

Liquid Air in the energy and transport systems

Opportunities for industry
and innovation in the UK

Full Report



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This report explores the technical, environmental
and business potential of Liquid Air as a new
energy vector.

ABOUT LIQUID AIR ENERGY NETWORK (LAEN)

LAEN is a newly created forum to explore and
promote the use of liquid air as an energy vector, with
applications in grid electricity, transport and waste
heat recovery.

Building on the findings of the Centre for Low
Carbon Future's report, LAEN will serve as the
global hub where new ideas are demonstrated and
shared, and promote liquid air as a potential energy
solution among researchers, technology developers,
manufacturers, energy producers and consumers,
and government. Its membership will be drawn from
the same groups. To contact LAEN, please visit www.liquidair.org.uk. Toby Peters, Founder LAEN

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Chapter 1 Do we need a new energy vector?

The imperative to decarbonise is driving the search for new energy vectors.

1. The Electricity Grid

2. Transport

3. Conclusions

Energy policy in Britain and Europe rests on three pillars: decarbonisation, energy security and affordability. In order to reduce emissions and keep the lights on at an acceptable cost, much of the policy debate has centred on how to generate sufficient low-carbon energy. However, the fundamental problem is not the adequacy of low-carbon energy resources - wind, solar, nuclear etc are in principle sufficient to meet our needs many times over - but how to package that energy into useful forms. The imperative to decarbonise is forcing us to rethink the way energy has been transformed, transported and consumed for decades, and many of the trickiest problems of the transition relate to the mismatch between the forms in which low carbon energy is produced and the forms in which we need to consume it. Arguably one of our biggest challenges is to develop new energy *vectors*.

A vector is not a source of energy but a means of transporting it from one time and place to another. Unlike primary fuels - coal, gas and oil - vectors are man-made, resulting from the transformation of one source of energy into another more useful form. The most widespread energy vector employed today is electricity, but there have been many others. Steam was the vector of the industrial revolution, carrying the energy from burning coal to locomotive wheels and factory equipment. At the turn of the 20th century many machines in Paris ran on a large compressed air network¹, while London's docks and West End theatres were supplied with hydraulic power from a pumping station in Wapping²; the vectors were air and water respectively. Such systems may no longer be widely known, but they do show that energy networks based on alternative vectors are entirely possible.

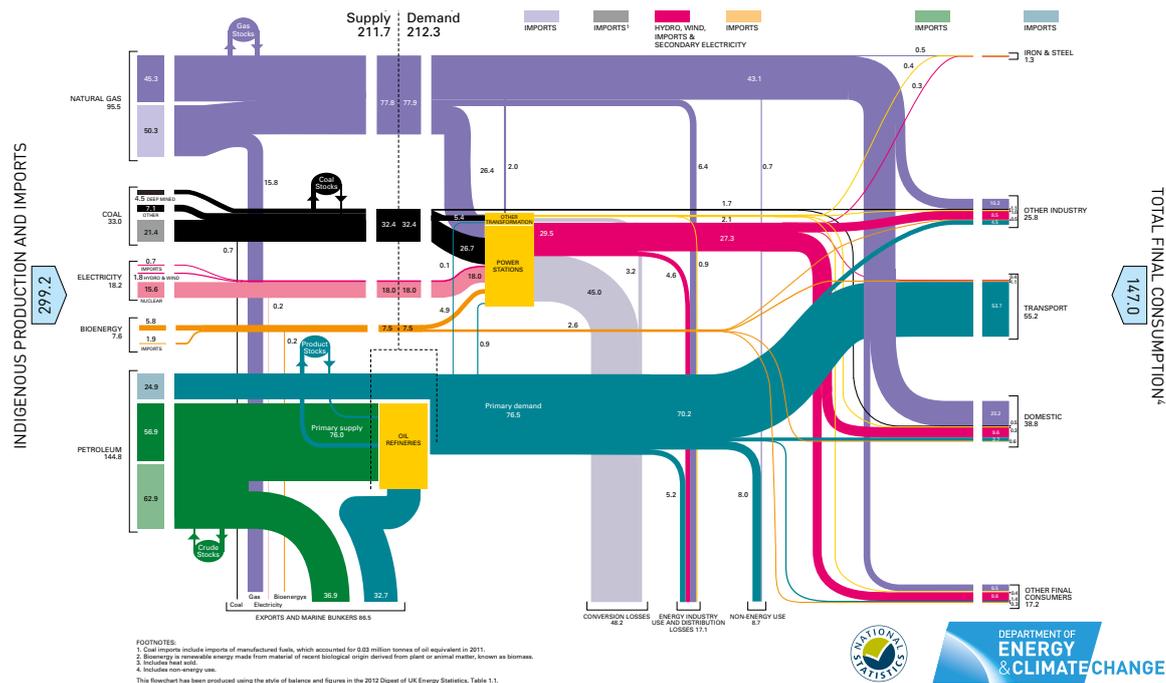
Traditionally, the term vector applies only to the movement of energy in *space* - ie from one location to another - and not time. The concept of energy storage - ie transferring it from one point in *time* to another - is usually regarded as distinct. However, in this paper we use the term vector to cover both functions, which is a far more demanding definition to satisfy. Electricity, for example, is an efficient means of transferring energy through space, but is difficult and expensive to store using current technologies. Under our definition, candidate technologies will be closer to the ideal if they are capable of both storing and transporting energy efficiently, so that consumption can be decoupled from production, and the vector can serve as a transport 'fuel'.

The need for new vectors is becoming more acute because of rapid changes in the energy system brought on by decarbonisation. Until recently energy was almost exclusively derived from primary fuels such as coal, oil and gas that are easy to store and transport, and which can deliver power on demand. Today we are shifting rapidly to renewable

forms of generation such as wind and solar, which, because they are intermittent, produce *energy* rather than *controllable power*. The energy they produce comes in the form of electricity, which is easy to move but harder and more expensive to store. It is the widening disconnect between energy and controllable power in the emerging system that creates the need for new vectors.

Thinking about energy vectors is already advanced in countries such as Germany, where the idea of an energy system completely supplied by renewable energy has been debated for several years.³ One proposal is to use hydrogen as a vector throughout the economy. 'Wrong time' renewable energy - such as wind power produced at night when there may be too little demand to make use of it immediately - could be used to electrolyse water to produce the hydrogen, which could then be stored to deliver electricity and heat when needed, and provide a low carbon transport fuel. However, the engineering and economic challenges of hydrogen remain formidable.⁴

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Our energy used to come almost wholly from coal, oil and gas, which are easy to store; today we are shifting to intermittent sources like wind and solar, which are not.

Figure 1.1: UK energy flow chart. Source: DECC

A glance at the energy flow diagram for the United Kingdom (Figure 1.1) shows the basic facts of life of our current system: profound dependence on primary fossil fuels (inputs on the left hand side); significant losses during various transformations of energy; and the overwhelming dominance of oil in transport. Electricity and biofuels are the only vectors in the current system with the potential to deliver low carbon energy, but both are small compared to final energy demand (right hand side).

It is widely accepted that cutting carbon emissions will mean a much larger role for electricity. Analysis by the Committee on Climate Change, the government's independent advisor, has shown that decarbonising the electricity supply is vital to achieving the country's overall climate targets. This is because power sector emissions account for almost 30% of total emissions; cutting emissions is generally cheaper in electricity generation than in other sectors; and low carbon electricity can then be used to help decarbonise heat and transport.⁵ This analysis formed the basis of DECC's 2050 Pathways report, and has been endorsed by a wide range of bodies including the Scottish Government, the Energy and Climate Change Select Committee, the Confederation of British Industry (CBI) and the Institution of Mechanical Engineers.

However, because electricity is difficult and expensive to store, a strategy of decarbonisation that relies on electrification presents two major challenges: 1) balancing supply and demand on a grid increasingly dominated by intermittent renewable generation, and 2) transforming low carbon electricity for use in transport - or even replacing it altogether. Both challenges might be amenable to a new low carbon energy vector.

1. The electricity grid

Electricity grids must keep supply in balance with demand from second to second or the system will fail, causing power cuts and damage to equipment. The role of network operators such as National Grid is to perform a continuous and dynamic balancing act to keep the system frequency and voltage stable. Demand changes throughout the day and generation must be raised or lowered to match. Such changes are generally incremental, but individual power stations or transmission lines can fail without warning, removing larger amounts of generation or demand. As things stand, however, demand is broadly predictable, existing coal and gas fired power stations are 'despatchable', and there is currently ample spare generating capacity for most eventualities.

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Grid balancing will become increasingly challenging over the coming decade, as the fraction of energy from intermittent renewable sources increases.

National Grid has traditionally balanced the system using a combination of coal and gas plants that can raise or lower their output quickly in response to unforeseen events; pumped hydro storage, which can absorb excess energy overnight and deliver it quickly when needed; and a few large industrial users with demand response contracts. Interconnectors to neighbouring countries are also a source of flexibility, although not directly controlled by grid operators, since they respond to relative price signals in the connected markets⁶ (Figure 1.2).

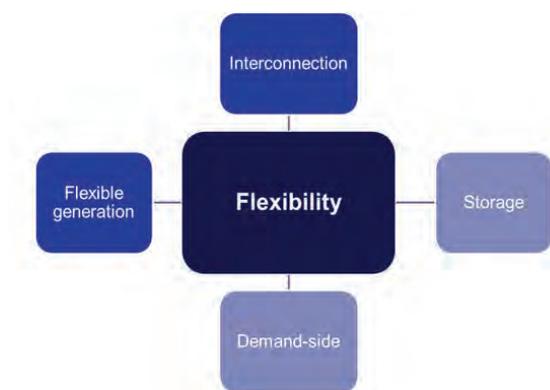


Figure 1.2: Grid balancing techniques.

Grid balancing will become increasingly challenging over the coming decade, as the fraction of energy from intermittent renewable sources increases. EU environmental legislation means around 12GW of controllable but highly polluting coal fired power stations must close by the end of 2015.⁷ At the same time around 7GW of ageing nuclear stations will stop generating by 2023, further tightening supply. On the other hand, while some 21GW of new generating capacity is either under construction or has secured planning permission, 7GW is in the form of intermittent renewables such as wind, which typically generates only around a third of its nameplate capacity over the course of a year. As a result, Ofgem, the gas and electricity market regulator, forecasts that derated capacity margins (spare generating capacity as a proportion of peak demand) will fall from a comfortable 14% today to just 4% in 2015/16. That means the risk of customer disconnections will increase from a negligible 1-in-3,300 years event at present, to a 1-in-12 years event by 2015/16.⁸

The increase in wind capacity adds another layer of complexity to the grid balancing equation. Although the accuracy of wind energy forecasting is improving, there is still inherent uncertainty in the timing of weather

fronts and the net power that will be produced as they move across the country. Further uncertainty is added because wind turbines are designed to cut out when wind rises above a maximum safe level, causing sudden shortfalls in generation. At low levels of wind penetration these problems are manageable, but at higher levels more active measures are required.⁹

The UK has committed to generate 15% of its energy from renewable sources by 2020, and this implies around 30% of our electricity will need to come from renewables by the end of the decade.¹⁰ In spite of the coalition's recent shift in emphasis towards gas¹¹, planning approvals for onshore wind have surged to record levels, and new investment in offshore wind has also grown strongly.¹² Although the government has no technology-specific targets, DECC estimates the UK could deploy up to 31GW of wind capacity by 2020, and well over 50GW by 2030.¹³ That compares with current baseload (the minimum level of supply required throughout the year) of 20GW and peak demand of 60GW. As renewable penetration increases, more balancing capacity will be required. National Grid estimates that balancing capacity needs to rise from 3.5GW today to some 8-13GW by 2020.¹⁴

So far we have considered the need to balance supply and demand over the short timescales required to keep the grid stable. However, maintaining energy security in a system increasingly dominated by renewables will also require balancing over longer timescales, and will involve shifting large amounts of supply or demand by hours or days. Much has been made of the potential impact on a wind-dependent grid of a high-pressure weather system in winter, bringing cold but windless weather for days or even a fortnight. Such conditions would simultaneously increase demand for energy and reduce the generation of electricity from wind turbines. However, the reverse problem would exist when demand is low and wind generation high - a hot but windy summer night for instance - when the difficulty would be to absorb large amounts of power for which there is no immediate use.

Periods of excess renewable generation are already beginning to occur in grids around the world. The surplus can be caused either by low demand, or by the lack of sufficient transmission capacity to move the electricity to where it is needed. In Texas and Germany power prices are frequently negative during periods of high renewable generation.¹⁵ There

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have also been periods of negative prices in the British and Irish markets^a, but in Britain the more common symptom is the occurrence of 'constraint payments' to wind farms, when operators are paid to produce electricity even though it cannot be used. Constraint payments have risen dramatically, from just £180,000 in the year to April 2011 to £34 million the following year.¹⁶

So far constraint payments have largely been caused by local bottlenecks in transmission lines, but it is not hard to foresee a situation in which wind generation could far exceed total demand, even if all grid bottlenecks were solved. For example, if Britain had baseload demand of 20GW, nuclear capacity (which is difficult to turn down) of 10GW, and wind capacity of 30GW, there might be occasions on which surplus generation of 20GW would need to be absorbed somehow, even if it were possible to turn off temporarily all remaining gas fired plant. But this problem is by no means exclusive to 'high wind' scenarios: the same difficulties would occur if the UK stopped building wind farms altogether and raised nuclear capacity to, say, 40GW. Whichever low carbon generating mix eventually emerges, finding ways to absorb such excess power will be vital to cutting emissions and maintaining security of supply at least cost. In this context storage has some clear advantages over the other grid balancing technologies shown in Figure 1.2.

Grid balancing technologies compared

With the phase-out of coal fired power stations, **flexible generation** will typically mean one of two types of plant: Combined Cycle Gas Turbines (CCGT) operating at below their maximum output in order to respond up and down as required, sometimes referred to as 'spinning reserve'; and Open Cycle Gas Turbine (OCGT) 'peaking plants' which are not kept spinning, but which can start up within a matter of minutes. Peaking plants, such as OCGT are inefficient and almost as carbon intensive as coal, emitting some 1,000 grammes of CO₂ per kilowatt hour, against a grid average of around 500g/kWh. They are also a 'one way' form of flexibility; peaking plants can generate when the wind fails to blow, but clearly cannot absorb wind energy in periods of low demand.

Interconnectors to neighbouring countries can shift large amounts of energy back and forth and the concept of a European 'supergrid' has gained support in recent years. Britain has interconnectors to France, the Netherlands and Ireland capable of importing or exporting 3.5GW, and National Grid expects capacity to rise to 5.7GW by 2020.¹⁷

Interconnectors can reduce the risk of a system-wide failure by allowing one country to access the generating capacity of another. If the generating capacity at the 'other end' is low carbon, interconnectors can cut emissions by displacing gas fired baseload plant, according to modelling by Pöyry.¹⁸ But separate Pöyry modelling also shows interconnectors may do little to smooth the intermittency of renewable generation across northwest Europe - the supergrid concept - since similar weather conditions may prevail over a distance of 1,000 miles.¹⁹ In periods of low wind, therefore, interconnectors may not be a reliable source of low carbon electricity. Pöyry's analysis also shows the benefits may be quite asymmetrical between countries - an interconnector between Britain and Norway would raise prices for Norwegian consumers, for example - which adds a political dimension to decisions about whether to build new interconnectors.

Interconnectors are a 'two way' form of flexibility, but usually offer no control over energy flows since this is driven by relative prices in the connected markets. The level of uncertainty about the impact of interconnectors is evident in Figure 1.3, taken from Ofgem's most recent Electricity Capacity Assessment. The base case forecast shows derated capacity margins (spare generating capacity as a proportion of peak demand) falling from a comfortable 14% today to just 4% in 2015/16. If all interconnectors were to import at maximum capacity during peak hours, margins could be as high as 9%, but if they were to export at full capacity margins would be negative. In other words, generating capacity would be lower than demand and this would result in an energy shortfall of almost 30GWh, equivalent to the annual consumption of 9,000 homes.²⁰ In light of this analysis, interconnectors may do little to ensure energy security when it is needed most. The government has acknowledged that Germany's closure of 8GW of nuclear plant in 2011 could raise German demand for British power at peak times.²¹

The challenge is not just to generate enough power when the wind dies, but also to absorb excess renewable energy when demand is low - so called 'wrong time' energy.

^aTwo separate electricity markets operate in the UK. Scotland, England and Wales combine to form the GB market, while Northern Ireland and the Republic of Ireland are served by the Irish Single Electricity Market (SEM). The British grid and the Irish grids are only weakly connected at present, although more interconnectors are planned.

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Energy storage is a two-way form of flexibility: it can absorb excess generation when demand is low and can deliver it back when needed.

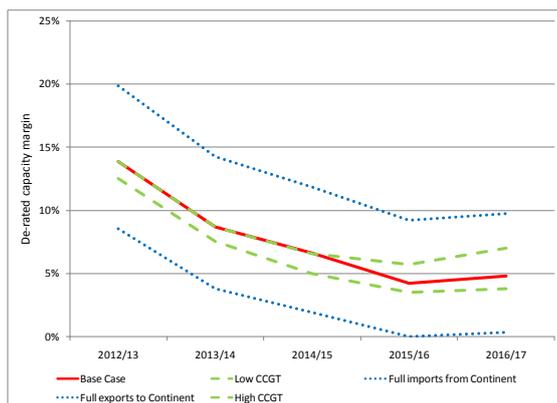


Figure 1.3: UK electricity capacity margins to 2017. Source: Ofgem²²

Demand Side Response (DSR) delivers flexibility to the grid by shifting consumption of electricity from peak to off peak times, often in response to a price signal. DSR has long existed in the industrial sector, where major energy users such as steelmakers and industrial gases companies have contracts with National Grid that reward them for curtailing their power consumption if necessary. Demand response is also used by distribution network operators to manage peaks in demand on their networks. Today the phrase 'smart grid' is taken to mean the extension of DSR to the commercial and domestic sectors, and some modelling suggests that this could have a major impact, particularly since increasing use of heat pumps and electric vehicles (EVs) is expected to make electricity demand more 'peaky'.²³ In this context, DSR could help cut emissions by displacing peaking plant, reduce wastage of wind energy and bolster security of supply. The planned roll-out of smart meters to every home in the country by 2020, at an estimated cost of £10.8 billion, is intended to enable domestic DSR.

Although DSR is already well established in industry, where energy costs are critical, extending it to the commercial and domestic sectors may prove harder. Research for Ofgem found that DSR in the commercial sector – including retail, education and offices – could trim peak winter demand by as much as 4.5GW. However, the researchers found there was little interest in DSR among companies in this sector, where energy bills form a small proportion of total costs, and that businesses were 'unlikely to accept any impact on service levels to accommodate DSR measures'.²⁴

Public engagement may also prove the biggest hurdle in the domestic sector.²⁵ Trials conducted so far have produced mixed results, but among the more statistically robust

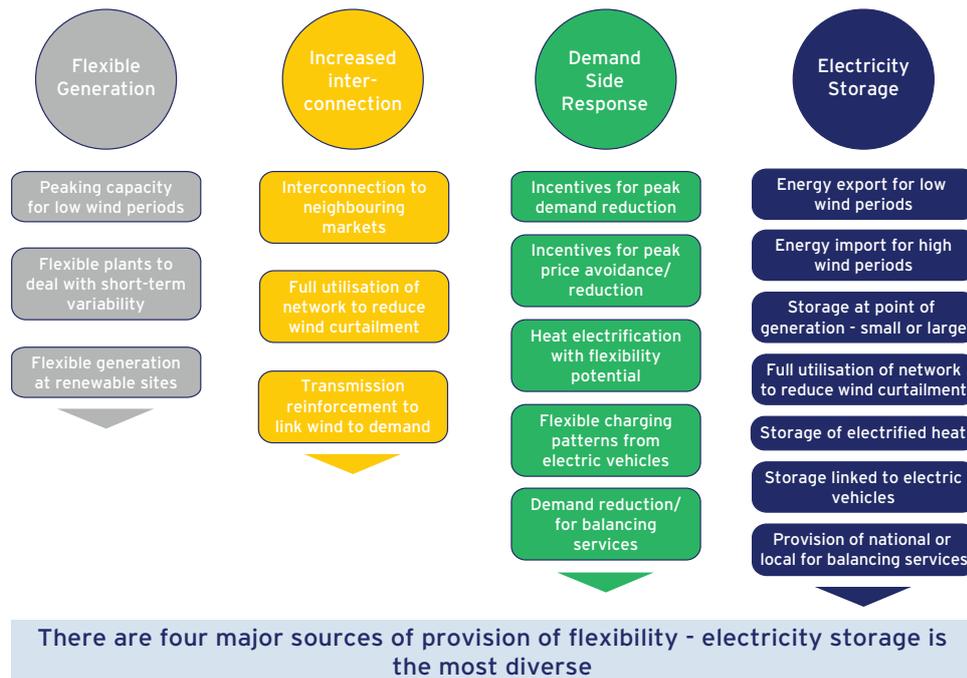
studies households have typically reduced peak consumption by up to 10% but overall electricity consumption by just 3%.²⁶ This suggests the financial savings to consumers may be modest. The government estimates the average household will save £40 on a dual-fuel bill in 2030.²⁷

Even if consumers are attracted by DSR tariffs, it is not yet clear which appliances they are prepared to use in a flexible way²⁸ and therefore how much demand can be shifted from peak to off peak times. Nor is there yet any robust evidence about household responses to real-time pricing²⁹, where prices to consumers change as frequently as every half hour, and which would best accommodate wind intermittency. The scale of time-of-day-price differentials required to stimulate major shifts in behaviour – making it more expensive to cook or watch television at peak times than off-peak – could prove politically difficult. Nor is it clear how prepared consumers would be to relinquish control of fridges, freezers and water and space heating to the energy companies. If financial savings of DSR tariffs are modest, consumers may be reluctant to countenance any potential disruption to their lives – even if this may in fact be minimal.

In Britain the take-up of DSR tariffs may also be hampered by public perceptions of the big energy suppliers, which were already poor even before the government moved to restrict each supplier to four core tariffs.³⁰ According to the results of one opinion poll, energy companies have 'the lowest public reputation in corporate Britain'³¹, and in a customer satisfaction survey by the consumer organisation Which?, only one of the big six suppliers scored higher than 50%.³²

Energy storage is a two-way form of flexibility: it can absorb excess generation when demand is low and can deliver it back when needed, over a variety of timescales. This can both lower emissions by displacing peaking plant with lower carbon electricity (chapter 10), and strengthen energy security by reducing imports and the wastage of wind energy, thus increasing the proportion of domestically generated energy (chapter 11). Storage can also generate major financial savings by reducing the need to invest in power stations and transmission line upgrades. Of the four forms of grid balancing, storage is the most diverse and flexible (see chapter 3), and one whose value could be enormous if fully exploited. A recent modelling study for the Carbon Trust led by Professor Goran Strbac of

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Energy storage is the most flexible form of grid balancing.

Figure 1.4: Storage compared to other grid balancing techniques. Source: Pöyry

Imperial College found the benefits of storage to the British electricity network could amount to £10 billion per year by 2050.³³ In contrast to DSR, storage is 'behind the plug' and does not require the same degree of public engagement. The advantages of storage compared to other forms of grid flexibility are summarised in Figure 1.4.

Electricity storage technologies compared

Although storage has, in principle, distinct advantages over other forms of balancing, most of the currently available storage technologies suffer from a range of technical and financial limitations, as shown in Table 1.1, suggesting the need for new storage media or vectors.

Pumped hydro is perhaps the gold standard of large-scale electricity storage. Such plants store energy by pumping water from one reservoir to another at higher altitude. When energy is needed, the water is allowed to flow down to the lower reservoir through a turbine to generate electricity. This means pumped hydro can provide large amounts of power and energy storage. The Dinorwig plant in Snowdonia, for example, can generate 1.8GW, equivalent to a large gas fired power station, for about five hours, and the plant can go from standby to full power in just 90

seconds.³⁴ However, the major disadvantage of this technology is that it is geographically constrained: there are few suitable sites left to exploit in the UK.³⁵

Compressed air energy storage (CAES) is theoretically suitable for both large scale and smaller-scale distributed energy storage. However, there are just two large CAES plants in operation worldwide, and both rely on natural gas turbines. The 'adiabatic' CAES technology that would dispense with the need for natural gas in CAES is still in its infancy. Although a number of potential new projects have been identified, progress has been slow. Large scale CAES requires suitable salt geology in which to create caverns to store the air, a process that can take up to five years and requires high capital expenditure. More recently there has been considerable research and development effort into improved thermodynamic cycles, but even with proposed improvements in efficiency it seems that large scale CAES, depending on cavern storage, is still some way from commercialisation. Small scale CAES has been under development for over a decade with limited progress, while other CAES concepts, such as those based on underwater containment, are still at an early stage.

Electrochemical systems comprising **batteries** and **hydrolyser-fuel cell** combinations are another potential solution with no geographical constraints. However, they are

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Existing grid storage technologies suffer from geographical constraints, technology challenges or dependence on high cost materials.

Device type	Low Capital Expenditure	Long life	Low Maintenance	Low through life costs	Fast response (seconds)	High energy storage capacity	Scalable	Geographical constraint	Development Stage
Pumped hydro	N	Y	Y	Y	N	Y	N	Y	3
Compressed air	Y	Y	Y	Y	N	Y	Y	Y	3
Compressed air - adiabatic	Y	Y	Y	Y	N	Y	Y	Y	1
Cryogenic	Y	Y	Y	Y	N	Y	Y	N	2
Flywheels	N	?	N	N	Y	N	N	N	2/3
Capacitors	N	N	N	N	Y	N	N	N	?
Superconducting Magnets	N	Y	N	N	Y	N	N	N	1
Batteries	N	N	Y	N	Y	N	Y	N	3
Fuel Cells	N	Y	Y	N	Y	Y	Y	N	1

Development stage: 1 = R&D 2 = Demonstration 3 = Mature

Table 1.1: Grid storage technologies compared.

capital intensive and tend to have shorter operating lifetimes than mechanical systems such as pumped hydro - typically 10 - 15 years compared to 25 - 40 years. Many types of battery are constrained in the combinations of energy storage capacities and power ratings they can offer. Battery types also need to be selected on the basis of the correct performance characteristics for the proposed operating regime, and operating regimes may have a significant impact on the lifetime of the product. Shorter operating lifetimes increase the economic and environmental costs, with the need for recycling and processing of materials and components.

Flywheels are generally considered to be robust, with long lifetimes and a relatively low cost per kilowatt of capacity. However, flywheels are far more suited to delivering high power over seconds or minutes than storing large amounts of energy for longer periods,

and this tends to limit their role on the grid to services such as frequency response.

In summary, since energy storage has, in principle, significant advantages over other forms of grid balancing, and since most of the currently available grid storage technologies suffer from a range of technical and economic drawbacks, it seems there is an opportunity for a new storage medium or vector, if it can overcome enough of these drawbacks. For the purposes of the grid, any new technology would ideally combine the high power rating and large energy storage capacity of pumped hydro, but without the geographical constraint; the fast response time of spinning reserve, but without the emissions; along with scalability, low costs, high efficiency and long operating life. At first glance liquid air appears to enjoy these characteristics, which we explore in depth in chapters 2 and 3. The case for a new energy vector in transport is discussed on the opposite page.

Chapter 1 Do we need a new energy vector?

2. Transport

Transport energy is overwhelmingly dominated by petroleum products: petrol, diesel and jet fuel. As high energy-density liquids, they have some of the properties of an ideal energy vector, allowing a large amount of energy to be stored in a small volume and to be moved easily from place to place. So great are these advantages that oil provides 95% of all transport energy.³⁶

However, oil-based transport fuels also come with major disadvantages. Fossil fuels are finite and supplies remain dependent on relatively few countries. Oil prices have risen dramatically over the past decade, as the 'easy' oil is increasingly depleted³⁷, and as global demand continues to rise in spite of the deep and persistent recessions of recent years.³⁸ Greenhouse gas emissions from transport make up more than a fifth of the total³⁹, and are growing far faster than any other sector - up by almost 50% in the twenty years to 2011.⁴⁰ Replacing oil-based transport fuels with low carbon alternatives is therefore essential to combat climate change, and may also make increasingly good financial sense. A number of alternative transport vectors have been proposed, but all have substantial drawbacks:

Natural gas can be used in normal internal combustion engine vehicles (ICEs), and retrofitting is straightforward. Natural gas is less carbon intensive than oil, but the emissions reductions are modest. In Europe, cars running on compressed natural gas (CNG) are calculated to deliver emissions reductions of between 10% and 25%, depending on the length and carbon intensity of the supply pathway.⁴¹ However, even if the higher end of the range could be achieved, there is currently no way to capture the remaining emissions from vehicle exhausts; these reductions would be essentially 'one-off'. In the US, the well-to-wheel (WTW) savings of CNG cars are calculated to have fallen to just 5% compared to petrol, because of upstream methane emissions from conventional and shale gas production.⁴² A new refuelling infrastructure would be required, which would also tend to lock in future emissions.

Biogas produced by anaerobic digestion of organic waste would deliver much larger emissions reductions, but the waste resource represents a fraction of our transport energy needs. One assessment found that if all the organic waste in the UK were devoted to

biogas, it could supply 15% of the country's transport energy.⁴³

Liquid **biofuels** share some of the advantages of petrol and diesel, although they are not quite as energy dense. In theory, biofuels from a combination of crops and agricultural waste might be capable of replacing up to 25-30% of projected road transport fuel demand within the 2030-2050 timescale.⁴⁴ However, biofuel production from edible crops has contributed to food price inflation, which has caused food riots in many countries in recent years. Biofuel production has also been blamed for deforestation through indirect land use change (ILUC), as rising food prices encourage farmers to clear forests or wetlands to produce food, so releasing large amounts of carbon stored in the trees and soil. This can eliminate any emissions reduction the biofuels might otherwise have delivered.^{45,46} Indeed, some biofuels are thought to increase rather than reduce greenhouse gas emissions.⁴⁷

The direct and indirect impacts of biofuel production have led policymakers to reduce support for first generation (food crop based) biofuels, and increase support for second generation biofuels made from non-food crops and agricultural waste, such as ethanol made from lignocellulosic feedstocks like switch grass and forestry residues. However, second generation biofuels are not gaining market penetration as quickly as hoped, largely because of the high costs of the enzymes required to break down the cellulose into fermentable sugars.⁴⁸ These factors have forced policymakers effectively to scale back their overall targets for biofuels.

The European Commission, for example, has recently published proposals to modify EU biofuels policy to mitigate the impact of ILUC.⁴⁹ The target of 10% low carbon transport fuel (by energy content) by 2020 remains in force, but only 5% will now be allowed from first generation biofuels. The remainder will have to come from more advanced, non-food crop biofuels. However, the Commission has also quadrupled the credits earned by second generation fuels under the scheme, meaning fuel suppliers can now satisfy the 10% target if they deliver just 6% low carbon transport fuel by energy content. This represents a 4% reduction in the EU target as a result of the slower than anticipated progress of second generation biofuels. For similar reasons,

Transport energy remains overwhelmingly dominated by oil, and greenhouse gas emissions from transport have risen almost 50% in the last 20 years.

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Alternative sources of transport energy such as biofuels, EVs and hydrogen are not progressing quickly enough. By some estimates, the UK needs 1.7 million EVs by 2020; scarcely 800 were sold in the first half of 2012.

the US Environmental Protection Agency (EPA) has been forced to issue waivers that substantially reduced the cellulosic biofuels obligation established under the Renewable Fuel Standard for the years 2010-2012.⁵⁰

Electric vehicles (EVs) and hybrids have the potential to deliver significant greenhouse gas emissions savings in road transport, since electric motors are extremely efficient and electricity can be produced with very low carbon emissions. However, EVs have higher manufacturing emissions than petrol or diesel engines due to their lithium batteries, and by some assessments this significantly reduces their lifecycle emissions savings⁵¹, although more research is required.⁵²

EVs will deliver bigger emissions reductions as the carbon intensity of grid electricity is reduced, but to achieve real growth they also require further breakthroughs in battery technology. Batteries are still heavy and extremely costly, making the vehicles much more expensive. The Nissan Leaf, for example, retails at £26,000, even after a government subsidy of £5,000. Along with 'range anxiety' this may account for the fact that EV sales have been far slower than hoped. Several analyses suggest that the UK needs 1.7 million EVs on the road by 2020 to hit its climate targets⁵³, yet just 814 new vehicles were registered in the first half of 2012.⁵⁴

EVs will also require an extensive recharging infrastructure, although this ought not be a limiting factor in the long run. Perhaps more problematic is the time vehicles take to recharge, a major disadvantage compared to petrol, diesel and biofuels. Electricity as a vector is fundamentally better suited to continuous and hard-wired processes such as lighting or electric trains rather than mobile, battery powered operations such as road vehicles.

Hydrogen has long been promoted as *the* 'fuel' of the future, a universal energy vector capable of converting low carbon electricity for use in everything from heating to grid storage to transport - the so-called 'hydrogen economy'. In many ways it is an attractive concept. Fuel cell vehicles (FCVs) that run on hydrogen are far more efficient than ICEs on a tank-to-wheel (TTW) basis, have much greater range than battery electric vehicles (BEVs) and their only 'exhaust' is pure water. They are also capable of providing low carbon transport if the hydrogen is produced using nuclear or renewable electricity. Yet hydrogen, perhaps more than any other alternative transport

energy vector, faces a range of technical and economic challenges that look unlikely to be solved in the near future.

Small test fleets of models such as the Honda FCX Clarity and Mercedes Benz F-Cell already exist, but the vehicles are still prohibitively expensive. FCVs seem likely always to remain more costly than BEVs since their powertrain includes not only a battery and electric motor, like a BEV, but also a fuel cell stack and hydrogen tank. In addition, the fuel cell relies on platinum catalysts which are inherently expensive. The amount of platinum required has fallen sharply as a result of R&D, but remains eight times more than needed for a petrol engine catalytic converter. A major study by analysts at Sanford Bernstein and Ricardo found that mass production of FCVs would see the price of platinum soar. A 10% penetration of the light vehicle market would take up two thirds of current global production, and 'this demand would be impossible to meet today'.⁵⁵ If all cars were FCVs, it would require 350% of current global supply. The market is already extremely tight.⁵⁶

Producing the hydrogen also raises issues, since most of the Earth's hydrogen atoms are tightly bound in molecules of water and hydrocarbons.⁵⁷ Almost all current hydrogen production is done by steam reforming of methane (CH₄), which is energy intensive and emits carbon dioxide. Further energy penalties are imposed by the need to liquefy hydrogen for transport and compress it to 340 atm for use in FCVs, meaning the well-to-wheels emissions reductions achieved may be little different from those of petrol hybrids.⁵⁸ Emissions reductions would be much greater if the hydrogen were produced by electrolysis of water using low carbon electricity, but this process is even more energy intensive. One study for the Department for Transport found that if the UK were to switch to EVs electricity demand would rise 16%, but if it were to switch to FCVs it would rise more than 30%.⁵⁹ The costs of manufacturing hydrogen remain high compared to other alternative energy vectors such as biofuels and electricity, even after decades of intense research and development.⁶⁰ Hydrogen would also need an entirely new distribution infrastructure⁶¹ and there remain significant challenges around storage and safety.⁶²

Predictions of the imminent commercialisation of FCVs have repeatedly disappointed. Researchers at Sanford Bernstein note that in the 1990s many in the car industry saw FCVs

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being commercially available in significant volumes within 12 years, but by the end of the last decade the lead time had fallen to 8-10 years, so '16 years of fuel cell research and development has brought us four years closer to launch' (their emphasis). At this rate FCVs will enter the volume market 'by 2030 at the earliest' (see Figure 1.5), and in the meanwhile they remain the 'worst economic choice of any powertrain option'.⁶³ The US Energy Department cancelled funding for FCV research in 2009.⁶⁴

In summary, the vast majority of transport fuels used worldwide remain oil-based, and the transition towards low-carbon, cost effective and fully sustainable alternatives is making far slower progress than expected and required. Much of this is due to the practical and economic drawbacks of the vectors that are currently being developed. While it is possible that a combination of smaller electric vehicles and larger ones running on biofuels could emerge at scale, there is still clearly potential for new energy vectors to play a significant role in making lower carbon energy more accessible in transport.

On the basis of current progress, there can be no guarantee that existing vectors will make a meaningful impact in time. This is a powerful argument for investigating new vectors - and urgently.

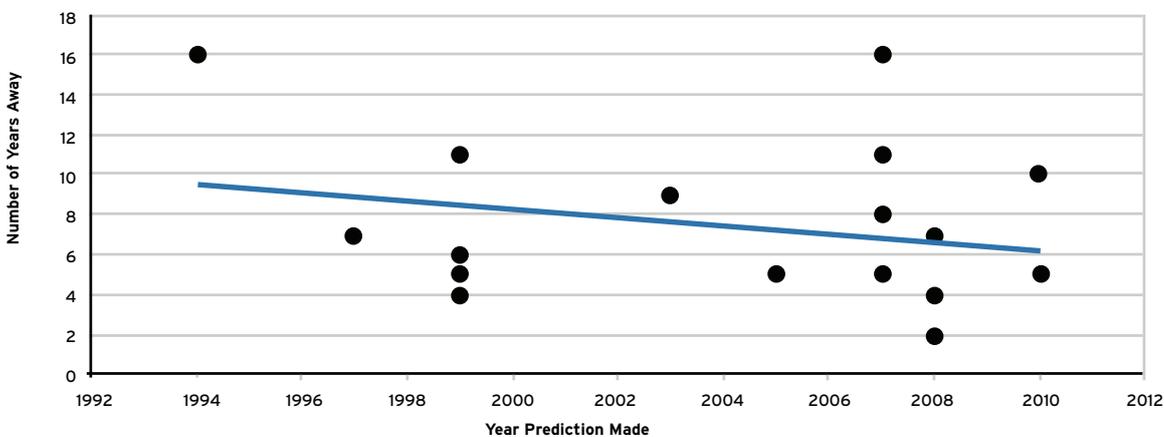


Figure 1.5: Slow progress of FCVs towards mass production. Over the last 16 years, predictions about how many years away FCVs are from mass production have shortened by just 4 years. Extrapolating these results would predict FCV volume production by 2030. Source: Ricardo and Sanford Bernstein⁶⁵

3. Conclusions

In both grid and transport applications there is a clear need to develop new energy vectors. This is not remotely to suggest that a new vector would produce a 'magic bullet' solution, nor to deny the potential for significant further progress in existing technologies, and indeed in technologies that have yet to be invented. However, on the basis of their rate of progress so far, there can be no guarantee that existing vectors will become commercial and make a meaningful impact in the timescales required.

Recognising the possibility of 'unknown unknowns', the evident limitations of existing technologies make a powerful argument for exploring new energy vectors - and urgently. In the chapters that follow we examine the case that liquid air could offer substantial benefits by capturing 'wrong time' renewable electricity and waste heat from a multitude of sources, so helping to balance the grid, decarbonise electricity and transport, and increase our energy security.

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Chapter 2 An introduction to liquid air

Attempts to develop liquid air as an energy vector date back to 1900, but recent technology breakthroughs make it worth considering again.

1. History

2. Air separation and liquefaction

3. Liquid air technologies today

4. Liquid air or liquid nitrogen?

5. Conclusions

The idea that the air that we breathe could turn into a liquid is counterintuitive to say the least, but scientists have known how to liquefy the constituents of air for well over a century, and the industrial gases industry now produces thousands of tonnes of liquid nitrogen and liquid oxygen every day. However, these gases need not be separated when liquefied, in which case the result is liquid air. A number of technologies are now being developed to exploit liquid air - or liquid nitrogen, its main constituent - as an energy vector.

Air can be turned into a liquid by cooling it to around -196C using standard industrial equipment. 700 litres of ambient air becomes about 1 litre of liquid air, which can then be stored in an unpressurised insulated vessel. When heat is reintroduced to liquid air it boils and turns back into a gas, expanding 700 times in volume. This expansion can be used to drive a piston engine or turbine to do useful work. The main potential applications are in electricity storage, transport and the recovery of waste heat.

Since the boiling point of liquid air (-196C) is far below ambient temperatures, the environment can provide all the heat needed to make liquid air re-gasify. However, the low boiling point also means the expansion process can be boosted by the addition of low grade waste heat (up to +100C), which other technologies would find difficult to exploit and which significantly improves the energy return. There are myriad sources of low grade waste heat throughout the economy (see chapter 5).

The industrial gases industry has been producing liquid nitrogen and liquid oxygen - the main components of liquid air - for over a century. These cryogenes have a wide range of applications including steel-making, food processing, medicine and superconducting technologies. Since oxygen and nitrogen liquefy at similar temperatures, and since there is four times more nitrogen than oxygen in the atmosphere but much less demand for it commercially, the industry has substantial spare nitrogen production capacity. The thermo-physical properties of liquid nitrogen and liquid air are similar, so a cryogenic energy vector could be provided by either.

There have been several attempts to exploit liquid air or liquid nitrogen as an energy vector over the past century without commercial success. However, technological advances and market evolution in the early years of this century appear to have made it a practical and economic possibility worth considering again. In this chapter we describe how liquid nitrogen

and liquid air are produced, and introduce the new technologies being developed to exploit them as energy vectors.

1. The history of liquid air

Attempts to develop liquid air as an energy vector date back to 1900, when the Tripler Liquid Air Company was formed in the US to develop a liquid air car that briefly competed with the steam and electric vehicles of the day.¹ But early liquid air vehicles required bulky and inefficient external heat exchangers, and soon the internal combustion engine came to dominate road transport, so it was not until the second half of the twentieth century that interest in cryogenic engines revived.

In the 1960s, self-powered cryogenic pumping systems² were explored as an alternative to

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electric pumps for fuel delivery in rockets. However, this was at the height of the space race and cold war, so very little information is available. With the arrival of the oil crises in the 1970s interest in cryogenic cars returned, and a number of patents were filed, although few, if any, vehicles were actually built.³ There was also interest in developing liquid air as a grid-scale energy store, evidenced by a paper presented to a conference of the Institution of Mechanical Engineers in 1978.⁴

The 1980s saw the first recorded work on hybrid or dual-fuel cryogenic vehicles, where fossil fuels were typically used to raise the temperature of a cryogenic working fluid to increase its energy density. The combination of cryogenic engine and internal combustion engine was found to produce synergistic increases in efficiency, which in one case delivered a 50% greater range than using each fuel on its own.⁵

Another engine proposed in 1984 with the help of US Department of Energy funding⁶ worked by superheating liquid nitrogen to very high temperatures in a furnace powered by any fossil fuel, before expansion in the cylinder. The fuel consumption of this configuration was 4.2 miles per gallon of liquid nitrogen and 132 mpg of petrol. At 1984 prices, projected driving costs were comparable to a similar specification petrol car. Systems using LNG as the fuel were also proposed.

In the early 1990s, the California Air Resources Board's Zero Emission Vehicle mandate created significant interest in alternative engine technologies. Recognising the limitations of electric vehicle concepts of the time, the Universities of Washington and North Texas began research programmes into cryogenic engines for transport, and built some demonstration units capable of achieving speeds of a few miles per hour.⁷

A number of utility-scale applications were also developed and tested, including one from Mitsubishi called LASE - Liquid Air Storage Energy System.⁸ The design involved producing liquid air during off-peak periods and then pressurising it to supply high pressure gas to the air inlet valve of a gas turbine to boost its output.

After a century of faltering attempts to exploit liquid air, what appears to have been a significant breakthrough came in 2001, when the British inventor Peter Dearman developed and patented the Dearman Engine. Mr Dearman's key insight was that liquid air could be vaporised inside the engine cylinder using

heat supplied by a thermal fluid mixture such as water and antifreeze, eliminating the need for the bulky and inefficient external heat exchangers of traditional cryogenic engines. This insight allowed Dearman to make simple modifications to a small car and run it on liquid nitrogen at speeds of more than 30mph.⁹

By contrast, in 2005 the Ukrainian Kharkov National Automobile and Highway University developed a two person lightweight road car whose design continued to rely on an ambient heat exchanger, and this achieved just 10 kph for 42 minutes on 22 kg of liquid nitrogen.¹⁰

After buying the rights to the Dearman Engine, Highview Power Storage went on to develop the grid scale energy storage system described below. In 2006, working with scientists at the University of Leeds, Highview developed a series of efficiency enhancements to the liquid air cycle by integrating the production and expansion processes to make use of waste heat and cold, so making the concept economically viable. In 2010, Highview spun off the Dearman Engine Company to develop a cryogenic engine for transport applications. Today a number of companies around the world are investigating the use of liquid air as an energy vector for transport and grid scale applications.

A key breakthrough appears to have been the invention of the Dearman Engine, which is more efficient than traditional cryogenic engines.

2. Air separation and liquefaction

Air is made up of nitrogen (78%), oxygen (21%) and argon (1%), and these components can be separated because they liquefy/boil at different temperatures: nitrogen at -196°C, oxygen at -183°C and argon at -186°C. This is done using an Air Separation Unit (ASU).

First the air must be cleaned through a dust filter, and compressed to a pressure of about 6 bar (Figure 2.1, step 1). The compressed air is then cooled down to a temperature of about 15°C (2). Then water and CO₂, which would otherwise freeze and block pipes in the ASU, are removed using a molecular sieve in a process known as adsorption (3).

The cleaned air is then cooled down to close to liquefaction temperatures by repeatedly compressing and expanding the gas and passing it through a heat exchanger, much like a domestic refrigerator (4). Most of the energy needed for air separation is consumed by this part of the ASU.

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The industrial gases industry has been producing liquid nitrogen and oxygen for over a century.

The extremely cold air is now separated into its components in two distillation columns (5), in which gas moves to the top and liquid falls to the bottom. In the first, medium pressure column, air is separated into nitrogen gas and an oxygen enriched liquid containing 30% oxygen. In the second, low pressure column, the full separation of oxygen and nitrogen is achieved, and both are available in liquid or gaseous form (6). These products are typically delivered to customers as compressed gases by pipeline or cylinder, or as liquids by road tanker.



Figure 2.1: Air Separation Unit. Source: Messer

The process inevitably produces excess nitrogen, because there is four times as much nitrogen as oxygen in the atmosphere but much less demand for it commercially. Some of the excess nitrogen is recycled to cool incoming air, so raising the energy efficiency of the ASU, but much is vented harmlessly to the atmosphere. Spiritus Consulting estimates excess nitrogen production capacity in the UK at 8,500 tonnes per day (tpd) (see chapter 6). Since this excess nitrogen is in gaseous form, exploiting it as an energy vector would require the construction of additional liquefiers at existing industrial gas production sites.

Air can be liquefied without separating the oxygen and nitrogen using only the 'front end' of an ASU - essentially steps 1-4 above. Air is cleaned, compressed and water and CO₂ removed, and the air then liquefied using a compressor, turbines and a heat exchanger (a 'liquefier'). There is no need for the distillation columns, and the liquid air can then be stored in tanks similar to those used for liquid oxygen or nitrogen. A diagram of this simpler process is shown in Figure 2.2.

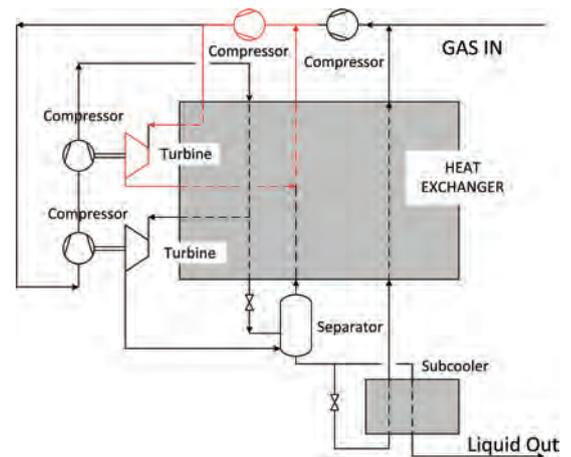


Figure 2.2: Air liquefier

The amount of energy required to produce a tonne of oxygen or nitrogen using 'best available technology' is shown in Table 2.1.¹¹ According to Messer, the German industrial gas company, of the 549kWh required to produce a tonne of liquid nitrogen, about 20% is consumed in the separation process. Producing a tonne of liquid air therefore consumes about 439kWh.

Benchmark specific electricity consumption (kWh/tonne) at 285k and 1,013bar		
Air separation plant product	Oxygen	Nitrogen
Gaseous (@40bar)	400	243
Liquid	638	549

Table 2.1: The energy consumption of oxygen and nitrogen production. Source: EIGA¹²

Liquefied gases can be stored in two types of tank: smaller vacuum insulated, and larger flat-bottomed. The advantage of vacuum insulated tanks is that they can be operated at any pressure required, depending on the construction material. They can be economically produced up to a size of 300m³. Any tank larger than 500m³ will be flat bottomed, insulated with the volcanic material perlite, and will operate at near-atmospheric pressure - typically 30-100mbar.

