The best use of waste cold from LNG re-gasification - Liquid air as an energy vector

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Summary

The European Commission draft issue paper SET-Plan ACTION no 6 correctly identified waste cold recovery from LNG re-gasification as a source of potentially huge energy savings. But to categorise this opportunity, as the issue paper does in Table 3, under the 'petrochemical refineries' sector would be a mistake. Re-cycling LNG waste cold through petrochemical processes means the cold is available only to industries near the LNG terminal, and only intermittently when LNG is actually being re-gasified. This in turn restricts the proportion of waste cold that can be used in the most efficient way.

The key to greater use is to decouple the production and consumption of cold through novel energy vectors that can store and transport it for use on demand in cities and further afield. The vast LNG waste cold resource could then be deployed to reduce the cost and environmental impact of booming demand for cooling throughout society - from data centres to air conditioning to food and pharmaceutical cold chains. This matters because cooling already consumes 17% of the world's electricity and produces 10% of its CO2 emissions, and energy demand for space cooling is forecast to outstrip that for space heating by mid-century – so greening cold should be an urgent priority.

One recent suggestion for the energy vector is liquid air (LAIR) or liquid nitrogen (LIN). Liquid nitrogen is already available throughout the EU, and is being demonstrated as a fuel for a novel zero-emission engine, the Dearman engine, which generates both cold and power from a single tank of cryogen for a variety of applications in vehicles and buildings. The first application as a zero-emission transport refrigeration unit (TRU) is already in demonstration, and economic without subsidy against both the highly polluting diesel TRUs that currently dominate the logistics industry, and evaporation-only nitrogen systems such as Frostcruise. Integrating the waste cold of LNG into air liquefaction would reduce the electricity required significantly and cut the costs by half. Cheap liquid air could then be used to provide low carbon, zero emission 'cold and power' to vehicles and buildings in Europe's cities through innovative enabling technologies such as the Dearman engine.

The waste cold from the LNG imports of just 7 EU countries in 2014 could have supported the cooling demand for 210,000 refrigerated vehicles, around a fifth of the entire EU fleet.[1] The IEA expects LNG imports into Europe to increase to 90bcm (69mt) by 2020[2], which could in principle support a fleet of more than 550,000 liquid air TRUs, well over half the current EU fleet. By extension a projected global LNG trade of 500mtpa in 2025 could support almost 4 million TRUs – about the size of current worldwide fleet.

The Dearman approach would be profitable without subsidy, and we estimate that re-cycling waste cold in this way could generate an economic value of up to £30 per tonne of LNG, raising the value of the gas by around 10%[3], which at projected 2020 European import levels represents a potential waste cold recovery market worth over £2 billion (€2.7 billion). Modelling suggests a 600tpd LAES plant built at the Isle of Grain LNG terminal in Kent, England supplying Dearman engine TRUs would have a net present value of £15 million and an internal rate of return (IRR) of 26%. Liquid air produced with LNG waste cold could alternatively be used for grid balancing through Liquid Air Energy Storage, but this novel electricity-to-electricity storage technology is uneconomic without subsidy in most current markets.

The energy savings and economics alone make a compelling business case, but the Dearman approach also generates huge savings in social costs. The zero-emission Dearman TRU displaces diesel TRUs which emit CO2 and grossly disproportionate amounts of NOx (nitrogen oxides) and PM (particulate matter) – the toxic pollutants that cause over 400,000 premature deaths in the EU each year. Transport refrigeration unit emissions are essentially unregulated in Europe – recent revisions to the NRMM regulations notwithstanding - meaning a diesel TRU can emit up to 29 times as much NOx and 6 times as much PM as a Euro VI propulsion engine (see Appendix 5). Put another way, modelling of a 17 tonne refrigerated truck shows that if its diesel TRU were replaced with a Dearman TRU, the vehicle's total NOx emissions would be reduced by 73% and its PM emissions by 92%. As a result, converting the EU TRU fleet to Dearman TRUs over the next decade would reduce health and other social costs by €8.7 billion (£6.4 billion).[4]

EASE, the European Association for the Storage of Energy, has pointed out that storing energy as cold rather than electricity would also increase the proportion of renewable generation in European electricity grids and save several million tonnes of carbon in the EU each year.[5] Liquid nitrogen is already well placed to achieve this, since liquefaction typically happens at night when the cost and carbon intensity of grid electricity is lowest. It could also be arranged to take advantage of periods of high solar PV output as experienced in Germany for example. The liquid nitrogen – or air – would then be stored and distributed to provide lower carbon, zero emission cooling at peak times.

