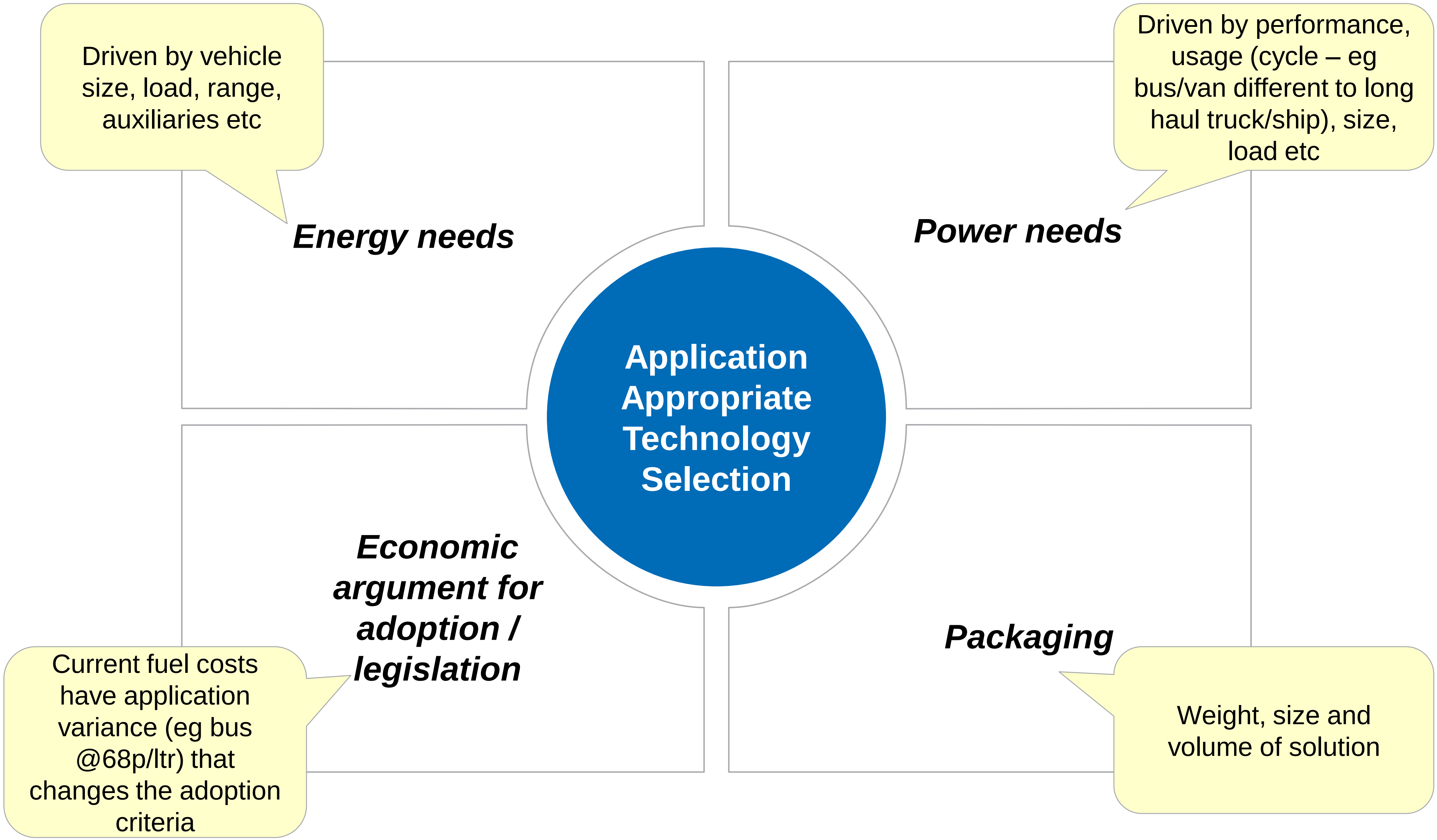
- CoolR LN_2 concept features:
  - Reduced end of compression temperature
  - Increase volume flow through engine
  - Reduced combustion temperatures (opportunity for at source NOx control)



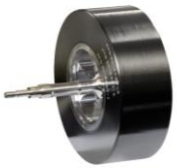
Recuperated Diesel Cycle with high CR & Isothermal Compression



Many factors affect the appropriateness of an energy vector to a transport application



Whilst Li-ion likely to dominate in the short term, Liquid Air, could offer opportunities due to lower costs and attributes that suit certain applications

		Opportunities:	Challenges:
	Li-ion	• High investments/progress • Incremental cost reduction • Next generation chemistries	• High cost - reductions limited by raw materials & process/quality reqs. • Thermal range/stability
	Pb Acid	• Low cost/specific energy • Improving specific power via bi-polar/high carbon configurations	• Low specific energy • Durability in high charge/discharge applications - limited life
	Sup. Caps	• Use in high power applications • Incremental cost reduction via materials and production techs	• High cost/specific energy • Variation in voltage & cost/weight of power electronics
	Flywheel	• Use for short term storage • Use of low cost materials enable significant cost reduction	• Immature technology & lack of product experience • Perceived safety issues
	LN_2	• High specific energy & low cost • Combination of function with other powertrain systems	• Immature/ • Historically low conv. Efficiencies
	Comp Air	• Low system cost • Use in applications with low energy requirements	• System pressure varies with energy stored limiting output • Low energy conversion efficiencies