Because the temperature outside the tank is typically ~200C warmer than inside, heat leaks inwards and causes some of the liquid to boil

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off. The boil-off rate for both vacuum insulated and flat-bottomed tanks is about 0.1-0.2% per day - although the rate for larger tanks can be as low as 0.07%. Because nitrogen boils at a lower temperature than oxygen, a tank of liquid air may gradually become oxygen enriched. As we discuss in chapter 8, this is a hazard that must be managed, since liquid oxygen is highly reactive.

3. Liquid air technologies today

Large scale energy storage

A large scale, long duration energy storage system based on the liquid air cycle has recently been developed by Highview Power Storage and demonstrated at a 300kW pilot plant in Slough. The plant is hosted by SSE (Scottish & Southern Energy) next to its biomass power station, and was partly funded by the Department of Energy and Climate Change (DECC). The pilot plant has been successfully tested against standards set by National Grid and other international electricity system operators (UK STOR and TRIAD markets, US PJM market). A 10MW commercial demonstration plant is now planned, and the company predicts efficiencies and costs will improve at progressively larger scales. The system is built from components already widely used in the industrial gases and electricity generating industries, but combined in a novel form that the company calls a Cryo Energy System, and describes more generically as Liquid Air Energy Storage.

The system consists of three main elements: charging, storage and power recovery (see figures 2.3 and 2.4). First, grid electricity is used to power an air liquefaction plant (the front end of an industrial gas separation unit) to refrigerate air to its liquid state. The liquid is then stored in an insulated tank at low pressure*, which functions as the energy store. When power is required, liquid air is drawn from the tank and pumped to high pressure and into a heat exchanger, where ambient and low grade waste heat turns the cryogen into a high pressure gas, which is then used to drive a turbine and generator to deliver electricity back to the grid.

*Cryogenic tanks that hold less than 100 tonnes are typically held at <10 bar, and those that hold over ~1,000 tonnes at fractionally more than atmospheric pressure.

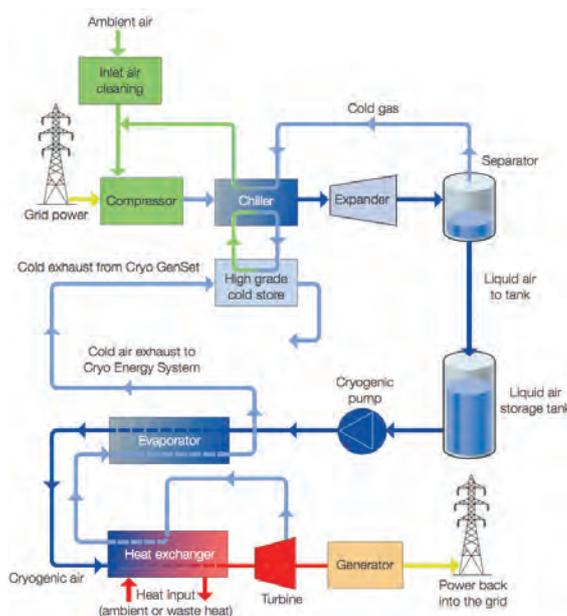


Figure 2.3: Schematic of a Liquid Air Energy Storage system. Source: Highview Power Storage

The efficiency of the process is increased by exploiting both waste heat and waste cold. The use of low grade waste heat during expansion generates additional power that improves the overall round trip efficiency of the cycle; the cycle's maximum efficiency is determined by the highest and lowest temperatures, so raising the higher temperature with waste heat increases the available work. At Slough, waste heat at around 60C is sourced from the biomass power station next door. Performance data shows this heat is converted into power at an efficiency of 50-60%.¹³



Figure 2.4: the Highview Power Storage pilot plant in Slough. Source: Highview Power Storage

Liquid Air Energy Storage of grid electricity has been demonstrated at a pilot plant in Slough, with backing from DECC.

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The Liquid Air Energy Storage concept uses waste heat and cold to raise efficiency to a projected 60% at commercial scale.

BOX 2.1: Liquid Air Energy Storage process

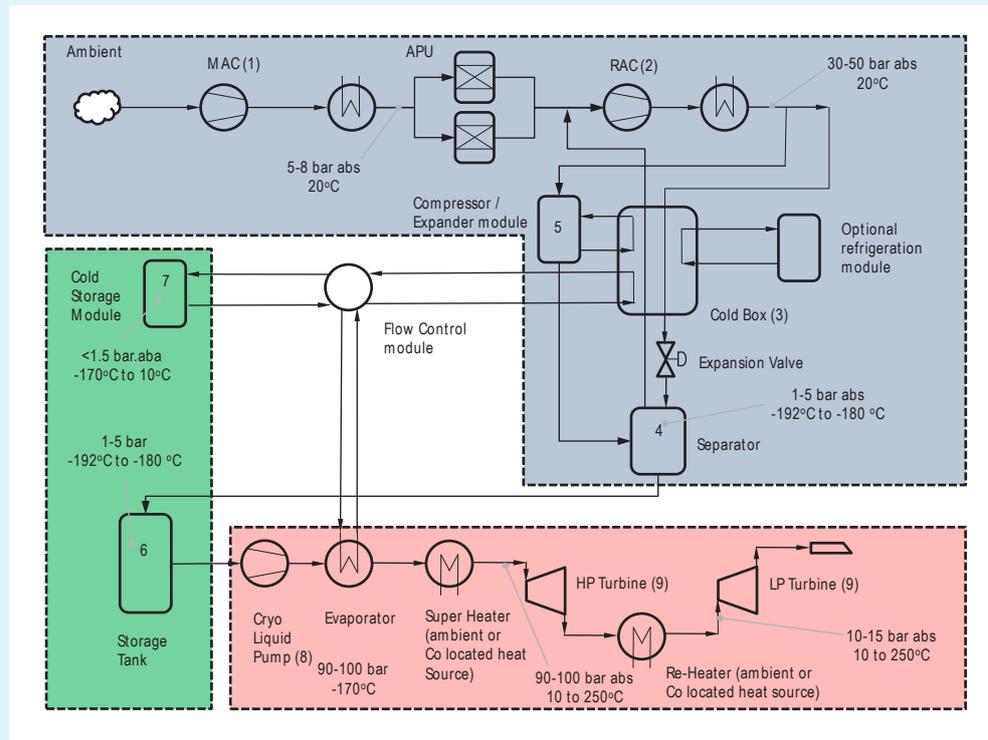


Figure 2.5: Schematic of a Liquid Air Energy Storage device. Source: Highview Power Storage.

The schematic separates the process into three sections: charging (grey); storage (green); and discharge or power recover (red). The air is first compressed (1) and passed through a filter to remove water and carbon dioxide, that would otherwise freeze and block the process. The air is compressed in a recycle air compressor (2) and then cooled in a series of heat exchangers, referred to as a cold box (3). The now very cold air is expanded where most of the flow condenses to liquid (4). The part of the flow that is not condensed returns through the cold box to cool the main high pressure flow. Part of the flow from the recycle compressor is diverted to a separate channel in the heat exchanger where it is cooled and expanded through a turbine (5). This achieves more efficient cooling and reduces the energy required to liquefy the air. The liquid air is then stored in an insulated tank (6). The discharge process follows the Rankine cycle. The thermal energy required to heat the cold liquid after compression is captured and stored in a thermal store (7) after the

liquid pump (8). The resulting warm high pressure gas is expanded through a series of turbines (9) to generate electricity.

The process as described could achieve an efficiency of around 25%. The efficiency is greatly increased by storing and recycling the thermal energy released during the power recovery process, more than doubling the process efficiency to 50-60%. This is achieved by capturing the cold thermal energy released during the power recovery process in a thermal store, typically a bed of gravel. The thermal energy stored in the gravel bed is then used to improve the efficiency of the liquefaction process by circulating dry air through the cold box and thermal store, transferring the thermal energy from the store to the cold box. The result of this 'cold recycle' is that less air is recycled round the process through the expansion turbines (5) and more of the air is turned to liquid during the expansion process at the separator (4), reducing the energy cost of manufacturing a specific quantity of liquid air.

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The turbine exhaust gas is also recycled as part of the process and its residual heat removed to help drive the evaporation of the cryogen. This then produces a very cold gas stream, the cold content of which is stored in a proprietary high-grade cold store, and used to pre-cool incoming air when liquefaction next takes place, so further raising the efficiency of the plant. The process is described in more detail in Box 2.1.

The pilot plant was fully commissioned in July 2011 and has been tested for cold recycle, reliability, response and heat to power performance. In testing against National Grid STOR criteria, the pilot plant proved 95% reliable, considered high for a pilot plant, and in testing against the US PJM self testing protocol, the plant was 99.8% compliant - against a pass mark of 75% - as reviewed by the PJM assessors. The plant was able to reach desired output within 2½ minutes, meaning that at larger scale the technology is a potential candidate for the fast reserve market as well as STOR. A full technical description of the Cryo Energy System provided by the company forms Appendix 1.

The pilot plant was built from standard components that are widely used in the industrial gases and power generation industries. The company is now planning a 10MW/40MWh Commercial Demonstration Plant with ~300 t/day liquefaction plant and a high grade cold store on the same basis. All of the main components of the system are more efficient at commercial scale, and the company has calculated this will raise round-trip efficiency to 60%.¹⁴ Other companies are also reported to be investigating the opportunity of liquid air storage, including Praxair, Air Products and Expansion Energy in the US, but there is no news to date of any hardware deployed.

Liquid air generation-only device

The Cryo Energy System is a fully integrated electricity storage system in which liquid air is produced and consumed on the same site. However, liquid air could also be produced in one place and used to generate electricity in another. The liquid would be transported between sites in the same way industrial

gas companies distribute liquid oxygen and nitrogen today - typically by road tanker (Figure 2.6). This might make sense for applications where the generator is too small, or used too infrequently, to justify the cost of building an on-site liquefier. It could also make use of an estimated 8,500 tonne per day surplus of nitrogen production capacity in the UK (chapter 6).

Highview Power Storage has developed a generation-only device to fulfil this function called the Cryogenet. It is essentially the same as the Cryo Energy System described above but without the liquefier, and whereas the storage system would scale from 10MW to several 100MW, the Cryogenet is designed for 3-10MW.

The Cryogenet is intended eventually to compete with diesel generators and Open Cycle Gas Turbines (OCGT) in their roles as corporate emergency back-up power and grid peaking plant that typically generate for less than 100 hours per year (chapter 3). It is estimated that UK companies have diesel generators with a total capacity of around 15GW, of which about 2.5GW are in units of 1MW or larger. National Grid currently contracts 493MW of diesel generation and 346MW of OCGT capacity as part of its Short Term Operating Reserve.¹⁵ The Cryogenet shares many characteristics of diesel gensets and OCGT, such as low capital cost and relatively fast start up times (less than 15 minutes), but with the added benefit of lower carbon emissions, since liquid air generated from off-peak electricity is likely to be less carbon intensive than diesel or gas when burned in inefficient open cycle plants (chapter 10).

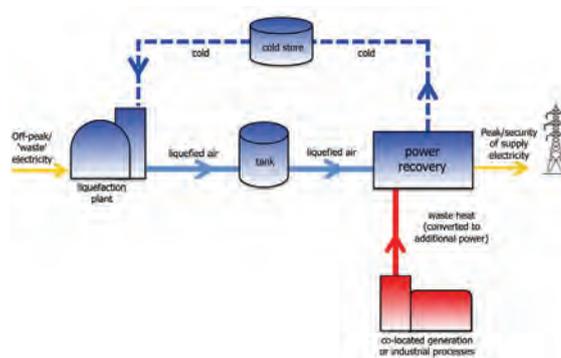


Figure 2.6: Schematic of a Cryogenet. Source: Highview Power Storage

A Liquid Air Energy Storage system liquefies air and uses it to generate electricity on a single site. But liquid air could also be produced centrally and distributed to small scale cryogenic generator sets.

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The Dearman Engine achieves efficient isothermal expansion of the cryogenic 'fuel' inside the cylinder by means of a heat exchange fluid.

The Dearman Engine

The Dearman Engine Company is developing a cryogenic engine that operates through the vaporisation and expansion of liquid air or liquid nitrogen. Ambient or low grade waste heat is used as an energy source with the cryogen providing both the working fluid and heat sink. Heat is introduced to the cryogenic fluid through direct contact heat exchange with a heat exchange fluid (HEF) inside the engine.

Figure 2.7 shows an overview of key parts of the Dearman Engine process. On the return stroke a warm heat exchange fluid flows into the cylinder filling nearly all of the dead volume. Just after top-dead centre the liquid air or nitrogen is injected directly into the heat exchange fluid. There is a large surface area and temperature differential and this causes the cryogenic fluid to boil very rapidly.

As the fluid turns into a gas it expands, and this expansion process drives the piston down the cylinder for the power stroke. During this process, the heat exchange fluid keeps giving up heat to the expanding gas ensuring a nearly isothermal expansion - the gas expands yet the temperature remains relatively constant.

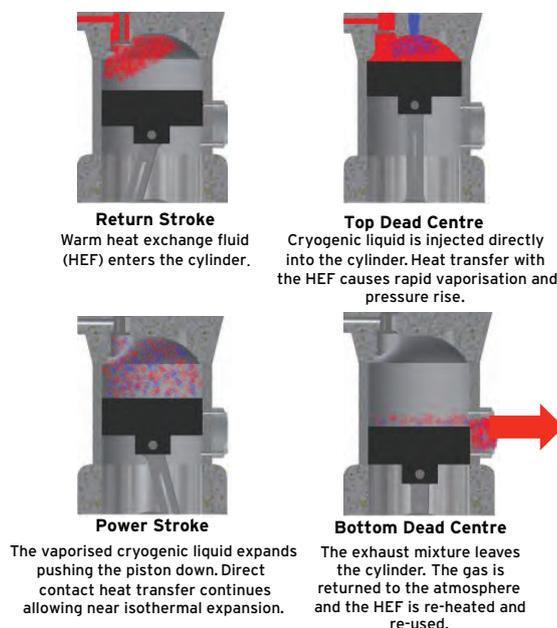


Figure 2.7: The Dearman cycle. Source: Dearman Engine Company

At bottom dead centre an exhaust valve opens allowing the mixture of gas and heat exchange fluid to exit the cylinder. The heat exchange fluid is recovered from the exhaust stream and reheated whilst the air or nitrogen gas is exhausted to the environment.

While cryogenic expansion engines are not new, previous incarnations have worked on an open Rankine cycle - similar to a traditional steam engine but operating across a different temperature range. Under this arrangement the cryogenic fluid is pumped to operating pressure and vaporised through a heat exchanger before expansion in the engine cylinder.

A number of drawbacks exist with this arrangement when applied to mobile applications, since the heat exchanger must be large to cope with the heat transfer rates, and heavy to withstand the high pressure. Since little heat is added to the gas during the expansion phase in the engine cylinder, it cools while expanding (near adiabatic expansion) so reducing the work output.

The novelty of the Dearman Engine lies in the use of a heat exchange fluid (HEF) to facilitate extremely rapid rates of heat transfer within the engine. This allows injection of the liquid cryogen directly into the engine cylinder where heat transfer occurs via direct contact mixing with the HEF. The heat transfer on injection generates very rapid pressurisation in the engine cylinder. Direct contact heat transfer continues throughout the expansion stroke giving rise to a more efficient near-isothermal expansion.

The inventive step is covered by a patent covering the European Patent Office (EPO), US and Japanese territories. In December 2011 the company filed a subsequent application covering insights derived from its engine testing experience.

The specific work available from an expansion over a variety of pressures is shown in Figure 2.8 for both adiabatic expansion, where no heat is added and the gas inevitably cools as it expands, and isothermal expansion, where heat is added during expansion to maintain a constant temperature, so increasing the work output. The dashed lines indicate the specific work from the expansion net of pumping work.

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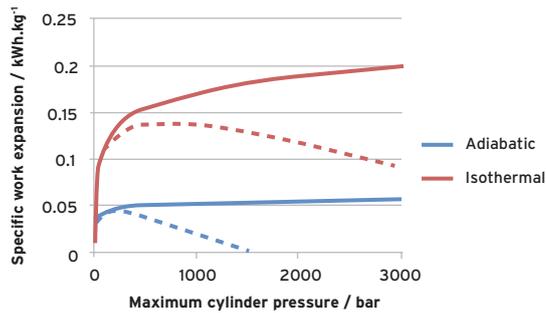


Figure 2.8: Specific work from the expansion of liquid air

The benefit of the pressurisation process taking place in the cylinder is to reduce the amount of pumping work required to reach a given peak cylinder pressure, meaning that the likely specific work from a kilogramme of liquid nitrogen is between the dashed and solid lines. The benefit of having a heat source present during the expansion stroke - the core Dearman Engine invention - is demonstrated by the difference in specific work availability between the adiabatic and isothermal processes. Taking the benefits of in-cylinder pressurisation and heat transfer together, the likely specific work from a kilogramme of liquid nitrogen is between the dashed and solid red lines.

The engine has two unique capabilities within the zero-emission engine space:

Heat to power

The Dearman Engine power cycle has a bottom temperature of about -196C and peak cycle temperature of ambient, meaning even relatively low grade heat can increase the peak cycle temperature and be converted into additional work at very high conversion efficiencies. The Dearman Engine can be deployed as a high yield thermal energy recovery system that could convert heat from the exhaust or coolant systems of an internal combustion engine into shaft power at conversion efficiencies of up to 50%. This would have the advantages of:

- reducing or eliminating the loads associated with heat rejection on the IC engine;
- enabling the IC engine to be downsized;
- displacing a material portion of transport related emissions into an energy vector (liquid air) that can be produced from renewable sources.

Initial comparison suggests that liquid air can be profitably substituted for on-highway hydrocarbons, so there is a fuel cost saving too (see chapter 6).

Fuel cells also give off large amounts of heat, so in future the Dearman engine could be used to raise the efficiency of vehicles powered by hydrogen (chapter 5) as well as fossil fuels.

Cooling

The engine absorbs significant quantities of heat during its operation and so can be viewed as a heat sink or cooling source. If there is a requirement for a heat sink or cooling source (eg air conditioning or refrigeration) then a Dearman Engine can simultaneously displace cooling loads and generate shaft power. The engine absorbs approximately twice as much heat as shaft power generated.

The liquid nitrogen split cycle engine

The auto engineering consultancy Ricardo is conducting engine development for the Dearman Engine Company, and a fully characterised bench prototype is expected to be completed by the end of 2013. However, Ricardo has also proposed another engine concept to exploit the potential benefits of liquid nitrogen. Whereas the Dearman engine uses liquid air as fuel, Ricardo's engine would run on petrol or diesel but incorporate a quantity of cryogenic gas into the cycle to make it significantly more efficient. The Ricardo design is based on advances in static electricity generation technology.

In power generation, a Combined Cycle Gas Turbine (CCGT) is extremely efficient in spite of its low compression ratio. This is because the temperature difference between the compressed inlet air (Figure 2.9 position 2) and the exhaust gas (position 5) is big enough to allow significant heat transfer, meaning that heat from the exhaust can be used to raise the temperature of the compressed air through a heat exchanger or 'recuperator' before combustion. This reduces the amount of fuel required to achieve the same output.

The Dearman engine can convert heat from the exhaust or cooling systems of an internal combustion engine into shaft power at conversion efficiencies of up to 50%.

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Modelling suggests the Ricardo liquid nitrogen split cycle engine could achieve efficiencies of more than 60%.

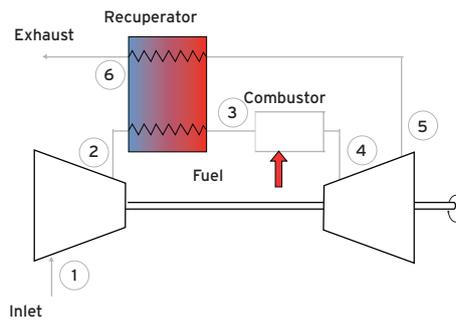


Figure 2.9: Combined Cycle Gas Turbine

By contrast, the ICE derives its efficiency from having a high compression ratio, and this means the temperature of the compressed air is too close to that of the exhaust to allow effective heat transfer; waste heat from the exhaust cannot be recovered. In addition, most ICE designs compress and expand the air in the same cylinder, making it impractical to introduce a recuperator into the system.

This problem can be overcome using a split cycle engine design similar to the Isoengine concept first developed by Ricardo in the 1990s and the Scuderi engine today. In such designs, compression takes place in one cylinder and expansion in another, which is similar in concept to a gas turbine. However, to make the split cycle thermodynamically efficient requires isothermal compression, in which the air remains at a relatively constant temperature despite being compressed. The temperature-entropy diagram in Figure 2.10 shows how isothermal compression allows the temperature difference between the compressed intake air and the exhaust gas to be maximised, so creating an opportunity for waste heat recovery.

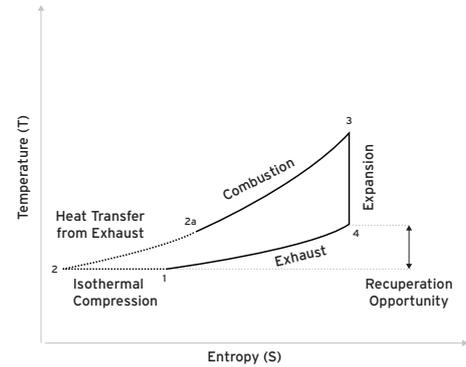


Figure 2.10: Recuperated diesel cycle with high compression ratio and isothermal compression. Source: Ricardo

Isothermal compression can be achieved by spraying a fluid into the compression chamber to absorb heat from the gas being compressed, and this approach has been tested in a 3MW power generation demonstrator using water. However, although this produced a large demonstrable gain, raising gas to electricity conversion efficiency to 59%, it also required large quantities of water because of the small temperature difference between it and the air being compressed, along with complex and expensive water management equipment.

The Ricardo split cycle invention replaces water with liquid nitrogen which is far colder at about -200°C , meaning that far smaller volumes are required. In addition, once vaporised during compression the nitrogen can then pass straight through the combustor and be exhausted to the atmosphere. As a result, the system can be made far more compact and suitable for vehicle engines.

Detailed modelling of this approach undertaken through the TSB 'CoolIR' programme has suggested an efficiency of more than 60%. As a result, a modest onboard tank of liquid nitrogen would extend the range of the vehicle by increasing the efficiency of the primary engine. Liquid nitrogen could also be produced by an onboard liquefier driven by the engine and boosted by regenerative braking.

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4. Liquid air or liquid nitrogen?

Technologies that use liquid air as an energy vector exploit its thermo-physical properties - its expansion between liquid and gaseous phases and/or its ability to absorb heat. Air and nitrogen have relatively similar thermo-physical properties and so most technologies under consideration (except the Ricardo split-cycle engine) could use either liquid nitrogen or liquid air. The choice is likely to be driven by existing supply, economics, infrastructure, safety and application-specific factors.

One major advantage of nitrogen is the industry has a substantial surplus of production capacity both in the UK and globally (chapter 6). This arises because there is four times more nitrogen than oxygen in the atmosphere but much less demand for it commercially. Spiritus Consulting estimates the surplus amounts to about 8,500 tonnes of nitrogen gas per day, which currently is simply vented to the atmosphere. To turn this into a cryogenic energy vector would require investment in additional liquefiers. If that were done, this surplus could absorb 4.6GWh¹⁶ of 'wrong time' wind generation and, at 60% round trip efficiency, deliver 2.8GWh back to the grid, enough to power the equivalent of 310,000 households.¹⁷ Alternatively it could potentially fuel the equivalent of 6.5 million car kilometers daily.¹⁸ Since the marginal cost of exploiting this waste product is low (chapter 6), it is likely that many early applications of 'liquid air' would in fact run on liquid nitrogen.

Once the nitrogen surplus has been exhausted, liquid air would have an economic advantage since its production requires less equipment and less energy than liquid nitrogen and should therefore be cheaper. A wide range of air liquefiers is already available commercially, ranging from small-scale units producing 2,000 litres per day, made by companies such as Stirling Cryogenics of the Netherlands¹⁹, to industrial plants of about 30 tonnes per day, such as the Chinese unit installed by Highview Power Storage at its pilot plant in Slough.

There is no barrier to scaling these liquefiers up to units of several thousand tonnes per day as they are typically based on industry standard designs for nitrogen liquefiers which are already available at these scales. Once investment in new plant is required to supply cryogenic energy vectors, these simpler and cheaper systems will have a cost advantage, and liquid air may therefore be preferred over liquid nitrogen.

One disadvantage of liquid nitrogen compared to liquid air is that its exhaust is not breathable since it contains no oxygen (safety issues are covered in detail in chapter 9). This would preclude its use in enclosed spaces such as mines or warehouses without appropriate ventilation and oxygen monitoring equipment - the same precautions employed for fossil fuel powered engines. In these circumstances liquid air would be the preferred option, since the exhaust is breathable. Both liquid air and liquid nitrogen would provide free cooling from cold exhaust.

The disadvantage of liquid air is the potential for oxygen enrichment, which is a potentially serious hazard, although one that has been safely managed by the industrial gases industry for decades. Liquid air can become oxygen-enriched because nitrogen has a lower boiling point than oxygen, and so can evaporate more quickly in some circumstances, raising the oxygen concentration to higher than that found in the atmosphere. As we discuss in chapter 9, this hazard can be managed using equipment to prevent such enrichment, monitoring and safety procedures.

In the case of liquid air that is produced and consumed over short periods or hours or days - a grid balancing unit operating in the STOR market, for example - there is no danger of enrichment in any event.²⁰ But for strategic energy storage over weeks or even months, the risk would be higher. In this case the risk could either be managed as described earlier, or eliminated entirely by using liquid nitrogen rather than liquid air (chapter 9).

The industrial gases industry produces 8,500 tonnes of waste nitrogen gas per day, which could be liquefied to fuel the equivalent of 6.5 car kilometres daily.

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Neither liquid air nor liquid nitrogen emit CO₂ at the point of use, and both can be low carbon energy vectors depending on the energy source used to produce them. Liquid nitrogen is already typically generated during off-peak hours when electricity prices and carbon intensity are lower. In future, production of liquid nitrogen and liquid air could be 'wind-twinning' - concentrated in periods when the proportion of wind generation is highest.

Nor do they produce the nitrous oxide (NO_x), sulphur dioxide (SO_x) or particulates (PM10) associated with diesel generators, so cryogenic backup generators could have a beneficial impact on air quality in urban areas.

On balance it seems likely that early applications will exploit the nitrogen surplus except where there are specific reasons to choose liquid air, and that over time, as new production capacity is built, the advantages of liquid air over liquid nitrogen will become more compelling.

5. Conclusions

From the discussion presented in this chapter we conclude:

- There is a sporadic history of failed attempts to exploit liquid air as an energy vector, but technological breakthroughs and market evolution since the turn of the century make it worth investigating once again.
- Liquid air is not currently produced commercially but easily could be. There is a large surplus of liquid nitrogen gas available for liquefaction, and this would offer similar thermo-physical properties to liquid air.
- Liquid air and/or nitrogen offer a means to exploit myriad sources of waste heat.
- A number of promising technologies to exploit liquid air have either been demonstrated already or are in development.

Chapter 2 Endnotes

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- ¹² Ibid.
- ¹³ Results from performance tests carried out by Highview at the Slough site, personal communication, February 2013.
- ¹⁴ Because of its small scale the pilot plant operates at a subcritical pressure (peak process pressure 13bar), whereas at commercial scale the plant would operate at a supercritical pressure (>38bar). This means that in the pilot plant the majority of the air is reduced to liquid by means of cooling to the saturation point, giving a low efficiency of 7-12%. In the commercial plant the air is cooled to a level above the saturation temperature and then expanded through a Joule-Thomson valve to reduce to liquid. This is a significant factor in the higher efficiency of a commercial scale plant, calculated to be 60%. Highview Power Storage, personal communication February 2013. For more detail see Appendix 1.
- ¹⁵ National Grid, personal communication.
- ¹⁶ Nitrogen liquefaction requires 549kWh/tonne (European Industrial Gases Association (EIGA), December 2010). 8,500 tonnes x 0.55MWh = 4,675MWh.
- ¹⁷ 2.8GWh x 365 = 1,022GWh per year, or 1,022,000,000kWh. Average annual household electricity consumption is 3,300kWh. (<http://www.ofgem.gov.uk/Media/FactSheets/Documents1/domestic%20energy%20consump%20fig%20FS.pdf>). 1,022,000,000 / 3,300 = 309,696.
- ¹⁸ We assume a small car has an energy requirement of 0.13kWh/km, on the basis that the Nissan Leaf has a 24kWh battery and range of 175km (24/175 = 0.13). At a practical energy density of 0.1kWh/kg this translates to a requirement of 1.3kg of liquid air per km for a liquid air prime mover, and 1.04kg/km for one operating with the benefit of waste heat from an ICE engine. The UK could produce 8,500T (8.5 million kg) per day of additional liquid nitrogen. At 1.3kg/km this would equate to 6.5m vehicle miles, increasing to more than 8m vehicle miles with waste heat. Cf http://www.nissan.co.uk/?cid=ps-63_296991&gclid=CIX476ulyrUCFcbKtAodfwOAbA#vehicles/electric-vehicles/electric-leaf/leaf/pricing-and-specifications/brochure.
- ¹⁹ <http://www.stirlingcryogenics.com/stirling-cryogenics-contact/>
- ²⁰ For example, a tank containing 60 tonnes of liquid air based with 0.5% nitrogen boil-off per day would see oxygen concentration rise by 0.1% per day. Liquid air is typically considered to be enriched at 23% oxygen. At this rate it would take about 17days to reach this level.

Chapter 3 Grid electricity

Under any likely scenario balancing the grid will become more challenging. Balancing capacity needs to rise from 3.5GW to as much as 13GW by 2020 according to National Grid.

1. Balancing the electricity grid

2. District Network Operators

3. Integration with fossil fuels

4. Conclusions

Under any likely scenario, balancing supply and demand on the electricity grid will become more challenging over the coming decades. About 19GW of firm generating capacity will close by the early 2020s, while large amounts of intermittent renewable and inflexible nuclear generation are expected to be added. At the same time, demand is forecast to rise and become more 'peaky' with the increasing use of Electric Vehicles (EVs) and heat pumps. As a result, National Grid estimates that balancing capacity needs to rise from 3.5GW today to some 8-13GW by 2020.¹ The balancing requirement can be expected to grow further as renewable penetration continues to rise to 2030 and beyond. One analysis suggests that, in the absence of other balancing mechanisms of up to 90GW of gas fired 'backup' capacity may be required by 2050.²

Balancing can be achieved in a number of ways, as discussed in chapter 1, but a number of factors suggest a growing role for storage, including the need to minimise the amount of renewable energy lost to curtailment as renewable capacity grows, and the need to constrain the carbon emissions of backup generation as they become more significant over time. Storage can mitigate both problems because it absorbs 'wrong time' renewable energy - such as wind power produced at night when there may be too little demand to make use of it immediately - to displace fossil generation at peak times. In chapter 2 we introduced two liquid air technologies, Liquid Air Energy Storage (LAES) and the Cryogenet, which are technically proven, geographically unconstrained and potentially highly competitive. In this chapter we explore in more depth the potential market for grid storage and make a more detailed assessment of liquid air against competing balancing and storage technologies.

Liquid Air Energy Storage is not only relevant to balancing the national electricity grid in 'high wind' scenarios however; a 'high nuclear' scenario would give rise to similar challenges. Storage may also offer specific benefits for regional electricity distribution network operators (DNOs), which we explore in section 2. Liquid air could also integrate into gas fired power plants and LNG terminals to achieve major increases in efficiency and reductions in cost. We explore some of these opportunities in section 3.

1. Balancing the electricity grid

The balancing challenge

Decarbonising the electricity grid is central to achieving the UK's carbon reduction targets, for the simple reason that power stations generate about a third of total emissions.³ The Climate Change Committee has suggested a target of less than 50gCO₂/kWh, a 90% reduction from current levels, which the government expects to achieve during the 2030s. To achieve this, the generation mix will need to change radically. There are many potential paths to a low carbon grid and

assessing the full range is beyond the scope of this paper. We assume a 'high wind' scenario similar to National Grid's 'Gone Green' scenario⁴ on the basis of government policy, technology readiness and the scale of the UK wind resource. DECC estimates the UK could deploy up to 31GW of wind capacity by 2020, and well over 50GW by 2030.⁵ That compares with current baseload (the minimum level of supply required throughout the year) of 20GW and peak demand of 60GW.

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Three high wind generation scenarios that have the potential to achieve the emissions reductions target are presented in Figure 3.1. The scenarios are taken from two major recent modelling studies into future grid balancing: *A Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future*⁶, a report for the Carbon Trust led by Professor Goran Strbac; and *Analysing Technical Constraints on Renewable Generation to 2050*⁷, a report to the Committee on Climate Change by the energy consultancy Pöyry. The studies took different approaches to the issue but the results are broadly consistent.

None of the scenarios is a forecast; they simply illustrate three pathways that deliver significant reduction in carbon emissions from the power sector in line with the government's emissions reduction targets. The Pöyry High and Strbac Grassroots scenarios are similar, and simply show a 'high wind' (roughly 100GW by 2050) generating mix that could deliver the necessary amount of low carbon energy over the course of a year, but without allowing for intermittency. The Strbac Grassroots Secure scenario, by contrast, shows what would be needed to deliver that energy and maintain security of supply at present levels. The difference, in the absence of any alternative balancing technologies, is an additional 90GW of gas fired generating capacity in 2050 (Figure 3.4). It is important to note this backup capacity would be used only rarely, and less frequently than current reserve capacity - typically less than 100 hours per year. This would make it challenging to recoup the necessary investment under current market arrangements and may require new subsidy or regulatory support of the sort being considered under the government's Electricity Market Review (EMR).^{8,9,10,11}

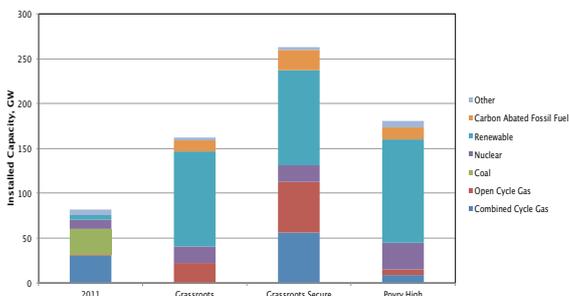


Figure 3.1 Projections of future generating mix in 2050 compared with the 2011 mix. Sources: Strbac¹¹; Pöyry¹²

Electricity demand is also forecast to rise significantly with the electrification of transport and domestic heating. Projected energy efficiency savings across the domestic and industrial sectors are forecast to be more than offset by increased demand elsewhere. Figure 3.2 shows that baseload is expected to remain essentially flat to 2050, whereas peak demand is forecast to more than double.

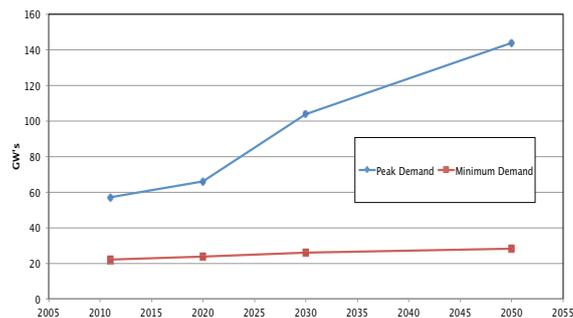


Figure 3.2: Forecast increase in UK electricity demand. Source: Strbac¹¹

This implies a significant increase in intraday and interseasonal variations in demand. In the absence of technologies to store energy generated at periods of low demand for use at peak times, the utilisation of generating assets will inevitably be lower than today, resulting in higher operating costs for the power network as a whole. This 'peaky' demand profile (Figure 3.3) will need to be managed effectively if the network is to avoid the need for significant reserve capacity that is rarely used.

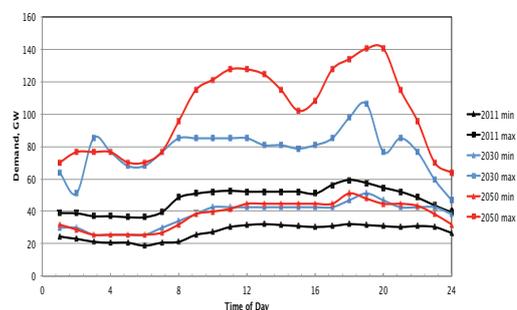


Figure 3.3: Maximum and minimum daily demand profiles in 2011¹³ and forecast for 2030 and 2050¹⁴

Electricity demand is forecast to become far more 'peaky' because of the electrification of heating and transport.

Chapter 3 Grid electricity

High wind scenarios present two problems: how to generate sufficient electricity when wind output is low; and how to absorb excess generation when wind output is high and demand is low. Liquid air could help with both.

What roles could be played by bulk energy storage technologies such as liquid air?

Balancing the grid in the future will require not only far more balancing capacity, but also different kinds of balancing technologies to accommodate the new challenges of balancing renewable generation with increasingly peaky demand. High wind scenarios present two distinct problems: how to generate sufficient electricity when wind output is low; and how to absorb excess generation when wind output is high and demand is low. In principle, the first can be tackled by extending existing solutions, but the second requires a new approach. There are potential roles for liquid air in both.

Today, the challenge of balancing the grid is about accommodating any divergence from forecast demand and any unexpected loss of supply through the failure of a generating asset or interconnection. This is largely achieved by holding some generating capacity in reserve. Typically this relies on a combination of Combined Cycle Gas Turbines (CCGT) operating at below their maximum output in order to respond up and down as required (sometimes referred to as 'spinning reserve'), and Open Cycle Gas Turbine (OCGT) and diesel generators ('peaking plants') which are not kept spinning, but which can start up within a matter of minutes.

There are two broad market services contracted by National Grid to balance the network: 'response', where generators need to be able to adjust their output within a matter of seconds; and 'reserve', where response times are measured in tens of minutes, but where the new output level may need to be maintained for several hours.¹⁵ Various response services are used to respond to extremely short term fluctuations to regulate network frequency at 50Hz, and there is currently about 1-2GW in this category. Fast Reserve is used to address a sudden loss of generating capacity or surge in demand, and Short Term Operating Reserve (STOR) to manage larger fluctuations over longer periods of up to four hours. About 2.6GW of reserve was required to balance the network in 2011.

The contractual arrangements for response and reserve services may well change as a result of the EMR, and some of the current contracts may disappear altogether. However the need to contract similar services

will remain, and many of the technical requirements will be unchanged.

National Grid estimates that an additional 6.5GW of reserve and 1GW of response capacity at maximum wind output may be required to manage the additional uncertainty of forecast renewable capacity in 2020.¹⁶ This suggests the balancing service most needed to deal with the early stages of increasing wind penetration is additional reserve. The largest reserve service is STOR (2.6GW), of which around 840MW is provided by OCGT and diesel generators, which share the characteristics of low capital cost, high carbon intensity and modest start-up times of several minutes. This in turn suggests an opportunity, as balancing capacity expands rapidly to 2030 and beyond, for a low carbon, despatchable generator with similar characteristics. The Cryogenet could fulfil this role, and we assess its potential later in this chapter.

Additional generating reserve can replace the lost output from wind farms when wind speeds are low, but it cannot absorb excess wind output when wind speeds are high and demand is low. Periods of excess wind generation can happen either because wind output exceeds total demand, or because grid bottlenecks prevent the power being transmitted to where it is needed.

Periods of excess renewable generation are already beginning to occur in grids around the world. In Texas and Germany power prices are frequently negative during periods of high renewable generation.¹⁷ There have also been periods of negative prices in the British and Irish markets, but in Britain the more common symptom is the occurrence of 'constraint payments' to wind farms, when operators are compensated for the electricity that they could have produced but which the network was unable to absorb. Constraint payments have risen dramatically, from just £180,000 in the year to April 2011 to £34 million the following year.¹⁸ In the absence of remedial measures this problem will worsen as wind penetration increases.

When the network is no longer able to absorb the power generated from a wind farm, the current solution is simply to 'turn off' turbines to reduce output until the system returns to balance. This approach maintains the integrity of the network, but at the cost of losing valuable low carbon energy. Clearly, the network would be more efficient if this energy could be captured and used when there is more demand. This could be achieved in a

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number of ways, including exporting energy through interconnection with other markets, increasing discretionary demand or through large scale energy storage.

Strbac¹⁹ has shown that the benefits of storage could be worth £10 billion per year to the network as a whole by 2050. However, as discussed in chapter 1, the only mature bulk storage technology, pumped hydro storage, is geographically constrained and other storage technologies remain technically and economically challenged. There is, therefore, an opportunity for a new bulk storage technology such as Liquid Air Energy Storage, capable of absorbing, storing and discharging excess renewable energy.

In summary, there are two distinct opportunities for new liquid air technologies. The first is as a low carbon fast, start-up generating device, potentially displacing incumbent solutions such as gas turbines and diesel generators. The second opportunity is as a storage device, which uses surplus renewable energy to manufacture liquid air that is then converted back into useful electricity when demand is high. The Cryogenset and Liquid Air Energy Storage systems introduced in chapter 2 could perform these roles. In the rest of this chapter we will estimate the opportunity for liquid air generation and storage technologies to help solve the balancing challenge and how these technologies compare with other solutions.

What is the scale of the opportunity?

Generation-only device

As wind penetration rises, most commentators expect a significant increase in the deployment of open and combined cycle gas plant operating as flexible and peaking plant. In the absence of alternative approaches, Strbac²⁰ calculated an additional 70GW of gas plant would be needed by 2030 to keep the network balanced and 90GW by 2050. The total and open cycle gas capacities are broken out in Figure 3.4.

Liquid air generating technologies could, in theory, service all the additional capacity requirements, suggesting up to 70GW by 2030. However, much of this additional capacity is likely to be operating regularly at a mid merit order capacity factors and so is better suited to plant operating on a primary fuel such as gas rather than synthetic fuel such as liquid

air (or hydrogen), where the energy cost of manufacturing the fuel becomes a significant contribution to the overall cost. We therefore assume the additional OCGT peaking plant requirements are a more realistic indication of the scale of the market opportunity for a liquid air generation device such as the Cryogenset. This still suggests a substantial opportunity of around 30GW by 2050.

Storage device

The balancing challenge presented by rising wind penetration is the subject of recent research by Pöyry²¹, National Grid²² and Strbac and colleagues at the Imperial College Energy Futures Lab.^{23,24} Strbac addresses the question most directly and our assessment of the market opportunity for liquid air storage and generating devices is largely based on their results. We also make the following assumptions:

- We assess bulk storage only, connected towards the top end of the distribution network or directly to the transmission network. This implies plant capacities of 10MW to 100MW plus, rather than smaller MW scale (or smaller) devices installed closer to the consumer in the distribution network. The opportunities for such devices are qualitatively assessed in section three.
- We consider the Grassroots (high wind) scenario only. Since storage is primarily a technology for balancing intermittency, if a firm flexible low carbon generation technology were to emerge at scale, the role of storage and hence liquid air technologies would be greatly reduced.
- We use the optimal value of storage calculated by Strbac with and without competing technologies, such as demand side response (DSR), to estimate an upper and lower limit for the market opportunity.
- We assume no contribution from flexible hydrogen generation to balancing.
- CAPEX figures were calculated assuming a 30 year life and 11.5% weighted average cost of capital (WACC), reflecting the expected long life of liquid air storage devices but also some investment risk in deploying a new technology into the energy market.

The potential value of storage to the network as a whole is estimated at £10 billion per year by 2050.

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The potential market available to Liquid Air Energy Storage and stand-alone generation devices could be 30GW by 2050.

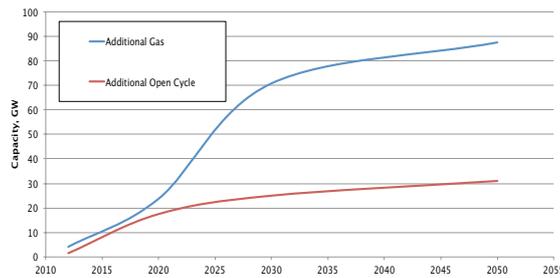


Figure 3.4: Forecast of additional capacity and additional fast response plant to balance the network

Strbac identified capital cost as a key factor in determining how much storage capacity is needed to maximise the overall benefit to the network. Another critical factor is the level of deployment of competing technologies such as DSR. Figure 3.5 presents the optimal installed storage capacity with competing technologies (Low) and without (High), at varying time horizons and against a range of assumed capital costs. We can assess the potential for Liquid Air Energy Storage by comparing its capex target of 750-1250 £/kW (see Appendix 1) against these ranges.

Up to 2020, the level of renewable deployment is insufficient to cause significant balancing issues and so there is little need for additional storage. By 2030, however, the additional storage requirement at target liquid air capital costs rises to 3GW (Low) and 6.5GW (High), and by 2050 it rises to between 7.5GW (Low) and 14GW (High). This represents a significant increase in the UK's current storage capacity of 2.8GW, primarily supplied by pumped storage.

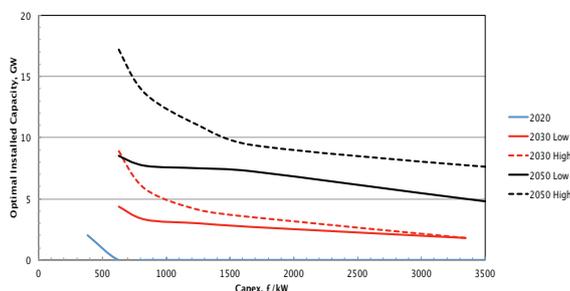


Figure 3.5: Projected future role of storage in a low carbon power network (derived from Strbac²⁵)

In summary, it is possible that by 2050 the market available to liquid air generators could be as large as 30GW, and that available to Liquid Air Energy Storage devices as much as 14GW. Extrapolating from Strbac, the value of this storage to the network would be some £10 billion per year. Since storage devices also generate, any growth in their capacity would tend to shrink the remaining market for generation-only devices. Thus the total market available to both technologies is judged to be 30GW.

What are the key technical requirements?

Generation-only device

Liquid air generation-only devices will compete with Open Cycle Gas Turbine and diesel generators, and in the absence of regulatory support will need to at least match those mature technologies, as well as any emerging technologies, against the following metrics:

- Capital cost is the most important. It is difficult to be precise, since costs vary by site, application and market even for mature technologies, but around £600/kW is typical for an Open Cycle Gas Turbine.
- Long operating life - implicit in a low capital cost contribution to the overall cost - of around 25-30 years would be typical for a peaking device.
- Rapid response time of several to tens of minutes (but not seconds) will be necessary to operate in the Fast Reserve or STOR markets, or their future equivalents.
- Generating costs of peaking plant are of secondary importance since the actual generating time is low, typically less than 100 hours per year.

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■ **Lower carbon emissions.** Fossil peaking plants are typically inefficient and carbon intensive, but since they operate for so few hours each year, total emissions are currently insignificant. This means liquid air generators are unlikely to displace fossil plants solely on the basis of climate benefits in the short to medium term. However, peaking plant emissions may become more significant in the 2030 to 2050 time horizon when emissions reduction targets become much harder to achieve, giving low carbon liquid air generators an additional competitive advantage.

Storage device

The key technical requirements for a storage device can be gauged from the characteristics of the only mature bulk storage technology, pumped hydro, but also from recent modelling by Strbac. This produced the surprising conclusion that the efficiency of a storage device has little impact on its value to a system with high wind penetration, until very high levels of storage have been installed. Figure 3.6 shows the total value of storage to the network, defined as the reduction in the overall cost of building and operating the network in 2030 and 2050, against its round trip efficiency. Two levels of storage capacity are assumed, High and Low, based on the same assumptions about the penetration of competing technologies presented earlier. The flatness of the lines in all scenarios shows there is very little difference in value to the system between a storage device that is 50% efficient and one that is 90% efficient.

To understand this counterintuitive result, we must consider the two roles energy storage plays in balancing the network: providing generating capacity at peak times; and ‘soaking up’ excess wind generation at other times.

The first role, generating at peak times, is performed rather infrequently. A peaking plant may be called on to generate for fewer than 100 hours per year, meaning the plant spends most of the time on standby. This means that operating cost, which for a storage plant is driven by round trip efficiency, is less important than capital cost. It is important to note that the device is still adding value to the power network when on standby, by providing the necessary reserve to ensure the integrity of the network. Like an insurance contract, reserve still has value even when not being called on.