Liquid air is not the only way to re-cycle LNG waste cold - R&D led by the University of Birmingham Centre for Cryogenic Energy Storage is intended to develop new phase change materials and technologies with greater energy density – but of all the current options, it produces the greatest energy, financial and environmental benefits.

The calculations that underpin this paper, based on work part funded by Innovate UK, are high level but robust, and certainly justify a full-scale feasibility study into the engineering and economics of a pilot project. The benefits of waste cold recycling would accrue not only to the end-user of the cold, but also the LNG terminal operator and society at large, meaning such a study could be jointly funded by industry, government and the EC. We urge stakeholders to consider our findings, shown in more detail below.

Territory	Year	LNG imports mt	TRUs supported	% of crnt fleet	Waste cold recovery market
UK	2014	8.4	67,000	80%	£252,000
7 EU countries	2014	26	210,000	20%	£792,000
Europe	2020e	69	550,000	55%	£2,000,000,000
World	2025e	500	4,000,000	100%	£15,000,000,000

Table 1: Potential scale and value of LNG waste cold recovery in zero emission transport refrigeration.

Background

After many years in the shadows of the energy debate, the importance of cold in our energy system is finally beginning to be recognised. Cooling matters because it is vital for the supply of food, medicine and data; demand is booming and current cooling technologies are energy intensive and highly polluting. Dearman is a global technology company dedicated to meeting this challenge.

If nothing is done, the environmental impact of cooling can only worsen. Cooling already consumes 17% of the world's electricity, emits 10% of its CO2 and leaks HFC refrigerants, which are themselves highly potent greenhouse gases. Transport refrigeration also emits grossly disproportionate amounts of toxic NOx and PM. Yet in many developing countries cooling is widely lacking, and badly needed to improve health and comfort, and to reduce shockingly high levels of post-harvest food loss. As a result, demand is projected to boom with economic progress and climate change.

According to the IPCC, the electricity consumed by air conditioning will soar 33-fold by 2100 to 10,000TWh, roughly half the total generated worldwide in 2010. The world's refrigerated vehicle fleet is expected by some to grow from 4 million today to as much as 18 million by 2025 impact. And by 2030, we calculate the energy required for cooling for all purposes will need an additional 140GW of generating capacity, more than that of Canada, causing CO2 emissions to rise by 1.5 billion tonnes per year. It is therefore vital that we raise the efficiency of cooling and constrain the amount of primary energy required to deliver it.

Although cooling is both polluting and expensive, vast amounts of cold are wasted during the re-gasification of liquefied natural gas (LNG) at import terminals. Re-cycling this cold to reduce the cost and environmental impact of cooling was one of the key strategies recognised by the Birmingham Policy Commission, *Doing Cold Smarter*, which reported last year.[6]

Dearman is developing a suite of products and services based on novel liquid air technology that provide low carbon, zero emission 'cold and power' while simultaneously reducing capital and lifecycle costs. Early applications include a transport refrigeration unit, a diesel-liquid air 'heat hybrid' engine for trucks and buses, and a back-up electricity generator - all based on the innovative and proprietary Dearman engine powered by the phase change expansion of liquid air or nitrogen (see Appendices).

Industrial gas production capacity exists in all industrialised markets to provide fuel for early deployment of the Dearman engine. But if we recycled waste cold from LNG re-gasification to help produce the cryogenic air or nitrogen, it would further reduce the energy requirement, greenhouse gas emissions and costs of cooling. The Dearman engine is an enabling technology because it offers a method of exploiting waste cold that might otherwise remain stranded.

Obviously turning LNG waste cold into liquid air to serve as an energy vector is not the only approach. There is also the traditional method of piping the cold 'over the fence' to nearby industrial users, and the more recent idea of using it to raise the efficiency of Liquid Air Energy Storage, a novel grid electricity storage technology (see Appendix 2). Both of these alternatives have serious shortcomings, however.

The idea of re-cycling LNG waste cold to provide cooling for industrial processes nearby has been pioneered over the past thirty years at Osaka in Japan. This approach saves energy, of course, but suffers some significant limitations: the cold is only available to industries next door to the LNG terminal; and only during periods when LNG is actually being re-gasified, which is determined by the needs of the gas grid not those of the cooling loads; and insufficient local demand for the highest grade cooling means that only a proportion of the waste cold can be exploited in the most efficient way. These constraints would be removed if LNG waste cold were re-cycled to produce liquid air or nitrogen as a zero-emission energy vector - a means of moving both cold and power in time and place – for instance to fuel Dearman engines in vehicles and buildings.

The Dearman approach is not the only novel use for LNG waste cold. Another suggestion is Liquid Air Energy Storage (LAES), a grid scale electricity storage technology, also being developed and in demonstration at the University of Birmingham. Grid storage is becoming increasingly important as the proportion of intermittent renewable generation rises, and LAES is an exciting and powerful new storage technology offering large scale storage without geographic constraint, but at the moment it is not the best use of waste LNG cold. Modelling suggests that a 600tpd LAES plant built at the Isle of Grain LNG terminal in Kent would never recover its capital costs, but the same sized plant dedicated to supplying Dearman engine TRUs would have a net present value of £15 million and an internal rate of return (IRR) of 26% - twice the level of standard energy industry hurdle rates.

So our work suggests a strong prima facie case for developing transport refrigeration based on liquid air produced with LNG waste cold, both in Britain and several other developed and developing economies we have studied – including Spain, Singapore and India. Following the Dearman approach, LNG cold recycling could generate an economic value of up to £30 per tonne of LNG, a 10% addition to the value of its chemical energy[7], which after repayment of capital would produce a gross profit of £7 per tonne. The IEA expects LNG imports into Europe to double to 90bcm (69mt) by 2020[8], which at £30/t represents a market worth over £2 billion or €2.7 billion.

What is the scale of the European opportunity?

Re-cycling LNG waste cold into liquid air to serve as an energy vector to displace fossil fuels in cooling would produce value because it:

- improves the business case of liquid nitrogen applications by reducing fuel costs by half
- improves the environmental case of liquid nitrogen applications by reducing electricity consumption and therefore CO2 emissions
- reduces the cost of securing the social benefits of clean cold technologies (e.g. zero emission cold chain) that use liquid nitrogen as an energy vector including:
    - NOx and PM abatement, leading to lower health and other social costs (developed countries)
    - reduced post harvest food loss, with consequential reduction in waste of water, land and other resources; less hunger; fewer vaccine-preventable deaths (developing countries).

The beneficiaries are the LNG terminal operators (value from waste re-cycling) cryogen producers (increased sales), fleet operators (lower costs) and society (reduced CO2, NOx and PM emissions, health/social costs, post harvest food and associated losses, infrastructure costs).

Dearman is developing several applications for its zero emission engine, powered by the phase change expansion of either liquid nitrogen or liquid air, and which produces both power and cooling from the same tank of cryogen for built environment and transport applications. These include:

- A highly efficient transport refrigeration unit (TRU), due to start fleet trials this year
- A diesel-liquid air 'heat hybrid' engine for buses and trucks, in which the two units exchange heat and cold to raise the efficiency of both and cut diesel consumption by 25%
- A bus air conditioning unit
- A static back-up electricity and cooling generator to displace highly polluting diesel gensets

All these units could run on liquid nitrogen, which is already universally available as an industrial gas, or liquid air, which is not yet produced commercially but would be cheaper since it requires about 20% less electricity. Cheaper still would be liquid air produced with the help of waste cold from LNG; each tonne of LNG releases around 240kWh of 'coolth' or cold energy during re-gasification, which can be re-cycled to reduce the electricity required for air liquefaction by more than 50%. This presents a significant opportunity, especially since the global LNG trade is projected to grow for at least the next 20 years.

In Europe, 2014 the LNG imports of seven countries (see Table 2) of around 26mt or 34bcm could produce enough LAIR per day, enough to fuel more than 210,000 fleet average TRUs[1], more than a fifth of the entire EU fleet of 1 million.[9] The IEA expects LNG imports into Europe to double to 90bcm (69mt) by 2020[10], which at £30/t represents a market worth over £2 billion or €2.7 billion. By extension a global LNG trade of 500mtpa in 2025 could support almost 4 million TRUs – about the size of current worldwide fleet, and represents a potential market of £15 billion.

[1] I.e. taking account of relative numbers of trailers, trucks and vans and of their differing fuel economy.

	LiN capacity tonnes per day	Estimated spare LiN capacity tonnes per day	Potential liquid air from LNG imports tonnes per day	TRU fleet supported by spare LiN units	TRU fleet supported by LNG LiN units
Belgium	500	150	980	1 181	7 716
Czech Republic	600	180	0	1 417	0
France	3 400	1 020	4 600	8 031	36 220
Germany	7 000	2 100	0	16 535	0
Italy	3 200	960	3 300	7 559	25 984
Netherlands	250	75	420	591	3 307
Poland	5 000	1 500	0	11 811	0
Portugal	250	75	980	590	7 716
Spain	1 900	570	8 000	4 488	62 992
UK	6 100	2 200	8 500	17 322	66 929
Total	28 200	8 830	26 780	69 527	210 866

Table 2: Liquid nitrogen (LiN) resources in EU10 countries. NB fleet estimates are based on the fleet weighted average fuel consumption of various different vehicle types. Sources: gasworld, Spritus, GIIGNL 2015.