The other role, soaking up excess wind generation, is typically performed over short durations, when there is a significant excess of power available for a relatively short period of time. It would be uneconomic to deploy enough storage capacity to capture all the excess power, and so there is a surplus of electricity to charge the storage device, and this also reduces the importance of plant efficiency.

Modelling produces the surprising result that efficiency has very little impact on the value of storage to the system until very high levels have been installed.

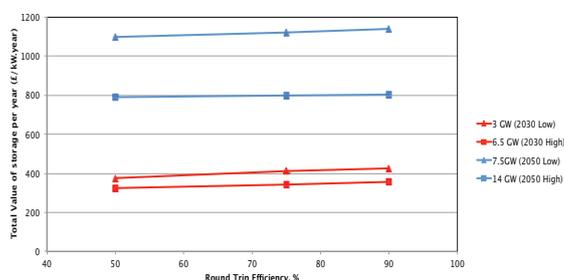


Figure 3.6: Effect of efficiency on the value of storage in 2030 and 2050 (derived from Strbac²⁶)

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At times of high renewable output storage can act both as reserve load and reserve power, meaning less spinning reserve is required to ensure security of supply.

The point is illustrated diagrammatically in Figure 3.7. In this example, 100MW of excess wind power is fed into two 10MW storage devices of differing efficiency. The power rating of storage devices describes their generation not absorption capacity, so an 80% efficient device is one that absorbs 12.5MW and delivers 10MW, while a 50% efficient device is one that absorbs 20MW and delivers 10MW. Of the 100MW, an 80% efficient storage device would lose 2.5MW in the storage round trip, meaning 87.5MW would be lost through curtailment of the excess wind energy. The 50% efficient device would lose four times as much energy (10MW vs 2.5MW) on a round trip, but would cause less energy to be curtailed (80MW vs 87.5MW). Naturally, a larger capacity storage device could be deployed but - as we have seen illustrated in Figure 3.5 - the optimal capacity of storage is very sensitive to capital cost, particularly at high levels of deployment. From Figure 3.5, we see the optimal capacity increases significantly as the capital cost approaches 6-700£/kW, the cost of an Open Cycle Gas Turbine, where storage will be competitive with and displace fossil fuelled peaking plant.

At higher levels of capital cost, storage plant must capture additional value through capturing surplus wind energy to be economic. In effect, storage is acting as a reserve load and follows a similar economic trade-off to reserve generators: low capital cost requirements, low sensitivity to operating costs. Strbac also noted that at times of high renewable output the fact that storage can act both as reserve load and reserve power means less spinning reserve is required to ensure security of supply. Storage therefore allows the system to absorb more renewable generation both through its primary role of arbitrage of excess energy, and by delivering renewable energy in to consumers in real time.

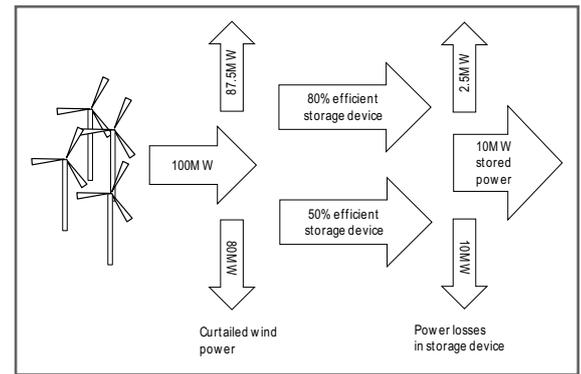


Figure 3.7: Illustration of the role of storage in capturing excess wind generation

Based primarily on Strbac²⁷, a liquid air storage device requires the following characteristics:

Metric	Target
Efficiency	>50%
Run time	2-6 hours
Cost	£750-1250/KW
Start up time	20 minutes
Life	>25 years

Table 3.1: Requirements of a liquid air storage device

Efficiency and run time were derived from Strbac. The target start up time is based on the assumption that the main requirement in future will be for additional reserve rather than response capacity. A target life of 25 years was assumed as a minimum for a utility scale asset. The capital cost target reflects the value proposed by Strbac to achieve a significant contribution from storage in balancing the network. This is also in line with the capex target set by Highview Power Storage for its Liquid Air Energy System.²⁸

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How do liquid air technologies compare with the market requirements and incumbent technologies?

Some of the key characteristics of a Cryogenet and a Liquid Air Energy Storage device are summarised in tables 3.2 and 3.3 below.²⁹

	Expected performance of a Cryogenet	Comparison with incumbent technologies
Plant size (Net Power)	3-20 MW	Good - diesel generators typically a few MW's, Open Cycle Gas Turbines typically up to 50MW
Specific liquid air consumption	0.13kWhr /kg	4-5kWhrs/kg diesel fuel. Liquid air has a lower energy density than fossil fuels
Start time to full generation (minutes)	< 10 minutes (pre-chilled cryo pumps)	Good - similar to diesel and gas turbines and in line with expected requirements for a reserve service
Expected mature capital cost at 10 -20 MW	£500 to 750/kW	Good - similar to typical Open Cycle Gas Turbine costs of £600/kW and £450 to £750/kW for a diesel generator
Expected operating availability	96%	Good - typical for the power industry
Expected reliability	99%	Good - typical for the power industry
Expected minimum calendar life	>30 years	Good - typical for the power industry
Site flexibility	Flexible	Good - important for the device to be installed at the optimal place in the network

Table 3.2: Key characteristics of a Cryogenet compared to incumbent technologies (see Appendix 1 for more detail)

	Expected performance of liquid air storage	Comparison with expected market requirements (Table 3.1)	Pumped Hydro (for reference) ³⁰
Plant size (Net Power)	10-250MW	Good - the range required for a transmission network connected storage device	100-5000MW
Round-trip AC-to-AC efficiency	50-60%	Good - based on Strbac >50% is required	75-85%
Round-trip AC-to-AC efficiency with waste heat	70% + , dependent on grade of heat		
Start time to full generation (minutes)	< 10 minutes (pre-chilled cryo pumps)	Good - in line with the requirements of a reserve plant	12 seconds (e.g. Dinorwig)
Expected mature capital cost at 10's MW	£750-1250/kW(dependent on application)	Good - in line with the range of costs identified for a significant (c. 10GW) contribution by storage by 2050	£1100-1250/kW ³¹
Expected mature capital cost at 100's MW	£500-750/kW (dependent on application)		
Expected operating Availability	96%	Good - typical for the power industry	>96%
Expected reliability	99%	Good - typical for the power industry	99%
Expected minimum calendar life	>30 years	Good - typical for the power industry	40-60 years
Site flexibility	Flexible (ie not restrained by geographic features as is the case with pumped hydro)	Good - important for the device to be installed at the optimal place in the network	Inflexible

Table 3.3: Key characteristics of a Liquid Air Energy Storage device compared to market requirements and pumped storage

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Storage requires not so much subsidy, but a market for grid balancing solutions that does not inherently favour gas peaking plants. If the market were created, barriers to liquid air would be low.

From Table 3.2, it is clear that a liquid air generation device could offer a viable alternative to the incumbent fossil fuel solutions, primarily Open Cycle Gas Turbines and diesel generators. Key technical characteristics are similar, the Cryogenset is competitive on capital costs in the lower half of its target range, and it has the potential to reach target costs in fairly short order since it is based on existing components and supply chains (chapter 8). It also has the advantage of using a synthetic 'fuel' that could be manufactured from low carbon energy.

However, liquid air generators are a new technology with associated technical and commercial risks, the market for reserve capacity is well established, and the incumbent technologies are extremely mature and deeply entrenched. These factors present high barriers to entry, and the Cryogenset would struggle to sell enough units to achieve its target capital cost without early support from government. Since current policies do not address this area of the energy market effectively (Summary Report and Recommendations), liquid air generators seem unlikely to displace significant amounts of fossil fuel peaking capacity in the short to medium term.

One exception may be in urban areas, where concerns over local air quality rule out the use of diesel gensets and OCGTs. The City of London for example has ruled that standby generators should not be used to export electricity to the grid³², so preventing companies from recouping the expense of maintaining back-up capacity and managing their energy costs through the Triad market.

The prospects of the Cryogenset might also improve if a wider 'nitrogen economy' were to develop - with extensive use of liquid air in transport and energy storage - since cryogenic generators could integrate with other applications at very little marginal cost.

If the case for liquid air generation-only devices seems tenuous at present, the situation for Liquid Air Energy Storage looks very different. A market in bulk electricity storage does not yet exist, and could only be created through regulatory reform. If that were to happen, there is no incumbent technology to displace; the only mature bulk storage technology is pumped hydro, for which there are very few suitable sites left in the UK. So if the market were created, barriers to entry remain low.

Liquid air storage technology matches very well with the predicted market requirements of low capital cost and the ability to deploy at scale. It also benefits from two income streams - as a peaking plant and a sink for surplus wind energy - which significantly improves the value proposition relative to the Cryogenset, which can only capture revenue as a peaking plant.

The potential value of storage to the electricity system is undoubted. Strbac estimates it could be worth £10 billion per year by 2050, but this figure represents the sum of benefits to many different players, and at present there is no mechanism to capture a slice of that value and transfer it to storage providers. Without such a mechanism the storage will simply not get built.³³ Storage requires not so much subsidy, but a market for grid balancing solutions that does not inherently favour gas peaking plants - which seems to be the likely outcome of the capacity mechanism proposed in the Energy Bill.

Assuming a level playing field were created, liquid air storage would face competition from other storage technologies, more sophisticated management of demand or extensive interconnection with other energy markets. We assess the prospects for Liquid Air Energy Storage against its principal rivals below.

Competing grid balancing technologies

There are four main approaches to grid balancing: flexible generation, DSR, interconnection and storage. These are illustrated in Figure 3.8, and their relative strengths and weaknesses are summarised in Table 3.4.

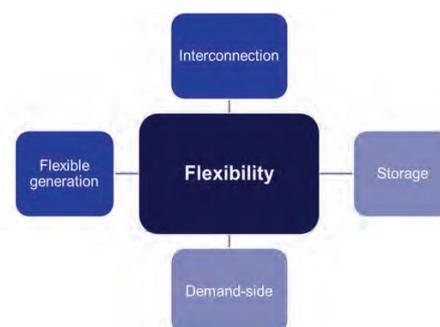


Figure 3.8: Four potential grid balancing solutions

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	Strengths	Weaknesses
Flexible generation	<ul style="list-style-type: none"> Well proven mature technology 	<ul style="list-style-type: none"> Potential financing problem in the future - hence the need for capacity payment mechanisms CO₂ emissions - CCS on these plants would be expensive
Interconnection	<ul style="list-style-type: none"> Well proven mature technology Opens access to low cost flexibility across wider geography / neighbouring markets 	<ul style="list-style-type: none"> Flows are dependent on what is happening in the neighbouring market - limited flexibility Benefits can be asymmetric between markets presenting challenges for acceptance Can only help balance Transmission networks, not Distribution, because too large
Demand side response	<ul style="list-style-type: none"> Significant potential for reducing the market impact of intermittent generation and eliminating wind curtailment (at the national level) Potential to reduce baseline network investment required to integrate RES 	<ul style="list-style-type: none"> Infrastructure/delivery costs Complex to implement Uncertainties as to how the system will work and be governed in reality Consumer acceptance/over-ride
Electricity storage	<ul style="list-style-type: none"> Highly versatile Significant potential for reducing the market impact of intermittent generation and eliminating wind curtailment Potential to reduce baseline network investment required to integrate RES Some technologies are mature (pumped storage) Applies to both Transmission and Distribution networks 	<ul style="list-style-type: none"> Many storage technologies are based on relatively immature technology and need development e.g. to become scalable Due to immaturity some storage technologies are expensive (hydrogen, batteries)

Storage compares well against other forms of grid balancing.

Table 3.4: Strengths and weaknesses of grid balancing technologies

All forms of flexibility are likely to be deployed, but research by Pöyry for DECC has demonstrated a number of important points about the interrelation between the various approaches. A summary of Pöyry's findings is included as Appendix 2. The main conclusions are:

- Deploying DSR or interconnection or storage or all three reduces the need for flexible thermal generation and cuts emissions.
 - Interconnection can be seen as complementary to DSR and storage.
 - Demand side response competes with storage.
- Of the potentially low carbon grid balancing technologies, storage competes most directly with DSM. A world with high deployment of DSM is therefore one with less need for storage. However, the extension of DSM from the industrial to the commercial and domestic sectors depends on a level of public engagement that may not be forthcoming. As we discussed in chapter 1, there are a number of reasons to believe achieving the necessary public 'buy-in' may be difficult:
- Research for Ofgem found that DSR in the commercial sector - including retail, education and offices - could trim peak winter demand by as much as 4.5GW. However, the researchers found there was little interest in DSR among companies

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Demand Side Management competes with storage, but DSR requires behavioural change from consumers and storage does not.

in this sector, where energy bills form a small proportion of total costs, and that businesses were 'unlikely to accept any impact on service levels to accommodate DSR measures'.³⁴

- Trials of domestic DSR have so far produced mixed results. Among the more statistically robust studies, households have typically reduced peak consumption by up to 10% but overall electricity consumption by just 3%.³⁵ This suggests the financial savings to consumers may be modest. The government estimates the average household will save £40 on a dual-fuel bill in 2030.³⁶
- Even if consumers are attracted by DSR tariffs, it is not yet clear which appliances they are prepared to use in a flexible way³⁷, and therefore how much demand can be shifted from peak to off peak times. Nor is there yet any robust evidence about household responses to real-time pricing³⁸, where prices to consumers change as frequently as every half hour, and which would best accommodate wind intermittency.
- The scale of time-of-day-price differentials required to stimulate major shifts in behaviour - making it more expensive to cook or watch television at peak times than off-peak - could prove politically difficult. Nor is clear how prepared consumers would be to relinquish control of fridges, freezers and water and space heating to the energy companies. If financial savings of DSR tariffs are modest, consumers may reluctant to countenance any potential disruption to their lives - even if this may in fact be minimal.

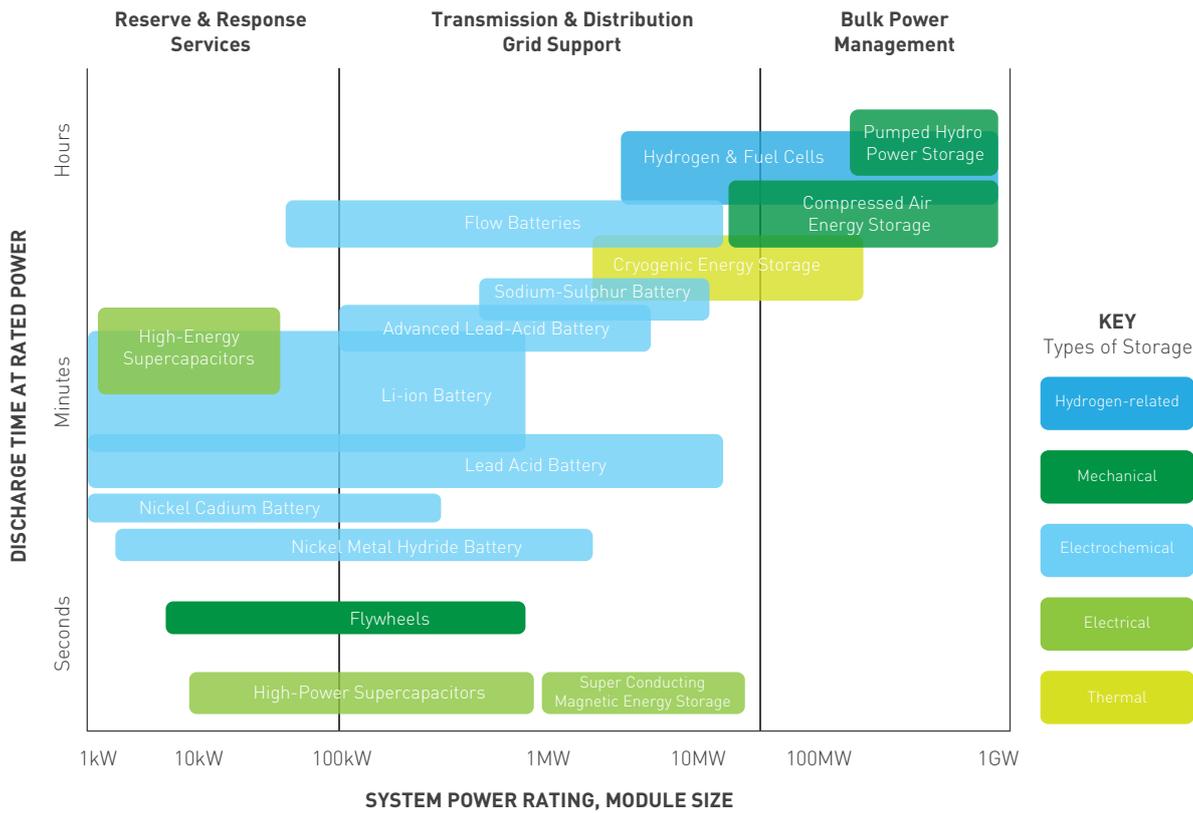
In light of these issues, and on the basis of the Strbac reports for both the Carbon Trust and DECC³⁹, we think storage has distinct advantages and is likely to play a major role in grid balancing in future.

Competing storage technologies

There are many different electricity storage technologies on the market or in development, with a wide range of characteristics in terms of power rating, duration, energy density and cost. These characteristics determine the specific applications for which a technology is suited. For example, a lithium-ion battery is well-matched to the needs of a laptop computer, but would never be considered for bulk energy storage; the opposite is true of pumped hydro.

The performance of the full range of grid-scale electricity storage technologies has been reviewed in several recent publications, including a comprehensive study from EPRI⁴⁰, and the power rating and duration of the main technologies are shown in Figure 3.9. In this paper, we focus only on those technologies suitable for bulk storage that would compete directly with liquid air - those with power rating above 10MW and duration of more than one hour. EPRI identified a range of such technologies, and in Table 3.5 we compare those which have reached demonstration phase or beyond (the long term characteristics of technologies that are still at the R&D stage such as Fe-Cr and Zn-Air redox batteries are impossible to assess at this point).

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Liquid air compares well with other bulk storage technologies.

Figure 3.9: Power rating and duration of various grid-scale storage technologies. Source: Centre for Low Carbon Futures⁴¹

System	Technical maturity ⁴⁰	Power rating ^{41,42}	Run time ^{41,42}	Life ^{41,42}	Capital cost ⁴⁰
Pumped hydro storage (PHS)	Commercial	100-5000MW	hours	30-60 years	£1,000-1,300/kW
Sodium sulphur batteries (NAS)	Commercial	Up to 8MW	hours	10-15 years	£1,700-2,200/kW
Advanced lead acid	Commercial-demo	Up to 40MW	Hours	5-15 years	£1,100-3,100/kW
Liquid Air Energy Storage(LAES) ²⁸	Demo	10-250MW	hours	>30 years	£500-1,250/kW
Compressed air storage (CAES)	Demo	5-400MW	hours	20-40 years	£470-800/kW
Zn/Br redox batteries	Demo	Up to 2MW	hours	5-10 years	£1,000-1200/kW
Vanadium redox batteries	Demo	Up to 3MW	hours	5-10 years	£2,100-2,600/kW

Table 3.5: Grid storage technologies compared. Sources: see endnotes.

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Pumped hydro and CAES are geographically constrained, and Liquid Air Energy Storage has the potential to be highly competitive against current and emerging alternatives.

From Table 3.5 we can see pumped hydro and sodium sulphur batteries are the only technologies available that are fully commercial at scale. Pumped hydro currently dominates the bulk storage market, with over 129GW installed worldwide. However, there are few remaining sites available in developed economies including the UK, so this technology is unlikely to compete significantly with Liquid Air Energy Storage.

From Table 3.1, it is clear that bulk storage needs to achieve a capital cost of less than £1,250/kW and preferably £750/kW, and this suggests liquid air's main competitor is Compressed Air Energy Storage (CAES), which has low capital costs, good scalability and long plant life. However, CAES is constrained by the need for suitable geographic features such as salt caverns in which to store the compressed air. There are a number of technologies under development in the lab that might offer superior characteristics to Liquid Air Energy Storage, but the development time for such technologies should not be underestimated. As a result, Liquid Air Energy Storage has the potential to be highly competitive against current and emerging alternatives.

2. Distribution Network Operators (DNOs)

Most discussion of the potential applications for electricity storage has focussed on grid balancing at the national level, which is the responsibility of the system operator National Grid and the large energy suppliers. However, storage could also be vital to another less well known set of players in the electricity system: the Distribution Network Operators.

DNOs manage the local electricity infrastructure including poles, transformers and feeder cables in the street, which form the link between the high-voltage transmission system and electricity customers. There are seven DNOs in the UK (see Box 3.1) each with a monopoly in its geographical service area. The business is currently regulated by Ofgem under DPCR5, primarily on a return on assets basis.

Traditionally DNOs have simply distributed electricity from the high-voltage transmission system to end users, through a series of networks of progressively lower voltage. However, DNOs are now expected to play a

much more active role in balancing supply and demand at a local level to cope with the challenges imposed by decarbonisation, as reflected in National Grid's 'Gone Green' pathway.⁴³ These include the rising proportion of inflexible and intermittent renewable generation (wind and solar capacity is usually connected to local, lower voltage networks), and increasingly 'peaky' demand from heat pumps and EV chargers. As a result, DNOs are expected to manage their networks far more actively and to evolve into Distribution System Operators - DSOs.⁴⁴

[Box 3.1 :] District Network Operators and Transmission Operators

GB DNOs:

- Scottish and Southern Energy Power Distribution, operating in two geographical regions.
- SP Energy Networks, operating in two regions.
- Electricity Northwest
- Northern Power Grid
- UK Power Networks (Ex-EDF Energy)
- Western Power Distribution (including former Central Networks)

NI DNO: Northern Ireland Electricity

There are also two **Independent Distribution Network Operators (IDNOs)**: GTC and Inexus. IDNOs are allowed to build and operate extensions to the existing network, which typically serve new developments such as business parks or housing estates.

The UK has four **high-voltage electricity transmission networks**: National Grid (England and Wales), SP Energy Networks and SSE Power Distribution (Scotland) and Northern Ireland Electricity.

In this context, energy storage in general, and liquid air storage in particular, could have distinct benefits for DNOs. The DNOs are obliged to facilitate lower carbon electricity while minimising the cost of network upgrades, and energy storage can help to reduce peak demands on transformers, overhead low voltage lines and feeder cables. DNOs are also obliged to maintain voltage within certain limits, and storage can provide voltage

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support and can deliver reactive/power factor correction and improved harmonic composition. DNO's are expected to deliver much of the functionality of the 'smart grid', and this also requires decentralised storage.

A report from Eurelectric⁴⁵ has found that storage could help balance local supply and demand, improve power quality and reduce investment costs by deferring network upgrades. However, it also points out the regulatory uncertainty around storage grid connections, access rights, ownership and rules of integration. In the UK, DNOs are currently prohibited from owning storage since it can be classed as a form of generation, and DECC has not yet clarified if or how DNOs would be able to own or operate storage under future regulations. Some of the issues are being explored in pilot projects supported through Ofgem's £500m Low Carbon Network Fund (LCNF)⁴⁶, but there is currently no certainty that DNOs, potentially among the biggest beneficiaries of storage, will indeed be able to benefit.

Applications where the DNO may find additional value from energy storage include:

- Overcoming grid connection constraints for medium-sized renewable generators - for example, where the existing connection point would be a limiting factor, storage can be co-located at the connection point.
- Reducing the cost of network upgrades.
- Commercial 'wind-twinning' arrangements - managing intermittency gap between supply and demand and providing assured demand for remote, wrong-time or excess renewable generation.
- Increasing the maximum supply capacity - placing storage closer to centre of extra demand.
- Participation in Demand Response Management - extension to include storage within large buildings.

We explore two of these benefits in more detail below.

Overcoming grid connection constraints for medium-sized renewable generators

When a developer decides to build a wind-farm or a larger solar array, the DNO is approached about providing a grid connection. However,

grid access is often constrained by an existing 11kV or 33kV distribution network, and by transformers intended to support only smaller current flows. Overcoming this constraint involves substantial expense: not just the costs of installing additional lines and transformers, but also securing planning permissions and the associated challenges and delays. One way to bypass these issues is to install electricity storage at the connection point.

For example, a proposed wind farm of 10MW may find the local 33kV network is unable to accommodate its full output. A new circuit is needed, but securing permission from landowners to erect poles for a new low voltage line may take a long time, or even require enforcement powers to be applied - as demonstrated in the Lincolnshire LCNF project.⁴⁷ There may also be popular resistance to the line if it is thought to support a wind farm development.

Installing storage at the connection point would allow the wind farm to be built without additional network capacity. Some or most of the wind farm output could be delivered over the existing line(s) and any excess stored until the wind falls, creating spare capacity to transmit the stored electricity. Of course, at some point during an extended windy period, the storage might become full and further generation might have to be constrained off. However, correctly sized storage ought to minimise the chances of this.

Reducing the cost of network reinforcement

Storage can also reduce the cost of network reinforcement, as demonstrated by a UK Power Networks pilot project at Hemsby in Norfolk.⁴⁸ The project secured LCNF funding because it would deliver significant new learning on commercial and operational arrangements for battery storage (6MW/10MWh) located at a 33/11kV primary substation. The results could also have significant implications for liquid air; although current liquid air storage technologies are better suited to larger capacity installations of 10MW or more, as the technology matures it is possible smaller capacity units may be developed to compete in this space.

The substation selected for the UK Power Networks trial has two 38MVA transformers and two overhead 33kV lines with 35.6MVA winter rating. Extending its capacity would require a third transformer circuit and around

Liquid Air Energy Storage could help District Network Operators overcome local grid bottlenecks and reduce the cost of network upgrades.

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UK Power Networks estimate that distributed storage systems of around 3MW each could provide an alternative to network reinforcement at nearly 700 primary substations.

20km of underground cable. The storage solution is intended to demonstrate a path to avoiding these costs, with projected lower capital investment.

The LCNF evaluation of the UK Power Networks project recommended that the duration of the store be reduced in order to contain the battery cost. The cost of battery storage scales in an almost linear fashion with its capacity or discharge duration. However, liquid air storage capacity can be increased with a relatively lower cost premium, because the basic storage medium is not in itself expensive. In order to scale up battery storage, additional capital-intensive batteries are required, although the inverter, grid connection and balance of plant is not materially altered. By contrast, liquid air storage capacity can be increased simply by adding a second tank, where the additional capital cost is restricted to the cryogenic vessel, additional floor area and commissioning.

Liquid air storage might also be able to generate for longer periods across the peak than competing technologies, because of its probable longer life and greater number of

cycles. So it is possible that the economics of liquid air storage could offer more operating days compared to batteries, where the marginal cost of depreciation would be higher.

UK Power Networks estimate that distributed storage systems of around 3MW each could provide a useful alternative to network reinforcement works at nearly 700 primary substations⁴⁹, to deliver an aggregate 2GW of electricity storage capacity. The footprint and location would not necessarily be a good match for a liquid air plant in every case, since a liquid air installation with capacity of 10MW requires around 4,000m², about two thirds the size of a football pitch, and incorporates two relatively tall structures (see Figure 3.10). The suggested capacity of 3MW is also substantially below the 10MW level at which the LAES is currently technically and economically viable.

This suggests that in order to be widely deployed at primary substations, liquid air storage plant would need to have a smaller floorplan and lower power rating than at present. This in turn would depend on the development of efficient and cost-effective small-scale liquefiers, which do not yet exist.

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

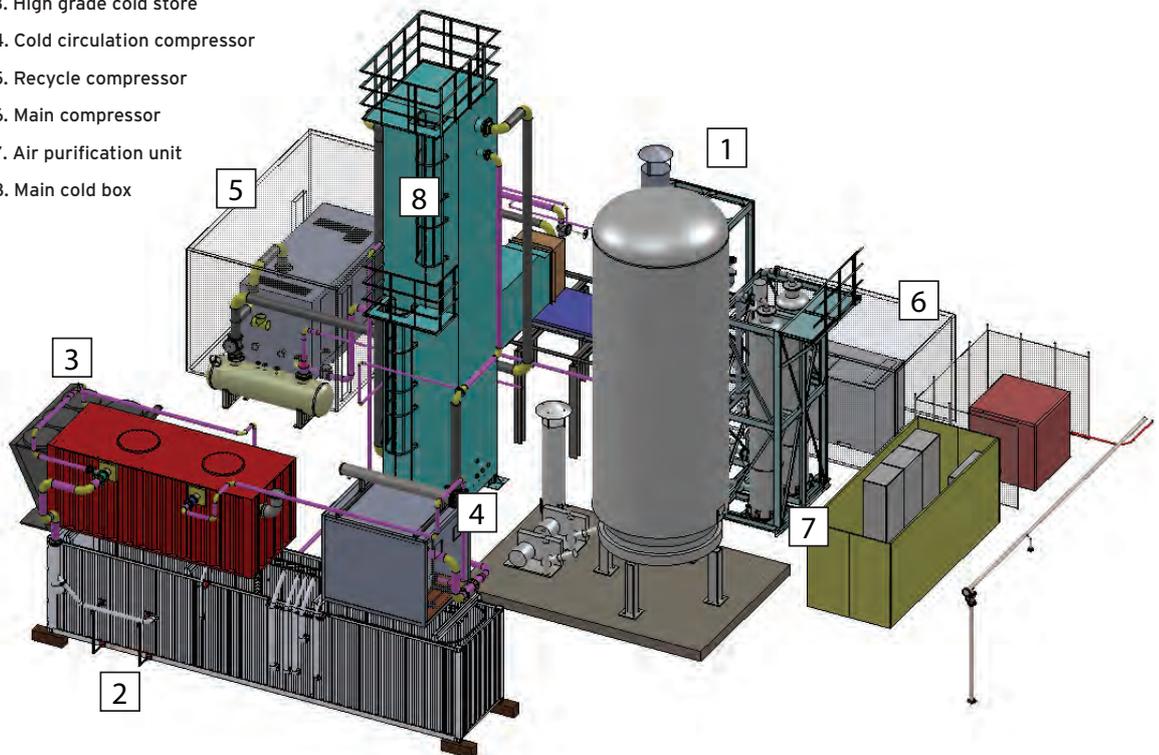


Figure 3.10: Illustration of main components of Liquid Air Energy Storage facility.

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3. Integration with fossil fuels

So far we have largely concentrated on the potential for liquid air technologies to help balance intermittent or inflexible low carbon generation - wind or nuclear - at both a national and regional level. However, liquid air concepts could also integrate into gas fired power plants and LNG terminals to increase efficiency and reduce cost. We examine two novel concepts below.

Low cost gas fired peaking plant with carbon capture

Most of the discussion so far has been around stand-alone Liquid Air Energy Storage units, which would produce and consume liquid air on a single site, or generation-only devices that could run on centrally produced cryogenics and/or the nitrogen surplus. However, there is another potential permutation: Air Separation Units (ASUs) producing both oxygen and nitrogen could be integrated with a gas fired generator to create a peaking plant that emits no CO_2 .

This novel system⁵⁰, proposed by Professor Yulong Ding, would produce oxygen and liquid nitrogen from grid electricity during off peak hours and store it for use during peak periods. At peak times, the gas plant would use the oxygen for efficient 'oxy-combustion', while the nitrogen would be expanded using waste heat from the gas plant to deliver additional power. As a result of the oxy-combustion process almost all the flue-gas CO_2 is captured as dry ice. Oxy-combustion is typically more expensive because of the need to produce the oxygen, but this novel system would have capital and energy costs comparable to a conventional Combined Cycle Gas Turbine (CCGT).

Figure 3.11 shows the process flow of the newly proposed cycle, which works as follows: During off-peak hours, when the rest of the plant is idle, grid electricity is used to run the ASU and produce oxygen and liquid nitrogen, which are stored in a pressurised vessel and a cryogenic tank respectively. During peak hours, natural gas is compressed in the compressor (C1) to the working pressure. The working fluid then mixes with the oxygen in the combustor (B) where combustion takes place, producing a high temperature and high pressure flue gas consisting of CO_2

and H_2O . Burning natural gas in an oxygen-rich environment can produce temperatures that are too high for the gas turbine (GT). To control the temperature, helium is mixed with the flue gas before entering the GT for power generation through a generator (G). Note the helium is not consumed but circulates in the system.

The flue gas then goes through a series of heat exchangers (HE1, HE2 and HE3) that convey its heat to a nitrogen stream from the ASU. During the heat recovery process, steam in the flue gas is removed via a condenser (WS), and CO_2 is removed in the form of dry ice through a solidification process in CS. Now the flue gas stream contains only helium, which is further cooled in HE3 and compressed in compressor C2 to the working pressure and finally goes through further heat exchange in HE2 and HE1 before flowing back to the combustor. Note, there may be a very small amount of CO_2 in the separated water stream (WS).

Meanwhile liquid nitrogen from the storage tank is pumped to working pressure by a cryogenic pump (P). The high pressure nitrogen is then heated in heat exchangers (HE3, HE2 and HE1 in series) using heat from the GT flue gas, and expands in two stages through a high pressure turbine (HT) and a low pressure turbine (LT) to generate electricity. Heat exchanger HE1 serves as an inter-heater between the two expansion stages. After expansion, the pure nitrogen can be used to purge the sorbent bed of the ASU dryer.

From this description, the new system consists of a closed-loop topping Brayton cycle with $\text{He}/\text{CO}_2/\text{H}_2\text{O}$ as the working fluid and an open-loop bottoming nitrogen direct expansion cycle. The topping Brayton cycle is shown in red and the bottoming cycle in blue. It is the combination of these two cycles that produce electricity at the peak hours. To summarise, the Brayton cycle uses a small amount of natural gas, which is burned in the pure oxygen produced by the ASU during off-peak hours. Helium is only used to control the turbine inlet temperature and is recirculated. The working fluid of the open cycle, nitrogen, is the actual energy carrier of the off-peak electricity. As CO_2 is captured, the exhaust consists of only water and nitrogen.

Air Separation Units producing both oxygen and nitrogen could be integrated with a gas fired generator to create a peaking plant that emits no CO_2 . Such a design should generate power almost as cheaply as baseload, and therefore deliver carbon capture effectively for free.

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Exploiting the cold from LNG regasification at UK import terminals could help produce 14.2 million tonnes of liquid air per year. This could in principle fuel 16.3 billion car kilometers, equivalent to 4.2% of GB car mileage in 2011.

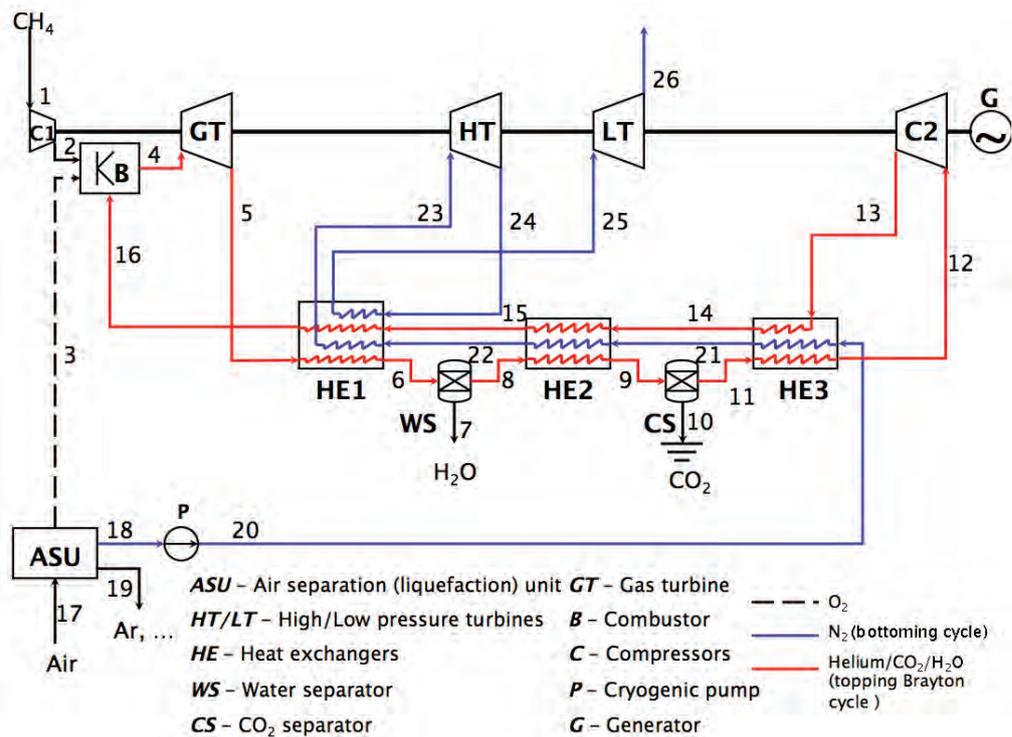


Figure 3.11: Diagram of the cryogenic energy storage-gas peaking plant

As a result, the optimal energy storage efficiency of such an integrated system is nearly 70% and the CO₂ in the flue gas is fully captured. Economic analysis shows that if the integrated system is used for energy arbitrage and peak power generation both the capital and peak electricity costs are comparable with CCGT, which are much lower than the oxy-NGCC if the operation period is relatively short.⁵¹ In other words, this design can be seen as a near-zero carbon peaking plant that generates power almost as cheaply as baseload, and therefore delivers carbon capture – although not storage – effectively for free.

LNG regasification plant

In chapters 2 and 5 we discuss the ability of liquid air to turn waste heat into additional power, but the technology can also make use of waste cold. There may be fewer ready sources of waste cold than waste heat, but some of them are significant. Britain has three LNG import terminals where large volumes of liquefied natural gas are stored at -160C before being regasified to enter the national gas grid. The LNG is normally regasified by heating with seawater, so the cold contained in the LNG is wasted. If a liquid air energy system were co-located at the LNG terminal,

and if air rather than seawater were used to provide heat for LNG regasification, the resulting cold air could then be fed into the air liquefier, potentially reducing its electricity consumption by as much as two thirds.

There are a number of nitrogen liquefiers in operation at LNG import terminals in Japan and Korea, which take advantage of this refrigeration to reduce the power consumption of the liquefier. An LNG assisted nitrogen liquefier uses one third of the electrical power of the equivalent conventional liquefier. Capital costs are currently roughly double for the liquefier itself, but developers believe these can be reduced significantly through engineering and process design.⁵² Liquefier sizes are in the range of 600-800 T/d of nitrogen in order to make this method economic.⁵³

In 2011 the UK imported almost 18 million tonnes of LNG, or about 24 billion cubic metres (bcm).⁵⁴ National Grid expects imports to decline until around the middle of the decade, but then start to rise again as demand recovers and gas production from the UK Continental Shelf continues to decline. Under three scenarios (Figure 3.12), National Grid expects LNG imports in 2030 to fall anywhere between just over 20bcm to just over 50bcm.⁵⁵ In the central 'Gone Green' scenario imports reach almost 30bcm in 2030.

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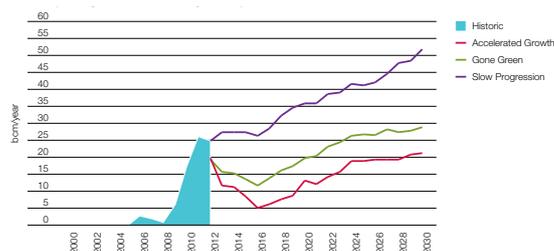


Figure 3.12: UK LNG imports, history and 3 future scenarios. Source: National Grid.⁵⁶

Assuming imports of 30bcm and assuming all the cold from this LNG were used in air liquefaction, it could help produce 14.2 million tonnes of liquid air per year.⁵⁷ This would consume just 2,340GWh of electricity rather than 5,673GWh that would have been required without the LNG cold. The 14.2m tonnes of liquid air produced would then deliver 1,418GWh back to the electricity grid over the course of a year. 1.4TWh is equivalent to 1.7% of total UK electricity consumption in 2012⁵⁸, of which almost two thirds - or 1% of 2012 UK electricity consumption - would have been produced from 'free' energy. Alternatively, 14.2mt of liquid air could in principle fuel 16.3 billion car kilometers, equivalent to 4.2% of the distance driven by cars in Great Britain in 2011.⁵⁹

The LNG cryogenic storage tanks at the Isle of Grain terminal (Figure 3.13) each hold 190,000m³ and a single tank filled with liquid air would represent about 16.6GWh, equivalent to more than 15 minutes of UK peak electricity consumption.⁶⁰ Alternatively, if the UK had 30GW of wind capacity whose output suddenly dropped by 5GW, such a tank could potentially make good the shortfall in power for three hours.



Figure 3.13: Isle of Grain LNG terminal. Source: National Grid

4. Conclusions

From the analysis presented above, we draw the following conclusions:

- Under any likely scenario, the electricity grid will require more balancing capacity in future.
- Balancing can be delivered by a variety of technologies but storage has distinct advantages.
- The potential market available to liquid air generators and Liquid Air Energy Storage systems is up to 30GW by 2050, and for storage alone as much as 14GW. The value of this storage to the network could be £10 billion per year.
- Liquid air generation-only devices have the potential to become competitive on capital cost but will struggle to reach that point without government support, except perhaps in urban areas where air quality is an issue.
- Liquid Air Energy Storage systems would be competitive in a future balancing or storage market, assuming a level playing field regulatory framework.
- Liquid air could offer major benefits for TNO's as a cost effective and scalable means of time-shifting energy to balance the grid.
- Liquid air could also offer benefits to DNOs, including overcoming network bottlenecks and reducing the cost of infrastructure upgrades, but may need a reduced floorplan and power rating to be widely deployed.
- Liquid air concepts could be integrated with fossil fuel assets such as power stations or LNG terminals to save fuel, carbon and cost.
- Tanks of the size already used in the LNG business could be used with liquid air to provide strategic levels of electricity storage.

A single 'gasometer'-style tank could store sufficient energy as liquid air to make good the loss of 5GW of wind power for three hours.

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Chapter 4 Transport

Vehicles are different because most must operate while disconnected from their source of energy. This places exacting demands on the energy vectors they use.

1. Why transport is different
2. Variation in the transport sector
3. Uses of liquid air in transport
4. Mapping liquid air to vehicle types
5. Conclusions

Transport of people and goods is generally considered as a distinct category within the wider energy debate. Not only is it a significant, identifiable economic bloc responsible for over a third of all energy consumed in the UK (Figure 4.1), it also places unique demands on the energy vectors deployed. In this chapter we assess the potential for liquid air in transport by first defining the essential characteristics of transport energy vectors; analysing the requirements of different market segments or modes of transport; describing various ways liquid air could be used; and finally mapping liquid air technologies against the transport energy landscape. We have restricted the discussion to surface transport since the energy density of liquid air is too low to be relevant to aviation.

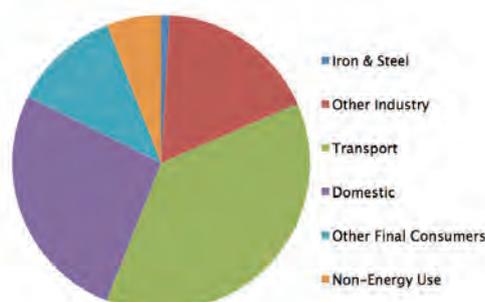


Figure 4.1: UK energy consumption by end use, 2011. Source: DECC

1. Why transport is different

The self evident but fundamentally defining fact about vehicles is that they are mobile. In most circumstances - with the exception of electrified trains and trams - this means they must be able to operate while disconnected from their source of energy. This in turn means that unlike static equipment - a fridge or a

production line, for example - vehicles must carry 'batches' of energy on board, and must periodically stop to refuel. Most vehicles must also be able to cope with 'mission variation', since each trip may vary by destination, route, duration, speed and payload.

The need for vehicles to operate untethered from their source of energy, and to be able to cope with mission variation, means the onboard batches of energy must be sufficiently energy dense to give the vehicle a range adequate to its role. It also means the refuelling network must be commensurate to the likely mission variation of the vehicle.

The capability of a vehicle deploying such a batch energy system is limited by the practical considerations of loading another batch of energy. These include safety and ergonomic factors, but the time taken to recharge the onboard energy store is critical to deciding the usefulness of an energy vector to any given transport application. We list the critical attributes of an onboard energy vector associated with mission variation overleaf.

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Critical attributes of an onboard energy vector

Energy density

The onboard energy store must be able to hold sufficient energy without compromising the vehicle's ability to do its job. That means the weight of the energy vector required to achieve the necessary range must not unduly limit the vehicle's capability to carry its load. Any increase in the weight of a vehicle will, all other things being equal, increase its energy and power requirements, so a vector with low energy density can have an adverse effect on range, payload and general flexibility. Similarly, the volume of fuel must not unduly limit the vehicle's ability to accommodate its load. The key units to express energy density are MJ/kg and MJ/m³.

Power density and the efficiency of energy conversion

A vehicle must also be able to convert the stored fuel into propulsion - or other activities such as hoisting or digging - at a sufficient rate to do its job, and at an efficiency that makes commercial and legislative sense. This is partly a characteristic of the engine - a wide range of power densities can be achieved in diesel engines, for example, through variations in design and capacity - but the characteristics of the energy vector should allow sufficient energy conversion rates to give a suitable range of power output.

energy is stored as chemical energy. There are few practical limits on how rapidly the fuel can be pumped from the tank, so the only factors that constrain the rate at which that energy is converted into torque are the characteristics of the engine itself. By contrast, for battery electric vehicles, the power requirements of the vehicle are a fundamental influence not only on the capacity but also the design of the battery. In general, there is a need to fit the powertrain into as small a space as possible to maximise the room for passengers or goods. Any increase in the weight of the engine will either reduce the payload the vehicle can transport or increase the weight of the vehicle. If the vehicle's weight is increased, its power and energy requirements will rise, as will its embedded CO₂ and cost. The key unit to express power density are kW/kg. Efficiency is usually expressed as a percentage.

Recharge rate

Current expectations for the passenger car market are that refuelling can be carried out in a few minutes. For other applications - such as electric buses, for example - where there is a predictable duty cycle with significant idle periods, longer charge times may be acceptable in exchange for significant perceived benefits. In any event, for an energy vector to succeed, its recharging times must match the expectations of the market.

Recharging infrastructure

Mission variation implies that the timing and location of recharging is generally unpredictable. The extent to which this is true depends on the vehicle sector, but in general a significant network of recharging stations is required to enable the full range of missions.

Onboard energy vectors in transport must have an energy density, power density and recharge rate adequate to perform their role.

2. Variation in the transport sector

While the general requirements for energy vectors used in vehicles are distinct from those of other energy consuming equipment, and apply broadly across the sector, there is considerable variation in the needs of different modes of transport. Clearly the energy needs of a passenger ferry are quite different from those of a motor scooter, but it is important to understand precisely why. The reason for such contrasts - and for many more subtle distinctions - lies in the fact that each of the criteria described above is more or less important to different types of vehicle depending on their function. We discuss the reasons for these differences overleaf, and then provide a short characterisation of the energy requirements of the most important categories of vehicle.

Why the demands on transport energy vectors differ between vehicle types

Energy and power

The most fundamental requirement for a vehicle's energy storage system is the total quantity of energy that must be stored on board; this is determined largely by another fundamental factor, the rate at which energy must be supplied to the engine - in other words, its power rating. Clearly, larger and heavier vehicles such as ships, trains and

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Different types of vehicle place different demands on their energy vectors.

trucks tend to require more power in operation than smaller ones such as cars and scooters, but other factors such as speed are also important. For example the locomotive for a heavy freight train typically requires 2.5MW of power, the equivalent of around 20 family cars, yet a modern intercity express train requires around 5MW, despite being shorter and lighter; the high power requirement stems from the need to accelerate rapidly up to a high speed and the large air resistance that must be overcome at this speed.

Distance between refuelling stops

A second fundamental factor that determines the quantity of energy to be stored on board is the distance over which it must be supplied between refuelling stops. In general, long journeys require more energy than short ones, so vehicles that operate over long ranges tend to need to carry larger quantities of energy. As range and energy storage requirements increase, storing energy becomes increasingly critical in terms of its impact on the vehicle's overall mass and its available space to carry goods or passengers. For example, a heavy goods vehicle must travel long distances to deliver its payload across continents, but is limited by law in its total weight and in its size. To minimise unproductive time *en route* the truck must refuel as infrequently as possible, but the amount of fuel carried must be traded off against the payload. Therefore it is absolutely critical for productivity to maximise the 'energy density' of its on board energy storage, and an energy vector with a low energy density will be significantly less attractive in terms of operating costs than the incumbent - diesel fuel. In contrast, for a similar truck covering much smaller distances between deliveries, more time is spent loading and unloading and the range between refuelling stops is far less critical; here, alternative, less energy-dense storage media such as compressed natural gas may pose no significant disadvantage compared to diesel.