Social and environmental value of LNG waste cold as liquid air for "cold and power"

The social benefits of converting to liquid air transport refrigeration were calculated in a recent report, *Liquid Air on the European Highway*, on the basis of NOx and PM damage costs and CO2 abatement costs calculated by Ricardo-AEA for the European Commission.[11] The report found that if the EU TRU fleet converted to liquid air over the next decade, the cumulative social benefit would amount to €8.7 billion (£6.4 billion), which equates to more than £27 per tonne of LAIR consumed. If the LAIR were produced with the help of LNG waste cold, the social benefits would equate to around £11 per tonne of LNG. For Britain the cumulative social benefit 2016-2025 would exceed €500 million (£368 million), with a similar value per tonne of LNG.

The savings are so large because the zero-emission Dearman TRU displaces diesel TRUs that emit not just CO2 but also grossly disproportionate amounts of NOx and PM. These are the toxic pollutants that kill over 400,000 people per year in the EU each year, and impose huge costs on society through lost productivity, medical treatment, and damage to buildings and crops. This situation persists because transport refrigeration emissions are essentially unregulated in Europe – recent revisions to the NRMM regulations notwithstanding - meaning a diesel TRU can emit up to 29 times as much NOx and 6 times as much PM as a Euro VI propulsion engine (see Appendix 5). Put another way, our modelling of a 17 tonne refrigerated truck shows that if its diesel TRU were replaced with a Dearman TRU, the vehicle's total NOx emissions would be reduced by 73% and its PM emissions by 92%.

There is *currently* insufficient LNG re-gasification in Britain or Europe to produce all the LAIR required for their respective TRU fleets, but the *benefits per tonne* of LAIR and LNG hold good, and in addition to the commercial value (£30/t LNG) already identified, they further increase the value of exploiting the waste cold of LNG for LAIR production by roughly a third (£11/t LNG).

APPENDIX 1: What is liquid air?

Air turns to liquid when refrigerated to -196C, and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat (including ambient) causes rapid re-gasification and a 700-fold expansion in volume, which can be used to drive a turbine or piston engine. The main potential applications are in electricity storage and transport, and in both, liquid air can provide the additional benefit of waste heat recovery and/or cooling.

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 boil. The low boiling point also means the expansion process can be boosted by the addition of low grade waste heat (up to +150C), which other technologies would find difficult to exploit and which significantly improves the overall efficiency.

Liquid air is not yet produced commercially, but liquid nitrogen, which makes up four fifths of the atmosphere and can be used in the same way as liquid air, is produced throughout the industrialised world. The industrial gas companies have large amounts of spare nitrogen production capacity for the simple reason there is far more nitrogen than oxygen in the atmosphere but proportionately less commercial demand. This surplus is being used in place of liquid air to support early deployment (across the EU spare liquid nitrogen capacity could support more than 70,000 zero-emission transport refrigeration units – enough for mainstream market penetration before any infrastructure investment is required). In future, liquid air would be cheaper to produce than liquid nitrogen, because there is no need to separate the nitrogen and oxygen, meaning liquefaction requires less equipment and around a fifth less energy.

Both liquid air and liquid nitrogen can be produced extremely cheaply by incorporating the waste cold from LNG re-gasification, which reduces the electricity required for air liquefaction by more than 50% and the costs by about half.

As with batteries or hydrogen, the purpose of liquid air is to store ‘wrong time’ low or zero carbon electricity, which can then be used to displace high carbon coal or gas in electricity generation and petrol or diesel in vehicles. The carbon intensity of liquid air depends on the source of electricity used to make it, and most industrial liquefiers operate at night when greenhouse gas emissions of grid electricity are lower than average. New liquefiers could be integrated with renewables to produce effectively zero carbon liquid air. Liquid air and nitrogen are in any case zero-emission fuels at their point of use, offering the same potential for dramatic local air quality improvement as electricity or hydrogen – but at far lower capital and lifecycle cost. A liquid air engine is likely to be significantly quieter than a well-silenced petrol or diesel engine, and would be made of common and easily recyclable materials.

APPENDIX 2: Liquid Air Energy Storage

LAES is a novel, large-scale, long duration energy storage system based on standard components from the industrial gases and power generation industries. Electricity is used to drive an air liquefaction plant to produce liquid air, which is then stored in an insulated tank. When power is required, the liquid is pumped to high pressure, and then through a heat exchanger where it converts into a high pressure gas that drives a turbine to generate electricity. Cold from the evaporation is recycled to reduce the energy required by the liquefier, and waste heat from the liquefier or an external source increases the energy recovered from the expansion of liquid air. Highview operated a 350kW/2.5MWh pilot plant in Slough between 2010 and 2014, which was connected to the grid. The pilot plant has now been relocated and recommissioned at the University of Birmingham. Highview is currently building a 5MW precommercial, **generation-only** (i.r. no front end liquefaction) demonstration plant with Viridor at the waste management company's Pilsworth Landfill facility in Manchester, which will integrate waste heat from landfill gas engines. The demonstrator was funded by DECC and is expected to operate for at least a year, testing its ability to provide balancing services including STOR and Triad avoidance.

Balancing the electricity grid will become increasingly challenging as the proportion of intermittent renewable generation continues to rise. This is not simply a question of holding power stations in reserve for when the wind drops, but also being able to absorb excess wind power when there is too little demand – often at night – a role for which storage is ideally suited. If such 'wrong time energy' is stored and used to displace fossil generators at peak times, CO2 emissions are reduced and 'constraint' (compensation) payments to wind farm operators avoided.

EASE (European Association for the Storage of Energy) has observed that the renewable cooling sector has been grossly undervalued. They state that the storage of cold (rather than electricity to electricity) by use of different storage technologies is key for the success of the EU's decarbonisation efforts, as it will allow for RES electricity to be consumed at times of low electricity demand and used later for cooling purposes. This will allow for a higher penetration of renewable energy onto the grid.

APPENDIX 3: The Dearman engine

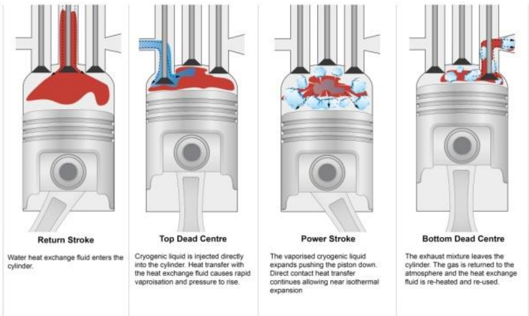
The Dearman engine is a novel piston engine powered by the phase-change expansion of liquid air or liquid nitrogen. In principle it works just like a steam engine only 300°C colder. It was invented by Peter Dearman, a classic British 'garden shed' inventor, and is being developed by the Dearman Engine Company ('Dearman') to perform a variety of roles.

Because it produces both power and cooling from the same unit of 'fuel', the Dearman engine can serve as an efficient and zero-emission transport refrigeration unit (TRU) to replace the highly polluting secondary diesel engines used on trucks today, which can emit up to 6 times as much NOx and 29 times as much PM as a modern lorry propulsion engine. The Dearman refrigeration engine is zero-emission, low carbon and now in on-vehicle trials with MIRA, and will go into British and international field trials in 2016. Our recent report, *Liquid Air on the European Highway*, showed that the cost of buying and running a zero-emission Dearman TRU for five years would be just 9% higher than a conventional TRU running on subsidised red diesel, which is still permitted in Britain, but 32% *lower* than one running on fuel priced fuel.[12] Across the EU, if the diesel TRU fleet were replaced with Dearman TRUs over the next decade, the diesel savings would be worth £30 billion at average EU prices in 2014.[13]

Because liquid air boils at -194°C (and liquid nitrogen at -196°C), its work output can be raised by the addition of waste heat from another source. This means the Dearman engine can be combined with a diesel engine or hydrogen fuel cell to form a 'heat hybrid', where waste heat and cold are exchanged between the engines to increase the efficiency of both and reduce fuel consumption. Modelling suggests this arrangement would turn waste heat into extra power at practical conversion efficiencies approaching 50%, and reduce bus and truck diesel consumption by 25%. A consortium including DEC, Air Products, MIRA, Cenex, TRL, The Manufacturing Technology Centre and The Proving Factory has been awarded nearly £2 million by Innovate UK to build a heat hybrid prototype in 2016 while further developing and testing is being undertaken at the Birmingham Centre for Cryogenic Energy Storage.

In the future, the Dearman engine could also be used as a stand-alone propulsion engine for smaller, shorter distance vehicles such as auto-rickshaws ('tuk tuks') in developing countries, where the exhaust of clean cold air would provide 'free' air conditioning. It could also be used as a static back-up electricity generator to replace highly polluting diesel gen-sets.