Refuelling infrastructure cost

Another critical factor affecting the relative attractiveness of different energy storage media is the complexity and cost of refuelling infrastructure, which is mainly determined by the number of different locations at which a vehicle may need to refuel. The most difficult operating patterns to support are those where transport routes extend over long distances (eg long-range heavy goods haulage), where they are highly variable (eg general-use private passenger car), and where vehicle range is limited (eg in the case of low-density energy storage). Infrastructure requirements are less demanding where vehicles operate within a relatively restricted zone. Examples include small cars in an urban area; specialist vehicles on a single site such as an airport or a warehouse; or where vehicles such as buses or delivery vans return to a limited number of depots to refuel. Clearly where an existing infrastructure exists - as with petrol and diesel for use on the roads, or existing electrified rail routes - it may confer an advantage to incumbent technologies against those for which a new infrastructure must be established.

Refuelling rate

This is another factor that differentiates potential energy storage media, with different transport applications having different degrees of sensitivity. Incumbent fossil fuels have the advantage of very rapid rates of energy transfer of several MW during refuelling at a filling station pump. Refuelling rate - and therefore time - is least critical for vehicles that spend significant downtime at dedicated facilities for loading and unloading such as commercial shipping, which may refuel simultaneously while goods and passengers are transferred. Depot-based commercial vehicles may also spend significant time standing overnight, during which refuelling can potentially be carried out over several hours without impacting their operating schedules. Private vehicles also tend to spend significant amounts of time during the day at rest and if the appropriate infrastructure is available then these too may be tolerant of low recharging rates. In all cases where vehicles may need to break a journey to refuel, however, a slow refuelling rate is likely to be prohibitively unattractive.

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Exhaust emissions

National and international regulations that limit pollutant emissions are now driving up the cost and complexity of ICE vehicles across virtually all transport sectors. These may be supplemented by more stringent local regulations designed to improve air quality in target zones such as dense urban or conservation areas, which in some cases explicitly encourage or even restrict vehicle use to 'zero emissions' technologies. Beyond regulatory control of vehicle emissions, some more specialist applications may, by their nature, favour low or zero emission technologies, such as those operating in confined spaces including warehouses or mines.

The typical energy characteristics of key vehicle types

Container ship

A large container ship typically travels long distances over long periods of time at a continuous, high power level. Efficient power delivery is therefore essential to minimise the inevitably significant energy costs involved and for the vehicle to remain competitive. In order to maximise productivity from each ship, cargo volume must be maximised, and because the quantity of energy that must be stored on board is large relative to the size of the vessel - fuel may be greater than 2% of cargo volume - volumetric energy density is an important factor. Refuelling is carried out at the vessel's dedicated berth while cargo is loaded and unloaded, so the rate at which this happens is relatively uncritical. Regulated exhaust emissions limits are comparatively lax in mid-ocean, but Emissions Control Areas on many coasts are much more stringent. There may also be additional pressure for still lower emissions within busy and densely packed port environments.

Passenger ferry

A small passenger ferry has a very different operating profile to a large container ship. Voyage lengths are typically much shorter, although several trips may be undertaken between refuellings, with more variable speed and power levels. The fuel volume to be carried is relatively small, so energy density may be less important than in other transport applications, although this is offset

by the need to maximise the space available for passenger accommodation and facilities. Refuelling typically takes place outside normal operating hours, so the refuelling rate is only moderately important. Since ferries often operate close to population centres there is more pressure to minimise exhaust emissions than for long-range cargo ships.

Trains

The widespread existence of electrified tracks in regions such as western Europe means many trains have no need for onboard energy storage, at least for primary propulsion. However, there remain many routes worldwide that are not electrified and for which trains must carry their own energy supply. Where new routes are being considered, the high cost of electrical supply infrastructure makes onboard energy storage potentially attractive. Refuelling can be carried out at a relatively limited number of depots, so the infrastructure is not as extensive as for most road transport applications. Energy storage density is not a particularly strong factor for locomotives, since there is some flexibility in the size of the vehicle. However, where propulsion units are integrated within passenger cars, as with Diesel Multiple Units (DMUs), then the space available on board is more limited, especially in the case of retrofitted technology.

Apart from these shared factors, operating patterns and requirements for different classes of rail vehicle vary widely. High speed passenger trains operate over long distances at the continuous and high power levels needed to overcome resistance forces. Refuelling rate becomes critical if trains cannot carry enough energy to operate continuously throughout a working day, as long refuelling breaks constrain scheduling and reduce asset utilisation. Freight locomotives must deliver high power levels for limited periods to accelerate away from halts and to overcome adverse gradients, but once the maximum speed has been reached and on downhill sections, as well as for long periods during loading and unloading, the power demand is very low. Local commuter trains feature highly transient operation, with frequent stops and associated acceleration and deceleration. Trains are not heavily loaded and maximum speeds are relatively low, however, so maximum power levels, required range and energy storage capacity are moderate. Because they operate in densely populated areas - and on some routes also underground - there may be additional local

Clearly the energy needs of a passenger ferry are quite different from those of a motor scooter, but it is important to understand precisely why.

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pressure to reduce exhaust emissions below otherwise regulated levels.

Long haul trucks

The energy storage needs of long distance, heavy duty haulage trucks are some of the most severe of any transport application. These vehicles typically operate point-to-point between distribution centres outside urban areas, with a single national or international return trip often taking several days. They spend a large proportion of time at close to their maximum speed and at high power levels, covering long distances over highly flexible routes with heavy or bulky loads, with tight constraints on their maximum size and weight. Energy conversion efficiency and energy storage density are highly critical to productivity. Refuelling must be performed relatively frequently, in many cases several times per trip, so refuelling rate also has a significant impact on productivity. Refuelling may sometimes be performed at base depots, but in general it is necessary for the refuelling infrastructure to be comprehensive across the entire route network. Exhaust emissions are tightly regulated, and technology solutions to achieve the regulated limits represent a significant up-front cost, as well as impacting on operating costs and range.

Medium duty trucks

Medium duty delivery trucks typically operate on inter-urban distribution routes, with a mix of urban and highway operation. They are likely to operate from depots on fixed routes. The requirements for trucks of this type share some similarities with those of heavy duty haulage vehicles, although the reduced range and power levels and the larger number of stops mean the demands on power, energy storage density and refuelling rate are less severe. Urban operation places higher priorities on compact vehicle dimensions, low noise and exhaust emissions, however.

Bus

Urban buses tend to operate under very different conditions to most heavy or medium duty trucks. They run almost exclusively within urban centres at low speeds, with very frequent stops and associated acceleration and decelerations. As a result, the distances covered in a single day are small and operation

from a single depot means that no distributed refuelling infrastructure is required. Although acceleration and hill climbing often require full engine power, maximum loads are relatively low compared with heavy goods vehicles and, since passenger numbers often vary widely during a working day, average loads are lower still. This combination of factors means that there are not particularly strong requirements for high energy storage density or rapid refuelling. Buses are high profile contributors to local air quality and noise issues, so quiet operation and low exhaust emissions are high priorities.

Light duty commercial vehicles

Vans perform a variety of different functions, but many operate mainly in urban areas, for example delivering goods street-to-street, with limited extra-urban collection trips. As with buses, average loads and required daily ranges for these vehicles are not high, so the required levels of energy storage capacity and energy density are moderate. Again, like buses, there may be an imperative for low exhaust emissions within cities, particularly for large fleets operated by local authorities or high profile companies. Where vehicles operate from depots, refuelling can be performed at a single location outside core operating hours.

Passenger cars

The uses to which cars are put varies widely, and it is useful to distinguish between two broad market segments:

Larger cars in segments D or E tend to be used for longer trips, often on motorways at relatively high and constant speeds. Driving range between refuelling stops is important, although ranges of well over 1,000km that can now be achieved by modern diesels may actually be greater than the market requires.

The unpredictable and potentially unlimited length of journeys undertaken means that refuelling infrastructure must be widely available with a high density of refuelling points to satisfy market demand. Refuelling must be performed flexibly and usually mid-journey, so a short refuelling time is important. Exhaust emissions for passenger cars - as for all light duty vehicles - are some of the most tightly regulated in transport, although there is unlikely to be pressure for zero emissions

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on long distance, cross-country routes for the foreseeable future.

Small cars in segments A or B are most frequently used for short journeys within urban areas, and long range capability is not a dominating requirement. The short distance of most journeys travelled means that energy vectors without an extensive refuelling infrastructure could still be viable especially in urban areas. Private cars are typically left parked for long periods, so charging overnight or at public parking locations may be feasible. Small cars' emissions are as stringently regulated as those of larger cars, and in urban areas zero emissions capability may be attractive.

Personal mobility

The definition of personal mobility vehicles includes small two-wheelers such as scooters and potential future ultra-light and highly compact vehicles for one or two people. This segment is expected to grow in future, particularly in developing markets and 'mega-cities'. Such vehicles are intended to be used in congested urban centres only, so the top speed and driving range can be low. However, they must be highly compact to make them manoeuvrable, affordable and energy efficient. Thus energy storage requirements are very low but tight packaging space and the low vehicle weight mean good energy storage density remains important. Refuelling time may be important, but the vehicle's low energy storage capacity means the refuelling rate is relatively uncritical. Exhaust emissions are currently mostly governed by two-wheeler regulations, but future growth in the market is likely to favour much lower or zero emissions capability to reduce air pollution in cities.

Other vehicle types

Other specialist vehicle types feature a combination of the requirements discussed above, as well as having some particular needs of their own. Some key requirements for selected specialist transport applications of interest to liquid air technology - such as forklift trucks - are covered in chapter 7, with a particular focus on refuelling infrastructure.

3. Uses of liquid air in transport

In the first decade of the 20th century there were a number of engine technologies competing to power the horseless carriage. Among these were steam, the internal combustion engine (ICE), battery electric, compressed air and liquid air. Figure 4.2 shows a liquid air vehicle in 1903.

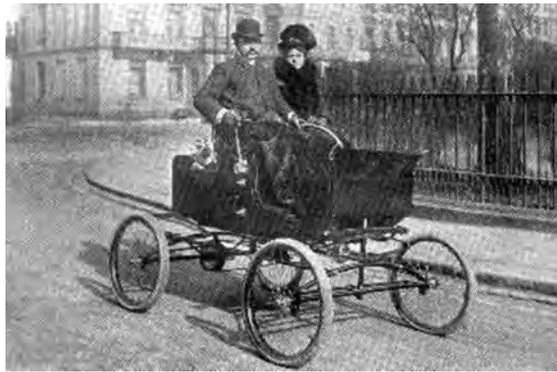


Figure 4.2: Liquid air vehicle 1903

Since then the ICE has become the dominant technology for reasons which are many and complex, but which reduce to convenience and range. The ICE was quicker to start and cleaner to refuel than the steam engine, quicker to refuel than battery electric, and had superior range to electric, compressed air and liquid air.

Circumstances have changed radically over the intervening century, however, and are now very different from those which fostered the dominance of the ICE. Populations and cities have boomed, societies are more affluent and vehicle ownership has soared, leading to increasing pressure on transport infrastructure and the environment. Transport CO₂ emissions represent around a fifth of the total, and in cities, local air pollution from transport is also a major issue, particularly in the developing world.

The urgent need to reduce both GHG emissions and local air pollution has increased the importance of developing low carbon and zero emissions energy vectors and some of the discarded technologies of the early 20th century may now be worth reviving. In particular, they may be suitable for light, urban vehicles with a range of about 100km. However, to be attractive in this market they would need to offer quick and easy refuelling and be competitively priced.

The internal combustion engine became the dominant technology in the early 20th century because of its convenience and range. But circumstances today are radically different.

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In transport liquid air can act both as a heat sink and a working fluid, and can also exploit waste heat traditionally thought too low grade for use in power hungry vehicle applications.

Characteristics and roles of liquid air in transport

Most common energy storage media such as batteries, capacitors or flywheels store 'positive' energy; energy levels within the store rise as work done to them. For example, supplying electrical power to a lithium ion cell will cause the energy levels in the cell to increase. Liquid air is uncommon in that work supplied to the plant will see the internal energy of the stored element fall. Liquid air can therefore be described as a 'negative' energy store; energy is released when the liquid air is exposed to ambient temperatures (or higher), causing it to expand back to its natural gaseous state. In the context of thermodynamic cycles in transport, this enables liquid air to act both as a heat sink and working fluid. An additional attraction is that low grade waste heat of up to 100C, traditionally considered too low in temperature to be useful in power hungry transport applications, could be exploited to generate meaningful amounts of additional energy.

The potential roles for liquid air considered below are those where the air is used as a heat sink and then as a working fluid within a heat engine. The heat engine can be deployed as either the prime mover - the only or principal source of power in a vehicle - or in a supporting role to recover waste heat from a conventional engine or fuel cell (chapter 5). In this secondary role the liquid air device can either be used to produce shaft power to reduce the load on the primary engine, or to power auxiliary functions such as refrigeration.

Liquid air as a prime mover

Compressed air

One way to exploit liquid air in transport would be to increase the energy storage density of compressed air vehicles.

Expanding compressed air from an ambient temperature store creates drive. At 300bar air has a specific energy of 140Whr/kg or 0.5MJ/kg. The vehicle manufacturer MDI deploys such an approach to power lightweight urban vehicles of the type shown in Figure 4.3. This 320kg vehicle has a 300 litre tank and claims an urban range of 100km, which falls to 50km at higher speed.²



Figure 4.3: MDI compressed air car. Source: MDP

If a vehicle of this type were to store the energy as liquid air, which has a specific energy of 214Whr/kg or 0.77MJ/kg, rather than compressed air, it would increase the specific energy density of the store by a factor of 1.52, increasing the urban range of the MDI vehicle to 152km. However, the density of liquid air is greater than compressed air, so for the same size of tank the energy content could increase by a factor of three, increasing the urban range to 300km.

The difficulty with increasing the range in this way would be to harvest sufficient heat from the environment to facilitate the pressurisation. Designing a heat exchanger capable of doing so would be challenging, but the large temperature difference between the liquid store and ambient - around 210C - would aid the process.

Liquid air directly into the engine

Using liquid air as the energy store for a compressed air engine as described in the previous section raises the energy density of the onboard store, which increases the range. However, if the compressed air store is at room temperature then the exhausted gas from the engine will be significantly colder, which reduces the work from the engine and creates practical issues with icing. These effects could be mitigated by designing an engine with multiple expansion stages interspersed with heat exchange, but this would add weight and reduce efficiency.

Another solution to the problem of temperature drop during expansion is to introduce further heat inside the expansion chamber. This would tend to make the expansion closer to an isothermal event (where temperature stays constant), so increasing the work output of the engine. Figure 4.4 shows the theoretical

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benefit of moving from the adiabatic case, where no further heat is added during the expansion, to the isothermal gas expansion case assuming 300K or 27C. The results are shown both with the impact of pumping work (dashed lines) and without (solid lines). At realistic working pressures this shows that an engine using an isothermal cycle could deliver as much as three times the work per kg of air as one using an adiabatic cycle. This means that compared to a compressed air engine with an air store at 300bar, a vehicle using this approach could produce around 7.5 times the work from the same size tank - depending on the maximum cylinder pressure and how close the cycle gets to isothermal expansion. This is because liquid air has around three times the volumetric energy density of compressed air, and the engine would use it 2.5 times more efficiently.

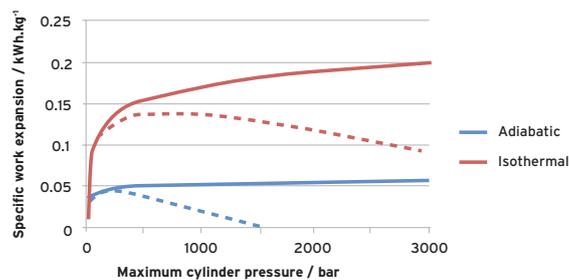


Figure 4.4: Work produced by adiabatic and isothermal expansion of 1kg of liquid air. Source: Ricardo

The engine being developed by the Dearman Engine Company and Ricardo, which uses this kind of heat exchange approach, should achieve a result close to isothermal expansion. The heat exchange is undertaken by passing a second Heat Exchange Fluid (HEF) into the expansion chamber, which mixes with the liquid air causing it to expand. The rapidity of the expansion defines the power density of the engine and the ultimate efficiency with which it extracts work from each kilogramme of liquid air. After each expansion cycle the heat exchange fluid is recovered from the exhaust and reheated to ambient temperature via a heat exchanger similar to a conventional radiator.

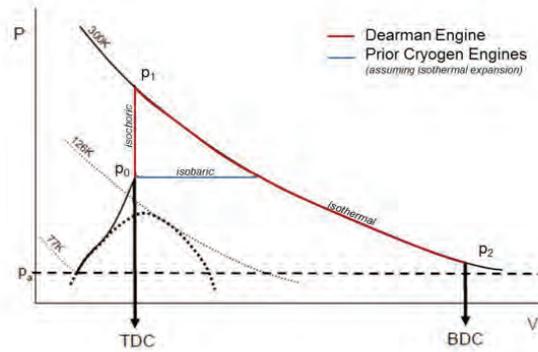


Figure 4.5: Thermodynamic cycle of the Dearman Engine. Source: Ricardo

The use of liquid air as a main energy source for a prime mover would require its storage in significant quantities on board a vehicle. Synergies with existing liquefied natural gas (LNG) technology for vehicles are likely to enable crossover solutions for onboard liquid air storage systems, and the growing popularity of LNG as a transport fuel will help to minimise costs.

Liquid air for heat recovery

The energy density of liquid air is relatively low when compared to diesel. As a result, it becomes increasingly inappropriate as the sole energy source as the power, range and mass of the vehicle increases, and the space and weight required for energy storage become more and more significant. The energy stored per kilogram of liquid air (0.77 MJ/kg) is around 56 times poorer than that of diesel fuel (43MJ/kg). Both fluids have a similar density, so this means that a liquid air storage tank must be 56 times larger than a diesel tank with the same energy content. In practical terms, however, the comparison is more favourable, because of the different way in which the energy is used in diesel and liquid air engines. In order to deliver the same amount of useful work, the quantity of liquid air required for an isothermal expansion engine, such as the Dearman engine, is reduced to around 20 times the equivalent quantity of fuel required for a diesel engine. As such, a truck with a fuel tank containing 350 litres of diesel fuel would still need a liquid air tank of more than 7,000 litres to deliver the same amount of useful work. Any operator opting for such a liquid air truck would therefore be faced with a far shorter range, much more frequent refuelling stops or a significant reduction in payload mass and volume.

Liquid air has far lower energy density than diesel, and so becomes increasingly inappropriate as the sole energy source as the range, power and mass of a vehicle increases.

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Heavy duty engines consume huge quantities of fuel, and liquid air concepts could deliver step changes in efficiency.

These considerations make diesel the energy vector of choice for heavier duty vehicles. However, the heavy duty engines consume an enormous value of fuel per accounting period, and this makes operators highly focussed on reducing fuel bills. This translates into constant pressure on vehicle manufacturers to increase engine efficiency by measures such as improved combustion management, turbo-charging and exhaust heat recovery. Each technology will produce a small incremental improvement, but together they will aggregate to a substantial improvement with time.

However, it is possible that disruptive technologies could be introduced that would produce a step change in efficiency, as illustrated in Figure 4.6. These technologies could come about either from fundamental breakthroughs in our basic understanding, or by cross-fertilisation from other market sectors.

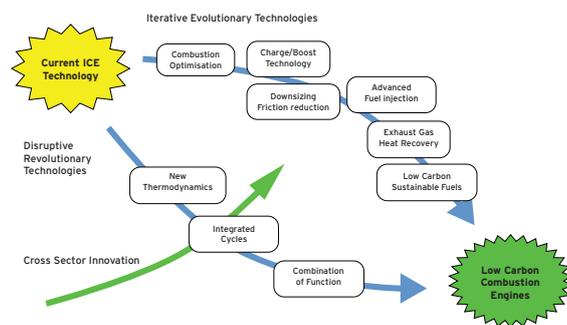


Figure 4.6: Incremental and disruptive technology innovation. Source: Ricardo

Heat recovery - intra-cycle: the liquid nitrogen split cycle engine

One example of a crossover technology is the liquid nitrogen split cycle engine proposed by Ricardo (US patent 20120103314), which borrows elements from a technology developed for static power generation to raise the efficiency of the internal combustion engine (ICE).

The efficiency of a simple gas turbine is generally less than a reciprocating engine but it can be increased by the use of an exhaust gas recuperator. The relatively low compression ratio of a simple turbine gives rise to a relatively low gas temperature at the end of compression as well as a high exhaust gas temperature. This situation can be used to drive heat transfer from the exhaust, in order to raise the temperature of the compressed air through a heat exchanger or 'recuperator' before combustion. This reduces the amount of fuel required to achieve the same output.

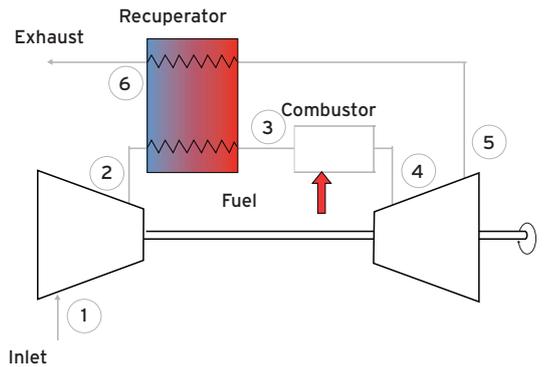


Figure 4.7: Recuperated Gas Turbine. Source: Ricardo

By contrast, the ICE derives its efficiency from having a high compression ratio, and this means temperature of the compressed air is too close to that of the exhaust to allow effective heat transfer; waste heat from the exhaust cannot be recovered in this way. In addition, piston-ICE designs almost always compress and expand the air in the same cylinder, making it impractical to introduce a recuperator into the system.

This problem can be overcome using a split cycle engine design similar to the Isoengine concept first developed by Ricardo in the 1990s and the Scuderi engine today. In such designs, compression takes place in one cylinder and expansion in another, which is similar in concept to a gas turbine. However, to make the split cycle thermodynamically efficient requires isothermal compression, in which the air remains at a relatively constant temperature despite being compressed. The temperature-entropy diagram in Figure 4.8 shows how isothermal compression allows the temperature difference between the compressed intake air and the exhaust gas to be maximised, so creating an opportunity for waste heat recovery.

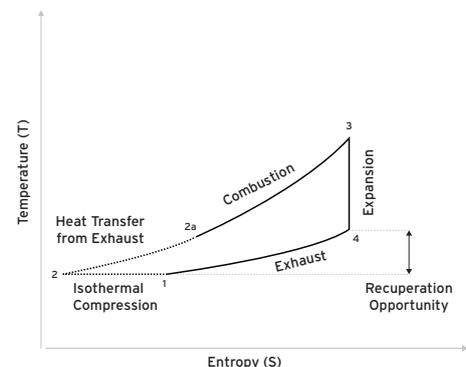


Figure 4.8: Recuperated diesel cycle with high compression ratio and isothermal compression. Source: Ricardo

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Isothermal compression can be achieved by spraying a fluid into the compression chamber to absorb heat from the gas being compressed, an approach that was tested in the 3MW Isoengine power generation demonstrator using water.⁴ However, although this produced a large demonstrable gain, raising gas to electricity conversion efficiency to 59%, it also required large quantities of water, because of the small temperature difference between it and the air being compressed, along with complex and expensive water management equipment.

The Ricardo split cycle invention replaces water with liquid nitrogen which is far colder at about -200C, meaning that far smaller volumes are required. In addition, once vaporised during compression the nitrogen can then pass straight through the combustor and be exhausted to the atmosphere. As a result, the system can be made far more compact and suitable for vehicle engines.

Detailed modelling of this approach undertaken through the Technology Strategy Board-funded 'CoolIR' project has suggested that a thermal efficiency of more than 60% is possible. As a result a modest onboard tank of liquid nitrogen would extend the range of the vehicle by increasing the efficiency of the primary engine. Liquid nitrogen could also be produced by an onboard liquefier driven by the engine and boosted by regenerative braking.

Heat recovery - auxiliary plant

The liquid air split cycle engine uses liquid air or nitrogen to recover waste heat intra-cycle - within the design of a single engine - but it is also possible to recover waste heat using a secondary unit to absorb heat from the cooling loop or exhaust of the prime mover. The ICE remains a flexible, highly evolved and low cost technology, but as fuel prices rise and emissions legislation becomes ever tighter, such secondary heat recovery approaches look increasingly interesting.

Technologies currently being developed to absorb ICE exhaust heat include organic Rankine cycle (ORC), turbo compounding, thermo-electric generation (TEG) and fuel reformation. However, a secondary cryogenic engine such as the Dearman Engine could also perform this role, and could offer major advantages because of the ultra-low starting temperature of the working fluid.

This secondary heat-engine would be implemented alongside the main internal-combustion engine, either as a simple tandem device that delivers power in proportion to the main engine's heat output, or as a hybrid device that uses the thermal inertia of a cooling circuit to offer a power peak-opping capability. The second approach allows the main ICE to operate more steadily and closer to its ideal efficiency - like an electric hybrid - and thus reduces air-quality emissions 'spikes' that can arise in transient operation, or the efficiency compromises that result from avoiding them.

Figure 4.9 shows the theoretical Carnot efficiencies of an ORC device and liquid air for converting heat into power at a range of source temperatures. At a typical exhaust temperature of 400C, the maximum theoretical ORC efficiency is 56% whereas the liquid air efficiency is 89%. In addition, as the exhaust temperature is not fixed but dependent on load, the efficiency variation due to exhaust temperature excursion is lower for the liquid air device, making the heat recovery process less sensitive to vehicle transients.

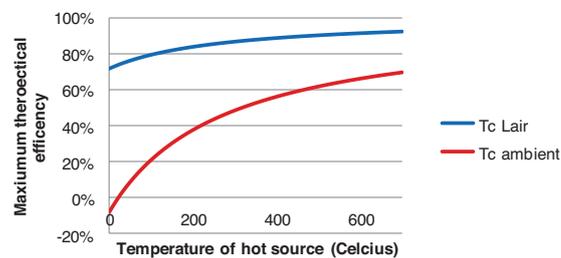


Figure 4.9: Carnot efficiency of liquid air and ORC. Source: Ricardo

The higher Carnot efficiencies of a liquid air cycle mean that unlike the other heat recovery technologies mentioned above, it could also recover meaningful amounts of heat from ICE cooling circuits as well as exhaust streams. At the typical coolant temperature of around 90C, systems that use ambient air or water as the heat sink would have a maximum theoretical efficiency of 20%, whereas for the liquid air approach this would be 79%, which is more than the other technologies achieve with a source temperature of 400C. The operating temperatures of automotive hydrogen fuel cells range from 60-80C, which could also be exploited using liquid air, as we explore in more detail in chapter 5.

Modelling suggests the Ricardo liquid nitrogen split cycle engine could have an efficiency of more than 60%, compared to around 40% for a modern diesel.

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The Dearman Engine could be used as an auxiliary unit to recover heat from an internal combustion engine as a 'heat hybrid', and deliver power and refrigeration from the same energy source.

It should be stressed that the efficiencies quoted here are Carnot efficiencies and represent the maximum theoretical efficiencies that could be achieved at the given temperatures. Only a fraction of these translate into vehicle fuel savings because of the transient nature of engine performance and the complexities of integration; analysis by the Dearman Engine Company suggests that a practical Dearman engine could achieve a real-world thermal efficiency of around 50% using coolant to warm the HEF.

Evidence suggests some of the conventional heat recovery methods cited earlier could deliver hydrocarbon fuel efficiency savings from 5% to 15%. Liquid air, because of its higher temperature differential and the lower impact of transients, could deliver bigger reductions of up to 25% in the case of a city bus. Against these benefits, an additional tank would need to be installed on the vehicle to hold the working fluid, which is consumed and not recycled. Any comparative assessment would also need to consider the purchase and operating costs of each technology.

Liquid air may also be interesting for vehicles such as buses and refrigerated lorries (see next section) that need to maintain cooling while stationary. In buses for example, it is possible to increase the volume of coolant to create a store of waste heat from the main engine, which could then power a small liquid air engine to keep the air conditioning going during stops. This would allow the prime mover to be fitted with start-stop technology to give significant fuel savings on urban routes.

Refrigeration

Conventional refrigeration equipment in trucks, trains and ships generally consists of a small diesel engine to drive the compressor of a closed cooling circuit, which is used to cool air for circulation in the cargo or passenger space. Such systems are typically inefficient, noisy and require regular maintenance. This inefficiency, combined with growing global demand, means transport cooling and refrigeration is a significant and expanding source of carbon emissions and there is increasing pressure on operators to develop alternative approaches.



Figure 4.10: Direct refrigeration by liquid nitrogen. Source: natureFridge⁵

A number of industrial gas companies such as Linde, Air Liquide and other market participants such as EcoFridge, have already developed systems that use liquid nitrogen as a heat sink to provide refrigeration in food transport.⁶ These systems either pass liquid nitrogen through a heat exchanger where it vaporises to absorb heat indirectly, or spray liquid nitrogen directly into the goods compartment. The second method has the advantage of being about a third more efficient, but means oxygen monitors and other safety equipment must be installed to prevent the operator entering the compartment until the atmosphere is breathable. Neither approach recovers any shaft power from the evaporation process, but it is no great leap to imagine that if substantial quantities of a cryogenic fluid such as liquid air were carried on board a vehicle as fuel for a cryogenic engine, the cold exhaust could also be used to keep goods or passengers cool.

Refrigeration by direct spraying

The simplest approach to cooling with liquid nitrogen or air is to spray it directly into the goods or passenger space (obviously nitrogen cannot be used in passenger transport). A heat exchanger vaporises the liquid air or nitrogen using ambient heat, driving it under pressure out of nozzles at the top of the space to be cooled. The cold gas sinks naturally, circulating air within the space and displacing warmer air to the environment. Such a system requires

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very few moving parts, is lightweight and operates silently, as well as being inexpensive. This approach displaces existing warm air and dissipates very effectively, and so can cool a volume of air rapidly.

In food transport, if liquid nitrogen is used rather than liquid air, there is the additional benefit of reduced spoilage since the produce is surrounded by an inert gas. However, this requires additional safety equipment to ensure the atmosphere in the goods compartment is breathable before the operator opens the doors to load or unload.

Systems of this type are already on the market using liquid nitrogen stored in tanks on board. For a large haulage truck with a fully refrigerated trailer, liquid nitrogen consumption is claimed to be 20-40 litres per hour, depending on ambient conditions.⁷

Refrigeration in combination with liquid air engine

A more complex but more efficient approach to cooling using onboard liquid air is in combination with a liquid air engine, which could be either the vehicle's prime mover or an auxiliary unit. In this approach, waste air from the engine is pumped into the space to be cooled. The waste air is considerably colder than the ambient air, so a similar cooling effect is achieved as with the direct spray approach. Since the liquid air has already been expanded in the engine to generate mechanical power, the additional consumption of cryogenic liquid would be small and the cooling effect achieved very efficiently. Such a system has been proposed by the Dearman Engine Company, and the potential fuel and carbon emissions savings of this approach are explored in chapter 10. If the cryogenic fuel were liquid nitrogen, in passenger transport the cooling system would have to be indirect.

Depending on the system design, further efficiency gains may also be available if the engine takes its intake air from the cooled compartment as well. This would allow further heat to be extracted from it, reducing the cooling energy required and thus minimising the consumption of liquid air.

Potential impact

Refrigerated food transport is a significant and growing source of carbon emissions. In the EU there are about 650,000 refrigerated road vehicles in use primarily for food distribution, of which about 8% or 52,000 are in the UK. In the UK, food transport - including motive power and refrigeration - accounts for 1.8% of total emissions.⁸ The potential emissions reductions that could be achieved by using liquid air or nitrogen in refrigerated food transport are explored in chapter 10.

4. Mapping liquid air to vehicle types

Having discussed the energy requirements of a wide range of vehicle types, and explored the characteristics of liquid air or nitrogen, we are now able to compare the two. In this section we assess the relative attraction for the main vehicle types of the main potential applications of liquid air - as prime mover, heat recovery device and refrigeration unit.

Liquid air as a prime mover

In order to evaluate the suitability of liquid air for use as the main energy source for propulsion in different vehicle types, the energy storage requirements of those vehicles are summarised by key criteria:

- Energy and power density sensitivity: how important is it for each application that energy storage and conversion technology is compact and/or lightweight?
- Infrastructure: how extensive must refuelling infrastructure be for each vehicle type to enable them to operate with the reach and flexibility required?
- Refuelling rate sensitivity: how important is it that refuelling can be carried out quickly?
- Emissions sensitivity: how highly is low- or zero-emissions capability valued in each application?

The relative importance of each of these criteria is shown qualitatively in Table 4.1, and the ability of liquid air to serve those requirements is shown in Table 4.2.

There are 650,000 refrigerated road vehicles in the EU, and this is a significant and growing source of carbon emissions. The potential emissions savings from liquid air are explored in chapter 10.

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	Storage density sensitivity	Infrastructure requirements	Refuelling rate sensitivity	Zero emissions requirement
Container ship	++	+	+	+
Small passenger ferry	+	+	+	+
Intercity train	++	+	+	+
Freight locomotive	+	+	+	+
Commuter train	++	+	+	+++
Heavy duty haulage truck	+++	+++	+++	+
Urban bus	+	+	++	+++
Medium duty truck	++	+	++	++
Urban delivery van	++	+	++	+++
Passenger car (large)	++	+++	+++	++
Passenger car (small)	++	++	+++	+++
Personal mobility	++	++	+++	+++

Table 4.1: Relative importance of energy storage criteria to various vehicle types

For prime mover engines, the key characteristics of liquid air or nitrogen that influence its attractiveness as a main energy source in different vehicle types can be summarised as:

- A relatively high consumption of liquid air - around twenty times the mass of 'fuel' per unit of useful work delivered compared to an internal combustion engine, which limits its attraction in vehicles that are used intensively.
- Zero emissions at the point of use except for air or nitrogen, which is attractive not only in environmentally sensitive outdoor environments, but also useful for indoor operation.
- A relatively low capital cost due to a lack of exotic materials in the heat engine or cryogenic tank, which means that the system is more attractive where the application is used less intensively or at low power levels.
- Currently no accessible refuelling infrastructure network, especially for long range road transport applications, although (as discussed in chapter 7) the establishment of a refuelling supply chain for applications such as on-site and return-to-base applications may be relatively straightforward.
- Potential for similarly rapid refuelling rates to hydrocarbon fuels, in contrast to some competing technologies - see discussion below.

These characteristics are captured in Table 4.2.

	Storage density	Refuelling infrastructure	Refuelling rate	Zero emissions
Liquid Air	---	--	-	+++

Table 4.2: The ability of liquid air to satisfy key energy storage criteria

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The scores in Tables 4.1 and 4.2 can be combined to assess how well the strengths and weaknesses of liquid air match the energy storage requirements of various vehicle types, and the results are presented in Table 4.3. The costs associated with liquid air energy conversion technologies and refuelling infrastructure are considered in other

chapters of this paper. A full consideration of application-specific system costs is beyond the scope of this study and is in any case difficult to quantify robustly at the current state of technology development. However, we assume the costs of liquid air technologies could become competitive against competing technologies with future development.

As a principal fuel, liquid air matches the needs of buses, vans, medium duty trucks, small cars and scooters either well or relatively well.

	Storage density	Refuelling infrastructure	Refuelling rate	Zero emissions	Overall suitability
Container ship	--	-	+/-	+	Low
Small passenger ferry	-	-	+/-	+	Med
Intercity train	--	-	+/-	+	Low
Freight locomotive	-	-	+/-	+	Med
Commuter train	--	-	+/-	+++	Med
Heavy duty haulage truck	---	---	-	+	Low
Urban bus	-	-	+/-	+++	High
Medium duty truck	--	-	+/-	++	Med
Urban delivery van	--	-	+/-	+++	Med
Passenger car (large)	--	---	-	++	Low
Passenger car (small)	--	--	-	+++	Med
Personal mobility	--	--	-	+++	Med

Table 4.3: How well does liquid air match the energy storage requirements of various vehicle types?

In general, liquid air is most attractive as a main energy vector for prime movers in applications that do not require high levels of energy density; do not require an extensive distribution network for refuelling; value high refuelling rates; and value zero-emissions at the point of use. For applications where liquid air is competitive with other energy storage options, its attractiveness may be increased if secondary benefits such as its use for refrigeration are considered important. On this basis, liquid air stands out as relatively attractive in several urban and/or limited range applications. In particular, buses match the profile of strengths of liquid air well on most counts. Vans and to a lesser extent medium duty commercial vehicles also rank relatively well, as do small cars and personal mobility vehicles - assuming that they are

used almost exclusively within a city and that zero emissions capability is valued there. For shipping, rail and long-range passenger car applications, the lack of a strong requirement for zero emissions at the point of use means that there is little to compensate for liquid air's relatively poor energy storage density and distribution infrastructure challenges. For heavy duty haulage prime movers, liquid air is uncompetitive with incumbent energy vectors in almost every respect.

This analysis has examined the attractiveness of liquid air as a prime mover fuel against the primary requirements for transport energy in mainstream applications. However, there are other, more specialist vehicle types that have their own additional, application-specific requirements, for which liquid air

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Liquid air compares well to other low carbon vectors as a main source of energy. For example, batteries remain expensive, and liquid air may deliver much lower costs per unit of energy stored.

propulsion may be particularly attractive. On this basis both fork-lift trucks used indoors and underground mining applications appear to be attractive for liquid air power. Both value the zero emission output of a liquid-air prime mover and the safety benefit of a non-flammable fuel, whilst having relatively undemanding infrastructure requirements through their operation on a single site.

The simple evaluation performed here gives an indication of the types of applications that may be more suited to the use of liquid air as an energy vector judged against a small number of fundamental criteria. A number of other factors are not taken into account that may affect feasibility but which are difficult to assess for generic concepts. These include: system durability and reliability (real or perceived), relative fuel prices, purchase or usage incentives, operability under different ambient conditions, technology cost, maintenance requirements and total cost of ownership. Likewise, safety and reliability are not considered for mainstream applications, since it is a given that vehicles must meet the requirements of the markets in which they operate. Another factor not examined here is the ready availability of ambient heat to facilitate continued vaporisation of liquid air within a prime mover. This potentially poses spatial challenges in vehicle design, but at this stage it is not possible to assess how critical these issues might be for each application. However, this issue might make the use of liquid air as a prime mover relatively more attractive in marine applications, since heat exchange with the sea is likely to be more effective than with air.

Liquid air vs competing low carbon prime mover energy sources

The success of liquid air as a main prime mover energy source would of course depend on the strength of its merits against other competing energy vectors. The key competitors, on the basis of good performance and a similar potential for low CO₂ emissions and zero emissions at point of use, are:

- hydrogen - stored as compressed gas, as a cryogenic liquid or by adsorption.
- batteries - using any chemistry with high energy density, such as Lithium-Ion.
- compressed air.

We have discounted ultracapacitors (electrostatic storage devices), flywheels and other mechanical energy storage devices, all of which can offer excellent *power* densities (i.e. high rates of charge/discharge) but have *energy* densities too low to be competitive for primary energy storage for vehicle propulsion, as shown in Figure 4.11.

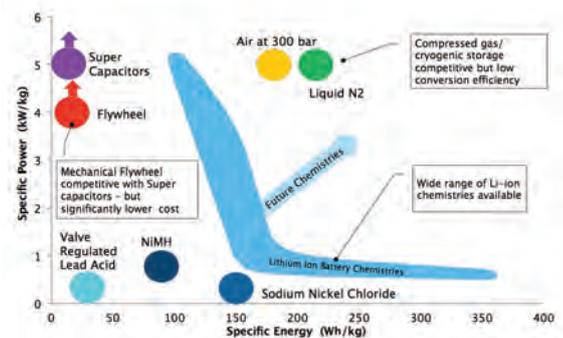


Figure 4.11: Power and energy densities of selected energy storage technologies
Source: Ricardo

Hydrogen

Compressed hydrogen at 700 bar using today's best available technologies is currently relatively costly but has an energy density around twice that of liquid air. For this reason it would represent liquid air's strongest competitor in the transport applications with more severe range, weight and space requirements - for example in the marine and rail applications covered here, as well as many of the road vehicle applications. Which technology might have more success would depend on several factors that are currently unknown, such as relative technology costs, raw material prices - to which a hydrogen fuel cell prime mover would be far more sensitive than a liquid air engine - and the prevailing refuelling infrastructure. In chapter 7 we discuss the extensive industrial and commercial distribution network that exists for liquid nitrogen, which does not exist for hydrogen. The low score for liquid air infrastructure in Table 4.2 reflects the fact no publicly accessible network of refuelling stations for liquid air or nitrogen currently exists, which would be a critical factor for usage by non-depot-based vehicles.

The nature of cost pressures on specific applications would also play an important role in any competition between hydrogen and liquid air. For example, for a heavy freight locomotive a hydrogen prime mover would be more expensive than a liquid air engine, but

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liquid air would require the vehicle to be made larger to cope with its relatively low energy density, so it is not yet clear which option would involve the higher incremental cost.

Batteries

Batteries represent the most mature energy storage technology for zero emissions today, with many vehicles in production on the open market. Improvements in cost, energy density and longevity are set to continue and will improve their competitiveness during the time it would take liquid air technologies to come to market. Innovative models for battery ownership and reuse may also help to reduce costs. However, since battery energy density is currently not significantly better than for liquid air, it appears that the two technologies could well compete head to head.

Battery electric power is likely to be most attractive in situations where vehicles can be readily charged overnight or between shifts (eg private ownership or limited daytime business use), and in locations where there is easy access to charging infrastructure. The controllability and flexibility of electric power on board vehicles is likely to make BEVs a more attractive choice for applications that benefit from significant kinetic energy recovery (eg through frequent acceleration and braking) or that make significant use of onboard auxiliary equipment, such as utility trucks. For buses, inductive charging whilst stationary at stops also may prove to be a way to minimise battery size and cost that makes battery energy storage much more attractive in this application.

Nevertheless, a number of factors give liquid air an advantage over battery technology. First, batteries remain expensive, while liquid air appears to have the potential to deliver much lower costs per unit of energy stored. Second, the cost uncertainty caused by electric powertrains' dependence on valuable raw materials makes alternative vectors such as liquid air that avoid this vulnerability appear particularly attractive. A further related issue is the relatively high levels of 'embedded' CO₂ associated with current battery and electric drive technology; while little analysis has been performed to date of the likely embedded emissions impact of liquid air technology, the lack of exotic raw materials or complex processing needed for their manufacture suggests that liquid air-based powertrains of

the future may have the edge over electric powertrains in this respect (see chapter 10).

Compressed air

Compressed air, as explained earlier in this chapter, may be seen as a simpler and cheaper alternative to liquid air, but its performance in terms of energy storage is inferior. On this basis, we conclude it is best suited to vehicles for which the required driving range is very low and for which there is a strong emphasis on low cost. This might include personal mobility vehicles and small cars for very restricted urban use, as well as some specialist industrial vehicles for indoor use, such as materials handling.

For the applications with the greatest need for high energy density, such as long-distance road haulage, it is highly unlikely that any of the competing zero-emission technologies would be feasible versus the incumbent hydrocarbon fuels such as diesel or natural gas. In these applications, however, liquid air is at its most attractive as an enabler for waste heat recovery - as discussed below.

Liquid air in heat recovery

Apart from their potential use as prime movers in transport, liquid air engines can also be employed to reduce vehicles' fossil fuel consumption through waste heat recovery. The characteristic that makes liquid air technology attractive here is its ability to use ambient or low grade waste heat, which is particularly useful in harvesting heat from internal combustion engine or fuel cell cooling systems, whose heat quality is typically too low (~100C) for more conventional heat recovery devices.

There are three main ways in which this can be achieved:

- Through the use of a split cycle internal combustion engine to reduce the fuel consumption required for propulsion.
- Through the use of a secondary liquid air engine to supplement the motive power of an internal combustion engine, and possibly allow it to operate more steadily and at higher efficiency.
- Through the use of a secondary liquid air engine to provide power for auxiliary loads, driven by waste heat from the main engine.

Liquid air can exploit low grade waste heat from internal combustion engines or hydrogen fuel cells and convert it into additional power at high levels of efficiency.

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As a heat recovery or refrigeration technology, liquid air matches the needs of a wide variety of vehicles extremely well, including vans, buses, lorries and some types of train and ship.

The first option is most attractive in applications for which fuel costs make up a significant proportion of total operating costs, and where the engine operates at high power levels for much of the time, such as heavy duty road haulage trucks and container ships. Here the extreme pressure on vehicle productivity and therefore energy storage density make it unlikely that liquid air or other zero emission energy vectors could compete with the incumbent hydrocarbon fuels. However, if liquid air is generated on board then minimal storage capacity is required, and this can be used to recapture energy from the exhaust stream and reduce the quantity of primary fuel needed to drive the engine. Depending on the cost and space within the vehicle, this system could also be applicable more widely, perhaps including rail locomotives, other commercial vehicles or even larger passenger cars.

The first option might employ onboard liquefaction, but the second does not, and therefore becomes attractive in return-

to-base vehicles such as buses and urban delivery trucks. Here the daily duty cycle may mean that use of liquid air or nitrogen as a sole prime mover fuel is impractical, but it could be attractive as a supplementary heat-harvesting fuel.

Under the third option, the attractiveness of liquid air for providing auxiliary power depends on two factors:

- a requirement for onboard auxiliary power in significant quantities relative to the power required for propulsion.
- a need for onboard auxiliary power for significant proportion of the time when the vehicle is at rest.

The greater the importance of these factors to a particular vehicle, the more valuable will be a dedicated, high-efficiency, quiet and clean-running auxiliary power unit, such as a liquid air system. Vehicles that satisfy these criteria include passenger ferries, passenger trains and buses, as shown in Table 4.4.

	Split cycle engine	Heat recovery for propulsion power	Heat recovery for auxiliary power	Liquid air refrigeration
Container ship	High	Med	Med	Med
Small passenger ferry	High	Med	High	Med
Intercity train	Med	Med	Med	Low
Freight locomotive	High	Med	Med	Med
Commuter train	Low	Med	High	Med
Heavy duty haulage truck	High	Med	High	High
Urban bus	Low	High	High	High
Medium duty truck	Med	High	Low	High
Urban delivery van	Low	High	Low	High
Passenger car (large)	Low	Low	Low	Low
Passenger car (small)	Low	Low	Low	Low
Personal mobility	Low	Low	Low	Low

Table 4.4: Vehicles' suitability for liquid air/liquid nitrogen auxiliary power

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Refrigeration

Liquid nitrogen is already used in commercial vehicles to provide continuous, efficient and silent refrigeration, particularly for those operating at night. However, at present the nitrogen is used only to provide cooling and no power is extracted from its evaporation. In any vehicle applications that would benefit from the use of liquid air as a prime mover fuel or for heat recovery, therefore, its additional use for refrigeration would represent a significant synergy with additional savings in complexity, weight and cost. Transport applications to which this could apply include all those carrying perishable goods or requiring extensive air conditioning for passenger accommodation, particularly in hot ambient conditions. So examples could include passenger ferries and cruise ships, freight trains, buses and all types of refrigerated haulage or delivery truck, with all likely to enjoy the greatest benefits in hot climates. However, the practicalities of supplying liquid air directly to each compartment that requires cooling are likely to make this most attractive for relatively compact applications such as road transport.

5. Conclusions

Liquid air is potentially attractive as an energy vector for future low CO₂ transport through the benefits it offers in terms of its zero emissions at point of use, energy and power density on a level with battery electric technology and its potential for high refuelling rates.

- A number of transport applications exist for which these benefits are valued, and for which the use of liquid air as a prime mover energy vector could be feasible.
- Key mainstream applications of interest include urban buses, small city cars and personal mobility vehicles, urban delivery vehicles and short-range marine craft.
- Further specialist applications for operation in enclosed spaces may also be a good match with liquid air's characteristics, such as indoor forklift trucks and mining vehicles.
- Beyond the liquid air's use as a primary fuel for propulsion, it has the potential to improve the energy consumption of internal combustion engines by capturing waste heat, either through 'heat hybrid' designs or split cycle engines with high thermal efficiencies.
- The use of liquid air on board vehicles in any of the above forms also gives rise to further potential synergies, such as through the implementation of simple, efficient and quiet refrigeration or air conditioning systems.
- Compared to the key alternative energy vectors for low CO₂ transport - hydrogen, batteries and compressed air - liquid air appears to offer a balance of characteristics that could make it competitive and worthy of further development.