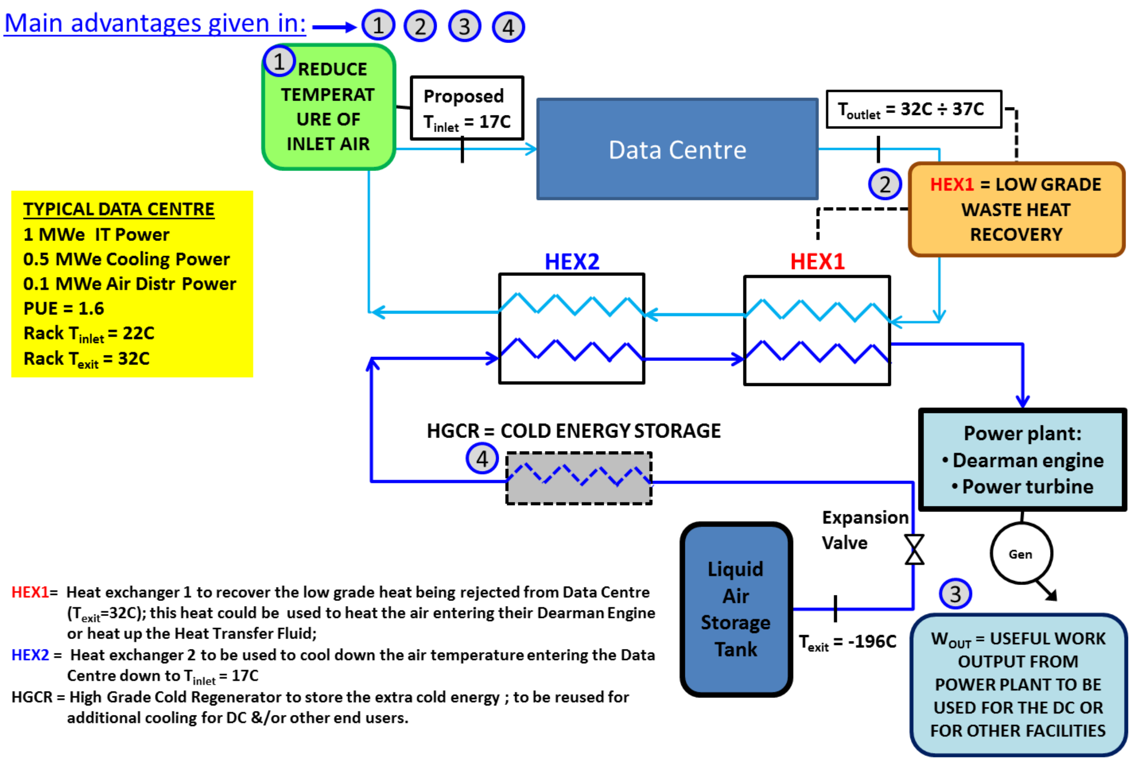
Cryogenic expansion engines have existed for over a century, but the Dearman engine is novel because it uses a heat exchange fluid (HEF, made of water and glycol, just like conventional radiator fluid) to promote rapid and efficient re-gasification inside the engine cylinder, allowing the DE to dispense with the bulky and inefficient external heat exchanger that handicapped earlier cryogenic engine designs. First, warm (or even ambient temperature) HEF is injected into the cylinder, followed by liquid air or nitrogen. Then, as the fluids mix, direct heat transfer causes the cryogen to boil and expand, so pushing the piston down. The HEF continues to provide heat throughout the power stroke, leading to efficient ‘isothermal’ expansion. Afterwards the cool gaseous air exhausts harmlessly to the atmosphere while the HEF is re-heated and re-used.



APPENDIX 4: The Dearman genset

The Dearman genset is a static electricity generator powered by the phase change expansion of liquid air or liquid nitrogen, which provides a zero-emission alternative to the highly polluting diesel gensets commonly used to provide back-up power in emergencies. It is highly efficient since it generates both cooling and power from a single tank of cryogen and absorbs low grade waste heat to produce additional energy – in contrast to a diesel engine that produces waste heat. These characteristics make the Dearman genset an ideal backup generator when there is also a heavy cooling load, such as data centres and supermarkets.