Chapter 4 Endnotes

¹ *Digest of United Kingdom energy statistics (DUKES) 2012*, <https://www.gov.uk/government/publications/digest-of-united-kingdom-energy-statistics-dukes-2012-printed-version-excluding-cover-pages>

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⁵ <http://naturefridge.com/>

⁶ *Special Report: Cryogenic Truck Refrigeration with Nitrogen*, Global Cold Chain News, February 2011, http://www.globalcoldchainnews.com/Global_Special_Report-Cryogenics.pdf

⁷ Ibid.

⁸ *Food Transport Refrigeration*, S.A. Tassou et al., Brunel University, Centre for Energy and Built Environment Research.

Chapter 5 Waste heat

Liquid air is inherently capable of converting waste heat into power because of its low starting temperature, and can exploit even low grade waste heat that would otherwise be difficult to recover.

1. Waste heat from industrial processes

2. Waste heat from hydrogen fuel cells in transport

3. Conclusions

Liquid air is inherently capable of converting waste heat into power because of its low starting temperature. The liquid air cycle works between -200C and ambient temperatures, meaning the addition of even *low grade* waste of up to 100C, which is otherwise difficult to exploit, can increase the work output significantly. Internal combustion engines produce waste heat at around 100C, raising the prospect of ICE-liquid air heat hybrids, discussed in chapters 4 and 10. Power generation produces *high grade* waste heat (typically above 400C), and we discuss the potential to integrate this with liquid air concepts in chapter 3 section 3. In this chapter we discuss the potential application of liquid air to plentiful low grade industrial waste heat, and to waste heat from hydrogen fuel cells in transport.

1. Waste heat from industrial processes

There is relatively little publically available data on the surplus heat resource associated with industrial processes in the UK. In its call for evidence on heat in 2008, the Department for Business, Enterprise and Regulatory Reform (BERR) provided an estimate of 40TWh per year¹, but a more detailed bottom up study by McKenna and Norman², which captured an estimated 90% of the energy intensive process industries, put the value at between 10 and 20TWh. It seems safe, therefore, to assume that the true value is in the 10-40TWh range. 40TWh is enough to heat 2.4 million UK homes for one year.³

Nor is there any precise or universally agreed definition of what constitutes 'low-grade' heat. BERR categorised high-grade heat as that typically above 400C, medium grade as that between 150-400C and low grade as that below 150C. One justification for this is the distance over which heat can be transported without significant loss: pipeline heat losses typically limit the distances heat can be moved economically to around 5km for steam (at 120C-250C) and a few tens of kilometres for hot water (100C-150C). Crook, on the other hand, defined low-grade heat as that below 250C and this threshold has subsequently been adopted by several workers in the field.⁴

McKenna and Norman analysed a range of industries and processes and produced a map showing their distribution (Figure 5.1). Steelworks have a high potential and produce high quality waste heat at three sites in the UK - one in south Wales and two in the north east of England. The other sites and processes with waste heat potential are more widely distributed although there is a distinct concentration in the Midlands, in a band extending from just north of Birmingham to just north of Leeds.

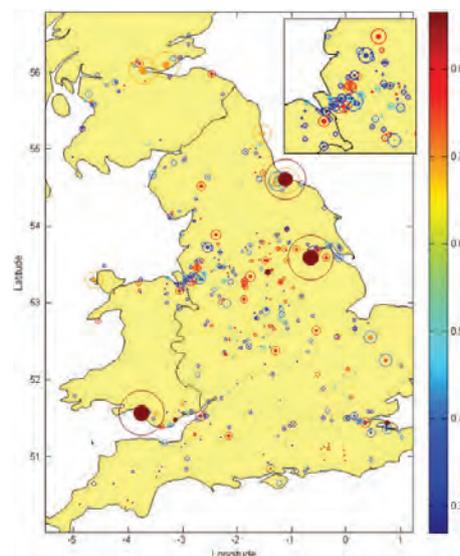


Figure 5.1: Map of UK waste heat resource. Source: McKenna and Norman⁵

Chapter 5 Waste heat

The range of industries and processes producing waste heat is quite wide, but the form of the resource is less so and a large proportion of it is composed of cooling water streams and flue gases. Therefore existing heat exchanger technology should in principle provide adequate access, although with some caution concerning corrosive or particle laden streams that could lead to damage or fouling of heat exchanger surfaces.

Power from waste heat conversion

When assessing potential uses for waste heat, it is thermodynamically preferable to re-use it as heat rather than convert it into work - for instance as electricity. However, this general rule fails to consider the relative demands for heat and power, or the relative costs of these two forms of energy. For instance, heat may be available but not required, while electricity is very much needed and would otherwise be bought at a high price.

Temperature is synonymous with quality (grade) and can be quantified by calculating the theoretical maximum (Carnot) efficiency of a heat engine operating between the waste heat (source) temperature and the temperature of the surroundings (sink). This value represents the maximum proportion of the waste heat that can be converted to work in a heat engine, and is one measure of the maximum recoverable energy. The Carnot efficiency η_c is given by,

$$\eta_c = 1 - \frac{T_{sink}}{T_{source}}, \quad (1)$$

and is plotted in Figure 5.2 as a function of the temperature at which the waste heat is available. In order to generate this figure, the representative average temperature of the surroundings in the UK is assumed to be 10C.

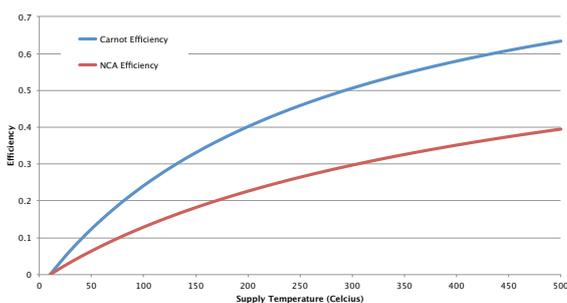


Figure 5.2: Theoretical maximum efficiency of waste heat conversion to work, as a function of the temperature of the waste heat

On this theoretical basis, and using BERR's categories, it appears we can recover 58% or more of the high-grade waste heat, 33% to 58% of the medium-grade and up to 33% of the low-grade.

These numbers are certainly overestimates of the true work that can be extracted from waste heat, because:

- they do not account for the fact that heat exchangers require a temperature difference to exist between streams to drive heat transfer, and therefore that the maximum temperature of the working fluid in a heat engine is less than the waste heat source temperature, and the minimum temperature in the cycle is greater than the sink temperature;
- nor do they consider that the source temperature falls as heat is extracted from it to operate the heat engine, and the sink temperature rises as heat is rejected from the heat engine.

The first of these two limitations can be addressed by considering the Novikov and Curzon-Ahlborn efficiencies, which are given by:

$$\eta_{NCA} = 1 - \left(\frac{T_{sink}}{T_{source}} \right)^{1/2}, \quad (2)$$

and have been shown to be a surprisingly good predictor ($\pm 10\%$) of the actual thermal efficiency of various existing plants. This efficiency is also shown in Figure 5.2 for comparison with the Carnot values. Now our earlier theoretical estimates of the proportion of recoverable waste heat can be revised down to 35% or more for high-grade heat, 18% to 35% for medium-grade, and up to 18% for low-grade.

As for the second limitation, a study by Markides⁶ demonstrates that the decreasing hot temperature and increasing cold temperature always result in a loss of efficiency, but that this should be tolerated to some extent as doing so increases the power output by exploiting more of the available energy per kilogramme of the waste heat stream.

The UK industrial waste heat resource is estimated at up to 40TWh per year, enough to heat 2.4 million homes.

Chapter 5 Waste heat

UK demand for heat is easily big enough to absorb the waste heat resource, but supply and demand of low grade heat rarely coincide in time or place.

Waste heat demand

If the UK waste heat resource amounts to 10-40TWh, total demand for heat is easily large enough to absorb it. McKenna and Norman assessed the heat demand of UK industry in selected temperature ranges, and Kuder and Blesl⁷ published a similar analysis for Europe. Both identified industries using low-grade heat as pulp and paper, gypsum, food and drink and some chemicals. UK energy intensive industries are estimated to have an overall heat demand of approximately 180TWh with about 25TWh in the less than 100C range and a further 42TWh in the 100-500C range.

The data provided on the previous page suggest demand for low-grade heat in process industries easily matches supply. However, this takes no account of the obvious fact that sources of low-grade heat are rarely co-located and coincident with demand. This suggests the need for a means to store and perhaps transport industrial waste heat.

Where it is not possible to exploit waste heat close to its source, through process integration, another obvious option is to use it for space heating through a district heating network. Such networks are common in parts of Europe and are starting to appear in the UK - in Birmingham city centre for example. However, they typically do not exploit an existing source of waste heat but create a new one - such as a new gas fired generator. Where business or domestic buildings do lie close to waste heat producing industry it is clearly possible to consider district heating. However, the cost of new infrastructure and back-up equipment is likely to be considerable if not prohibitive, meaning technologies that convert waste heat into a more readily useable form of energy may still be preferable.

Waste heat and heat pumps

Technologies for harnessing low-grade heat include heat pumps, which upgrade the heat and improve its utility by increasing the options for process integration, and organic Rankine cycle devices, which allow energy from waste heat to be transformed into its most versatile and transportable form - electricity.

There are various types of heat pump. In the domestic arena ground source and air source heat pumps, using an electrically driven vapour compression cycle, extract heat from

a very low grade source (the environment) and improve its quality to the point where it can be used for space/comfort heating. They can also be used to provide cooling/air conditioning by rejecting heat to the same environment. Heat pumps operating by the same physical process can also be used in an industrial setting, but the maximum delivery temperature is currently limited to about 120C.⁸

The most common heat pumps found in industry are probably mechanical vapour recompression heat pumps. In their simplest 'open' form process vapour is compressed and returned with an elevated condensation temperature. In 'semi-open' form heat from the recompressed vapour is returned to the process via a heat exchanger. This type of heat pump can achieve high coefficients of performance (COP) of 10-30 and can deliver heat at temperatures of up to 200C.⁹

Chemical and thermochemical heat pumps operating via adsorption or absorption cycles require very little or no electrical power input because the vapour compression process is replaced by a heat driven adsorption/desorption process. The latest generation of such heat pumps can have a delivery temperature of as much as 120C, but COP values are relatively low at 1.2 to 1.4.¹⁰

Overall, heat pumps can provide a very effective way of recovering waste heat, particularly if there is a local need for it as part of a scheme for process integration. Where there is no such need, however, spatial and temporal constraints severely limit this potential. With the possible exception of the mechanical vapour recompression type, heat pumps are not yet widely used for low grade heat recovery and are not yet fully technically mature in this setting.¹¹

Waste heat and heat engines

Most of the world's electricity is generated by heat engines operating on either the Joule/Brayton or Rankine thermodynamic cycles. The Rankine cycle can operate with water as the working fluid, but this requires high input temperatures such as those produced by coal combustion. When the source is low-grade waste heat, the Rankine cycle needs a working fluid with a lower boiling point. There are a variety of candidates, many of which are organic - hence 'organic Rankine cycle' (ORC).

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This technology is relatively mature and has been applied with a variety of heat sources including: geothermal, solar, biomass as well as waste heat. ORC equipment is commercially available for waste heat recovery and Tchanche¹² provides 17 examples of installations with capacities ranging from 125kW to 6.5MW.

The biggest advantage of ORC waste heat recovery is that it produces electricity that can be fed into the grid to overcome all spatial and temporal constraints, giving it a commercial value whether or not it can be used within the plant. The main disadvantage is its relatively low efficiency. Large ORC units that use turbo-expanders can be up to 25% efficient, but for smaller units with outputs measured in tens of kW turbo-expanders are not economic. Alternative solutions based on screw expanders are typically less than 10% efficient.

We conclude that even if all process integration opportunities were exploited there would still be a very substantial waste heat resource available from manufacturing and process industries. We also think the best way to access this resource is to generate electricity. In the context of opportunities for waste heat recovery using liquid-air, this suggests the ORC is the main competing technology.

ORC vs liquid air

ORC machines benefit from relative technical maturity, a growing foothold in the market and from the fact that they are stand-alone units requiring no additional services or inputs. By contrast, any liquid air generator intended to be used for waste heat recovery would need a supply of liquid air or nitrogen. One option would be to install a Cryogenet (chapter 2) and run it on liquid air supplied from a remote, large-scale production facility. The alternative would be to install a full Liquid Air Energy Storage (LAES) unit that produces its own liquid air on site using cheap off-peak electricity. In both cases waste process heat would be used to enhance the recovery of the stored electricity when needed - or when electricity market prices make it economic. In both cases the liquid air acts as a waste heat enhanced energy storage system rather than as a waste heat based generator like the ORC. This suggests that ORC and liquid air are not directly competing technologies. Nevertheless, it is interesting to consider if there is an economic case for the operator

of a waste heat generating process plant to purchase a liquid air energy storage set rather than an ORC waste heat generator.

The first law efficiency of liquid air based systems, based on predictions and operational data from the pilot plant (chapter 3, and Appendix 1), are far greater than can be achieved using ORC plant at the same temperatures. The former is predicted to operate at typically 56% whilst the latter operate in the 10-25% range and at the lower end of this range for temperatures around 100C. It therefore seems reasonable to conclude that a liquid air based waste heat recovery system would generate up to five times as much electricity as an ORC system operating under similar conditions with low grade heat. The round trip efficiency of energy storage using liquid air has been estimated to be 50-70%, when enhanced by waste heat. If 50% is assumed for the relatively small scales that would be associated with a process plant, we can compare ORC and liquid air systems for capacity and economics.

If a process plant generates 10MWh of low grade waste heat an ORC set might convert this to 1MWh of electricity to be used on site or sold. A liquid air system would generate 5MWh having previously consumed 10MWh of electricity to generate the liquid air. Given that the power generated can be exported, at a system level the use of liquid air would increase the overall generating capacity at times of peak demand. However, the same effect could be achieved if the liquid air based storage technology were located at existing power stations or industrial gas production sites. The question then is whether the electricity market could provide an economic case for liquid air systems at the sites of industrial process plants.

The levelised cost of electricity (LCOE) generated using ORC has been predicted to be in the range £25-40/MWh (Markides) and it seems reasonable to expect it to be at the high end of this range where low-grade heat is used as the energy source. If we assume that the electricity generated can be sold at £100/MWh then the 10MWh of low grade waste heat would generate a profit of £60.

Using liquid air, the revenue would be £500 and profit would depend of the cost of operating the plant and buying either sufficient liquid air from a centralised generating plant or 10MWh of off-peak electricity to produce the liquid air locally. If non-fuel operating costs - ie operation, maintenance and capital costs -

Even if all opportunities to make use of waste heat as heat were exhausted, there would still be a very substantial waste heat resource available. The best way to access this is to generate electricity.

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Liquid air could offer an economically attractive way to exploit industrial waste when the ratio of peak to off-peak electricity prices is 2.5x or greater.

for the liquid air plant were the same as those of the ORC plant and we take these to be £40/10MWh of waste heat used then, to make the same level of profit (£60/10MWh waste heat) the liquid air plant would need to be able to generate or buy its 'fuel' for no more than £400, the equivalent of £40/MWh electricity.

This analysis is very simplistic and takes no account of a number of operational and performance factors such as intermittent and part-load performance which could be highly influential. It also excludes an analysis of the relative capital costs, although this is far less influential on the cost of producing liquid air than energy prices (chapter 6). It does, however, identify a key factor in establishing the LCOE with liquid air - the price ratio of peak to off-peak electricity. Whatever other incentives might exist - such as feed-in-tariffs or capacity payments, for example - we have indicated above that if the effective ratio of selling to purchase price is 2.5 or greater¹³, liquid air could represent an economically attractive proposition to process plant operators.

In countries with inadequate primary generating capacity, such as South Africa and Thailand, the ratio of peak to off-peak electricity prices is as high as eight times even today.¹⁴ In countries or regions with rising renewable generating capacity power prices can already turn negative in periods of high wind and low demand, and the effects of weather and renewable intermittency are expected to increase price volatility in the coming decades. By some analyses the peak to off-peak ratio could rise to well beyond 2.5 times. Figure 5.3 shows projections for price volatility in France and Germany and the effect is expected to be similar in the UK.

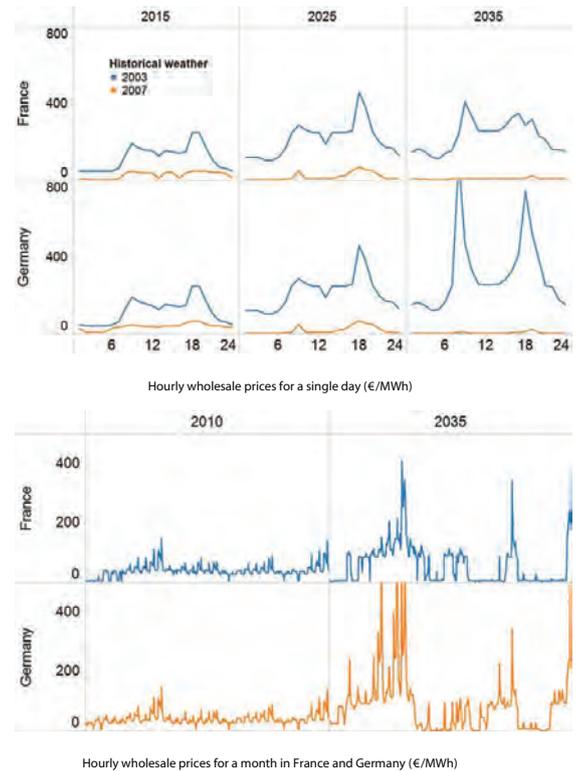


Figure 5.3: The impact of renewable intermittency on hourly power pricing. Source: Poyry⁵

Chapter 5 Waste heat

2. Liquid air waste heat recovery in fuel cells for transport

Fuel Cells (FC) are devices that convert chemical energy into electricity with efficiencies typically higher than direct combustion.¹⁶ Depending on the charge carrier and electrolyte, FCs can be further sub-divided into the Proton Exchange Membrane Fuel Cell (PEMFC), Alkaline Fuel Cell (AFC), Phosphoric Acid Fuel Cell (PAFC), Molten Carbonate Fuel Cell (MCFC), Solid Oxide Fuel Cell (SOFC) and Direct Methanol Fuel Cell (DMFC).¹⁷ Of these technologies, PEMFCs are currently receiving most attention in the transport field due to their relatively high power density and quick start-up time.¹⁸

The typical operating temperature of a PEMFC is in the range of 60-80C.¹⁹ Higher operating temperatures can lead to degradation and performance issues arising from the dehydration of the membrane²⁰, while lower temperatures slow the speed of chemical reactions and make water management harder.²¹ The amount of thermal energy removed by the reactant and product streams is typically negligible (1.6%) with most of the heat being removed by the cooling system.²² This is significantly different to an Internal Combustion Engine (ICE) where 60% of the heat is typically removed by the exhaust.²³ Methods of thermally managing PEMFCs include: air cooling, water cooling and cooling using phase change materials.²⁴ The most commonly used cooling method is a mix of deionised water and ethylene glycol combined with a radiator. The high specific heat capacity and sub-zero tolerance make this ideal for automotive applications.²⁵

In high pressure FC systems, the thermal management of the compressor and the air is also integrated into the cooling system, due to the heat generated from the compression of the reactant stream.²⁶ It is often preferable to keep the air temperature slightly below that of the stack to avoid condensation, which can cause flooding and loss of performance.²⁷ However, too low an air temperature should also be avoided because it reduces the air's ability to carry water.

High pressure systems are often preferred in PEMFCs because it makes humidification easier and raises performance due to the increased speed of electrochemical reactions.²⁸ For high pressure systems, positive displacement or centrifugal compressors are preferred.²⁹

Air mass flow rates for an 80kWe stack may typically be in the range of 91 grammes per second with operating pressures in the range of 1.5-2.5 atm and efficiencies of 30-50%.³⁰ Outlet temperatures for air compressors and subsequent heat exchangers can exceed 80C depending on pressure ratios.³¹

The challenges of integrating fuel cells and liquid air

Any attempt to integrate a liquid air engine with a fuel cell to convert waste heat into power would face three key challenges: space, power blending and thermal management.

Space is always an issue for fuel cells; although the gravimetric energy density of hydrogen is approximately three times that of petrol (120 MJ/kg vs 43 MJ/kg), its volumetric energy density is six times lower (just 4.7 MJ/L at 70 MPa vs 31.7 MJ/L). This means the volume of the fuel tank is an important consideration in any hydrogen application where space is limited such as transport. Any future design for a PEMFC-liquid air hybrid vehicle would need to accommodate the extra space required for a tank of liquid air, although this may be offset by a smaller FC and cooling system.

The **power** generated by the liquid air engine would need either to be mechanically blended with the electric motor, electrically connected to the drive system BUS via a generator, or stored using an additional energy buffer. Finding the optimum operating points of both the FC and the coupled liquid air engine therefore requires a detailed understanding of the heat generation and temperature dependant behavior of both devices.³²

The **thermal management** of both devices therefore becomes a critical consideration in the design of any PEMFC-liquid air hybrid. PEMFCs work best at an operating temperature of approximately 80C. Excessive cooling could result in reduced performance, and could also cause large thermal gradients across the stack which would themselves reduce performance.³³

Hydrogen fuel cells in vehicles operate at up to 80C, similar to the coolant temperatures of an internal combustion engine, and liquid air could be used to recover this waste heat.

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Hydrogen fuel cells are less efficient when running under dynamic conditions, and a hybrid FC-liquid air engine may allow for greater efficiencies and component lifetime by load levelling.

The benefits and potential early applications of a fuel cell-liquid air hybrid

FCs are less efficient when running under dynamic conditions than at steady state; the more transient the load the more inefficient the operation meaning more heat is generated.³⁴ Highly dynamic loads and irregular temperature distributions can lead to faster degradation of PEMFCs.³⁵ A hybrid FC-liquid air engine may allow for greater efficiencies and component lifetime by load levelling of the FC.

Work has already been done to analyse the performance impact of coupling various types of FC and heat engine, and the results show there are significant efficiency gains to be achieved from waste heat recovery.³⁶ This research has mainly focused on higher temperature FCs (usually static), where the temperature gradient between the rejected fluid and the environment is large enough to drive a heat engine. PEMFCs operate at a lower temperatures, so waste heat recovery with heat engines has not been extensively studied.

The automotive markets where FCs are being considered include buses, where high utilisation, regular routes and centralised refueling address many of the current barriers to mainstream adoption of the technology.³⁷ The size of a bus FC is typically around 250 kWe for a pure FCV and 20-40 kWe for a hybrid FCV.³⁸ For a pure FCV, heat dissipation often requires a sizable radiator and considerable thermal energy is lost. Waste heat recovery would therefore be attractive because of the amount of energy available to be recovered, and because hydrogen's low volumetric energy density is less significant for buses than for smaller vehicles.

Another vehicle class considered ideal for fuel cells is the taxi, where tighter emissions legislation in urban areas and high utilisation gives the FCV certain advantages over Battery Electric Vehicles (BEV) where a standard eight hour recharge time is desirable.³⁹

One market where fuel cells have already started to be deployed is forklift trucks, where legislation prevents the use of diesel engine vehicles indoors, and again, their high utilisation makes battery electric recharge times problematic.

Economic and performance impact

The greatest barriers to mainstream adoption of fuel cells are currently durability and cost.⁴⁰ The most fragile component in a PEMFC is the Membrane Electrode Assembly (MEA), which is required to last 5,000 hours for light-duty vehicles with less than 10% performance decay.⁴¹ Highly dynamic loading of PEMFCs typically accelerates degradation, and research shows this factor accounts for 28% of typical performance fade in transport applications.⁴² As the FC is the most expensive component in the powertrain, maximising the lifetime of this component is important.

One of the main contributors to the cost of a FC is price of the platinum required for its catalyst, estimated at around \$48/g in 2010.⁴³ A typical 50kWe FC currently requires 46g of platinum, meaning the catalyst alone will cost \$2,240. Manufacturers are targeting major reductions in the amount of platinum used, but this has performance implications. For an 80kWe PEMFC, for example, reducing platinum to around a quarter of current levels would increase heat generation by 50% at peak load and 23% at a continuous load of 61kWe. So the need to cut platinum costs will increase the importance of thermal management in future FC designs and perhaps also the potential value of liquid air technology.

The cost of hydrogen is currently estimated to range from £20/kg to a few hundred £/kg depending on the level of demand and the production method, but the price is forecast to fall to between £4.5/kg to £19/kg.⁴⁴ A PEMFC in automotive applications is approximately five times the cost of its ICE equivalent, with the cost of an ICE being in the region of \$25-35/kW.⁴⁵ A hybrid FC-liquid air engine may make the FCV more economical because it would allow the FC and thermal management system to be downsized, and additional electrical energy to be generated from the waste heat recovery.

The opportunities to develop FC-liquid air hybrids, and the potential benefits of doing so, should increase as FCV deployment spreads. The US Federal Transit Administration is providing \$16 million under the National Fuel Cell Bus Program to coordinate research amongst manufacturers, engineering firms and transit agencies.⁴⁶ In London, eight FC buses entered operation in 2011 forming Europe's largest FC bus fleet. London also aims to have at least 65 FC powered vehicles on the road by the end of 2013 including five FC taxis.⁴⁷

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Despite currently high costs of FC systems, carmakers are investing heavily in the development of FCVs. Toyota anticipates the cost of its FCV to fall by 95% from \$1 million in 2005 to \$50,000 by 2015, when various manufacturers plan to launch FCVs

commercially. Other carmakers share a similar outlook, with projected costs of \$75,000 in 2015, falling to below \$50,000 after five years and an eventual plateau of \$30,000 by 2025.⁴⁸ Table 5.1 compares different vehicle platforms.

	Conventional	Hybrid	Hydrogen	Battery
Reference vehicle	Volkswagen Golf VI	Toyota Prius III	Honda FCX Clarity	Nissan Leaf
Fuel weight (kg)	40.8	33.3	4.1	171
Storage capacity (kWh)	500	409	137	24
Storage system weight (kg)	48	40	93	300
Specific energy storage (Wh usable/kg total equipment)	374	489	260	55
Average conversion efficiency (%)	21	35	60	92
Purchasing price (\$)	29,400	33,400	80,000	High
(estimated, launch 2015)	41,250	High	Low	High
Running cost (\$/mile)	0.22	0.14	0.07	0.02
Equivalent mpg	45.6	72.4	81	99
Range (miles)	552	716	240	73-109

Table 5.1: Comparison of petrol, hydrogen and electrical storage systems in four leading vehicles⁴⁹

Summary

PEMFCs are the current technology of choice in the emerging field of FCs for transport applications, based on their relatively fast start-up time and high power density. The main barriers to mainstream adoption are cost and fragility. Most of a PEMFC's waste heat is dissipated through a cooling loop that operates at approximately 80C. Typically this low grade heat is rejected to the atmosphere through a radiator, since the temperature difference between the fluid and the atmosphere is too small to drive a heat engine. With the development of the liquid air engine there is an opportunity to recover this low grade waste heat to increase FC system efficiency and lifetime, and possibly reduce

cost through downsizing. The integration of a PEMFC with a liquid air engine has not yet been studied, and discovering the optimal configuration will require extensive analysis of the temperature dependant performance of both systems.

The markets where a FC-liquid air engine hybrid would offer most immediate benefit and greatest chance of success have been identified as buses, taxis and forklift trucks. These vehicles have a high utilisation and centralised refueling infrastructure, or are used in situations where government legislation creates a supportive context.

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3. Conclusions

From the discussion presented above we conclude:

- The UK industrial waste heat is in the range of 10-40TWh per year. Industrial demand for heat is easily as large, but rarely co-located or coincident with supply, suggesting the need for a means to turn waste heat into a more easily transportable form of energy such as electricity.
- The existing technology for turning waste heat into power, the organic Rankine cycle, is best seen as a baseload generator while liquid air devices act as an energy storage system, so while both exploit waste heat, they are not direct competitors.
- However, based on a comparison with ORC costs, liquid air devices could be economically attractive for waste heat recovery at industrial process sites if the ratio between peak and off-peak electricity prices is 2.5 times or higher. By some forecasts this ratio could be substantially exceeded on a monthly and even daily basis within the next two decades.
- In transport, PEM fuel cells operate at around 80C, not dissimilar to ICE coolant temperatures, meaning they too could be combined into heat hybrids with a Dearman Engine or similar. This could improve the economics of hydrogen vehicles by allowing the PEMFC to be downsized.
- FCs are less efficient when running under dynamic conditions than at steady state, and a hybrid FC-liquid air engine may allow for greater efficiencies and component lifetime by load levelling.
- Manufacturers are constantly trying to reduce the amount of platinum used in fuel cells, but this increases heat generation, meaning thermal management will be increasingly important.
- The markets where a FC-liquid air hybrid would offer most immediate benefit and greatest chance of success have been identified as buses, taxis and forklift trucks.

Chapter 5 Endnotes

¹ *Heat - Call for Evidence*, Department for Business Enterprise and Regulatory Reform (BERR), 2008.

² *Spatial modeling of industrial heat loads and recovery potentials in the UK*, R. C. McKenna et al., *Energy Policy* 38, 2010, pp5878-5891.

³ The average UK home consumes 16.5MWh of gas per year most of which is used for heating. 40TWh / 16.5MWh = 2.4 million, <http://www.ofgem.gov.uk/Media/FactSheets/Documents/domestic%20energy%20consump%20fig%20FS.pdf>

⁴ *Profiting from low grade heat - The Watt Committee on Energy report No. 26*, A. W. Crook, IEEE Energy Series 7, 1993, ISBN 0852968353.

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⁶ *The role of pumped and waste heat technologies in a high efficiency sustainable energy future for the UK*, C. N. Markides, *Applied Thermal Engineering*, 2013. In press, available online at dx.doi.org/10.1016/j.applthermaleng.2012.02.037.

⁷ *Technology orientated analysis of emission reduction potentials in the industrial sector in the EU-27*, R. Kuder et al., International Energy Workshop (IEW), Stockholm, 21-23 June 2010.

⁸ IEA Heat Pump Centre, www.heatpumpcentre.org, accessed January 2013.

⁹ Ibid.

¹⁰ Ibid.

¹¹ *A review of chemical heat pumps, thermodynamic cycles and thermal energy storage technologies for low grade heat utilization*, A. P. Roskilly et al., *Applied Thermal Engineering* 50, 2013, pp1257-1273.

¹² *Low-grade heat conversion into power using organic Rankine cycles - A review of various applications*, B. F. Tchanche et al., *Renewable and Sustainable Energy Reviews* 15, 2011, pp3963-3979.

¹³ The ratio of 2.5 is calculated as follows:

Waste heat input: $Q_h = 10\text{MWh}$

$$\text{Profit}_{\text{ORC}} = \eta_{\text{ORC}} \cdot Q_h \cdot P_p - OM$$

$$\text{Profit}_{\text{LA}} = \eta_{\text{LA}_g} \cdot Q_h \cdot P_p - OM - \frac{\eta_{\text{LA}_g} \cdot Q_h \cdot P_{op}}{\eta_{\text{LA}_s}}$$

where:

Q_h = Amount of waste heat (MWh)

η_{ORC} = 1st law efficiency of an ORC generator

η_{LA_g} = 1st law efficiency on a liquid air generator

η_{LA_s} = Round trip efficiency of liquid air storage

OM = Operating and maintenance costs

P_p = Peak price of electricity (selling price)

P_{op} = Off peak price of electricity (buying price)

If we assume that the OM costs are the same in both cases and that both plant have access to 10MWh of waste heat then we get the same level of profit if:

$$\frac{P_p}{P_{op}} = \frac{\eta_{\text{LA}_g}}{\eta_{\text{ORC}} \cdot \eta_{\text{LA}_s} \cdot \left(\frac{\eta_{\text{LA}_g}}{\eta_{\text{ORC}}} - 1 \right)}$$

For :

$$\eta_{\text{LA}_g} = 0.5$$

$$\eta_{\text{ORC}} = 0.1$$

$$\eta_{\text{LA}_s} = 0.5$$

we get:

$$\frac{P_p}{P_{op}} = 2.5$$

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Chapter 6 Liquid air production and cost

1. The industrial gases industry in the UK

2. The cost of producing liquid air

3. Conclusions

Liquid air is not produced commercially today since demand is for the individual components of air: oxygen, nitrogen and argon. Small quantities of liquid air are used in niche applications such as cryotherapy, but this is supplied as 'synthetic' liquid air - liquid oxygen and nitrogen that have been produced separately and then blended in a ratio of 20:80.¹

The industrial gases industry in the UK sells 9,000 tonnes per day (tpd) of oxygen (gas and liquid) and 8,000tpd of nitrogen. However, Air Separation Units inevitably produce excess nitrogen, because there is four times as much nitrogen as oxygen in the atmosphere but much less demand for it commercially. Spiritus Consulting estimates conservatively that excess nitrogen production capacity in the UK amounts to at least 8,500tpd, and this gas is currently vented to the atmosphere (the glut would be even larger but for the fact that producers adopt various measures to optimize the oxygen output of their ASUs). The thermo-physical properties of air and nitrogen are similar, and either could serve as a cryogenic energy vector. In the early stages of a liquid air economy, therefore, waste nitrogen gas could be liquefied to use in place of liquid air (see chapter 2 section 4). If the entire estimated daily nitrogen surplus was used for this purpose, it could absorb 4.6GWh² of 'wrong time' wind generation and, at 60% round trip efficiency, deliver 2.8GWh back to the grid, enough to power the equivalent of 310,000 households.³ Alternatively it could potentially fuel the equivalent of 6.5 million car kilometers daily.⁴

Producing liquid air directly - as opposed to synthetically - would be simpler and cheaper than producing liquid oxygen and nitrogen, since the gases need not be separated. Air liquefaction can be achieved with less equipment required to separate oxygen and nitrogen, and consumes about a fifth less energy. We calculate that current production costs are between 3p and 4.5p per kilogramme, but there is potential to reduce these costs by almost half through measures such as co-locating production with LNG terminals. The delivered cost, after distribution by road tanker, would be roughly double, but local production at refueling stations would eliminate this cost.

The industrial gases industry in the UK

Industrial gases were first manufactured in the UK in 1886 by the Brin brothers who produced oxygen using a high temperature barium oxide process. The main application for gaseous oxygen at that time was to generate 'limelight' for theatres. In 1903, a major market emerged with the development of the oxygen acetylene cutting and welding process, and at about the same time Carl Von Linde devised the cryogenic production process described in chapter 2 section 2. The industry developed significantly during both World Wars, as huge

quantities of oxygen were required for cutting and welding to produce ships, tanks and other machinery.

In the 1950's rising demand for cars, white goods and other consumer items significantly increased the demand for industrial gases, and plants capable of producing 50 - 100tpd of oxygen became the norm. In the 1960s, improvements in the steel production process continued apace, further increasing the demand for oxygen, and by the mid 1970's plants capable of producing 750 - 1,000tpd

Chapter 6 Liquid air production and cost

were supplying British Steel through pipelines linked directly to blast furnaces.

Through many decades of operational experience the industry has developed an enviable record for reliability, where plant on line times of over 99.5% are not uncommon, and typically maintenance intervals are once every five years. This reliability coupled with modern process control systems means the plants can be operated with a minimum of manning, usually on day shifts only.

Production levels

For every tonne of oxygen produced about 3 tonnes of nitrogen and small amounts of argon are co-produced, and throughout the 1970's and 80's new uses for these gases were found in food freezing, electronics, welding, metal finishing and safety at chemical plants. However, there is still insufficient demand for all the nitrogen produced, meaning an estimated 8,500tpd is vented to the atmosphere. Today the UK industry supplies:

	tpd
Pipeline oxygen	8,000
Pipeline nitrogen	4,200
Liquid oxygen	1,100
Liquid nitrogen	3,800
Liquid argon	360
Est. nitrogen vented	8,500

Table 6.1: UK industrial gas sales. Source: Spiritus Consulting

Major production sites

The biggest users of industrial gases are steel producers, chemical plants and general manufacturing, and the location of industrial gas production sites reflects this, as shown in Figure 6.1. The production facilities at Teesside, Manchester, Sheffield, Margam, Hull and Fawley supply customers with gas products by pipeline and co-produce liquids for distribution by road tanker; this combination is the economic ideal for industrial gas companies. The sites at Motherwell, Thame and Didcott produce liquids only, because of the historical decline in industrial (pipeline) customers in those areas. The only area of the country that is not well served by a local industrial gases production site is East London, for the same reason. This area is supplied from Thame, Didcott and Fawley.

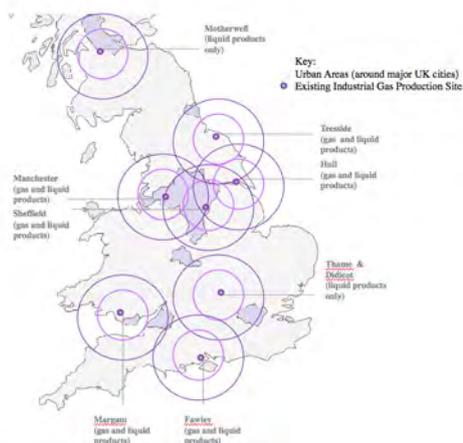


Figure 6.1. Map of major UK industrial gas production sites. Each site is marked with a 50 and 100 mile radius to indicate potential delivery catchment area.

The industrial gases industry in the UK has developed over the last century, and almost all of the country is within easy delivery distance of one of its production sites.

Air Separation Unit operations

Pipeline customers require product 24 hours a day so, by definition, gas production at plants such as Teesside, Hull and Fawley runs continuously. However, it requires around twice as much power to produce liquids as it does gases, so liquids production is typically operated when electricity prices are lowest - overnight and at weekends. Power management is a major feature of any gas company operation, and during peak periods in the winter months they work with energy suppliers to help balance the national grid. Over the course of a year, industrial gas producers consume about 3% of the entire UK electricity supply.

It is possible that ASUs may be managed even more actively in future. With modern control systems, plants producing 800 - 1,000tpd of liquid can be started, at the push of a button, in 45 minutes without affecting supplies to the pipeline customer. They can also operate at anywhere between 50% and 100% capacity with no loss of product purity, although there is some reduction in efficiency. An ASU running at 50% can be brought up to full load in four to six hours; a plant running at 80% in about two hours. These lead times coincide quite well with the horizons of short term wind forecasting.

To minimise operating costs and maximise the benefits of low cost electricity, industrial gas companies have oversized their liquid production facilities so that all the customer demand can be met by producing only during off - peak periods. So while sales of liquid nitrogen are currently ~3,800tpd, output could be doubled to ~6,500tpd with no

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For every tonne of oxygen produced, up to 3.5 tonnes of nitrogen is produced as a co-product for which there is far less commercial demand. Spiritus Consulting estimates that ~8,500 tonnes of nitrogen is vented daily, which could be liquefied and used as an energy vector.

additional investment - although this would mean producing liquids at peak periods when electricity is much more expensive.

However, there is another source of surplus nitrogen which could be regarded as virtually 'free'. Because of the ratio of oxygen and nitrogen in the atmosphere, for every tonne of oxygen produced, between 3 and 3.5 tonnes of nitrogen is produced as a co-product for which there is far less commercial demand. At present, Spiritus Consulting estimates that ~8,500 tonnes of nitrogen is vented daily, mainly at Teesside, Carrington, and Scunthorpe, Hull and Margam. A more accurate figure could only be developed with access to individual plants and their associated commercial contracts.

If this nitrogen surplus were to be used as an energy vector, then additional liquefaction plant, storage and generating equipment would be required. The sites at Teesside, Scunthorpe and Margam have land that could be used to site additional equipment, but clearly the detail would have to be agreed with individual gas producers. Land may also be available on other sites but this would require detailed investigation to determine potential suitability.

The liquefaction of the surplus nitrogen gas would cost considerably less in capital than an air liquefaction facility built from scratch, since the air would have already been cleaned and all impurities including carbon dioxide and hydrocarbons removed.

2. The cost of producing liquid air

There are three main elements to the cost of producing liquid air: the capital cost of the plant, the energy required to run it and operation and maintenance costs.

The first liquid air production plant would probably be built by converting a nitrogen cycle liquefier for use with liquid air and adding air drying and purification systems. This equipment is mature and well understood. The cost of an installed plant at a level site with grid connection, including two years' worth of spare parts, is likely to be:

- £10,220,000 for a 300T/day unit⁵
- £15,432,200 for a 600T/day unit⁶

An order for multiple or significantly larger plants would be cheaper as plants typically

scale by the 6/10 rule: a plant twice the size costs about 1.5 times as much. Storage costs for a vacuum insulated storage tank are of the order £1,500,000 for 1,000 tonnes.

The main input required to produce liquid air is electricity. According to a 2010 EIGA position paper⁷ the energy requirement to produce liquid nitrogen is 0.549MWh/T. According to Messer Group about 20% of this energy is used for separation, meaning that to liquefy air consumes around 0.44MWh/T. A larger plant would benefit from efficiency improvements and process optimisation, and a reduction in energy consumption of less than 10% would deliver air liquefaction at 0.4MWh/T.

Operation and maintenance (O&M) costs typically amount to between 1.5% and 3% of the plant purchase price per annum. That is equivalent to:

- £153,300 - £306,600 per annum for a 300T/day unit
- £231,500 to £463,000 per annum for a 600T/day unit

The main maintenance event is a two week shut down every five years, although there is also a brief shut down for inspection every year.

Production cost per tonne

To calculate the annual repayments required to finance each plant we need to make assumptions about the finance period and discount rate. We assume a finance period of 20 years, and discount rates of 6% and 9%, giving annual repayments of between about £1 million and £1.9m.

	300T/day plant		600T/day plant	
Plant cost	£10,220,000		£15,432,000	
Storage cost	£750,000		£1,500,000	
Total cost	£10,970,000		£16,932,000	
Finance period (years)	20		20	
Interest rate	6%	9%	6%	9%
Annual payment	£956,415	£1,201,725	£1,476,209	£1,854,841

Table 6.2: Capital costs at discount rates of 6% and 9%

The contribution of the capital component to the price of liquid air depends entirely on the usage pattern of the plant and production volumes at different load factors. These impacts are shown in Table 6.3. This element

Chapter 6 Liquid air production and cost

of costs could be eliminated altogether if using existing production plants with spare capacity that has already been paid for.

	300T/day (6%)	300T/day (9%)	600T/day (6%)	600T/day (9%)
Max annual capability	109,500 T		219,000 T	
Price contribution at 100% capacity	£8.73/T	£10.98/T	£6.74/T	£8.47/T
Price contribution at 75% capacity	£11.65/T	£14.63/T	£8.99/T	£11.29/T

Table 6.3: Capital costs at load factors of 100% and 75%

Under DECC guidelines these plants would qualify as large or very large users of electricity, for whom power prices including Climate Change Levy have averaged £73/MWh in recent months.⁸ On the basis of these prices, the energy costs of liquid air production for each plant are shown in Table 6.4.

	300T/day plant	600T/day plant
Energy consumption	0.44MWh/T	0.4MWh/T
Energy price	£73/MWh	£73/MWh
Energy cost per tonne	£32.12/T	£29.20/T

Table 6.4: Energy costs of liquid air production

In practice, plant operators would achieve lower effective energy prices through participation in the balancing market, co-location with generation to avoid Transmission and Distribution charges, Triad avoidance and off-peak operation. They would also typically operate multiple plants meaning they could negotiate lower prices for electricity. As an indication of the possible importance of these factors, energy costs based on a price of £55/MWh are shown in Table 6.5.

	300T	600T
Energy consumption	0.44MWh/T	0.4MWh/T
Energy price	£55/MWh	£55/MWh
Energy cost per tonne	£24.20/T	£22.00/T

Table 6.5: Energy costs of liquid air production at finer electricity prices

Operating and maintenance costs are very closely related to the operating regime and maintenance schedule of the plant. However, by using the rules of thumb identified above, the effective O&M costs can be calculated on an effective per tonne basis for the high and low production rates. The averages have been calculated to give indicative values for the contribution of this component to production costs of liquid air.

	300T	600T
Full loading (1.5%)	£1.40/T	£1.06/T
Full loading (3%)	£2.80/T	£2.11/T
Average	£2.10/T	£1.59/T
75% loading (1.5%)	£1.87/T	£1.41/T
75% loading (3%)	£3.73/T	£2.82/T
Average	£2.80/T	£2.11/T

Table 6.6: Effective O&M costs per tonne of liquid air

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Liquid air could be produced for between 2p and 4.5p per kilogramme, but costs could be halved again if production exploited the waste cold from LNG re-gasification at UK import terminals.

Total cost of production

From these workings above we can now calculate total costs for liquid air production under eight scenarios:

	300T @100%	300T @75%	600T @100%	600T @75%
Capital cost	£8.73	£11.65	£6.74	£8.99
Energy cost	£32.12	£24.20	£29.20	£22.00
O&M cost	£2.10	£2.80	£1.59	£2.11
Total cost	£42.95	£38.65	£37.53	£33.10

Table 6.7: Total liquid air production costs at 6% discount rate

These numbers suggest that the total cost of production of liquid air including construction of the plant and interest at 6% is between £33 and £43/Tonne, or roughly 3-4p/kg, and the marginal cost of production from a pre-existing plant is likely to be in the range of £22-32/Tonne, or 2-3p/kg.

	300T @100%	300T @75%	600T @100%	600T @75%
Capital cost	£10.98	£14.63	£8.47	£11.29
Energy cost	£32.12	£24.20	£29.20	£22.00
O&M cost	£2.10	£2.80	£1.59	£2.11
Total cost	£45.20	£41.63	£39.26	£35.40

Table 6.8: Total liquid air production costs at 9% discount rate

With a 9% interest rate, liquid air production costs including capital and interest is between £35 and £45/tonne, or 3.5 to 4.5p/kg.

Future cost reduction potential

There may be scope to reduce capital costs in future through the following methods:

- Integration with an existing ASU, when the only requirement would be an additional nitrogen liquefier, since the gas would already have been cleaned and dried.
- Paying some portion of the plant capital cost with other services such as energy storage or high value industrial gas production.

Industry evidence suggests capital costs can reduce with volume orders or repeat production, and a cost down learning curve of 17.5% for is a recognised industry average. The experience of comparable plant - for instance the Combined Cycle Gas Turbines constructed in the first 'dash for gas' in the 1990s - suggests that cost reductions of 20% or higher may be possible through repeat orders and learning effects. The impact of this at 20% is shown in the table below for the 6% and 9% interest rates. However, since capital costs are small relative to energy costs, this has a limited effect and final product prices remain around ~3.1 to 4.3p/kg.

	300T @100%	300T @75%	600T @100%	600T @75%
Capital cost	£7.11	£9.48	£5.51	£7.35
Energy cost	£32.12	£24.20	£29.20	£22.00
O&M cost	£2.10	£2.80	£1.59	£2.11
Total cost	£41.33	£36.48	£36.30	£31.46

Table 6.9: Impact of reduced capital costs on total costs at 6% discount rate

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	300T @100%	300T @75%	600T @100%	600T @75%
Capital cost	£8.93	£11.91	£6.93	£9.23
Energy cost	£32.12	£24.20	£29.20	£22.00
O&M cost	£2.10	£2.80	£1.59	£2.11
Total cost	£43.15	£38.91	£37.72	£33.41

Table 6.10: Impact of reduced capital costs on total costs at 9% discount rate

There may be further opportunities to reduce energy costs and liquid air prices in the longer term including:

- Co-location with generation to avoid electricity grid use of system charges.
- Provision of additional energy market services.
- Process optimisation leading to potential efficiency improvements and cycle development in the longer term.

Perhaps the most promising means of cutting the cost of liquid air would be to exploit the 'free' cold from LNG re-gasification terminals (see chapter 3 section 3) during liquid air production. This would reduce the electricity required for air liquefaction by about 60% to 0.165MWh/tonne. The cost impacts of this reduction in energy consumption are shown in the tables below for the larger 600T/day plant only, since LNG regasification cold sources tend to be very large. The effect is dramatic, roughly halving production costs to ~1.6 to 2.1p/kg.

	600T @100%	600T @75%
Capital cost	£5.51	£7.35
Energy cost	£12.05	£9.08
O&M cost	£1.59	£2.11
Total cost	£19.15	£16.18

Table 6.11: Impact of reduced energy consumption for reduced capital cost scenario at 6% discount rate

	600T @100%	600T @75%
Capital cost	£6.93	£9.23
Energy cost	£12.05	£9.08
O&M cost	£1.59	£2.11
Total cost	£20.57	£20.42

Table 6.12: Impact of reduced energy consumption for reduced capital cost scenario at 9% discount rate

Distribution costs and consumer prices

It is a rule of thumb among industrial gas companies that distribution accounts for roughly 40-50% of total cost, or put another way, the delivered cost will be almost double the cost of production. However, commercial experience gained by liquid air technology developers also suggests there may be considerable flexibility in the application of this 'rule'. Nevertheless, if we simply double the production costs, the results for three scenarios are shown in Table 6.13.

	Highest cost LIN	Lower cost LIN	LNG LIN
Pence/kg	3.3 - 4.5	3.2 - 4.3	1.6 - 2.1
Pence/litre	2.4 - 3.6	2.6 - 3.5	1.3 - 1.7
Delivered cost/litre	4.8 - 7.2	5.0 - 7.0	2.6 - 3.4

Table 6.13: Delivered cost of liquid nitrogen

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The fuel costs of a Dearman Engine car are lower than those of a petrol car of average fuel economy in all but one scenario. The running costs of an EV are lower still but this should be seen in the context of much higher capital costs.

In the transport context, onsite production of liquid air at refuelling stations would be economic at higher volumes, and this would eliminate distribution costs. However this would not be possible with liquid nitrogen produced using LNG cold, since this is restricted to a few locations. Table 6.13 provides a range of potential price assumptions for liquid air or nitrogen 'at the pump', which we use to calculate fuel costs per kilometre in Table 6.14 and Figure 6.2. In all but one scenario the per-kilometre fuel costs are lower for a Dearman engine car than for a petrol car of average UK fuel economy.⁹ The running costs of an EV are lower still, but these should be seen in the context of much higher capital costs; the Nissan Leaf costs £26,000 even after a government grant of £5,000, around twice the price of an equivalent sized ICE. A Dearman car would have similar capital costs to an ICE in the early stages of production, and probably lower in the longer term since the engine can be produced from much lighter materials (chapters 2 and 8).

	DE, high cost LIN Delivered	DE, low cost LIN Delivered	DE, High Cost LIN Local	DE low-cost LIN local/ LNG LIN Delivered	ICE Petrol	Nissan Leaf (for litres read kWh)
Pence per litre	7.2	5	3.6	2.5	130	13
Litres/km	1.6	1.6	1.6	1.6	0.075	0.13
Pence per km	11.7	8.1	5.9	4.1	9.8	1.7

Table 6.14: Cost per kilometre of Dearman engine car compared to ICE and EV¹⁰

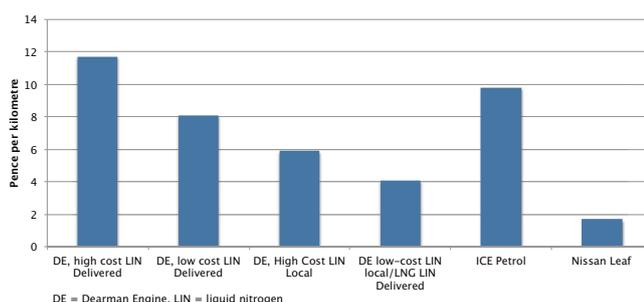


Figure 6.2: Cost per kilometer of Dearman engine car compared to ICE and EV

The low energy density of liquid air and high volumes required would tend to restrict the on-road use of the Dearman engine as a prime mover to urban settings. The case for liquid air or nitrogen as a secondary or hybrid fuel for long distance, refrigeration and other applications is explored in chapters 4 and 10, and prices within the range discussed earlier are likely to support it.

3. Conclusions.

From the discussion presented above we conclude:

- The industrial gases industry and its production technology are extremely mature.
- There exists an estimated 8,500tpd surplus of gaseous nitrogen that could be liquefied for use as an energy vector in transport and other applications. This could be used to absorb almost 4.7GWh¹¹ of 'wrong time' wind generation or fuel the equivalent of 6.5 million car kilometers daily.
- The costs of producing liquid air from newly built plant are estimated to be reasonable, and amenable to substantial reduction by measures such as co-location with LNG terminals.
- The likely costs of liquid air mean it is likely to be competitive – and perhaps highly competitive – with fossil fuels in a range of transport and other applications.

Chapter 6 Endnotes

¹<http://www.morsowanie.info/morsowanieinfo-in-english/103-types-of-cryochambers>

²Nitrogen liquefaction requires 549kWh/tonne (European Industrial Gases Association (EIGA), December 2010). 8,500 tonnes x 0.55MWh = 4,675MWh.

³2.8GWh x 365 = 1,022GWh per year, or 1,022,000,000kWh. Average annual household electricity consumption is 3,300kWh. (<http://www.ofgem.gov.uk/Media/FactSheets/Documents1/domestic%20energy%20consump%20fig%20FS.pdf>); 1,022,000,000 / 3,300 = 309,696.

⁴We assume a small car has an energy requirement of 0.13kWh/km, on the basis that the Nissan Leaf has a 24kWh battery and range of 175km (24/175 = 0.13). At a practical energy density of 0.1kWh/kg this translates to a requirement of 1.3kg of liquid air per km for a liquid air prime mover, and 1.04kg/km for one operating with the benefit of waste heat from an ICE engine. The UK could produce 8,500T (8.5 million kg) per day of additional liquid nitrogen. At 1.3kg/km this would equate to 6.5m car kilometres, increasing to more than 8m car kilometres with waste heat. Cf http://www.nissan.co.uk/?cid=ps-63_296991&gclid=CIX476ulyrUCFcbKtAodfw0AbA#vehicles/electric-vehicles/electric-leaf/leaf/pricing-and-specifications/brochure.

⁵*Feasibility, costs and economics of a 300 MT/d and 600 MT/d Air Liquefier*, Turnbull Smith Project Services Ltd report for Highview Power Storage, unpublished, July 2010.

⁶Based on a scaling rule of 0.6, i.e. a plant that is twice the size of the 300T unit would cost $2^{0.6}$ times more = 1.51 times.

⁷*Indirect CO₂ emissions compensation: Benchmark proposal for Air Separation Plants*, European Industrial Gases Association (EIGA), position paper #33, December 2010, http://eiga.org/fileadmin/docs_pubs/PP-33-Indirect_CO2_emissions_compensation_Benchmark_proposal_for_Air_Separation_Plants.pdf

⁸*Energy Price Statistics*, Department of Energy and Climate Change, October 2012 Update.

⁹Average UK ICE fuel economy is 38MPG or 7.5L/100km, <http://www.fuel-economy.co.uk/calc.shtml>

¹⁰Average UK ICE fuel economy is 38MPG or 7.5L/100km, <http://www.fuel-economy.co.uk/calc.shtml>, and the Nissan Leaf has a 24kWh battery and claimed range of 175km, http://www.nissan.co.uk/?cid=ps-63_296991&gclid=CIX476ulyrUCFcbKtAodfw0AbA#vehicles/electric-vehicles/electric-leaf/leaf/pricing-and-specifications/brochure

¹¹Nitrogen liquefaction requires 549kWh/tonne (European Industrial Gases Association (EIGA), December 2010). 8500 tonnes x 0.55MWh = 4,675MWh.

Chapter 7 Infrastructure

1. Existing distribution infrastructure

2. Future transport fuel distribution requirements

3. Conclusions

The emergence of a liquid air or 'nitrogen economy', in which cryogenic liquids are widely used as an energy vector in transport and small-scale electricity generation, would require an extensive distribution network. It is one of the strengths of liquid air compared to some other potential energy vectors that this requirement is already broadly satisfied; thousands of tonnes of liquid oxygen and nitrogen are already distributed across the country every day. In this chapter we describe the existing cryogenic liquids distribution network and assess its ability to support an emerging liquid air economy. We find that the existing distribution system has ample capacity in the short to medium term.

1. Existing distribution infrastructure

The industrial gases industry supplies customers across the UK in a number of ways, the choice being determined by technical factors such as volume, pressure, flow rate and purity:

- **Cylinders** are normally used when customers need small volumes of gas at high pressure. Cylinders can be delivered by the supplier or picked up by the customer from some 600 outlets around the country.
- **Liquid deliveries (Bulk Gas Supply)** are normally used when customers require between 0.25 and 5 tonnes per day. A vacuum insulated storage tank is installed at the customer's site, which is filled by road tanker as required. The customer can also opt for a network-connected level measure on the tank which automatically re-orders product as necessary.
- When the customer needs to use the product as a gas, the liquid is pumped through a vaporiser where it is brought up to ambient temperature and delivered at the required flow rate. At present the energy released by this expansion is not exploited, but in principle it could be used to drive a small cryogenic motor such as the Dearman Engine to generate 'free' electricity. We estimate there are around

1,100 larger industrial gas users with tanks of 15 tonnes or bigger that could benefit from this idea.

- **Liquid supplies (Mini-Bulk Supply)** are suitable for customers who require small amounts of cryogenic liquid such as hospitals and laboratories. A small tank of 200 - 1,000 litres is installed on site, and refilled from small delivery vehicles with a maximum capacity of 5 tonnes.
- **Onsite or pipeline supply** is used by customers who need oxygen and/or nitrogen in volumes ranging from 5 - 2,000tpd. This can be supplied either by pipeline from the gas company's site to the customer, or produced by a plant installed at the customer's site; all the gas suppliers have extensive portfolios of production plants to meet any combination of flows and pressures. Ideally the gas companies would prefer to build a production facility on their own site and send gas by pipeline to the customer, because this allows them to co-produce liquid products to distribute to other customers by road tanker (the 'merchant' market).

All the industrial gas production sites listed in chapter 6 and Figure 7.1 on page 84 will keep 2-4 days liquid storage. The actual volume will be set based on the liquid back-up required by

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the pipeline (gas) customers, and the number of liquid customers in the catchment area. Some sites may have additional storage left over from a previous pipeline contract. The risk to customers in the event of a plant failure is minimised by the fact that:

- The distance between the various production sites is such that in an emergency customers can be supplied from a site outside their optimum location.
- Gas companies can pick up product from a competitor's site.
- In a medical or safety related emergency a gas company will supply a competitor customer on a short term basis.

In some cases gas companies will rationalise their production facilities and replace any shortfall by sourcing from a competitor's site as a permanent arrangement. This practice is well established in the petroleum and diesel industry where, for example, all fuel supplied into the south and south west of England is likely to have been supplied from the Esso refinery at Fawley.

The level of storage on production sites is highly *unlikely* to be sufficient to provide liquid nitrogen for regular use as an energy vector. The supply chain is very short for liquids, and in almost all cases the product is essential for the customer's business. In chemical plants it is also vital for safety purposes. If the decision were taken to install liquid air or liquid nitrogen power generation equipment at an industrial gases production site additional storage capacity would be required.

There are 5,500-6,000 storage tanks on customer sites, with capacities ranging 3 to 60 tonnes. The size of a customer storage tank is determined by a number of factors such as daily usage, distance from production sites, vehicle access, safety and the level of product security required.

These tanks are serviced by a fleet of about 400 tankers with carrying capacities of 5-22 tonnes, which is the maximum payload that can be delivered under current UK road regulations. The maximum delivery distance from a production site will be in the region of 100 miles with the average being in the range 20-50 miles. There are a few exceptions to this, one example being a delivery from Fawley to the east side of London. Typically a driver will make two to five deliveries in a shift. Most of the deliveries are done on a two shift system, night deliveries being restricted

by customer access hours and in some cases noise. The logistics, driver and transport engineering standards used by the gas companies are almost identical to those used in the petroleum industry. The transport and logistics part of the industrial gases business has, in common with the production facilities, an excellent safety record (chapter 9).

The population of storage tanks is serviced by a network of regionally based project and service engineers whose main roles include site surveys, installation, maintenance and responding to customer emergencies. The installation work undertaken by these teams includes applications and end use equipment, electricians and control systems as well as the storage tanks. All the gas companies have centrally based 'tank farms' (where customer storage tanks are refurbished) and a stock of tanks to enable them to respond quickly to customer requirements.

The current network of production locations, distribution centres, vehicle fleets and customer service engineers provides good geographical coverage and could certainly be used and adapted to support the introduction of liquid nitrogen or liquid air as an energy vector.

Figure 7.1 shows the location of the major UK industrial gas production sites and LNG terminals where liquid air could be produced extremely cheaply by exploiting the cold from LNG regasification (see chapter 3 section 3). Each site is marked with a 50 and 100 mile radius to indicate its potential delivery catchment area. The map also shows the location of major logistics warehouses, haulage depots and supermarket distribution centres, which could be among the earliest bulk users of liquid air in transport, particularly for refrigerated food distribution. It is clearly shown that almost all such potential users fall within the catchment areas of one or more existing or potential liquid air production sites.

The industrial gas companies have an estimated surplus of 8,500 tonnes per day of gaseous nitrogen available for liquefaction, which, for illustration, could fuel the equivalent of 6.5 million car kilometers daily.¹ If all the cold available from British LNG import terminals were used to assist air liquefaction, it could produce enough cryogen to fuel the equivalent of a further 45million daily car kilometres, equivalent to 4.2% of the daily distance driven by cars in Great Britain in 2011.²

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The existing distribution network for cryogenic liquids provides good geographical coverage and could certainly be used to support the introduction of liquid air or nitrogen as an energy vector.

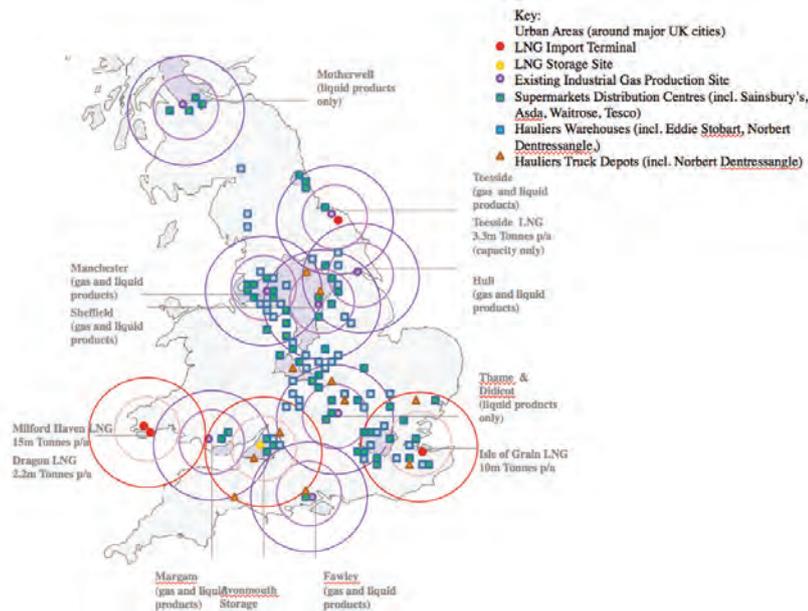


Figure 7.1: Potential liquid air suppliers and users

2. Future transport fuel infrastructure requirements

Liquid air or liquid nitrogen could be used as a “fuel” in a number of transport or mobile applications, as explored in chapter 4. The characteristics of liquid air and the heat engines that run on it determine the most suitable transport applications for the technology, and these in turn determine the refuelling/infrastructure requirements. To date there has been very little deep analysis of the economics of distribution of liquid air or nitrogen as a fuel, although its distribution for process industries is well known and described in section 1 above. For this reason we have developed a qualitative narrative based on lessons from the distribution of process-industry liquid nitrogen, and from other new fuels such as hydrogen and liquefied natural gas (LNG).

Liquid air applications and refuelling models

The most attractive applications for liquid air in transport are defined by the characteristics of liquid air heat-engines and their fuel, as explored in chapter 4. These factors govern the type of vehicles that might use liquid air or nitrogen as either a primary fuel or secondary fuel, and hence their refuelling needs:

- On-site applications:** as we found in chapter 4, potential on-site applications could include prime-movers (the main engine) for fork-lift trucks and other industrial equipment; mining equipment where safety is an important consideration; and short-range marine craft.
- Return-to-base applications:** chapter 4 identified a number of these, either as prime movers, or as waste heat recovery devices that increase the efficiency of conventionally powered vehicles, especially where a cooling load can be integrated into the cycle. Analysis by the Dearman Engine Company and E4tech has shown that buses with air-conditioning and refrigerated delivery lorries are the most promising initial applications.
- Long-haul applications:** In this category, the relatively high fuel consumption of the liquid air heat engine limits its use. It is more likely that the cryogen would be used in an advanced internal-combustion concept such as the Ricardo split-cycle engine, applied to long-haul trucks, locomotives or shipping (chapter 4).

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Each type of application has its own fuelling needs, which are explored below.

On-site industrial applications

Zero-emission prime movers such as fork-lift trucks would require a supply of cryogen to a refuelling point, either by regular delivery or on-site production. To place the fuelling requirement in context, initial estimates by Dearman and E4tech suggest that an indoor fork-lift of the type commonly powered by battery today, of 20kW peak power and 5kW mean load factor, would use around 120 tonnes of liquid nitrogen per year if operated for 12 hours per day and five days per week. However, the same fork-lift would use just 10 tonnes per year (200kg/week) if used for around an hour a day. The options for meeting this range of needs for a small fleet of equipment are:

- **Regular delivery:** Industrial equipment is likely to be found on industrial estates where there is already a regular delivery of liquid nitrogen for purposes such as engineering and food processing. It would appear logical that these cryogen-fuelled prime movers would be fuelled by extension of the local liquid nitrogen supply, as this yields economy of scale and requires a minimum of new equipment or training. However, the existing high-value industrial processes may use relatively small quantities of liquid nitrogen, in which case the market tolerates a much higher price-point, typically 10p/kg or more. Robust viability as a 'fuel' in high utilisation applications requires a lower price, of 5p/kg or less, which is only realised in the highest volumes of supply. To put this in context, a single, low utilisation vehicle requiring a 200kg weekly delivery offers a fuel value of just £10-20 per delivery with this price range. The challenge for the cryogen supplier is to secure a profitable balance between increased market volume and potentially lower price per unit of liquid nitrogen. However, at a site with five or more forklift trucks, a small liquid air or nitrogen tank would be economic, and would fit exactly with the operating model of industrial gas suppliers. If a cryogenic engine is required for safety reasons - such as indoor operation - then it would be less sensitive to the price of liquid air.

- **On-site production:** Hydrogen fuel is often produced on-site, so it is worth considering the case for doing the same with liquid air or nitrogen. However, liquid nitrogen can be transported as a liquid at higher temperatures than hydrogen; is a larger molecule and therefore less prone to leak and presents no fire or explosion hazard. It is, therefore, easier to transport - apart from the fact that more energy is required to deliver each unit of energy - and benefits from a mature distribution network covering the industrialised world. Taken together these factors start to erode the case for small-scale, on-site production of liquid air or nitrogen.

Air and nitrogen are also harder to liquefy at small scale because of the characteristics of the Joule-Thompson Cycle. This process has an ideal coefficient of performance - heat extracted per unit of work input - of just 34%, and in practice this number is challenging to approach. This efficiency tends to fall even further at lower production volumes due to the inefficiency of small turbo-compressors. By contrast, the ideal efficiency is easier to approach at large scale, and in this type of centralised plant synergies with hot and cold fluid streams in other industrial processes can be realised to further improve efficiency, as can energy storage or buffering principles (chapter 2). Although liquefaction equipment is available in almost any size, existing markets have tended to focus on liquefiers that produce either:

- Very small amounts of cryogen - a few kilogrammes per day for a laboratory, for instance - and in these quantities the efficiency of the process is irrelevant and has not been the subject of much development; or,
- Larger quantities of cryogen - 100 to 1,000 tonnes per day, for example, for industrial applications - where the plant is most efficient at the upper end of this range, and may require around 30% more energy per unit of cryogen at the lower end.

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There is currently a lack of mature technology for highly efficient localised production in volumes suitable for small fleets of vehicles, of the order of 1 tonne/day. A contemporary unit of this size has an electric energy consumption of around 1.6kWh per kg of liquid nitrogen produced³, whereas the largest plants (1,000 tonnes/day) consume just 0.4kWh/kg. For this reason, it is likely that delivery from a central production site will remain the preferred option for liquid air and nitrogen – in contrast to hydrogen. For orders of 1 tonne/day the industrial gas companies will always want to ensure that a liquid delivery is the most economic way to supply and will price accordingly.

On-site mining applications

Mining applications would differ significantly from the light industrial requirement described on previous pages because:

- The power and utilisation levels would both be higher, indicating a higher fuel demand;
- The asphyxiation risk presented by using large quantities of liquid nitrogen underground means mining equipment powered by a cryogenic engine would almost certainly run on liquid air;
- For mining in remote locations, tanker supply of liquid cryogen may be challenging and expensive. Some large mines in Africa and South America already have their own air separation units, but no mines in the UK do.

These factors may suggest a preference for local manufacture of liquid air, which could also serve as a two-way buffer for the mine's main supply of electricity, thus relieving the peak loads on either grid supply or local generation. The economics of such a proposition would be very much application-dependent and have not been the subject of published study.

Return-to-base applications

Return-to-base vehicles such as city buses and goods delivery vehicles are seen as an attractive target for new fuels or energy vectors. This is mainly because they are able to use a single refuelling point at or near their operational base. However, another important factor is that these vehicles tend to have high public visibility and are often operated or licensed either by city authorities with an environmental agenda, or by companies with a desire to meet social responsibility targets and promote a 'green' image. These factors combine to improve the business case and have been the subject of much study for hydrogen and electricity as transport fuels.

One promising application described in chapter 4 is the combination of an ICE and liquid air engine for heat recovery. Some initial analysis performed by Dearman and E4tech based on a city bus has indicated a 12-hour shift would consume around 200-300kg of liquid nitrogen, around 4-6 times the diesel requirement by weight. This indicates a daily requirement of 2-5 tonnes of liquid nitrogen for a small fleet of ten vehicles, depending on whether day-only or 24-hour operation is assumed and 20-50 tonnes for a 100-vehicle fleet. The upper extreme of these volumes is approaching the range in which mature industrial liquefaction technologies are available. Dearman estimates that a 100 tonne/day plant would have a capital cost of around £5m, compared for illustration to around £10m for 100 standard buses and £5m annual diesel costs (100 hybrid buses would cost around £25m). At this level of demand local production could be justified, especially if it could be matched to local grid management needs.

However, this level of demand could equally well be supplied by a cryogenic tanker making one or more daily deliveries. Centralised liquid air or nitrogen production will always be more efficient than local production and the industrial gases companies would prefer to install storage tanks at bus depots and supply them by tanker. Operationally this would not be difficult, since they have fleets of vehicles of different sizes which can operate in inner cities, and frequently deliver at night to avoid congestion.

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Long-haul applications

Heavy duty, long-haul applications such as trucks, diesel locomotives and ships tend to make the best business case for exhaust heat recovery, due to the high and relatively constant engine load factors imposed by their duty cycles. In these applications a supplementary heat-engine such as the Dearman Engine can be effective at saving fuel, but the weight and cost of cryogen may weaken the case unless there is a specific need for refrigeration.

An alternative is the 'split cycle' engine proposed by Ricardo (chapters 2 and 4). This concept uses the cryogen to reduce the air compression losses of an internal combustion engine as a form of intercooling and allows internal recuperation of exhaust heat. The consumption of cryogen in weight terms is similar to that of diesel, so carrying cryogen on board and refuelling would be logistically possible. However, the concept can also generate its own cryogen on board via a small engine-driven liquefier. This device gives a theoretical efficiency gain in the steady-state, but is over-driven during deceleration as a form of regenerative braking for greater system efficiency gain. The technology is too immature to assess the relative benefits of onboard liquefaction and external refuelling, but the quantities involved would require cryogen delivery logistics on a similar scale to those of truck diesel fuel. The benefit of this doubling of fuel delivery logistics would be a substantial reduction in fossil fuel use - Ricardo claims that up to 30% is possible. Again, there has not yet been any detailed study of the economics of cryogen supply for this application.

A final factor that could prove relevant in long-haul applications is the resurgent interest in liquefied natural gas (LNG) as a fuel. A number of factors are driving this:

- From the supply side, rising crude oil prices have coincided with the prospect of relatively cheap shale gas - already a reality in the US.
- On the demand side, the rising popularity of diesel cars in Europe and the requirement to remove sulphur from marine fuels have led to pressure on middle distillates, while growing awareness and potential regulation of environmental issues such as land-use change limits the likelihood of a substantial increase in bio-diesel use.
- Adaptation of a heavy duty engine to use LNG is relatively low in risk and cost compared to other alternatives and yields an immediate reduction in CO₂ emissions.

LNG is relevant because, like liquid air or nitrogen, it is a low temperature liquid. This means that:

- Some synergy in distribution and fuel stations may be possible, at least in terms of a shared need for insulation and maintenance of low temperatures; boil-off of liquid air or nitrogen - which is harmless if vented to an open atmosphere - can be used to maintain the more damaging LNG at low temperature.
- Similar synergies (insulation, boil-off) can be exploited in the vehicle's fuel tanks, while the evaporation of LNG supplied to the engine can be used either to keep liquid nitrogen cool or assist onboard liquefaction.

LNG is currently a niche fuel, with most vehicles having converted 'dual fuel' diesel engines which retain the use of diesel injection both as an ignition source and as a backup fuel supply should LNG be unavailable. However, engine manufacturers are known to be working on dedicated LNG engines in the truck sector, and products are already available for marine propulsion. So the synergies described above could become relevant, especially in the 2020-30 timeframe as demand for LNG transport fuel rises.

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The existing industrial gas distribution network is a promising starting-point for fork-lifts, refrigerated trucks and buses. Together these might represent a big enough market to stimulate further technology development.

Prospects for liquid air fuelling infrastructure

The discussion above has explored the refuelling options for liquid air and nitrogen in a number of potential scenarios. It is clear that the future of transport fuels itself will inevitably become more complex, with the traditional choices of gasoline, diesel and kerosene being supplemented or displaced by biofuels, natural gas, hydrogen and electricity. In this context, it is unlikely that liquid air will dominate or displace these, but there is a substantial case to be made for it finding a place alongside them in the right applications.

Building on the analysis presented in chapter 4 Table 7.1 provides an assessment of the potential for liquid air under four main scenarios, based on the characteristics of each transport application and the potential refuelling infrastructure. The colour of the cells indicates the relative risk presented by each factor, with green and indicating the lowest risk and orange the highest.

	Key success factor	Application type & possible fuel / engine option			
		On-site - Industrial	On-site - Mining	Return-to-base	Long-haul
		Heat engine prime mover; tanker delivery	Heat engine prime mover; on-site liquefaction	Waste heat recovery & cooling; tanker delivery	Split-cycle ICE; onboard liquefaction
Infrastructure	Quantity of fuel compatible with delivery or onsite production	Compatible if critical mass	Compatible	Compatible	May not be needed
	Maturity of fuel production & supply	Mature - industrial LN ₂	Immature (onsite)	Mature - industrial LN ₂	Immature (onboard)
	Other benefits	Fast safe refuelling	No explosion risk	Fast cooling possible	Air quality, brake wear
	Fuel risks	Cryo handling	Asphyxiation	Cryo handling	Cryo handling
Application	Economic attractiveness of liquid-nitrogen engine	Attractive for low utilisation	Not known	Attractive	Potentially attractive
	Maturity of liquid-nitrogen engine	Lab stage (TRL2-4 - Dearman)			Concept (TRL 1-2 - Ricardo)
	Lifecycle CO ₂ benefit	See text	See text	With de-carbonised grid	Yes, up to 30%

Table 7.1: Comparison of several liquid air transport applications by technology and refuelling options

This exercise exposes some interesting points. First the immaturity of liquid air engine technologies generally presents a greater risk to success than the availability of fuel, because the favoured applications in the table do not require a widespread new fuelling infrastructure (those applications were selected because they were suited to liquid-air engines, not because they required no new infrastructure). Second, the existing industrial cryogenic gas distribution network is a promising starting-point for at least two types of application and three specific vehicle types - fork-lifts, refrigerated trucks (see also

chapter 10), and buses - and between them these might represent a sufficient market to stimulate further technology development. And third, every application sees other benefits from a move to cryogenic fuels: fast, safe refuelling of fork-lifts; fire-safe fuels; the ability of the cryogen to deliver rapid temperature reduction in refrigerated vehicles; the possibility of using injected nitrogen as a NO_x suppressant in diesel engines; and the potential to use over-driven onboard liquefaction as a form of regenerative braking.

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3. Conclusions

On the basis of the discussion presented above, we conclude:

- There exists already a well-established distribution network for cryogenic fluids in the UK and across the industrialised world.
- Surplus production capacity in liquid nitrogen (chapter 6) and the existing distribution network are more than adequate to supply the short to medium term fuel needs of an emerging 'nitrogen economy'.
- Specifically, the existing distribution infrastructure is more than adequate to supply the early development of on-site, return to base and some long-haul transport applications.
- In the longer term, a mix of local production of liquid air and nitrogen, and centralised production combined with distribution by cryogenic tanker, is likely be able to satisfy any foreseeable demand.
- There is a need to develop higher efficiency mid-sized liquefiers in the low single-digit tonnes per day range.

Chapter 7 Endnotes

¹ We assume a small car has an energy requirement of 0.13kWh/km, on the basis that the Nissan Leaf has a 24kWh battery and range of 175km ($24/175 = 0.13$). At a practical energy density of 0.1kWh/kg this translates to a requirement of 1.3kg of liquid air per km for a liquid air prime mover, and 1.04kg/km for one operating with the benefit of waste heat from an ICE engine. The UK could produce 8,500T (8.5 million kg) per day of additional liquid nitrogen. At 1.3kg/km this would equate to 6.5m vehicle miles, increasing to more than 8m vehicle miles with waste heat. Cf http://www.nissan.co.uk/?cid=ps-63_296991&gclid=CIX476ulyrUCFcbKtAodfw0AbA#vehicles/electric-vehicles/electric-leaf/leaf/pricing-and-specifications/brochure.

² See chapter 3 section 3. UK LNG cold could be used to produce 14.2mt of liquid air per year. 1 tonne of liquid air contains 1,150 litres, and Dearman Engine Company expects a car running on liquid air to achieve 1km/litre. This multiplies to 16.3 billion car kilometers per year or 44.7 million per day. Transport Statistics Great Britain 2012.

³ <http://www.stirlingcryogenics.com/products/liquefaction-plants/stirlair/>

Chapter 8 Manufacturing and pathways to deployment

1. Grid storage

2. Transport

3. Conclusions

If liquid air as an energy vector benefits from a pre-existing 'fuel' distribution network (chapter 6), it may gain further advantage from the characteristics of the equipment that would run on it. Liquid air devices can generally be made substantially from existing components drawn from mature supply chains with few bottlenecks to hamper expansion. And unlike many other low carbon technologies - such as EVs - liquid air technologies require no rare earth or other precious metals. In this chapter we assess the manufacturability and sustainability of liquid air technologies against a number of criteria, and where relevant compare them to competing technologies.

1. Grid storage

Liquid Air Energy Storage (LAES) systems such as that developed by Highview Power Storage rely on equipment widely used in the energy and industrial gases sectors that has been developed over the last century. The liquefier, for example, is one section of a standard Air Separation Unit (ASU) - a process developed by the German chemist Dr Carl von Linde in 1902 - while the turbines and generators, compressors, pumps and electric motors required are commonly used in the power and process industries. In this section we survey the global supply chain for the key components of a Liquid Air Energy Storage system, which can be broadly divided into three main elements: the charging device, storage components and discharge device.

Global supply chain for LAES components

Because the LAES **charging device** is effectively one section of an ASU, a 'first to market' system could be drawn substantially from units commonly used in the industrial gases industry today. For example, as shown in Table 8.1, both the main air compressor and recycle air compressor fall well within what is currently available in standard designs,

and can readily be sourced from several manufacturers globally. Other areas, such as plant controls, offer no significant requirement over and above that of a typical liquefaction or industrial process plant. Unsurprisingly the same is true of the expansion turbines, APU and coldbox, including the main coldbox heat exchangers and vessels.

Compressor and turbine efficiencies improve with scale, peaking at a capacity of several hundred tonnes per day, a plant size that is regularly built today. This fits well with a grid scale LAES with a power output 50-100MW and an energy storage capacity 200-400MWh, which is considered the optimum size for the technology.

The **storage components** of a LAES system include a low pressure cryogenic liquid storage tank and a separate high grade cold store, which stores the cold captured in the discharge phase for later use during the charging process.

The cryogenic liquid air store would typically consist of either a single tank or a series of smaller tanks. An early system would probably use established twin walled vacuum insulated tanks commonly used in the industrial gases business for storing cryogenic fluids. These tanks consist of a stainless steel low pressure

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tank within a carbon steel tank, in which the space between the tanks holds a vacuum and perlite insulation. For much larger capacities of up to 200,000m³ it would be possible to use bespoke tanks with concrete walls and stainless steel lining similar to those used in the LNG industry.

The high grade cold store is also a low pressure device, which not only reduces any safety risk but also the cost and difficulty of manufacture at scale. The store uses granite shingle, a cheap and widely available material, as the thermal store medium, which means that costs at scale are kept within acceptable limits.

The **discharge device** consists of a power turbine and generator. Power turbines of the design and type required in the LAES system are currently available from leading turbo machinery manufacturers up to 45MW. These machines use a standard gearbox design which helps reduce costs. Larger total outputs can be achieved by means of multiple machines, adding increased flexibility in turndown for a given efficiency drop, as well as increased resilience in case of breakdown and unplanned maintenance. Larger individual machine outputs are possible with the use of a direct coupled design. Unsurprisingly, the size and availability of suitable generator technology is closely related to the power turbine range which drives it, and therefore matching components are available.

Pumping cryogen to high pressure while maintaining required flow rates represents the greatest challenge to existing technologies in the supply chain. In order to maximise the energy retrieved from the cryogen it is necessary to pump the liquid to a high pressure, but there is a trade-off between the higher energy return and the pumping work needed to achieve it. Cryogenic pumps that are currently available operate up to 120 bar at 20kg/s, which falls short of 200 bar optimum. However, the optimum is considered achievable with further development in the supply chain. Larger flow rates can simply be achieved by using multiple pump configurations.

Heat exchangers for evaporation, reheat and superheat are all components that present little challenge to the current supply chain, with both pressure and temperature extremes within operating ranges of existing heat exchanger technology.

Balance of plant represents a significant proportion of materials required. Components include valves, circulation pumps, instrumentation, ancillary circuits and systems etc, all of which can easily be sourced from the local industrial utilities supply chain.

Liquid Air Energy Storage systems rely on components widely deployed in the industrial gases and power generation sectors and developed over the last century.

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Equipment area/item	Key req'ts at commercial scale	Major materials	Potential suppliers	Existing supply chain	Can be sourced in UK?
Motor-driven main air compressor	100 to 1500 T/d flow rate, centrifugal type design (screw type at lower size range). Variable speed, 2 to 4 stage intercooled.	Aluminium, stainless steel and carbon steel, copper windings in motor.	Atlas Copco, GE, Siemens, Dresser-Rand, Cooper, MAN Turbo.	< 7000 T/d, centrifugal type design (screw type at lower size range). Variable speed, 1 to 6 stage intercooled.	
Motor-driven recycle air compressor	300 to 4500 T/d flow rate, centrifugal or axial type design. Variable speed depending on application, 1 to 6 stage intercooled.	Aluminium, stainless steel and carbon steel, copper windings in motors.	Atlas Copco, GE, Siemens, Dresser-Rand, Cooper, MAN Turbo.	< 7000 T/d, centrifugal and axial type designs available (axial at larger sizes). Variable speed, 1 to 6 stage intercooled.	
Cold turbo-expander	150 to 2500 T/d flow rate, centrifugal, potentially multistage subject to application. Typically compressor loaded (although generator loaded is a possibility subject to application). Max inlet pressure <60bar, min temperature >-196C.	Aluminium, stainless steel and carbon steel.	Cryostar, Atlas Copco, ACD.	Centrifugal designs available with flows of <25000 T/d and inlet pressures <150bar and temps >-196C. Both compressor and generator loaded layout possible and previously used in industry.	
Inlet air cleaning skid	100 to 1500 T/d filtration flow rate, using atypical industry standard processes such as pressure swing adsorption (PSA) method. Standard air separation air quality levels.	Filtration material; active alumina, molecular sieve. Carbon steel, aluminium, stainless steel.	Linde, Air Products, Air Liquide, other smaller design companies.	PSA plants with feed air flow rates > 4000 T/d already exist with air purity standards higher than required for an ASU.	Complete skid can be manufactured in the UK.
Main cold box and associated heat exchangers	Capable of withstanding pressure <60bar, and temperature variation from -196C and +40C.	Aluminium, carbon & stainless steel.	Linde, Zhongtai, Sumitomo, Chart.	Heat exchangers to withstand pressures <200bar, and temperatures between -200C and +40C.	Plate fin exchangers will be imported. Cold boxes are and can be manufactured in the UK. Interconnecting pipework can be sourced in the UK.
Principal cryogenic and other critical valves	Capable of withstanding pressure <60bar, and temperature variation from -196C and +40C.	Aluminium, stainless steel, bronze.	AVCO, Flowserve, Spirax Sarco, CPC-Cryolab, Herose GmbH, Severn Glocon.	Components capable of withstanding pressures <200bar, and temperatures between -200C and +40C.	Can be sourced in the UK.
Control system	No inherent requirements over a standard process industry control system, PLC or DCS based SCADA system.	n/a.	Siemens, ABB, Honeywell, GE Fanuc, numerous smaller. Industry standard can be sourced in the UK.	PLC or DCS based SCADA systems.	
High grade cold store	Low pressure <10bar, temp >-190C, 150kg/s to 300kg/s flowrate, equivalent to PRU output of 50MW to 100MW. Thermal energy capacity of 200MWh to 400MWh, which is equivalent to 7000 to 14000 T of gravel.	Carbon steel, stainless steel, river bed shingle, perlite insulation.	Metal fabrication workshops.	Current materials and manufacturing processes to support fabrication of modular cell based store capacity to exceed requirements.	Standard steel units; all materials and manufacture can be sourced in the UK.
Plant pipework	Pipe sizes 10mm to 1000mm, pressures 0bar to 200bar, temperatures +200C (APU regen cycle) to -200C (note not same pipe).	Aluminium, stainless steel, carbon steel, bronze, copper.	Industrial pipe manufacturers and stockists.	Sizes > 1500mm, pressures 0 to 200bar, temps +200C (APU regen cycle) to -200C (note not same pipe).	Manufactured in the UK.

Table 8.1: Supply chain evaluation of key components of liquid air energy storage systems

continued >>

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Equipment area/item	Key req'ts at commercial scale	Major materials	Potential suppliers	Existing supply chain	Can be sourced in UK?
Power turbine	10MW-200MW total power generating capacity, likely to be configured of multiple units, with 2 to 6 stage expansion in anyone machine.	Stainless steel, carbon steel, aluminium.	GE, Cryostar, Atlas Copco, Dresser-Rand, Siemens, MAN Turbo, several US, Japanese, Chinese.	Up to 45MW (limited by shaft power) for a single turbine.	
Generator	10MW-200MW total power generating capacity, likely to be configured of multiple units.	Carbon steel, copper.	ABB, Siemens, GE, also Chinese and Japanese.	Up to 45MW (limited by shaft power) for a single generator.	
High pressure cryogenic heat exchangers	Capable of withstanding pressure <200bar, and temperature variation from -196C and +40C.	Stainless steel.	Heatric. Specialist design required from AP/AL/ Linde etc.	Heat exchangers to withstand pressures <400bar, and temperatures between -200C and +40C.	Can be manufactured in the UK.
Pipework and containerised assembly	No inherent requirements over a standard process industry.	Aluminium, stainless steel, carbon steel.	Metal fabrication workshops.	Current materials and manufacturing processes exist to support fabrication of necessary pipework and assemblies.	All assembly work can be done in UK fabrication facilities.
Cryogenic feed pumps	Discharge pressures up to 200bar, with flowrates <300 kg/s, multistage centrifugal pumps with variable speed drives.	Aluminium, stainless steel, copper windings in motor.	Cryostar, ADC Cryo.	Discharge pressures of <120bar at flowrates of <20kg/s for a single pump unit. Multiple units could be configured to reach required total flowrate.	
High voltage transformers	Modular units, can be built to suit any power loading.	Steel, copper.	ABB, GE, Siemens, ATL	Standard industry units, available from an international and UK Supply chain.	Can be sourced in UK.
Cryogenic storage tanks	Storage capacity will vary widely according to unit size, cycle type and site factors. At 10MW a range of 100-1000 tonnes (150-1500m ³) might be expected.	Stainless steel, carbon steel.	Chart Ferox, AP, Linde, AL plus several international suppliers.	Industry utilise twin walled vacuum insulated tanks at smaller sizes and bespoke concrete walled, stainless steel lined tanks at scales <200,000m ³ notably LNG storage applications. Capacities can be achieved by multiple smaller tanks.	Can be manufactured in the UK. The larger tanks would be site built by UK companies.
High voltage electrical control panels	Modular units, can be built to any size to control motors >25MW.	Steel, copper.	Merlin Gerin, ABB, Siemens, GE.	Standard industry units, available from a mature international and UK supply chain.	Can be sourced in UK.
Cooling towers	Modular units, can be built to any size.	Concrete basin, GRP and wooden structures.	Marley, Davenport, CPS.	Standard industry units, available from a mature international and UK supply chain.	

Table 8.1: Supply chain evaluation of key components of liquid air energy storage systems

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The major components of a Liquid Energy Storage system would probably be manufactured overseas, but we estimate that up to 60% of the total value of a new LAES plant could be captured by the UK.

Sustainability of materials

The main construction materials in air liquefiers are aluminium and steel of various types, including high alloy steels for compressors and turbines and low-temperature sections of the process. There is clearly no shortage of steel or bauxite, but the high energy cost of the conversion to aluminium has to be considered in any sustainability analysis.

Copper is more of a concern, however. Copper-based metals have been widely used in heat exchangers because of their heat transfer and corrosion resistant qualities, and a global shortage is pushing prices higher. This has driven the search for alternative materials and it is now common for ASUs to use aluminium and stainless steel in heat exchangers, columns and pipework. Copper is also significant in electrical machines such as motors and generators because of its excellent conductivity.

For safety and operational reasons some parts of valves, compressors and turbines may need to be made from high-alloy steels containing chromium, nickel, zinc and molybdenum. However, the quantities used are very small compared to the steel and aluminium. Unlike renewable energy technologies such as permanent magnet wind turbines, batteries and PV cells, LAES systems require no rare earth metals or other exotic materials, which are costly and finite.

Steel, aluminium and concrete are the main materials of construction and are all easily recyclable; when an ASU is demolished it is quite normal for 95% of the materials to be reused. The used adsorbents and oils would need to be disposed of by a specialist contractor and large foundations below ground level can be covered with soil and landscaped or rebuilt on. If necessary the foundations can be broken up and removed altogether.

UK manufacturing, the global supply chain and pathways to deployment

As liquid air plant sizes increase, the selection of turbo-machinery should become easier rather than harder; the equipment at the Highview Power Storage pilot plant is smaller than the standard range of many manufacturers. This does not imply that larger equipment is available 'off-the-shelf'; indeed it may take many months to manufacture. However, the basic designs will already exist and components will be selectable from a standard range.

The major components for a LAES facility such as the turbines and generator sets, compressors and motors, cryogenic pumps and plate fine heat exchangers in the cold box would have to be manufactured overseas. The inlet air cleaning skid, storage vessels, cold store vessels, high voltage electrics, cold box manufacture and all interconnecting pipework could be sourced from the UK. For larger LAES plants, the number of manufacturers capable of fabricating large cold boxes, heat exchangers and pressure vessels becomes more restricted, but if greater capacity is required, the UK still has shipbuilding or oil rig construction plant capable of handling the largest components.

A round-table discussion of industry experts held at the Institution of Mechanical Engineers in March 2013 concluded that if design, civil engineering and construction work is added to domestically produced components, around 50-60% of the value of a LAES installation could originate in the UK.^a This is not to say the UK *would* necessarily capture so much of the value, however; after 30 years of globalisation, it is now commonplace to outsource manufacturing to countries such as Brazil, Russia, India and China, where costs can be half those in the UK. However, other factors such as transport, efficiency, reliability and communications may affect the balance.

^a Notes on each of the round table discussions held for this report can be found at the www.liquidair.org.uk.

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Although a large amount of manufacturing capability has been relocated overseas, the UK does maintain a significant capability to design, integrate and package individual process units and machines into complete operational facilities. It is envisaged that from start to finish one of these plants could be brought on stream in 20-22 months. If the intention is to build multiple units of the same design, the round-table concluded total installation costs could be reduced by some 15% (see chapter 3, Appendix 1 and round table reports). This would also allow operators to hold low volumes of centrally held stocks of major spares. LAES plants should also be long-lived since they generate no corrosion or combustion products; all the major industrial gas companies operate large scale air separation plants that are more than 40 years old.

The equipment used in a LAES comes from a mature manufacturing and operational background and so would be expected to operate with very high levels of reliability; plant on-line times in the air separation industry are in the region of 99.5%. If a LAES plant was installed at an existing industrial gas production site the manpower and expertise required to run it could be provided from within the current workforce. For a LAES plant installed at a standalone site, the unit would be stopped, started and monitored from a remote location. A technician would only be required to visit the site once a week or to deal with a site emergency.

The visiting technician would be expected to undertake routine maintenance tasks; major maintenance on this type of equipment would only be required every 5 years at which point a shutdown of five to seven days would be required. The main drivers for maintenance frequencies tend to be safety valve testing and the cleaning of cooling systems.

In overseas markets, the main potential export would probably be engineering design and project management, which can be high value. However, the approach would differ between markets. Some countries where technical capabilities are low may require 'turnkey' plants; others may need only technology licencing and engineering consultancy.

In summary, the supply chain for liquid air technology is mature, global and extensive and the UK has the industrial capacity to deliver more than half the value of a LAES plant. There is no reason why the international supply chain should not deliver a target of 500MW of LAES capacity in the UK by 2020 (Summary Report and Recommendations), or supply the UK market potential of 14GW by 2050 (chapter 3). To achieve the earlier target, orders would need to start to be placed this year, but the current international supply chain is capable of delivering these levels of capacity without creating a bottleneck.

The economic value to UK manufacturing

At this early stage it is clearly not possible to quantify with any certainty the potential value of liquid air to the entire UK economy. However, it is possible to make a high level estimate of the value of grid-based LAES technology to UK manufacturing, on the basis of the results presented elsewhere in this report and a number of simple assumptions.

Other recent advances in low carbon technologies - such as offshore wind, for example - have delivered disappointingly little economic benefit to the UK, because we lack the relevant manufacturing base. However, liquid air plays to the UK's traditional strengths in mechanical engineering and cryogenics and therefore has the potential to achieve a relatively high proportion of UK content. If the technology proves cost effective the economic benefits to the UK could be significant.

This analysis considers the potential for liquid air to increase Gross Value Added (GVA) - one measure of output in an industry or sector - and to create jobs. We adopt three different approaches but with a single set of assumptions. We assume the market for grid storage achieves the potential identified in chapter 3, and that LAES captures 25% market share (Table 8.2). The analysis is calculated in today's prices - ie excluding inflation - or 'real'.

	2020	2030	2050
Market capacity for grid storage (GW)	2	6.5	14
Liquid air market share	25%	25%	25%
Liquid air capacity	0.5	1.625	3.5

Table 8.2: Assumed storage market and liquid air capacity

There is no reason why the international supply chain should not deliver a target of 500MW of LAES capacity in the UK by 2020, or supply the UK market potential of 14GW by 2050.

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A high level estimate of the value of liquid air to UK industry suggests by 2050 it could be worth up to £1 billion per year and sustain 20,000 jobs - excluding its potential impact on the transport sector.

It is not yet clear how highly the electricity market will value the additional flexibility brought by liquid air, particularly in light of the continuing uncertainty around Electricity Market Reform. Detailed analysis has been undertaken by Strbac and colleagues¹, but this leaves us with a wide range of scenarios and variables. In any event, Strbac considers the issue from a whole system perspective and not from the point of view of technology developers looking to generate an economic return. At this stage, therefore, any assessment of economic benefits must necessarily be broad brush.

For the purposes of this indicative analysis, we have considered three approaches. These produce a wide range in terms of potential impact on GDP, although given the large number of variables it should be stressed that outcomes could fall outside this band. It should also be noted that this analysis derives from the Strbac/DECC 'Grassroots' pathway and therefore assumes a 'high wind' scenario.

Model 1: Annualised cost of storage

Strbac calculates a range of annual savings in 2020, 2030 and 2050, based on a spread of annualised costs of storage. Liquid air is assumed to have an annualised cost of £150/kw/year and a market share of 25%, except in 2020, when Strbac's cost of storage range falls below the projected cost of liquid air and the market share is therefore assumed to be zero. On these assumptions, liquid air revenues are estimated to be £244 million in 2030 and £525m in 2050.