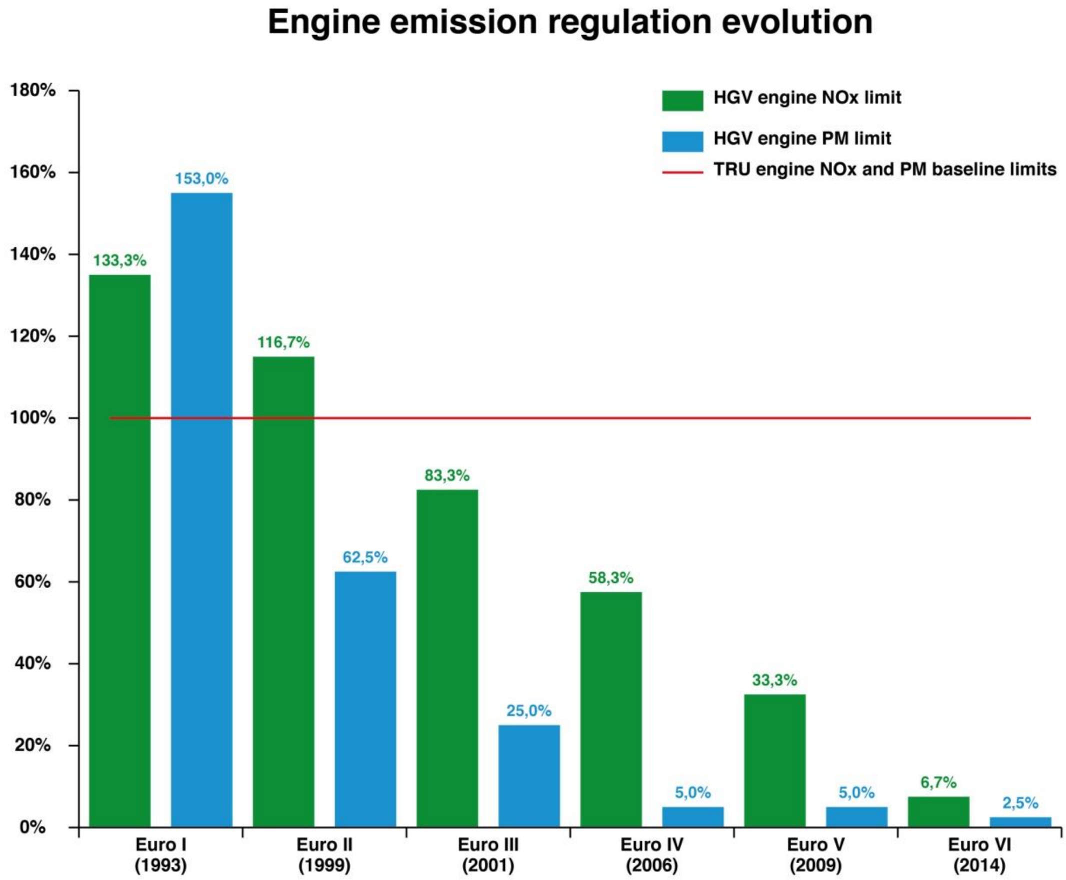
The system consists of a storage tank containing liquid air or nitrogen, a series of heat exchangers, a Dearman engine and an electricity generator (see diagram below). When the grid electricity supply fails, liquid air or nitrogen is re-gasified through a heat exchanger warmed by building inlet air, which is itself cooled for use in the building. The re-gasified liquid air then passes through another heat exchanger to be further warmed by exit air, and then into the Dearman engine where it expands to drives a piston, and this in turn powers the electricity generator. During this process the re-gasification also gives off high grade cold which is stored to provide cooling later and reduce the building's electrical load.



APPENDIX 5: NOx and PM

It may be hard to believe, but the TRU cooling an articulated trailer emits many times more NOx and PM over the course of a year than the (Euro VI) tractor unit hauling it around. This situation has developed because the 'Euro' regulations covering truck propulsion engines have become far more stringent over the past 20 years, whereas TRU emissions remain effectively unregulated.

TRUs *are* covered by the EU Non Road Mobile Machinery (NRMM) regulations, but at present these impose no emissions limits whatsoever on engines rated at less than 19kW – which includes all TRUs. Brussels is soon expected to approve legislation revising the regulations to match existing standards in the US, but these are hardly stringent. Figure 1 below compares the amount of NOx and PM that successive generations of European truck propulsion engines have been allowed to emit against a baseline of what TRUs *will* be allowed to emit under the new standards. This shows that for each kWh produced, the latest Euro VI propulsion engine is allowed to emit only 7% of the NOx allowed for a TRU, and just 2,5% of the PM. In other words, under the new European standards, a trailer TRU will still be allowed to emit 15 times more NOx and 40 times more PM per unit of energy consumed than the tractor unit pulling it around.



Euro truck engine emission standards compared to the proposed NRMM Stage 5 TRU standard.
Source: European Commission; DieselNet.[14]

A TRU consumes less energy than a propulsion engine, however, so the *annual* emissions comparison is not quite as extreme, but shocking nonetheless. Based on standard duty cycle assumptions[15], we calculate that over the course of a year a diesel TRU currently emits up to six times as much NOx and 29 times as much PM as the Euro VI truck pulling it around (Table below). Compared to a Euro 6 diesel car, a diesel TRU is likely to emit 93 times as much NOx and 165 times as much PM.