Model 2: Investment cost model

We assume that at the lower end of the expected cost range (£750/kw) there is sufficient value in the liquid air proposition for investors to generate a real return on capital of 9%. In addition, revenue will be generated through operations and maintenance of the facilities. We have assumed that this will equal around 10% of the capital cost. This is higher than the 1.5% - 3% quoted elsewhere in this report (chapter 6) in order to adjust for the relatively high expected labour intensity of the whole life cycle of the projects including the supply chain.

Given the length of time expected for the storage market to develop, significant project

activity will not start to take place until after 2020. As a result, annual revenues are projected to rise from £60m in 2020 to £200m in 2030 and £570m by 2050.

Model 3: Share of Benefits Analysis

Strbac projects a range of gross and net annualised benefits according to the projected annualised cost of the storage solutions. The net benefits are projected at around £1bn in 2030 and £8bn in 2050 for a cost of £150/kw/year. It is assumed that half of the net benefits generated are attributable to the storage solution and the remainder shared between other stakeholders. There is zero projected benefit in 2020 because the annualised cost range used by Strbac is below the expected level for liquid air, but there are benefits of £125m in 2030 and £1 billion in 2050.

GDP and Jobs Assessment

The economic analysis resulting from these approaches uses data from the Annual Business Survey 2011 (Provisional Results), showing annual revenues and gross value added per sector. We have taken the figures from the sub-sector *Production - Electricity, Steam, Gas and Air Conditioning* as the nearest proxy. The 2011 GVA percentage for this sub-sector was 24%. After calculating GVA in line with this sub-sector, we have assumed that 50% of the costs (revenues less GVA) are derived from a UK source and that there is an Induced Spending Multiplier (additional spending in other sectors that arises from this activity) of 120%. This produces the total GDP Added figures shown in Table 8.3. We have also calculated the potential for job creation by using the median gross annual earnings from the relevant sectors of the Annual Survey of Hours and Earnings 2011. The number of new jobs created in these scenarios ranges from 10,000 to almost 20,000, also presented in Table 8.3.

It should be stressed that this analysis is high level and indicative, and the results are highly dependent on assumptions about the size of the storage market. Nor does it consider the potential economic impact of liquid air in the transport sector.

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	2020	2030	2050
Employment			
Model 1	n/a	4,655	10,027
Model 2	1,605	5,215	11,233
Model 3	n/a	2,387	19,099
GDP Added			
Model 1	n/a	£181m	£390m
Model 2	£62m	£203m	£473m
Model 3	n/a	£125m	£1,000m

Table 8.3: GDP and employment impact of LAES to 2050

2. Transport

The Dearman Engine is a reciprocating (piston) engine that operates at near ambient temperatures, and as a result it is unlikely to offer many unfamiliar challenges to vehicle engine manufacturers. The most unfamiliar part of the system is likely to be the part exposed to cryogenic working fluid – liquid air or nitrogen. However, cryogenic technologies are mature and have been used in the industrial gas and liquefied natural gas (LNG) industries for decades.

There is a wide variety of materials suitable for use in cryogenic systems that are plentiful and relatively low cost, including stainless steel, aluminium alloys, PTFE and polyethylene.² The availability and cost of these materials compares favourably to some of those required for other low carbon vehicle technologies, such as platinum in hydrogen fuel cells and lithium and neodymium in battery electric vehicles.

The Automotive Council has created a framework for assessing technologies on the basis of their technology (TRL) and manufacturing (MRL) readiness levels.³ The Dearman Engine relies on the integration of sub-systems that are already in widespread use in existing vehicles around the core technology, and so has a relatively advanced manufacturing readiness level. We assess the MRLs of the key sub-systems below.

Manufacturing readiness of key Dearman Engine sub-systems

Working fluid storage. Cryogenic liquids such as liquid nitrogen can be stored in a variety of commercially available vessel types. Where LNG or liquid nitrogen are used in or transported by road vehicles today, the cryogenics are typically stored in vacuum insulated stainless steel tanks, which are available in a variety of sizes.⁴ As a result, on a scale of 1 to 10, the MRL of the liquid air energy store would be about 8.

LNG costs considerably more per kilogramme than liquid air or nitrogen and is flammable when it boils off, so the design of these tanks is probably more complicated than may be required for liquid air. However, existing designs are likely to be suitable for early deployment of liquid air vehicles. Longer term there is a development opportunity for the cryogenic tank to become cheaper and simpler. For example, lightweight tanks made of plastic or aluminium are already commercially available for use in static applications in capacities up to tens of litres.⁵

Working fluid delivery. Pumps capable of pressurising cryogenic fluids to very high pressures are a mature technology in a range of static and mobile applications. In transport they have been used in LNG lorries, and high efficiency ultra-high pressure submersible pumps are deployed commercially by companies such as Westport.⁶ The MRL of this part of the system is therefore likely to be 7 or 8.

Dearman Engine. This is the novel part of the system currently in development at Ricardo. The Dearman Engine is a reciprocating engine that operates between a few degrees below ambient and low grade waste heat temperatures of around 90C. Peak cycle pressures of about 200 to 300 bar are unlikely to be prohibitive in this temperature range; some diesel engines operate at this pressure and higher temperatures.⁷ First generations of the Dearman Engine are likely to be made from steel, aluminium and other alloys using known engine manufacturing techniques. In the longer term the ambient operating temperature range of the Dearman Engine as a prime mover could allow it to be made of lightweight materials such as plastics.

Like Liquid Air Energy Storage, the Dearman engine is constructed from familiar components widely used in industry today.

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Heat exchange fluid system. The heat exchange fluid is a water/glycol mix much like that found in conventional vehicles today, and the storage and transfer of this type of fluid is mature low cost technology. The reheat arrangements are likely to involve standard vehicle radiator technology or, in the case of ICE-Dearman heat hybrids, standard liquid-to-liquid heat exchangers. These are commodity items supplied by companies such as Alfa Laval and SWEP, and so require no significant manufacturing process development to be integrated into a Dearman Engine.⁸

Market need

The main sub-systems of a Dearman Engine may present no significant challenge for Original Equipment Manufacturers (OEMs) or

their Tier 1 Suppliers, but the question remains whether the industry would choose to develop the technology for mass markets. One way to assess this is to compare the characteristics of liquid air vehicles against the technology roadmap developed by the New Automotive Innovation and Growth Team (NAIGT) since 2008.⁹ The roadmap (Figure 8.1) represents the industry consensus around how the vehicle technology and manufacturing will evolve over the next 30 years, and has been used to develop a common research agenda (Table 8.2). Liquid air could address a number of the automotive industry's key research challenges.

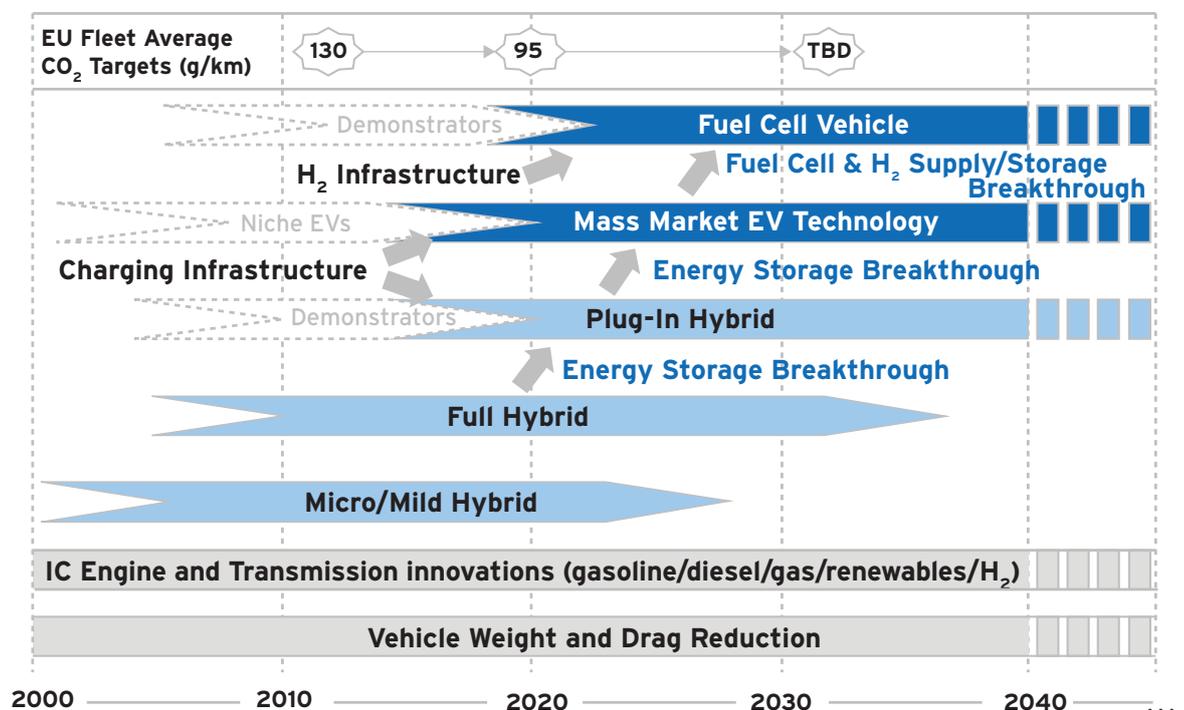


Figure 8.1: NAIGT Technology Roadmap Source: NAIGT

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	SHORT TERM 5-10 years from production	MEDIUM TERM 7-15 years from production	LONG TERM 10-20 years from production
	INDUSTRY		UNIVERSITIES
Propulsion	<ul style="list-style-type: none"> IC engine optimisation Boost systems for downsizing Flexible valve/actuation for engines/transmissions Low cost compact e-motors 	<ul style="list-style-type: none"> Higher efficiency IC engines Capacitive boost systems All electric actuation systems Optimised range extender engine Lower cost e-motor Heat energy recovery (e.g. E-turbine) 	<ul style="list-style-type: none"> Super high efficiency motors (superconducting) New IC engines with 70% + thermal efficiency Advanced heat energy recovery (e.g. thermoelectric) Motor/Fuel Cell materials
Energy storage	<ul style="list-style-type: none"> Improved quality/durability 200+ Wh/kg & \$800/kW.h cost battery systems Low cost power electronics 	<ul style="list-style-type: none"> Next gen batteries 300+ Wh/kg and \$500/kW.h costs Flexible power elec. modules Other forms of energy recovery (mechanical/chemical etc) 	<ul style="list-style-type: none"> 3rd gen batteries 400+ Wh/kg & \$200/kW.h cost New low cost solid state power conversion systems Hydrogen storage technology
Vehicle efficiency	<ul style="list-style-type: none"> Lightweight structures and interiors Low rolling resistance tyres/brakes 	<ul style="list-style-type: none"> New vehicle classes and configurations Combination of function to reduce weight/cost Minimised weight/losses 	<ul style="list-style-type: none"> Flexible re-configurable multi-utility vehicle concepts 50% weight reduction from 2008 Advanced aerodynamic concepts
System control	<ul style="list-style-type: none"> Information enabled control (Topology, V2V, V2I, traffic etc.) Optimised vehicle energy mgmt. Intelligent thermal management 	<ul style="list-style-type: none"> Advanced information enabled control Intelligent P/T and HVAC mgmt. 	<ul style="list-style-type: none"> Autonomous P/T and vehicle control integrated with active safety
Energy + fuel supply	<ul style="list-style-type: none"> Optimised 1st gen biofuels processes New 2nd gen biofuel processes 	<ul style="list-style-type: none"> Intelligent energy/re-fuelling infrastructure (e.g. fast charge) Industrial scale demonstration of new 2nd gen biofuel processes 	<ul style="list-style-type: none"> 3rd gen biofuel processes 2nd gen industrial scale biofuel production infrastructure
Processes + tools	<ul style="list-style-type: none"> Process + delivery tool development and connectivity 	<ul style="list-style-type: none"> Auto-optimisation methods using virtual systems 	<ul style="list-style-type: none"> Artificial intelligence to deliver complex multi-criteria system optimisation

Table 8.4: NAIGT common research agenda summary. Source: NAIGT

Liquid air addresses some of the motor industry's key research and development targets. The cost of liquid air energy storage using an imported tank today is already half the industry's long term target price.

Propulsion. The use of liquid air for waste heat recovery could help increase the thermal efficiency of the IC engine and therefore allow it to be downsized, a key aim of the research agenda for propulsion.

Energy storage. Liquid air can also contribute to meeting the industry's energy storage objectives particularly on cost. Cryogenic tanks for energy storage can be produced for as little as £4,500 for a 200 litre 'one-off' in the UK, or £1,000 in China. A 200 litre tank will hold 160kg of liquid air and approximately ten kg are required to generate 1kWh of electricity. This means the price of energy storage using liquid air today is ~\$450/kWh using a tank produced in the UK, which is already lower than the NAIGT's medium term cost target; and \$100/kWh using an imported tank, about half the long term energy storage target. There is also likely to be scope for further cost reduction if alternative materials or high volume manufacturing techniques are employed. Improvements in energy density could be achieved by elevating peak cycle temperatures and pressures, but the imperative to do so is reduced by the rapid refuelling times that liquid air can deliver.

Vehicle efficiency. Liquid air may be able to raise vehicle efficiency by reducing weight if plastic engines and tanks are developed. As a waste heat recovery device, it could also contribute to engine downsizing and significant improvements in aerodynamic efficiency if it allows designers to dispense with the need for a conventional radiator.

Pathways to deployment

Passenger cars. Vehicle manufacturers are slow adopters of new technologies because of the scale and risk of the necessary investment. It will cost an OEM such as Ford or GM more than £1 billion to develop a new passenger vehicle from scratch, and failure would be disastrous. Even incremental changes to existing designs take three to five years to introduce. The Euro 1-6 emissions standards that require modifications to existing diesel engine technology, have taken many years to implement. Euro 6, which was legislated in 2007, will come in to force for new vehicle sales in January 2015.¹⁰

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The industry's roadmap foresees the introduction of zero emission vehicles in the 2020s, and liquid air vehicles could be developed in this timeframe.

A new passenger car typically takes seven years to develop: three years from engineering prototype to programme approval, then four years to volume production. Changes to an existing model typically take three years from initiation to volume production. The development timelines of commercial vehicles are similar, while off-road vehicles may be quicker.

It may take over ten years for a zero emission technology to be fully adopted as a prime mover on volume vehicles. However, liquid air may have some advantage because the main sub-systems are similar to those of IC engines. The NAIGT technology roadmap foresees the introduction of zero emission vehicles such as EVs from the 2020s, and it seems liquid air vehicles could be developed in broadly this timeframe.

Another advantage of liquid air to the OEMs is that it could extend the time before it becomes necessary to replace the ICE altogether, by raising its efficiency and reducing its emissions through ICE-Dearman hybrids or concepts such as the liquid nitrogen split cycle engine (chapters 2 and 4). Billions of pounds have been spent to date on the development of internal combustion engine vehicles and liquid air could help OEMs retain some of that value. This could mean liquid air is developed in hybrid, emissions-reducing applications sooner than as a prime mover, zero emissions concept.

Vehicle fleets. OEMs are not the only route to market for liquid air. Operators of depot-based fleets such as buses or delivery vehicles could be early adopters, since the risks to them of product failure are much lower than for an OEM,

so they are prepared to take greater risks on new technologies if the business case is strong enough. Production volume requirements for the fleet sector are also more compatible with early stage technologies. Fleet retrofit is also likely to be the fastest adopter of liquid air technology since installing liquid air production or storage capacity at depots can be achieved more quickly than creating an entire filling station network.

There is scope for the waste-heat-to-power and refrigeration applications of liquid air to be retrofitted, which could lead to rapid take up of the technology in the fleet sector. This could be achieved on the basis of the existing cryogenic supply chain (chapters 6 and 7) without the need for significant OEM or Tier 1 involvement. This could accelerate take-up in the mass markets through demonstration of the technology.

The cryogenic equipment supply chain is currently geared to produce a few to tens of thousands of units per year. This is because of the low level of current demand rather than any materials or manufacturing capability constraint. Companies such as Productiv, which is developing a 'proving factory' specifically to bring early stage vehicle technologies to the level of manufacturing 10,000-20,000 units per year, offer a route for liquid air technologies to be produced in low commercial volumes. This may then allow the technologies to be demonstrated in niche markets and perhaps justify the OEM investment needed to develop the production lines necessary to deliver mass market volumes.

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3. Conclusions

From the discussion presented in this chapter we conclude:

- Liquid air technologies are based on mature components which can be readily sourced from mature supply chains.
- The key components of a liquid air energy storage (LAES) plant can be readily sourced from existing manufacturing capacity in the UK and abroad and 50-60% of the plant's total value could in principle be sourced from the UK.
- Existing supply chains could, in principle, deliver 500MW of LAES capacity in the UK by 2020 if orders were placed soon, and could also deliver estimated UK storage market potential of 14GW by 2050.
- The Dearman Engine would be made mainly from components similar to those of a conventional internal combustion engine (ICE) and cryogenic components similar to those already used in LNG vehicles.
- The NAIGT technology roadmap calls for the introduction of zero emissions vehicles in the 2020s and liquid air vehicles could be developed in this timeframe.
- Liquid air technologies could extend the time before it becomes necessary to replace the ICE altogether by raising its efficiency and reducing its emissions.

Chapter 8 Endnotes

¹ *Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future*, report for the Carbon Trust, Strbac et al., June 2012, <http://www.carbontrust.com/media/129310/energy-storage-systems-role-value-strategic-assessment.pdf>

² <http://www.iom3.org/technical-bulletin/materials-cryogenic-applications>

³ *Automotive Technology and Manufacturing Readiness Levels*, Low Carbon Vehicle Partnership and Automotive Council, January 2011, <http://www.automotivecouncil.co.uk/wp-content/uploads/2011/02/Automotive-Technology-and-Manufacturing-Readiness-Levels.pdf>

⁴ *HLNG Vehicle Tanks Specification Sheet*, Chart LNG, 2012 <http://www.chart-ferox.com/getattachment/cbe66c42-2bd1-4ceb-8fc6-a42662ac2cad/14771738.aspx>

⁵ http://www.appletonwoods.co.uk/acatalog/Liquid_Nitrogen_Storage_Dewars.html, http://www.coleparmer.co.uk/Product/All_plastic_Dewar_flask_10_L/WZ-06726-80

⁶ <http://www.westport-hd.com/>

⁷ <https://www.avl.com/single-cylinder-research-engines-and-testbeds>

⁸ <http://www.alfalaval.com/about-us/Pages/About-us.aspx>; <http://www.swep.net/en/Pages/default.aspx>

⁹ *An Independent Report on the Future of the Automotive Industry in the UK*, New Automotive Innovation and Growth Team (NAIGT), February 2008, p45, <http://www.bis.gov.uk/files/file51139.pdf>

¹⁰ *Reduction of pollutant emissions from light vehicles*, http://europa.eu/legislation_summaries/environment/air_pollution/l28186_en.htm

Chapter 9 Safety

1. Overview of hazards related to liquid air
2. Specific hazards and mitigation
3. Managing oxygen enrichment - Highview Power Storage
4. Hazards and mitigation in transport
5. The safety record of the industrial gas producers
6. Conclusions

Cryogenic liquids present significant but familiar and manageable hazards because of their intense cold and substantial gas production when warmed. There are three principal areas of hazard: physiological, physical and chemical. Physiological hazards include frostbite, respiratory ailments and the specific effects of certain materials such as oxidisers on body tissues. Physical hazards include the effects of over-pressure, low temperatures, oxygen enrichment and cryogenic embrittlement. Chemical hazards include the ignition of flammable mixtures, the propagation of flame and explosions.

However, the risks of handling cryogenic liquids can be minimised using standard safety equipment and well understood procedures. The operational experience of Highview Power Storage further suggests that even the most significant hazard of liquid air - oxygen enrichment - can be managed effectively and safely. The safety record of the industrial gases industry more generally has improved dramatically over the past 40 years and is now comparable to that of many world class companies.

1. Overview of hazards related to liquid air

Since liquid air is not yet produced in commercial volumes, less health and safety literature has been published than for its separated constituents: liquid oxygen and liquid nitrogen. However, three big players in the cryogenic distillation field - Air Liquide, Air Products and Praxair - have produced Material Safety Data Sheets (MSDS) for this product (see Appendix 3). These describe liquid air as a refrigerated, non-toxic, non-flammable gas that presents cold burns/frost bite, oxidation and strong support of combustion as the principle hazards.

The general rules for distribution and transportation of liquid air are similar to other cryogenic fluids, and purpose designed cryogenic equipment is required. Transport of

large quantities of liquid air may be by road tanker, ship or pipeline. Smaller quantities are conveniently handled in portable Dewars, cylinders and other insulated vessels. In all cases distribution must be accomplished in complete safety and with minimum loss of liquid air. There are many established documents from leading cryogenic companies, such as those mentioned earlier, about large scale cryogen transport by road tanker and pipeline that could be applied to liquid air.

The hazards associated with liquid air, liquid oxygen and liquid nitrogen are compared in Table 9.1. The relative severity of the hazard is represented by the number of Xs. The potential hazards must all be considered individually and collectively in the design and operation of any cryogenic system.

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Hazards		Liquid air	Liquid oxygen	Liquid nitrogen
Physiological	Frostbite	X	X	X
	Asphyxiation	XX		XXXXX
Physical	High pressure effect	XX	XX	XX
	Low temperature effect	XX	XX	XX
	Oxygen enrichment	XXX	XXXXX	XX
Chemical	Oxidation	XX	XXXXX	X
	Flammability	XX	XXXXX	X
	Fire	XX	XXXXX	X
	Explosion	XX	XXXXX	X
Combined effect	BLEVE (Boiling Liquid Expanding Vapour Explosion)	XX	XXXXX	X

Table 9.1: Relative severity of cryogenic fluid hazards

In most areas of potential risk, the hazards associated with liquid air are more severe than those of liquid nitrogen but less than those of liquid oxygen, which is highly reactive. Comparing liquid air with liquid nitrogen, many hazards, such as cold effects, and over-pressure effects are the same, but in one respect liquid air is safer than liquid nitrogen.

When liquid cryogenics are expelled into the atmosphere at room temperature, they will evaporate and expand ~700-800 times their liquid volume very rapidly. In the case of liquid nitrogen, even small amounts of liquid can displace large amounts of air and decrease the oxygen content of the atmosphere below a safe level, raising the possibility of asphyxiation. In the case of liquid air, since it is made up of oxygen and nitrogen in the same proportion as the atmosphere, its evaporation will produce oxygen gas as well as nitrogen. Provided there is adequate ventilation, this will not cause the same level of oxygen deficiency as the evaporation of liquid nitrogen.

For liquid air, additional care must be taken against the possibility of oxygen enrichment and associated chemical hazards. Oxygen enrichment occurs because nitrogen, oxygen and argon have different partial vapour pressures at the same temperature. As vapour pressure is the driving force for both condensation and evaporation of a mixture of gases, a selective phase change process can take place over time and oxygen enrichment of liquid air is to be expected. Therefore we suggest handling of liquid air should follow many of the procedures for handling liquid oxygen, which are well understood and have been in operation in the industrial gases industry for decades.

2. Specific hazards and mitigation

Most of the health and safety issues of liquid air can be referred to established protocols relating to liquid nitrogen and liquid oxygen. The most likely issues relating to the use of liquid air or liquid nitrogen in the power and energy sectors are:

- Cold burn or frostbite (both).
- Pressure build-up (both).
- BLEVE (Boiling Liquid Expanding Vapour Explosion) (both).
- Materials structure and integrity (both).
- Oxygen deficiency (mainly liquid nitrogen).
- Oxygen enrichment (mainly liquid air).

Cold burn or frostbite

The extremely low temperatures of cryogenic liquids mean that liquid, cold vapour or gas, can produce serious health problems. In general, frostbite occurs only after prolonged exposure of tissue to temperatures below 0°C. Because blood delivers heat to the affected part, the amount of heat actually removed from the tissues and the rate at which it is removed determine the extent of frostbite when it occurs. Other cold hazards include:

- **Contact of the skin with cryogenic liquids** (or even cold gas) can cause severe cryogenic burns.
- **Contact with non-insulated and even**

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insulated parts of equipment or vessels containing cryogenic liquids can produce similar damage - eg cold pipework and other surfaces.

- **Inhalation of cold vapour** can reduce the blood temperature, cause damage to the lungs and trigger asthma attacks.
- **Hypothermia** is a risk, depending on the length of exposure, the atmospheric temperature and the individual. The internal organs are cooled by the blood from the outer parts of the body. If the heart and brain are cooled to any great extent it can be fatal.

Though potentially serious, these hazards can be mitigated by proper insulation, protective clothing and suitable ventilation for those working in close proximity/contact with cryogenic fluids, pipework, containers and gases. Protective measures should include:

- Protective clothing for handling low temperature liquefied gases serves mainly to protect against cold burns.
- Non-absorbent gloves (leather or PVC) should always be worn when handling anything that is in contact with liquid air or its cold vapour. Gloves should be a loose fit so that they can be easily removed should liquid splash on or into them.
- If there is a risk of severe spraying or splashing, eyes should be protected with a face shield or goggles.
- Trousers should be worn outside boots and have no pockets.

A number of health and safety documents have been produced and procedures are well established for handling different cryogenic fluids.

Pressure build-up

As cryogenics are usually stored at or near their boiling point, there is always some gas present in the container, so the high pressure gas hazard is always present. Upon phase change, cryogenic liquids vaporise with a volume expansion to ~700-800 times. The rate of evaporation will vary, depending on the characteristics of the fluid, container design, insulating materials, and environmental

conditions. Without adequate venting or pressure-relief devices on containers, large pressures can build up on cryogen evaporation. In extreme cases this can lead to Boiling Liquid Expanding Vapour Explosion (BLEVE).

Due to the large temperature difference between cryogen and ambient temperature, heat flux into the cryogen is unavoidable regardless of the quality of the insulation. Cryogenics boil as they sit in their storage vessels or transfer pipes by absorbing heat from the surroundings. Since cryogenic fluids have small latent heats and large expansion ratios, even a small heat input can create large pressure increases, especially in a confined space. Cryogenic Dewars lose roughly ~1% of their contents to evaporation per day.

A number of situations can cause high pressure to build-up. Measures including good ventilation, pressure relief valves, venting lid and proper operations are needed to prevent an explosion. Pressurisation can occur because:

- Ice forms on the venting tube, plugging it and preventing gas release.
- Equipment damage results in cryogenic fluids leaking into small areas, where the cryogenic liquid vaporises and causes pressure build up.
- A cryostat or Dewar loses vacuum.
- Direct contact of the cryogenic liquid with water or some other ambient liquid in a tube may result in rapid vaporisation of the cryogenic liquid and can cause the tube to explode.

A number of common measures are used to reduce these risks, which include:

- Pressure relief devices must be provided on each and every part of a cryogenic system. Satisfactory operation of these devices must be checked periodically and may not be defeated or modified at any time.
- Vents must be protected against icing and plugging. Vents must be kept open at all times.

These are well established measures that are currently incorporated into cryogenic container and system design.

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Boiling Liquid Expanding Vapour Explosion

Boiling Liquid Expanding Vapour Explosion (BLEVE) is an explosion caused by the rupture of a vessel containing any pressurised liquid above its boiling point, and typically occurs when the tank is exposed to fire. As pressure increases a point is reached when the walls of the container can no longer withstand the pressure and the vessel bursts. This produces instantaneous depressurisation, meaning the temperature of the liquid will be higher than that which would correspond to it according to the saturation curve on a Pressure-Temperature diagram, and the liquid will be superheated. As a result, homogeneous nucleation takes place in the liquid, which will rapidly and continuously generate vapour that accelerates the explosion process.

BLEVE can happen with any liquid, whether flammable or not, but the greatest hazard is with flammable liquids such as liquefied natural gas (LNG), where a number of accidents during transport have been reported.¹ When BLEVE occurs in non-flammable cryogenic gases such as liquid air or nitrogen the hazard is less severe since it produces no combustion.

Measures to mitigate the risk of BLEVE include:

- Install pressure relief valves so that if tanks are subjected to external heat they will vent cryogen harmlessly to the atmosphere before the pressure rises to dangerous levels.
- Use tanks with good fire resistance, drawing on experience from the LNG industry.
- Keep any combustible material away from tanks.

Low temperature effect on materials structure and integrity

As the properties of most materials are altered with decreases in temperature, the design of cryogenic systems and prevention of hazards requires knowledge of the strength, thermal expansion, thermal conductivity and heat capacity of the construction materials over the operational temperature range. Materials which are normally ductile at atmospheric temperatures may become extremely brittle when subjected to temperatures in the cryogenic range, while other materials may improve their ductility.

Materials must be carefully selected for cryogenic service because of the drastic changes in the properties of materials when they are exposed to extremely low temperatures. Cryogenic liquids can cause many common materials such as carbon steel, some types of plastics and rubber to become brittle, or even fracture under stress. Some metals which are suitable for cryogenic temperatures include stainless steel (300 series and other austenitic series), copper, brass, bronze, monel, and aluminum. Non-metal materials which perform satisfactorily in low temperature service are Dacron, Teflon, Kel-F and asbestos impregnated with Teflon, Mylar and nylon.²

Oxygen deficiency (mainly for liquid nitrogen)

Oxygen deficiency is defined as the condition of the partial pressure of atmospheric oxygen being less than 135 mmHg.³ At higher altitudes the same effects generally occur at greater volume concentrations since the partial pressure of oxygen is less. If exposure to reduced oxygen is terminated early enough, effects are generally reversible. If not, permanent central nervous system damage or death can result.

Respiratory ailment effects are a risk in enclosed areas. However, risks can be mitigated through use of oxygen concentration meters and proper ventilation. Health and Safety procedures for the amount of ventilation required for an environment with cryogenic inert gases are well established. In general, there are well established measures and precautions to deal with oxygen deficiency hazard (ODH).⁴

Oxygen enrichment (mainly for liquid air)

Air is composed primarily of nitrogen, oxygen and argon, which have different partial vapour pressures at the same temperature. As it is a mixture, the gases can be separated by contact with cold surfaces. The equilibrium composition diagram for nitrogen and oxygen is shown in Figure 9.1. As the temperature of mixture A (air, 21% oxygen and 79% nitrogen) is lowered, a condensate first appears at the dew point, approximately 82K

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(-191°C). The composition of this condensate is approximately 50% oxygen and 50% nitrogen. These equilibrium values are approached by the condensate that forms on uninsulated lines and other exposed solid and liquid surfaces at temperature below 82K. When liquid B boils at 1 atm, the vapor contains approximately 6% oxygen and 94% nitrogen so the liquid phase residues slowly becomes enriched with oxygen. The enrichment rate decreases as the liquid oxygen concentration increases. The last part of the liquid to be evaporated contains approximately 50% oxygen. Thus with air, oxygen enrichment can be expected in the liquid phase as a result of both the condensation and vaporisation processes.

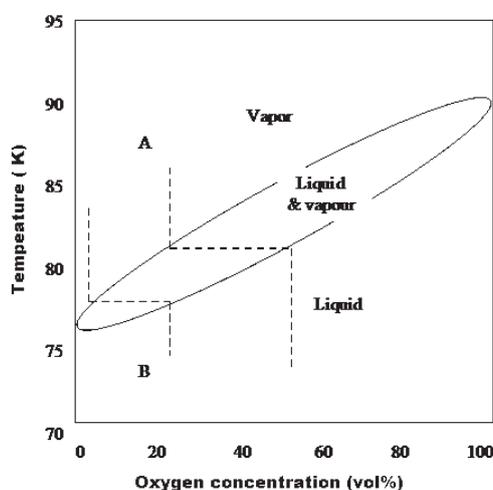


Figure 9.1: Oxygen and nitrogen phase diagram

As evaporation makes liquid air progressively richer in oxygen, potentially as high as 50%, we suggest for safety reasons that in circumstances where liquid air may be stored for long periods it should be handled according to liquid oxygen handling procedures. The MSDS documents for handling pure liquid oxygen from Air Liquide and BOC appear in Appendix 3.

The causes of oxygen enrichment include:

- Condensation by cooler cryogenics:** When transferring liquid nitrogen through uninsulated metal pipes, the air surrounding a cryogen containment system can condense. This can cause oxygen enrichment on the surface or entrapment in unsuspected areas.

- Condensation on cold metal surface:** Extremely cold metal surfaces are also capable of condensing oxygen from the atmosphere.

- Evaporation of liquid air:** As explained above, liquefied inert gases such as liquid nitrogen which have a lower boiling point than oxygen, will evaporate first, and this could lead to oxygen enrichment up to 50%.

Measures to minimise the risk of oxygen enrichment include:

- Use properly insulated systems.
- Monitor the oxygen content of liquid air.
- Adopt active measures such as systems proposed by Stirling Cryogenics and Refrigeration⁵ and BOC.⁶
- Keeping organic materials such as oil, grease, kerosene, cloth, wood, paint, tar and dirt away from the oxygen source as they may combust in an oxygen rich environment.
- In the event that air is condensed and some repair work is needed, special care must be taken especially where the use of open flames or other potential sources of ignition is intended.
- Installing equipment that reduces oxygen enrichment, such as the systems developed by Stirling Cryogenics and Refrigeration and BOC.⁷

3. Managing oxygen enrichment - Highview Power Storage

The potential of oxygen enrichment within the storage tank of a liquid air energy system such as the Highview pilot plant in Slough presents a real but controllable risk, particularly if the system is operated for reserve and peaking services where the storage period is greater than several weeks.

Significant oxygen enrichment within the bulk storage vessel of a cryogenic energy storage device would present increased operational hazards in both the storage and power recovery phases. This would limit the

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suitability of the technology and significantly increase its installation and operating costs.

Operational experience gained from Highview's pilot plant suggests that localised enrichment in stagnant pipes can occur after five to seven days, but concentrations were shown to return to normal levels once lines were purged from the tank, indicating no significant enrichment within the bulk liquid. No further indications of oxygen enrichment were observed within the bulk liquid.

The potential of oxygen enrichment within the cryogenic storage vessel is likely to be lower in larger tanks - where the higher ratio of volume to surface area favours the retention of cold - and those where the storage period is measured in hours or days.

Previous solutions

Previous solutions to the problem of oxygen enrichment (e.g. patents US5,571,231 and US3,260,060) broadly use cold from low pressure streams, such as the venting stream, to condense the gaseous vapour and stabilise the concentration of the liquid. However, not all cryogenic energy storage vessels are equipped with such a gaseous venting stream.

Operational experience at Highview Power Storage

The pilot plant in Slough uses an industry standard, vacuum insulated steel cryogenic storage tank of about 60 tonnes capacity. Apart from standard equipment supplied by the manufacturer to monitor fluid level and pressure in the tank, instrumentation was limited to monitoring the composition of the fill and discharge streams. The tank and cryogenic pumps were cleaned to oxygen handling standards and the process stream on the suction side of the pumps was closely monitored to ensure oxygen concentrations did not exceed 23% while the power recovery turbine was in operation. During the performance testing programme, marginally elevated oxygen levels were noted at sample points in the discharge line after extended down periods (>five to seven days, depending on atmospheric conditions), and this was most noticeable while the tank was less than half full. However, by simply extending the pre-run pump cooling cycle times by 50%, oxygen concentration was observed to return to

normal (21%). This suggests the enrichment had occurred in the stagnant lines, where thermal losses are higher, resulting in locally elevated liquid temperature and not in the bulk storage tank.

Implications for commercial-scale plants

An energy storage device can provide a wide variety services to the network operator, generators and consumers of power, ranging from daily balancing to rarely-called back-up capacity. The nature of each service will influence the size and duration of the storage required, and this in turn has implications for the management of the oxygen enrichment hazard.

There are two types of liquid air plant: the Cryo Energy System (CES), where liquid air is produced, stored and used to generate power on a single site; and the Cryogenset, which is a generation-only device that runs on cryogenics delivered from a remote or centralised production site.

The **Cryogenset** would typically be used to provide emergency back-up for companies and/or peaking plant for the grid, both of which would probably involve the storage of relatively small amounts of cryogen for weeks and possibly months depending on market and infrastructure conditions. As a result the risk of oxygen enrichment would be higher, and it would make sense to eliminate the risk entirely by running the plant on liquid nitrogen rather than liquid air. This might make the 'fuel' more expensive, but since the plant would run so infrequently - typically less than 100 hours per year - it should not critically undermine the economics. As discussed in chapter 6, there is estimated to be an 8,500tpd daily surplus of nitrogen gas available for liquefaction.

A full-scale **Cryogenic Energy System**, on the other hand, could perform a variety of roles with different implications for oxygen enrichment. A CES plant used for shaping inflexible nuclear power or firming intermittent renewable generation is likely to be cycling at least once a day, meaning the storage period would be far too short for any significant oxygen enrichment to occur - a point supported by operational experience of the Slough plant. A commercial-scale CES would also typically have larger storage tanks with proportionally lower thermal losses, further reducing the risks.

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A CES plant running on liquid air would be most at risk of oxygen enrichment if providing a reserve or peaking service. However, the risk is thought to be low because of the operating schedule, which would involve long periods of charging followed by relatively short periods of discharge. This is because the liquefaction plant - if correctly sized for the application - should take almost the entire period between discharges to fully charge the store. Assuming the plant is running at a constant rate, this in turn means the effective storage period of the total stored capacity is only half the total storage period. It also means the vessel is no longer full of stagnant cryogenic fluids for a long period, but continually being mixed with sub-cooled liquid air, which would help to reduce boil off and any oxygen enrichment.

4. Hazards and mitigation in transport

The hazards associated with liquid air or liquid nitrogen are fundamentally identical in static and transport applications. However, since these cryogenes are not currently widely used as transport fuel, some further discussion is warranted. The hazards and potential mitigation measures relating to some key transport-specific situations are summarised in Table 9.2.

In transport, the risk of cold burn would be greatest during refuelling, either from spillage or contact with cold surfaces. However, this risk can be eliminated by design, using adequate insulation and locking fuel hoses, as it has been at LNG refuelling stations for heavy trucks.⁸ The industrial gas company Messer has developed a refuelling system for cryogenic nitrogen called Ecolin, for which the data sheet appears in Appendix 4.

The risk of pressure build-up and explosion would be highest if the vacuum insulation of a vehicle fuel tank were penetrated during a collision, but this could be mitigated with appropriate pressure-relief valves and burst disks.

The risk of asphyxiation would be highest if a vehicle fuelled on liquid nitrogen were left idle in an enclosed space such as a garage for an extended period. However, this hazard could be mitigated by legislating appropriate passive ventilation standards, oxygen monitoring equipment or both.

The risk of oxygen enrichment would be higher in the fuel tanks of vehicles left standing for an extended period than for large static tanks (see section 3), since the lower volume to surface area ratio means small tanks do not retain their cold so well. This hazard could be eliminated using technical solutions such as the AirLock System proposed by Stirling Cryogenics⁹ or the system for storing a multi-component cryogenic fluid proposed by BOC.¹⁰

Situation	Hazard	Liquid air	Liquid nitrogen	Mitigation
Refuelling	Cold burn	X	X	Adequate insulation, locking fuel hoses, as with LNG truck fuel ¹¹
	Oxygen enrichment	X	X	See under 'Measures to minimise the risk of oxygen enrichment'
Fuel tank loses vacuum in crash, or insulation deteriorates over time	Pressure build-up/ BLEVE	X	X	Pressure relief valves, with redundancy Regular service checks of the vacuum and insulation system
Cryogen boil-off in enclosed space such as garage	Asphyxiation		X	Ventilation standards, oxygen monitoring
Preferential nitrogen boil-off if vehicle left standing for long period	Oxygen enrichment / heightened risk of oxidation	X		See 'Measures to minimise the risk of oxygen enrichment', could also include technical solutions, such as those proposed by Stirling Cryogenics and BOC

Table 9.2: Hazards and mitigation in transport applications

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More generally, there is good reason to believe the hazards associated with the use of liquid air and liquid nitrogen as transport fuel can be managed to acceptable levels, because:

- The industrial gas industry transports thousands of tonnes of cryogenic liquids by road tanker daily (see section 5, and chapters 6 and 7).
- LNG and LPG is increasingly used as lorry fuel, and the hazards of transporting liquid air are expected to be much lower than for either LNG/LPG or for liquid oxygen, which is also commonly transported by road.
- Early applications of liquid air in transport are likely to involve commercial vehicles with fully trained operators.
- Hazardous fuels such as petrol and diesel are routinely used by the public and the hazards have been managed to acceptable levels.

5. The safety record of the industrial gas producers

The safety record of industrial gas producers in Europe has improved dramatically over the past forty years. Data supplied by the European Industrial Gas Association (EIGA) shows the Lost Time Injury Rate (LTIR) has fallen from around 30 days lost per million hours worked in 1978 to just 1.7 in 2011 (Figure 9.2). That compares well to the performance of the wider chemicals industry of which the industrial gases business is a sector. The last published figures showed an LTIR of 6.6 for the European chemicals industry in 2008 and 4.57 for the global chemicals industry (Figure 9.3).

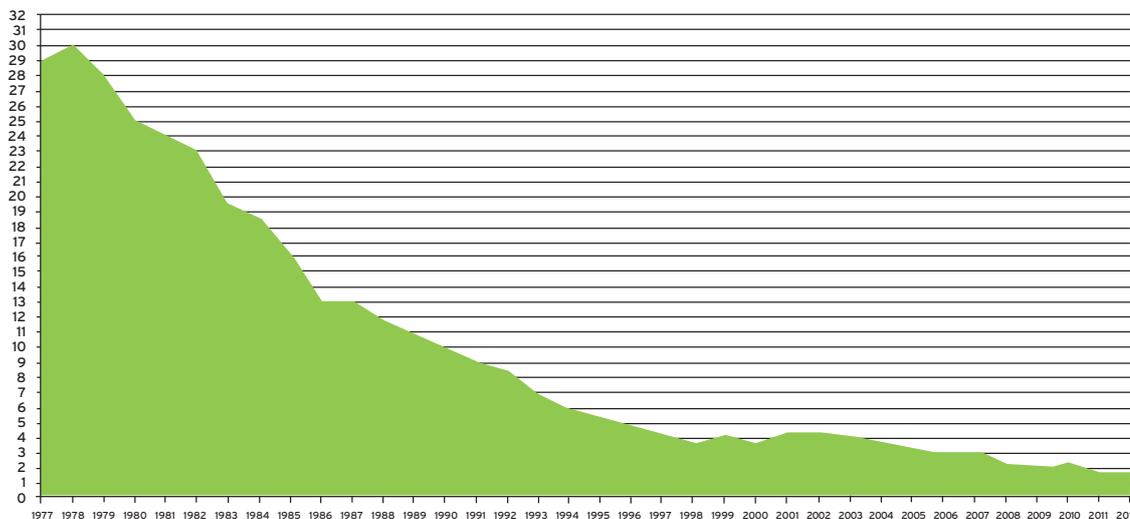


Figure 9.2: EIGA LTIR 1977-2012. Source: EIGA¹²

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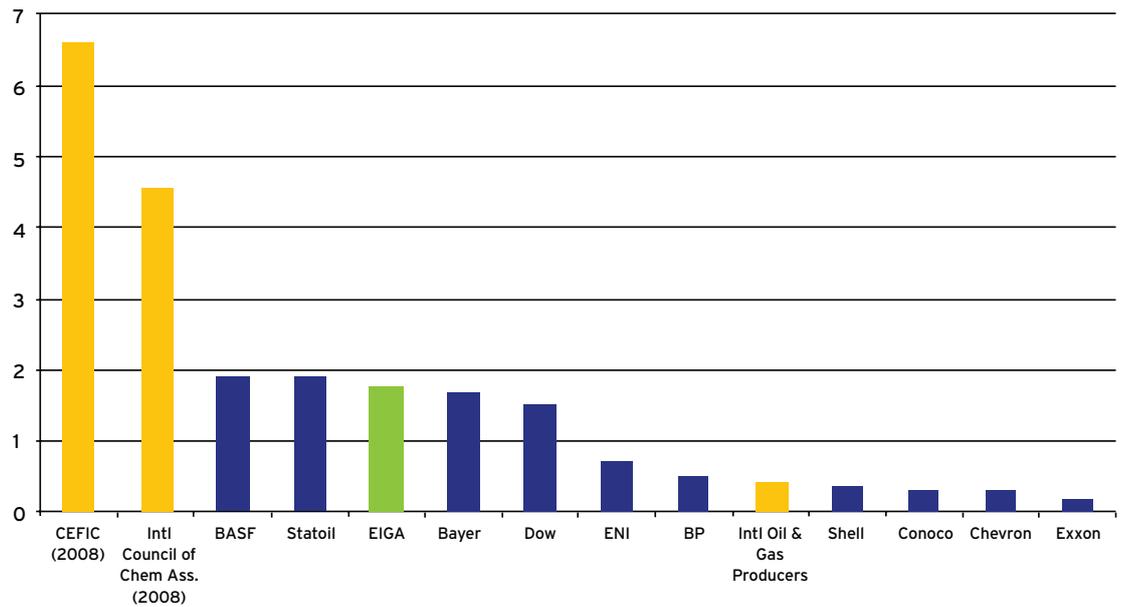


Figure 9.3: LTIR comparison between EIGA and related industries and companies. Source: EIGA¹³

EIGA data also shows that injuries in the industrial gases industry were largely related to routine workplace hazards - over 40% were due to trips and falls, falling from height, and over exertion - while far fewer were caused by cryogenic hazards. 3.5% of injuries were due to exposure to heat or cold, while 5.5% were caused by fire, energy release or flying particles (Figure 9.4).

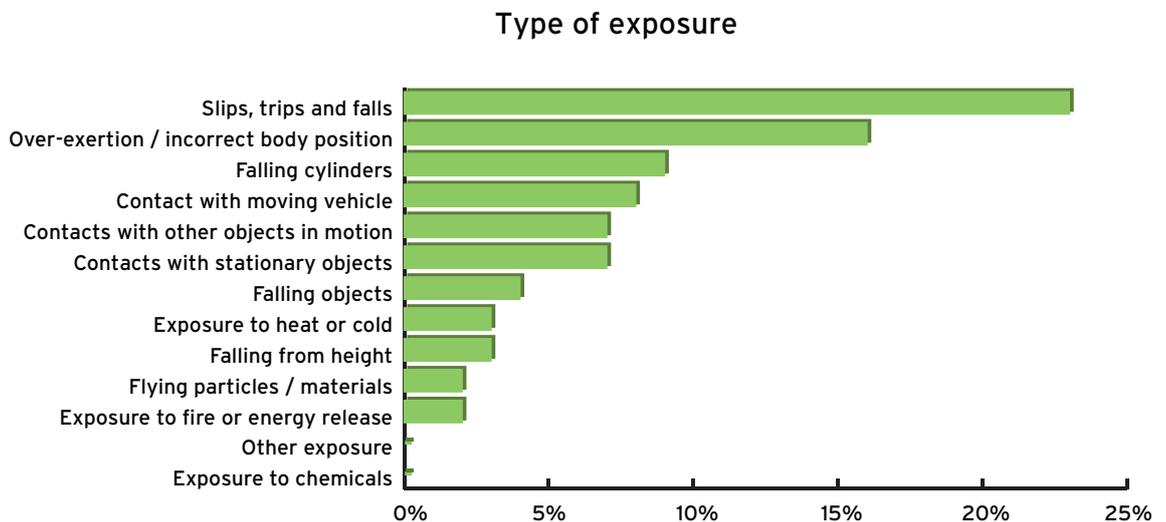


Figure 9.4: EIGA LTIR accidents by cause. Source: EIGA¹⁴

EIGA's LTIR performance is worse than that of the international oil and gas industry, which stood at 0.43 in 2011, but its Fatal Accident Rate (FAR) is much lower. The oil industry's 10 year average FAR is 3.6 per 100 million man hours worked per year, against 1.7 for EIGA.¹⁵

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6. Conclusions

This survey of safety and liquid air suggests the following conclusions:

- Any use of liquid air or liquid nitrogen as an energy vector presents serious but familiar and manageable hazards of cold, oxygen enrichment and asphyxiation.
- These hazards are well understood and subject to standard industry safety procedures, regulations and equipment.
- The experience of Highview Power Storage in managing oxygen enrichment is encouraging, as is the safety record of the industrial gases industry.
- Safety considerations may suggest liquid air is preferable to liquid nitrogen in some circumstances and vice versa.
- Any use of liquid air or liquid nitrogen by members of the public would require it to be as safe or safer than using petrol or diesel, and all relevant technologies would need to be designed and engineered to ensure this.
- There is no insuperable safety reason why liquid air and/or liquid nitrogen should not be widely deployed as an energy vector in both grid and transport applications.

Chapter 9 Endnotes

¹ *Potential for BLEVE associated with marine LNG vessel fires*, Pitblado, *Journal of Hazardous Materials*, 140, 2006, pp527-5346.