	NO_x	PM
Euro VI, g/kWh emissions limit	0,40	0,01
NRMM Stage 5, (<19kW), g/kWh emissions limit[11]	7,5	0,4
NRMM g/kWh / Euro VI g/kWh	16x	14x
Annual emissions, TRU / Euro VI	6x	29x
Annual emissions, TRU / Euro 6 diesel car	93x	165x

TRU emissions compared to Euro VI trucks and Euro 6 diesel cars. Sources: European Commission; DieselNet.[16]

Smaller TRUs - those used in vans and a minority of trucks - are driven by the vehicle's propulsion engine through a belt drive or an alternator. NOx and PM emissions from this source may decline over time, as the fleet is progressively replaced with cleaner Euro VI propulsion engines - although against that, these engines may still need to idle continuously when the van is stationary to keep the cargo cool. But larger TRUs, used in the majority of trucks and virtually all articulated trailers, are powered by a separate diesel engine, and the emissions from these engines will be scarcely constrained even after the new NRMM Stage 5 standards have been introduced. If nothing more is done, the significance of truck and trailer TRU emissions will only grow as propulsion engines are progressively replaced with cleaner Euro VI models over the next decade.

END NOTES

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[1] *Liquid Air on the European Highway,* Dearman, 2015, http://media.wix.com/ugd/96e3a4_aec136c0fe1e4b0fb5dab3a8e15cfaf1.pdf

[2] Medium Term Gas Market Report, IEA, 2015. To be precise the figure quoted is for OECD Europe, meaning EU plus Switzerland and Norway. In effect this means EU imports, however, since Switzerland is landlocked and Norway a major gas producer.

[3] $6 - $7 / MMBtu in October 2015, https://www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf. 1t LNG = 48.6 MMBtu, BP Statistical Review 2015.

[4] *Liquid Air on the European Highway,* Dearman, 2015, http://media.wix.com/ugd/96e3a4_aec136c0fe1e4b0fb5dab3a8e15cfaf1.pdf

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[6] http://www.birmingham.ac.uk/research/activity/energy/policy/cold/doing-cold-smarter.aspx

[7] $6 - $7 / MMBtu in October 2015, https://www.ferc.gov/market-oversight/mkt-gas/overview/ngas-ovr-lng-wld-pr-est.pdf. 1t LNG = 48.6 MMBtu, BP Statistical Review 2015.

[8] Medium Term Gas Market Report, IEA, 2015. To be precise the figure quoted is for OECD Europe, meaning EU plus Switzerland and Norway. In effect this means EU imports, however, since Switzerland is landlocked and Norway a major gas producer.

[9] *Liquid Air on the European Highway*, Dearman, 2015, http://www.dearman.co.uk/#!reports--guides/c10lo

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[11] Update of the Handbook on External Costs of Transport, Ricardo-AEA, January 2014, European Commission DG MOVE, http://ec.europa.eu/ transport/themes/sustainable/studies/doc/2014- handbook-external-costs-transport.pdf

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[13] *Liquid Air on the European Highway,* Dearman, 2015, http://media.wix.com/ugd/96e3a4_aec136c0fe1e4b0fb5dab3a8e15cfaf1.pdf

[14] *Brussels, COM(2014) 581 final*, European Commission, 25 September 2014, http://www.europarl.europa.eu/meetdocs/2014_2019/documents/com/com_com(2014)0581_/com_com(2014)0581_en.pdf; DieselNet, https://www.dieselnet.com/standards/eu/hd.php.

[15] Assumptions: 12 metre frozen articulated truck using 100% auxiliary diesel power, governed by EU NRMM Stage IIIA; Euro VI HGV, 42 000km per year, fuel consumption 0,37L/km; Euro 6 Diesel car, 12 000 miles per year. NRMM IIIA is an entirely theoretical assumption, since it relates only to engines above 19kW; real world emissions for engines of less than 19kW may in fact be higher still. Compared to NRMM IIIA, Stage 5 would reduce permitted emissions of PM/kWh by a third, but NOx emissions would remain unchanged.

[16] *Brussels, COM(2014) 581 final*, European Commission, 25 September 2014, http://www.europarl.europa.eu/meetdocs/2014_2019/documents/com/com_com(2014)0581_/com_com(2014)0581_en.pdf; DieselNet, https://www.dieselnet.com/standards/eu/hd.php.