² *Boiler and Pressure Vessel Code, Section VIII Unfired Pressure Vessels*, American Society of Mechanical Engineers, 2010, <http://files.asme.org/Catalog/Codes/PrintBook/32477.pdf>

³ *Cryogenic Safety Manual*, Argonne National Laboratory, <http://www.phy.anl.gov/division/esh/Cryogenic/Appendix%203/Appendix%203.htm>

⁴ See for example *Oxygen Hazard Safety booklet* from Jefferson Lab, <http://www.jlab.org/accel/safetylb/ODH-book.pdf>

⁵ *The AirLock System, preventing O2 enrichment in liquid air vessels*, Stirling Cryogenics and Refrigeration, [http://www.d-h-industries.us/~uploads/paragraph/file/AIRLOCK\(1\).pd](http://www.d-h-industries.us/~uploads/paragraph/file/AIRLOCK(1).pd)

⁶ *Apparatus for storing a multi-component cryogenic liquid*, US Patent 5571231A, BOC, <http://www.google.com/patents/US5571231>

⁷ Ibid.

⁸ <http://www.shell.ca/en/aboutshell/media-centre/news-and-media-releases/2013-new-and-press-releases/03062013-ing-station.html>

⁹ *The AirLock System, preventing O2 enrichment in liquid air vessels*, Stirling Cryogenics and Refrigeration, [http://www.d-h-industries.us/~uploads/paragraph/file/AIRLOCK\(1\).pdf](http://www.d-h-industries.us/~uploads/paragraph/file/AIRLOCK(1).pdf)

¹⁰ *Apparatus for storing a multi-component cryogenic liquid*, US Patent 5571231A, BOC, <http://www.google.com/patents/US5571231>

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¹² <http://www.eiga.eu/index.php?id=158>

¹³ Ibid.

¹⁴ Ibid.

¹⁵ *Safety performance indicators - 2011 data*, International Organization of Oil & Gas Producers (OGP), <http://www.ogp.org.uk/pubs/2011s.pdf>; and EIGA personal communication, February 2013.

Chapter 10 Climate change

1. CO₂ emissions reduction in grid electricity

2. CO₂ emissions reduction in transport

3. Conclusions

The ability of liquid air to reduce carbon dioxide emissions depends largely on the carbon intensity of the electricity used to produce it. However, the scale of emissions reductions is also application specific: some liquid air concepts such as refrigerated food transport would reduce carbon emissions even based on current grid average carbon intensity; others would start to deliver emissions reductions only on the basis of lower carbon electricity.

The carbon intensity of the grid is projected to fall significantly over the next two decades as coal fired power stations close and more wind generation continues to be added. This will reduce grid emissions overall, but will have an even more pronounced impact on off-peak or overnight carbon intensity, when demand is lower and nuclear and wind capacity will on average deliver a bigger proportion of the necessary power.

This is important because at present liquid nitrogen is invariably produced at night to take advantage of lower cost electricity. This coincidence of lower cost and lower carbon electricity means emissions from liquid air technologies will fall faster than if they were charged at the grid average. It means for example that a diesel-cryogenic hybrid bus running on overnight liquid air would start to emit less CO₂ than a standard diesel from 2015, and emissions would continue to improve thereafter.

As well as reducing transport emissions, liquid air can also further reduce emissions from grid electricity in two ways. First, it can harvest excess wind power that would otherwise be wasted ('curtailed') at times of low demand, and use it to displace carbon intensive generators at peak times. Second, it allows fossil plant to run more efficiently at full load rather than 'ramping' up and down to accommodate variable wind generation, as this role is assumed by storage. These two factors have the effect of lowering average emissions from grid electricity beyond any reductions achieved by simply changing the primary generating mix.

In this chapter we explore how, and under what conditions, liquid air can help reduce carbon emissions on the grid, and show how some liquid air transport concepts could have the lowest lifecycle emissions of any competing vehicle by 2030.

1. CO₂ emissions reduction in grid electricity

Of the many benefits electricity storage could potentially contribute towards future electricity systems, its CO₂ reduction potential is among the least understood. Only a small proportion (around 4%) of the benefits of storage identified by stakeholders relates directly to CO₂ savings¹, and many commentators do not regard emissions reduction as the primary reason for installing storage.²

As a result, policy tools such as the DECC 2050 emissions calculator do not attribute any CO₂ reduction to the deployment of storage.³ Indeed, many of the models used to support the 80% UK emissions reduction target for 2050 do so by imposing an external emission constraint, which they try to meet at least cost. Including storage in these models can open up new plant mix options and reduce the overall cost, but the total emissions

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remain unchanged because they constitute the externally imposed limit.⁴ Exceeding the constraint is not 'optimal' within the narrative of such models.

Nevertheless, storage has the potential to improve system operation and lead to CO₂ reductions - even if that is not the owners' main motivation. We deliberately calculated CO₂ reductions for *commercially operated* storage, rather than seeking to maximise this emissions reductions *per se*. In other words, the model was instructed to make money rather than cut carbon and any emissions reductions were a side-benefit. This is a conservative assumption: bigger carbon savings could be achieved by optimising emissions reductions directly, but we wanted to see what might be achieved under 'real world' conditions.

Storage can help to reduce grid emissions by:

- Capturing excess wind or other lower carbon overnight power and using it to displace carbon intensive generators at peak times.
- Allowing fossil plant to run more efficiently at full load, while storage devices assume their 'load following' role - raising or reducing output to match demand.

To estimate the potential savings offered by the first factor, we adopt the dynamic wind and demand model for the UK developed by Grünewald and colleagues and assume 40GW of wind capacity. This would generate around 116TWh a year, of which around 17TWh might need to be curtailed according to our model - the energy equivalent of around 3,000 x 2MW wind turbines. Storage could, to some extent, reduce this curtailment and in turn displace high emitting plants. Assuming an emissions factor of 473gCO₂/kWh* for those displaced generators, up to 8 million tonnes of CO₂ (Mt/CO₂) could in theory be avoided. For this scenario, in which grid emissions total 125MtCO₂, the projected savings are equivalent to around 6.5%.

Estimating the impact of the second factor is more involved, since emissions reductions come from rescheduling of generation from high emitting plant to more efficient generators and from the more efficient operation of those plants by running at closer to full capacity and avoiding ramping (raising or lowering output). We calculate the *combined* impact of this and avoided wind curtailment on system-wide emissions below.

System-wide emissions reductions through storage

The analysis presented here is based on a techno-economic model for the assessment of the role of electricity storage in low carbon energy systems developed by Grünewald and colleagues.⁵ It consists of a data-rich representation of load and wind profiles across the UK, scaled to suit selected decarbonisation pathways. The model balances supply and demand based on a simple merit order stack with hourly resolution. Storage operation is optimised for maximum revenue in an assumed competitive wholesale market. Generally speaking, storage charges during periods of low net load (demand-wind) and discharges when net loads are high or rising fast, thereby displacing costly dispatch from peaking plants.

Since peaking plants also happen to have higher emissions factors than base load and mid-merit plants, one would expect a reduction in emissions when comparing a given scenario with added storage compared to a counterfactual case without storage. This approach differs from previous studies in that the plant mix is not 're-optimised' after storage has been added to the system, so that the 'before' and 'after' emissions can be compared.

It is worth noting that this model does not seek to maximise emission reductions as its objective function, which could lead to bigger savings. Instead, the reported figures are a 'by-product' of a revenue maximising strategy for storage operation.

Storage is represented through technology agnostic high level parameters, such as the installed capacity [GW], the round trip efficiency [%], and the storage duration [h], which is the ratio of the energy storage capacity [GWh] and the installed capacity. The round trip efficiency of storage in low carbon, high wind scenarios has been shown by Strbac and colleagues⁶ to have a minor impact, and efficiency of 75% was assumed.

Our **scenario assumptions** are informed by the DECC 2050 Grassroots pathway. The plant mix evolving from 2010 to 2050 is shown in Figure 10.1. We assume deployment of 40GW of wind, which in this scenario would occur around the mid 2020s.⁷

Storage can reduce grid emissions by using excess off-peak renewable energy to displace fossil fuel generators at peak times, and by allowing fossil plant to run more efficiently at full load. In a 'high wind' scenario the first factor alone could cut emissions by 8 million tonnes per year or 6.5%.

* Based on interpolated values from the DECC Grassroots scenario for all plants other than wind and nuclear

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In a 'high wind' scenario, 20GW of storage capacity could cut system-wide emissions by 14 million tonnes per year, while 30GW would save 24Mt or almost a fifth of total grid emissions.

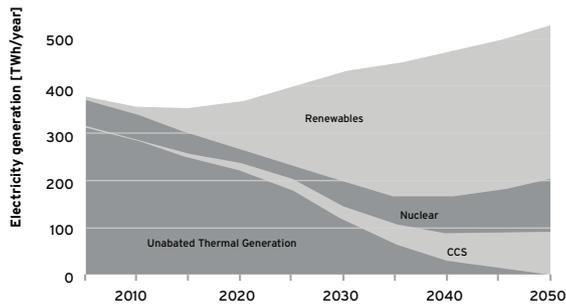


Figure 10.1: Generating mix evolution to 2050. Source: DECC Grassroots scenario

Assumed emission factors are based on Macleay and colleagues⁸ and shown in Table 10.1. The average emissions apply to the entire fuel based generation across the year. The emissions factor for peaking plants is more than twice the average, due to lower efficiencies and less favourable operating conditions. In high wind scenarios this capacity operates at low load factors of below 20% and is required to ramp up and down to suit the combined slew rate of demand and wind. Wind and nuclear plants on the other hand are assumed to serve base loads and have marginal emission factors assumed as zero.

Class	Symbol	Emissions factor [t/GWh]
Peaking	e_{pk}	915
Mid merit	e_{mm}	598
Average	e_{mean}	400

Table 10.1: Assumed emissions factors. Source: Macleay, 2010⁸

The reduction in output from peaking capacity and mid merit capacity is calculated for each storage configuration and the resulting emission reduction is calculated as:

$$\eta_{CO_2, str} = \frac{(E_{pk_{ref}} - E_{pk_{str}}) \times e_{pk} + (E_{mm_{ref}} - E_{mm_{str}}) \times e_{mm}}{\sum E_{ref} \times e_{mean}}$$

where E is the total energy output from a given merit order class (pk = peaking plant, mm = mid merit plant). The suffix ref denotes the reference case without storage and str are outputs after storage has been added to the system.

The results presented in Figure 10.2 show the impact of storage on overall emissions in our scenario with 40GW of wind. The first 10GW of storage delivers only modest emission reductions of less than 5% compared to the counterfactual scenario under the operating strategy simulated here.

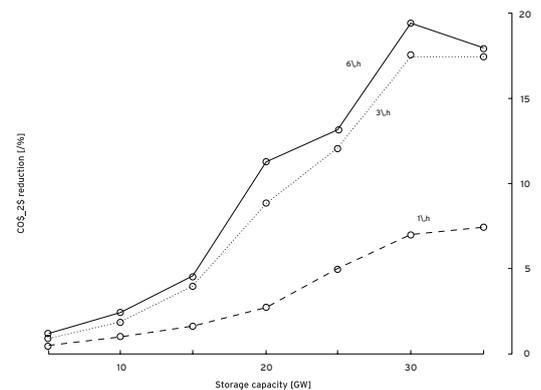


Figure 10.2: The impact of storage on emissions with 40GW wind capacity

Higher capacities of storage with longer durations, such as those achievable by liquid air energy storage devices, can displace larger shares of peaking capacity and thereby increase the CO_2 reductions. One hour storage, even with large scale deployment, produces maximum savings of around 7-8%. This level can be achieved with around half the capacity if storage durations exceed three hours. At six hours' storage duration, easily achievable with Liquid Air Energy Storage, 15GW of storage capacity would save 5.6 million tonnes (Mt) while 20GW would save 14Mt. A far more ambitious scenario of 30GW would save 24Mt, or almost a fifth (19.4%) of total grid emissions of 125Mt.

In this scenario, emissions reductions reach a saturation point at around 30GW of six hour storage. Additional capacity can even lead to lower emission reductions as round trip losses - simulated here as 25% - begin to outweigh the gains from displacing high emitting plant, as shown in Figure 10.1. Further extension of storage durations beyond six hours have also been simulated, but these deliver only marginal improvements over the results shown here.

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Off-peak emissions intensity

Since liquid nitrogen is invariably produced overnight when power prices are lowest, it is important to understand the likely evolution of the off-peak carbon intensity of grid electricity. To calculate this we make some simplifying assumptions and build on scenarios from DECC's 2050 pathway analysis. We focus here on a highly renewable scenario, as this illustrates most clearly how storage can support decarbonisation of the wider energy system. The generation mix is the same as illustrated in Figure 10.1.

The simulation uses static conditions as opposed to dynamic simulation, and we assume that storage charges only for up to 10 hours during the night when demand is below 35GW. The lower we set this operating threshold, the better the environmental performance of storage would become. 35GW is, therefore, a conservative estimate which coincides with the highest night time demand presently experienced during the winter months in the UK. The underpinning DECC Grassroots pathway suggests reductions in overall electricity demand towards 2030. Instead of reducing the night time load threshold over time, we keep this value at a constant level to allow for additional demand from storage, which could contribute towards off-peak demand. The results are therefore not expected to be adversely affected by storage itself increasing the night time emissions factor.

We also assume that nuclear and wind capacity are dispatched whenever possible, thereby displacing unabated plant during periods of low demand. Based on a load factor of 33% for wind, we estimate that the share of zero carbon generation during these low demand periods could increase from 42% in 2020 to as much as 80% in 2030 (Table 10.1).

The emissions factors for the remaining fleet have been derived from the DECC scenarios by dividing the total emissions for the respective year by the electricity provided by all plants other than wind or nuclear.

As shown in Figure 10.3 and Table 10.2, the emissions factor for 'non wind and nuclear' plants remains relatively high in this pathway, whereas the increasing share of wind and nuclear generation reduces the emissions factor during low demand periods to levels that are well below the average. By 2030 the emissions factor during low demand periods could become as low as 53gCO₂/kWh, for a system that on average still emits 93gCO₂/kWh.

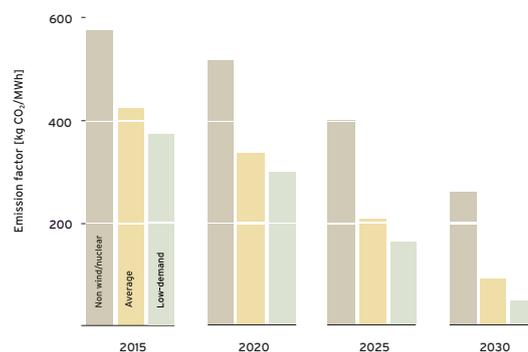


Figure 10.3: Reducing emission factors in Grassroots scenario. During low demand periods the emissions factor is lower than average. The combined emissions factor for plants other than wind and nuclear—here labelled as 'non wind/nuclear'—also falls over time, but the ratio between these generators and low demand emissions increases, favouring the use of storage from an emissions perspective.

Year	2015	2020	2025	2030
Wind installed capacity [GW]	17.8	33.0	52.5	68.7
Nuclear installed capacity [GW]	7.2	4.9	4.9	7.3
Mean share of wind and nuclear at times of low demand [%]	36	42	59	80
Average emissions from non wind/nuclear generation [tCO ₂ /GWh]	575	516	402	261
Emission during low demand [tCO ₂ /GWh]	369	298	165	53

Table 10.2: Emission factors in the DECC Grassroots scenario. Charging storage over night during low demand (here defined as below 35GW) leads to reduced emission factors. Assuming 33% load factor for wind, the contribution of zero-emitting plants towards low demand periods increases substantially over time. Emissions during these periods therefore reduce faster than average emissions, giving storage the opportunity to reduce emissions by shifting energy between low and high demand periods.

Liquid nitrogen is invariably produced at night when power prices are lowest, and the carbon intensity of overnight electricity will fall faster than grid average. This reduces the emissions from liquid nitrogen or liquid air used as transport fuel.

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The emissions profile of liquid air vehicles benefits from progressive reductions in the carbon intensity of overnight electricity, and lower embedded emissions than EVs or FCVs.

2. CO₂ emissions reduction in transport

In conventional vehicles, the dominant source of greenhouse gas emissions is the combustion of fossil fuels in the vehicles themselves. Life-cycle studies¹⁰ have shown that, for a passenger car, about 80% of total emissions come from fuel use - overwhelmingly from the exhaust pipe, with a much smaller fraction caused by oil production and refining - and 20% from 'embedded' emissions due to manufacturing and disposal of the vehicle. In commercial vehicles, which are used more intensively, fuel use accounts for an even higher share of lifecycle emissions - typically 90% or more.

For alternative technologies such as electric vehicles (EVs), hydrogen fuel cell vehicles (FCVs) and future vehicles powered by liquid air engines such as the Dearman Engine (DE), emissions are dominated by the carbon intensity of the electricity used to make the 'fuel' and the efficiency of the powertrain. This makes the lifecycle emissions of all three technologies sensitive to the pace of decarbonisation of the electricity grid. On a 'well-to-wheels' basis, which considers emissions from fuel use only, emissions from a DE vehicle would be twice those of an ICE today, but fall to less than a third by the 2030s assuming overnight grid emissions intensity falls as projected in section 1. ICE-DE hybrids could produce carbon savings from 2015.

Another significant factor is embedded emissions. EV's and FCVs have higher embedded emissions than internal combustion engine (ICE) vehicles because of the lithium and platinum needed to make batteries and fuel cells. However, DE vehicles are likely to have embedded emissions similar to ICE vehicles in the early years of production, and probably lower in the longer term, since the DE runs at ambient temperatures (10-20C) and could therefore be manufactured from lighter materials (chapter 8). Even disregarding this last factor, we calculate that DE lifecycle emissions will be lower than those of current EVs and FCVs by the 2030s.

One application, food transport refrigeration, could achieve major CO₂ reductions even on the basis of the current grid average carbon intensity. We calculate a large refrigerated lorry fitted with a Dearman Engine to provide both shaft power and cooling could save 38 tonnes

of CO₂ per year, a reduction of 80% against conventional diesel-powered refrigeration. If applied across the entire sector, this would amount to savings of 240,000 tonnes per year, or 0.04% of total UK greenhouse gas emissions.¹¹

The analysis below considers the impacts on CO₂ emissions of using grid average and overnight electricity to produce liquid air for three potential applications.

Prime mover applications

The 'well-to-wheels' emissions of a DE vehicle are strongly related to the carbon intensity of the electricity used to produce liquid air. At current grid average of 547gCO₂/kWh the DE is likely to produce emissions of 2188gCO₂/kWh at the drive shaft - more than twice the emissions of an ICE.¹² However, at 50gCO₂/kWh, which is roughly the level we project for overnight power in 2030 in section 1, and which is also the Climate Change Committee's target for average emissions in a 'decarbonised' grid, the DE would emit around 200gCO₂/kWh, less than a third of those from a 30% blend of biodiesel, but still higher than those of an EV or FCV (Table 10.3).

Technology	gCO ₂ /kWh at shaft now	gCO ₂ /kWh at shaft 2030
Baseline - diesel engine	840 (fossil fuel)	700 (B30 second gen)
Grid carbon intensity	547g/kWh	~50g/kWh available overnight
Dearman Engine ¹³	2,188	200
EV ¹⁴	707	65
Hydrogen fuel cell (electrolysis) ¹⁵	2,068	189

Table 10.3: Well-to-wheels emissions of various powertrains compared

However, embedded carbon also has a significant impact on lifecycle emissions. A recent report by Ricardo for the Low Carbon Vehicle Partnership estimated carbon emissions from the production and disposal of a variety of powertrains for a medium sized car (Table 10.4).¹⁶ A cryogenic engine such as the Dearman Engine is likely to be made from similar materials to an ICE - at least in the early years of production - and is therefore likely to have comparable emissions during its production and disposal.

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Technology	T CO ₂ emitted during manufacture	T CO ₂ emitted during disposal	Total
IC engine (gasoline)	5.6	0.3	5.9
Dearman Engine	5.6	0.3	5.9
EV	8.8	0.4	9.2
Hydrogen fuel cell	6.7	0.5	7.2

Table 10.4: Embedded emissions of various powertrains compared. Source: Ricardo⁷

Ricardo went on to calculate the lifecycle emissions of ICE, EV and FCV cars on the basis of the embedded emissions in Table 10.2, and making uniform assumptions about lifetime mileage (150,000km) and the amount of energy required per kilometre driven (0.13kWh/km), meaning each powertrain would need to deliver 19,500kWh of shaft power over its lifetime. If we apply the same assumptions to the DE, on the basis of the overnight grid carbon intensity projected in Table 10.1 its lifecycle emissions are lower in 2030 than all other powertrains (Table 10.5). Until 2030 EVs have the lowest lifecycle emissions under all grid carbon intensity assumptions, but at that point the lower embedded emissions of the DE tip the balance. In all cases, the FCV

produces the smallest carbon savings of the three powertrains. Both the FCV and the EV are likely to have higher capital costs than the DE.

DE lifecycle emissions could fall further as the technology develops, since the engine runs at ambient temperatures, and could therefore be built with lighter materials and potentially produced using 3-D printing (chapter 8).

If the electricity used to make liquid air is supplied through 'wind-twinning' arrangements that contractually connect cryogen production to the output of a specific wind farm, then substantial emissions reductions would be achieved sooner than on the basis of overnight carbon intensities. Emissions would also be low in a number of countries that already have low carbon electricity due to nuclear or renewable generation:¹⁸

- Brazil 87g/kWh.
- France 78g/kWh.
- Norway 3g/kWh.
- Sweden 41g/kWh.
- Switzerland 7g/kWh.

A Dearman Engine car has lower lifecycle emissions than EVs or FCVs on the basis of overnight electricity by 2030.

	Efficiency assumption	Lifetime energy kWh*	Total CO ₂ emissions (inc manufacture and disposal)			
			2015	2020	2025	2030
Grid avge.						
EV	77%	25,194	19.87	17.63	14.44	11.55
FCV	26%	73,734	40.42	33.88	24.41	16.08
DE**	25%	78,000	38.93	32.01	21.99	13.18
Overnight						
EV	77%	25,194	18.5	16.7	13.36	10.54
FCV	26%	73,734	36.43	31.16	21.38	13.11
DE**	25%	78,000	34.7	29.13	18.79	10.04
* Shaft power required (19,500kWh) x efficiency						
** at ambient						
Green = lowest carbon emissions						

Table 10.5: Lifecycle emissions of various powertrains compared

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A Dearman Engine could be combined with an internal combustion engine to make a "heat hybrid" that consumes less fossil fuel. A bus based on this design and overnight electricity would cut emissions from 2015.

Heat hybrids

The efficiency of cryogenic engines such as the Dearman Engine is increased by the addition of waste heat, raising the possibility of an ICE-DE hybrid. The simplest formulation would be small cryogenic engine to harvest waste heat from the ICE radiator fluid to generate extra shaft power.

An ICE-DE hybrid would effectively substitute shaft power that would otherwise be generated by the ICE for shaft power generated by vaporising liquid air. Different applications would require different relative sizes of DE and IC engines, but a general picture of the type of carbon impacts that could be achieved by this approach can be shown by comparing CO₂ emissions from producing a kWh of shaft power with liquid air and those produced by a kWh of diesel power.

Waste heat from an ICE at 90-100C would increase the specific energy of liquid air by about 20%. So at current grid average carbon intensity, a DE waste heat hybrid would emit 1823gCO₂/kWh of shaft power.¹⁹ However, the balance changes as grid carbon intensities fall, as shown in Table 10.6. On the basis of the grid average and overnight carbon intensities projected in Table 10.1, Dearman Engines and Dearman heat hybrids produce lower emissions than diesel under all scenarios by 2025, and lower emissions than biodiesel by 2030.

Burning a litre of diesel causes 3.24kgCO₂e emissions, which corresponds to 0.839kgCO₂e/kWh of shaft power²⁰, while burning a litre of pure biodiesel is estimated to emit 2.49kgCO₂e²¹, which equates to 645gCO₂e/kWh of shaft power. By contrast, at a grid carbon intensity of 53gCO₂/kWh, the DE prime mover would emit 212gCO₂/kWh, and the heat hybrid would emit 177gCO₂/kWh. Switching from diesel to biodiesel cuts emissions by only 23%, whereas switching from biodiesel to a heat hybrid saves a further 70% when based on 2030 overnight grid carbon intensity. Switching from diesel to the heat hybrid would save almost 80%. The carbon intensity of crude oil can be expected to increase over time as production shifts to more energy intensive unconventional resources.

	gCO ₂ /kWh			
	2015	2020	2025	2030
Diesel (gCO ₂ e/kWh)	840	840	840	840
Biodiesel (gCO ₂ e/kWh)	645	645	645	645
Dearman carbon intensity per kWh (ambient)				
Grid average electricity (gCO ₂ /kWh)	1,694	1,339	825	373
Overnight electricity (gCO ₂ /kWh)	1,477	1,191	661	212
Dearman Engine carbon intensity per kWh (waste heat)				
Grid average electricity (gCO ₂ /kWh)	1,412	1,116	687	311
Overnight electricity (gCO ₂ /kWh)	1,231	993	551	177
Yellow cells are lower than diesel.				
Green cells are lower than biodiesel.				

Table 10.6: DE heat hybrid emissions compared to diesel and biodiesel emissions

This calculation shows the idealised emissions reductions that could be achieved in principle by switching fuels and powertrains, but takes no account of the practical factors that affect vehicle performance in the real world. The Dearman Engine Company and E4tech have conducted more detailed modelling that includes factors such as embedded carbon, tank size, cooling constraints and operating strategies that use the system to best effect on a city drive cycle. The results suggest a smoother trajectory: Dearman heat hybrids would offer emissions reductions compared to a standard diesel almost immediately, but emissions reductions in the long term would not be as large as shown as shown above - although this does not take account of the likely long term reductions in embedded emissions.

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The two key conclusions of this modelling are that a Dearman heat hybrid would allow the ICE to be downsized significantly, perhaps by a factor of 2 or more where the duty cycle allows, as it has been in some EV hybrid buses. The other is that, with the right configuration and operating strategy, emissions break-even is achieved with electricity at around 400g/kWh, meaning that such hybrids would deliver emissions reductions on the basis of the projected carbon intensity of overnight electricity in 2015. At 50g/kWh, roughly the projected overnight carbon intensity for 2030, such a hybrid would deliver more than 20% well-to-wheel CO₂ saving and a short payback time. In all cases, consumption of diesel is around 25% lower than baseline.

Transport refrigeration

Refrigerated food transport is a significant and growing source of carbon emissions. The global market is growing fast because of changing diets in Asia, and the rise of home delivery in western countries. At the same time, mobile refrigeration equipment is inevitably less efficient than static, since it has to fit into a smaller space and deal with a wider range of conditions. Both factors put pressure on the food industry to find ways to cut emissions from refrigerated transport.

In the UK, food transport - including propulsion and refrigeration - accounts for 1.8% of total emissions.²² About a third of this is from refrigerated transport, and refrigeration accounts for about 8% of these vehicles' fuel consumption, meaning food transport refrigeration alone accounts for 0.05% of total UK emissions, or about 295,000 tonnes of CO₂e per year.²³

Mobile refrigeration units are typically powered by an alternator on the main vehicle engine or a co-located diesel generator. These systems are typically very inefficient because they have to be affordable and mobile and accommodate highly variable cooling loads caused by door openings or the addition of a warm payload.²⁴

Liquid nitrogen absorbs about 112Wh/kg of heat when it is vaporised and heated up to 0C.²⁵ A number of industrial gas companies such as Linde and Air Liquide, and other market participants such as EcoFridge, have

developed systems that use liquid nitrogen as a heat sink to provide cooling. These systems either pass liquid nitrogen through a heat exchanger where it vaporises to absorb heat indirectly, or spray liquid nitrogen directly into the compartment. The second method has the advantage of being about a third more efficient, but means oxygen monitors and other safety equipment must be installed to prevent the operator entering the compartment until the atmosphere is breathable. However, neither approach recovers any shaft power from the evaporation process.

If a Dearman Engine or similar were used to exploit the nitrogen vaporisation process, it could generate as much as 50Wh/kg²⁶ of shaft power. If this shaft power were used to drive a refrigeration cycle with similar efficiency to those used in other mobile refrigeration applications, then about 25 to 75Wh/kg of extra cooling could be available.²⁷ Expanding from a high pressure to low also creates a temperature drop, so as much as another 40Wh/kg of cooling may be available from this source. In total then between 65 and 115Wh/kg of additional cooling may be available from recovering some work from vaporisation and this would correspond to a 58% to 102% improvement in cooling available per kilogramme of liquid nitrogen, or a reduction in nitrogen consumption of about 37-50%.

The analysis below is based on figures produced by Air Liquide for a truck carrying frozen products for eight hours a day, 300 days per year with five door openings per day.²⁸ Table 10.7 shows the CO₂ savings achieved by the Air Liquide approach against conventional diesel refrigeration, and in the final column we have calculated the additional reductions that could be obtained by exploiting the vaporisation of liquid air or nitrogen with a Dearman Engine or similar. The calculation assumes current grid average carbon intensity of 547gCO₂/kWh.

The Air Liquide approach saves 31tCO₂/year/vehicle compared to diesel refrigeration, while the DE approach saves 38tCO₂/year, a reduction of 80%. If applied across the entire sector, this would amount to savings of 240,000 tonnes of CO₂ per year, or 0.04% of total UK greenhouse gas emissions. On the basis of projected overnight carbon intensity in 2030, the DE approach would emit less than 1 tonne, a saving of almost 47 tonnes or 98%.

A refrigerated food lorry typically emits 48 tonnes of CO₂ per year from refrigeration alone. A Dearman Engine, which produces both power and cooling from liquid air, could cut this by 38 tonnes or 81%.

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Per Vehicle	Conventional diesel-powered refrigeration	Liquid nitrogen (data from Air Liquide)	Dearman Engine (40% reduction LN ₂ consumption)
Diesel			
Consumption	14,470 litres		
Emission factor	2.94 kgCO ₂ /l		
CO ₂ emissions	42.5 Tonnes CO₂		
Refrigerants			
Losses	1.35 kg		
Emissions factor	3,743.4 kgCO ₂ /kg		
CO ₂ e Emissions	5.1 Tonnes		
Liquid Nitrogen			
Consumption		76,046 kg	45,628 kg
Emissions Factor		0.219 kgCO ₂ /kg ²⁹	
CO₂ emissions			
Total CO ₂ emissions	47.6 Tonnes	16.6 Tonnes	10 Tonnes
CO ₂ saving over diesel		68%	81%

Table 10.7: Annual CO₂ emissions from refrigeration by diesel and liquid nitrogen compared
Source: Air Liquide³⁰, and Liquid Air Energy Group calculation

The potential emissions savings from such an approach should increase over time, since demand for refrigerated transport is growing strongly in both developing and developed economies. Global sales of mobile refrigeration equipment are expected to exceed \$6.5 billion per annum in sales by 2015.³¹ The largest market is North America with \$1.25 billion sales in 2010.³² In the EU there are about 650,000 refrigerated road vehicles in use primarily for food distribution, of which about 8% or 52,000 are in the UK.

Outlook

While the analysis presented above is simple and has a low level of hardware validation, it indicates significant potential for liquid air once the realities of a highly transient energy grid, future renewable generation capacity growth, and the synergies with the heat-wasteful internal combustion engine are considered. During the transition to a low carbon grid, liquid air transport applications appear to offer CO₂ reductions of at least 25% and sometimes much more.

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3. Conclusions

From the discussion presented in this chapter we conclude:

- The carbon reduction potential of liquid air technologies depends heavily on the carbon intensity of the electricity used to produce liquid air.
- Liquid air storage could reduce emissions from grid electricity, by harvesting excess wind power that would otherwise be wasted and by increasing the efficiency of fossil generating plant.
- Savings from avoided wind curtailment alone could amount to 8 million tonnes of CO₂ per year and the energy equivalent of 3,000 x 2MW wind turbines. Total system savings could reach 24MtCO₂ per year, or almost a fifth of total grid emissions in a 40GW wind scenario.
- The carbon intensity of overnight electricity used to produce liquid nitrogen and liquid air will fall faster than the grid average, increasing the emissions reductions achievable from liquid air technologies over time.
- On the basis of projected overnight grid carbon intensities, a Dearman heat hybrid would start to cut emissions compared to a standard diesel from 2015, and the Dearman Engine has lower lifecycle carbon emissions than either the EV or the FCV in 2030.
- A Dearman Engine used to provide refrigeration in food transport could save 38 tonnes of CO₂ per lorry per year, a reduction of 80%, on the basis of current grid carbon intensity, and 47 tonnes or 98% on the basis of projected overnight carbon intensity in 2030.
- If applied across the sector, the emissions savings in food transport on current grid average carbon intensity could save 240,000 tonnes of CO₂ per year, or 0.04% of total UK greenhouse gas emissions.

Chapter 10 Endnotes

- ¹ *The socio-technical transition of distributed electricity storage into future networks - System value and stakeholder views*, P. H. Grünewald et al., Energy Policy 50, pp449-457.
- ² *Energy Storage (presentation)*, D. J. C. MacKay, 6 June 2012 at University of Oxford Department of Physics.
- ³ *2050 Pathway Analysis*, DECC, 2010, www.decc.gov.uk/2050, accessed 1 February 2011.
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- ⁵ *The role of large scale storage in a GB low carbon energy future: Issues and policy challenges*, P. Grünewald et al., Energy Policy 39, 2011, pp4807-4815.
- ⁶ *Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future*, report for the Carbon Trust, G. Strbac et al., June 2012.
- ⁷ Ibid.
- ⁸ Digest of United Kingdom Energy Statistics (DUKES), Technical Report, I. MacLeay et al., DECC, 2010.
- ⁹ Ibid.
- ¹⁰ *Preparing for a lifecycle CO₂ measure*, Ricardo, August 2011, <http://www.lowcvp.org.uk/news/1644/lowcvp-study-highlights-importance-of-measuring-whole-life-carbon-emissions/>
- ¹¹ Figures derived from those supplied by Professor Savvas Tassou, Brunel University, personal communication, February 2013.
- ¹² The energy cost to produce 1kg of liquid air is about 0.4kWh/kg at scale. The UK grid average emissions for electricity is 547gCO₂/kWh. Therefore CO₂ emissions per kg of liquid air produced are 218.8gCO₂/kg if the UK grid average is used. Practical energy density is likely to be around 0.1kWh/kg, therefore shaft power generated by the Dearman Engine produces 2188gCO₂/kWh. The Committee on Climate Change believes the carbon intensity of UK grid can be reduced to less than 50gCO₂/kWh during the 2020s. This would have the impact of reducing Dearman Engine's CO₂ emissions to 200gCO₂/kWh.
- ¹³ Ibid.
- ¹⁴ Assumes 90% charging efficiency and 86% discharging efficiency (energy to the shaft).
- ¹⁵ Assumes energy consumption of 60.5kWh/kg H₂ and 16kWh/kg H₂.
- ¹⁶ *Preparing for a lifecycle CO₂ measure*, Ricardo, August 2011, <http://www.lowcvp.org.uk/news/1644/lowcvp-study-highlights-importance-of-measuring-whole-life-carbon-emissions/>
- ¹⁷ Ibid.
- ¹⁸ <http://www.ipcc.ch/pdf/special-reports/sroc/Tables/t0305.pdf>
- ¹⁹ The energy cost to produce 1kg of liquid air is about 0.4kWh/kg at scale. The UK grid average CO₂ emissions for electricity is 547gCO₂/kWh. Therefore CO₂ emissions per kg of liquid air produced are 218.8gCO₂/kg if the UK grid average is used. For a waste heat hybrid, practical energy density is likely to be around 0.12kWh/kg, so shaft power generated by the Dearman Engine produces 1823gCO₂/kWh under this arrangement.
- ²⁰ Burning 1 litre of diesel causes 3.24kgCO₂e emissions, and the lower calorific value of diesel is 43.4MJ/kg (http://www.engineeringtoolbox.com/fuels-higher-calorific-values-d_169.html), equivalent to about 9.6kWh/litre (multiply by 0.8 for density of diesel then divide by 3.6 to convert to kWh). Practically, diesel engines may achieve about 40% thermal efficiency under optimal load conditions, and much less if they are at part load or idling. This would practically correspond to about 3.86kWh/litre. The kgCO₂e emissions for producing a kWh of shaft power under optimal conditions can be calculated therefore as follows:
- $$\frac{3.24\text{kgCO}_2\text{e/litre}}{3.86\text{kWh/litre}} = 0.839\text{kgCO}_2\text{e/kWh}$$
- ²¹ DEFRA Emission Factor from 2012 *Guidelines to Defra / DECC's GHG Conversion Factors for Company Reporting*, produced by AEA for the Department of Energy and Climate Change (DECC) and the Department for Environment, Food and Rural Affairs (Defra), 2012, p41.
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Chapter 11 Energy security

1. Geopolitical security

2. Price security

3. Physical security

4. The potential impact of liquid air on energy security

Energy security is a widely used but poorly defined term. Even the government has no categorical definition¹, despite having published an energy security strategy in November 2012.² More generally, the phrase is taken to mean the lights will stay on, homes remain warm and vehicles keep moving in all but the most exceptional circumstances.

Conditions that weaken a country's energy security include a high level of import dependency; over-reliance on a single type of energy, supplier or delivery route; low stocks of fuel; and lack of redundancy or spare capacity in energy supply infrastructure such as refineries or the electricity grid. More concrete threats range from political events such as the Arab Spring, the Russia-Ukraine gas transit dispute and the UK petrol protests; natural disasters such as Hurricane Sandy or the tsunami that destroyed the Fukushima nuclear reactors; and technical faults, such as those that reduced supply from the Langeled gas pipeline from Norway in early 2010 and led to industrial gas customers being cut off.

Although the government has not precisely defined energy security, a report³ for DECC by the late Malcolm Wicks MP in 2009 identified three different aspects:

- Geopolitical security: avoiding undue reliance on specific nations so as to maintain maximum degrees of freedom in foreign policy.
- Price security: avoiding unnecessary price spikes due to supply/demand imbalances or poor market operation.
- Physical security: avoiding involuntary physical interruptions to consumption of energy.

The three categories are clearly closely intertwined, and a threat to one form of energy security may well imply a threat to the others. But the reverse is not always true; strategies to strengthen one form of energy security may weaken the others. For example, building large amounts of renewable generation may improve geopolitical security by reducing imports, but worsen physical and price security by increasing intermittency and price volatility. However, at first glance it seems liquid air could strengthen energy security under all three headings (Table 11.1).

1. Geopolitical security

Energy security does not require self-sufficiency; access to international markets helps diversify sources of energy if domestic production is interrupted by, for example, an event such as the Piper Alpha disaster. However, a high level of import dependency raises the proportion of the energy supply over which we have far less control. A recent study by the UK Energy Research Centre identified lower imports as a key indicator of energy system resilience.⁴

By this yardstick, UK energy security has been getting worse since the turn of the century. Oil production on the UK Continental Shelf peaked in 1999, and gas production in 2000, and since then output of each has fallen by around 60%.⁵ Production has declined at about 6.5% per year on average, although gas output slumped by 21% in 2011 alone. The UK, previously self-sufficient in hydrocarbons, became a net importer of gas in 2004 and of oil in 2006. In 2011 we imported 29% of our oil and 44% of our gas.⁶ National Grid and Ofgem expect gas import dependency to reach some 90% by 2030⁷, and the gas generation strategy⁸ announced with the 2012 Autumn Statement is likely to exacerbate this trend, despite the government's decision to allow the resumption of shale gas exploration.⁹

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Rising gas imports are vulnerable to a range of geopolitical, physical and price or market risks. In 2011 a fifth of UK gas consumption was supplied by pipeline from Norway, while almost a quarter arrived in the form of LNG from Qatar. However, since the UK traditionally buys gas on short term contracts, there is no guarantee supplies will arrive when needed. During cold periods when demand for gas is greatest, Norway tends to favour European customers who have committed to long term contracts. This could be critical in any resurgence of the Russia-Ukraine gas transit dispute, or any interruption to other supplies to mainland Europe.

LNG supplies are vulnerable to competition from buyers in Asia, where prices are typically higher, because UK contracts usually have no 'destination clause' that would prevent Qatar from redirecting shipments to the highest bidder. Qatari imports also come with geopolitical risk: Lord Howell, who served as Energy Secretary under both Edward Heath and Margaret Thatcher, has described the threat to Qatari gas from a potential Islamist insurgency in forthright terms.¹⁰

Oil imports are rising more slowly than gas, but are also vulnerable to a range of geopolitical risks, the most obvious being any conflict around the Straits of Hormuz, which carries some 20% of global oil supplies, and natural hazards such as Hurricanes Katrina and Rita in the Gulf of Mexico in 2005. Concern about approaching geological shortage of oil ('peak oil') has abated somewhat following a resurgence of US production, yet there is still a strong case for a structurally tight global oil outlook, in which prices continue to rise and remain likely to spike in response to short term outages.

2. Price security

A working paper from economists at the IMF has argued that the dramatic increases in oil prices so far this century were almost entirely explained by the increasing geological difficulty of producing oil, and that meeting global demand would require real oil prices to rise to \$180 by 2020.¹¹ Financial analysts at Barclays Capital have predicted \$185 per barrel in 2020 for some time. At the same time, highly subsidised domestic consumption among oil producers is cannibalising exports, and on current trends Saudi Arabia will

become a net importer of oil by 2038.¹² Combined with relentless demand growth among developing economies, this has kept oil prices at historically high levels in spite of recession in much of the developed world. Brent crude recorded its highest ever annual average at just under \$112 in 2012.¹³ The impact of high oil prices goes far beyond any narrow definition of energy security; the spike to \$147 per barrel in 2008 is estimated to have cost the global economy \$150 billion.¹⁴ Some analysts argue that economic growth is simply unsustainable oil prices higher than about \$120.¹⁵

In Europe, the link between oil and gas prices loosened in the wake of the financial crisis, but the majority of pipeline imports to the continent are still bought under oil-indexed contracts. In recent years European spot prices have traded closer to the oil-indexed level again and UK prices have tended to track those in Europe.¹⁶ LNG cargoes, as noted earlier, are subject to competing demand from Asia and elsewhere, and last year UK imports fell by almost half, in part because Qatar found higher bidders elsewhere.¹⁷

If shale gas production were to develop in the UK it might moderate the rapid decline in UK gas production and bolster energy security. However, it would be unlikely to affect materially the wholesale price of gas in Britain, which would continue to be set by the need to attract large volumes of imports from Europe and further afield and by European demand for British gas.

The overwhelming consensus among energy experts is that shale gas production will not make a significant impact in Europe before 2030. A study from the Oxford Institute of Energy Studies has concluded there will be no significant shale gas production in Europe before 2020, and that "unconventional gas will not be a price setter at a European level".¹⁸ Research by VTB Capital concludes that European shale gas looks geologically and commercially "challenged" compared to the US, and that "Shale gas will not be transformative in Europe".¹⁹ BP predicts Europe's net gas imports will rise 48% by 2030 because shale output is too small to offset the rapid decline of conventional production.²⁰ A report by the Energy Contract Company concludes "shale will not be a 'cheap' source of gas and there is unlikely to be a repeat of the US experience".²¹ And a study by Pöyry suggests that if UK shale production were to reach 20% of GB supply by 2030, prices

UK oil and gas production peaked at the turn of the century, economists at the IMF predict the oil price will hit \$180 per barrel by 2020, and gas import dependency is expected to reach 90% by 2030.

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On the electricity grid, spare generating capacity will fall to precarious levels by 2015, significantly increasing the risk of power cuts. National Grid says backup capacity needs to double by 2020.

would be just 2-4% lower than if there were no shale production.²²

However, prices are still expected to rise in absolute terms. In the International Energy Agency's 'Golden Age of Gas' scenario, which assumes the most favourable conditions for unconventional gas production, European prices rise from \$7.4 per million British thermal units in 2009 to \$10.9/MBtu in 2035.²³ Rising gas prices could be further inflated by high carbon costs, according to the Climate Change Committee, the government's independent advisor, which concludes "the average annual household bill in a gas-based system could be as much as £600 higher in 2050 than in a low-carbon system if gas and carbon prices turn out to be high".²⁴

3. Physical security

While rising imports lead to lower levels of geopolitical and price security, at home the physical security of the electricity system is also worsening, as a result of the closure of coal and nuclear plant and the growth of intermittent renewable generation (chapter 1). Physical security is threatened by both the increasing complexity of balancing the grid over minutes and hours and by the impact of longer-duration threats such as a winter anticyclone producing a windless week in February.

The UK has committed to generate 15% of its energy from renewable sources by 2020, and this implies around 30% of our electricity will need to come from renewables by the end of the decade, the bulk of it from wind.²⁵ As renewable penetration increases, more balancing capacity will be required. National Grid estimates that balancing capacity ('operating reserves') will need to rise from 3.5GW today to 8GW by 2020.²⁶

However, Ofgem's most recent Electricity Capacity Assessment shows that the physical security of the grid will worsen at least until the middle of the decade. It forecasts that derated capacity margins (spare generating

capacity as a proportion of peak demand) will fall from a comfortable 14% today to just 4% in 2015/16, and warns, "the risk of customer disconnections will appreciably increase from a negligible 1-in-3300 years event at present, to a 1-in-12 years event by 2015/16". Margins would fall to below zero if high European power prices caused interconnectors to export at full capacity, resulting in an energy shortfall of 30GWh, equivalent to the annual consumption of 9,000 homes.²⁷

Declining capacity margins also seem likely to worsen price security, particularly for industrial customers, by increasing the volatility of electricity prices.

4. The potential impact of liquid air on energy security

It is hard to avoid the conclusion that UK energy security has worsened significantly since the turn of the century and will continue to do so in the absence of remedial action. Import dependency continues to rise in spite of falling oil and gas demand in recent years, increasing our vulnerability to supply disruptions and price spikes, and at home electricity capacity margins are falling towards precarious levels. In these circumstances, liquid air could help improve energy security by:

- Reducing gas imports by storing excess off-peak wind power to displace gas fired peaking plant. This would a) reduce vulnerability to any geopolitical, technical or weather-related interruption to gas imports, b) reduce vulnerability to high and volatile gas prices, and c) reduce the gas import bill in any event.
- Reducing imports of oil, petrol and diesel by converting low carbon electricity into a transport energy vector/fuel. This would a) reduce vulnerability to any geopolitical, technical or weather-related interruption to imports, b) reduce vulnerability to high and volatile oil prices, and c) reduce the oil import bill in any event.

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- Improving the physical energy security of the electricity grid by mitigating intermittency of renewable generation. This would reduce the risk of power cuts, smooth price volatility and reduce average power prices.

- Providing strategic electricity storage. Since liquid air or liquid nitrogen storage capacity is cheap, substantial amounts of liquid air could be stored against a windless week in February, and other longer-duration threats. A single cryogenic storage tank of 190,000m³, such as those used to store LNG, filled with liquid air would represent about 16.6GWh, equivalent to more than 15 minutes of UK peak electricity consumption.²⁸ Alternatively, if the UK had 30GW of wind capacity whose output suddenly dropped by 5GW, such a tank could potentially make good the shortfall in power for three hours.

- Improving price security by reducing the need to invest in flexible generation and grid reinforcement, and reducing wind wastage. A study for the Carbon Trust led by Professor Goran Strbac of Imperial College found the total benefits of storage to the British electricity network could amount to £10 billion per year by 2050.²⁹

- Increasing 'autogeneration' among British companies:

- Existing commercial users of nitrogen who store it as liquid but use it as a gas could use the regassification process to generate electricity, especially where there is a source of low grade waste heat. Increased autogeneration could reduce demand on commercial generators at peak times, and/or more generally.

- Companies with large amounts of emergency diesel generator capacity, such as water companies, could replace it with cryogenic generating equipment and liquid air/nitrogen storage. This would provide the same level of energy security to the companies concerned but with lower emissions, provided the liquid air/nitrogen was produced from excess off-peak low carbon generation. It would also reduce imports of petrol and diesel and exposure to volatile oil prices. Such cryogenic generating capacity could potentially also be used to help balance the grid on a more regular basis, through STOR or any future arrangement introduced through the EMR.

Liquid air benefit	Energy Security Type		
	Geopolitical	Price	Physical
Reduce gas imports	✓	✓	
Reduce oil imports	✓	✓	
Mitigate renewables intermittency		✓	✓
Strategic energy storage	✓	✓	✓
Reduce invest in flex gen & grid infrastructure		✓	
Reduce wind curtailment		✓	
Increase autogeneration		✓	✓

Table 11.1: Potential energy security benefits of liquid air

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