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Assessment of LNG Cold Energy utilization for Road Vehicles and Data-Centres cooling using Liquid Air

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Abstract

This paper assesses a novel use for LNG cold energy utilization which liquefies air to be used in cryo-cogeneration systems adopted in road vehicles and data centres. The study investigates four scenarios which contemplate different combinations and levels of integration between the LNG terminal, the cryo-cogeneration system, the road vehicles (namely Transport Refrigerated Units and Public buses). The comparison amongst the four scenarios was conducted by considering the impact of the proposed solutions on CO_2 emissions reduction and running costs savings.

Keywords: Liquid Air Energy Storage; Data Centres; Transport Refrigeration Units; Liquefied Natural Gas; Cold Energy

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1. Introduction

Data centres are essential to the modern, digital age. They enable the processing and storage of the data that underpin our life style, from global financial markets to food distribution, from governments to social media networks which connect people around the planet. Demand for data processing and warehousing is expected to increase significantly in the next years, since more and more people become interconnected and digital communications

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entrench every element of their lives, e-commerce grows, and the ‘internet of things’ collects information from even seemingly mundane equipment.

However, the infrastructure which is required to support this proliferation of data has been, to date, energy intensive and not environmental friendly. Data centres, in facts, are among the 10 most unsustainable industries, due to their consumption of huge amounts of electricity. Currently, data centres consume 7% of Singapore’s total power generation capacity, thus placing a strain on the power grid and indirectly contributing to greenhouse gas (GHG) emissions. This figure is going even to rise with the expected growth in data centre deployment.

A substantial portion of energy (typically around 33%) is used to provide cooling to servers and systems which would otherwise overheat. Google suggest that “most data centres use almost as much non-computing or "overhead" energy (like cooling and power conversion) as they do to power their servers”. A conservative estimate suggests that today 700 million MWh of electricity is consumed annually by data centres worldwide, resulting in 519 million metric tonnes of CO_2 equivalent emissions. The impact of data centres is worsened by the use of polluting diesel generators to provide backup power, which contributes directly to CO_2 levels and to localized air pollution issues in Singapore due to emission of particulate matter (PM) and NOx. Therefore, addressing both power supply and cooling simultaneously, while making data centres more energy efficient, would have a positive impact on sustainability.

In addition to this, Transport Refrigeration Units (TRUs), the secondary diesel engines used to cool refrigerated lorries and trailers, can emit up to 6 times as much NOx and 29 times as much PM as a modern (Euro VI) lorry propulsion engine, for example, and also leak refrigerants that are highly potent greenhouse gases. Cooling demand is also responsible for the use of similarly polluting diesel generators (‘gensets’), particularly in countries with weak electricity grids. Singapore’s grid is extremely reliable, but gensets are still in use to provide backup power to cold stores, data centres, hospitals and any other facility with critical loads to be covered.

Current cooling technologies are often self-defeating, since they work by expelling heat into their immediate surroundings, and this often creates the need for yet more cooling. For example, vehicle exhaust in cities contributes to the heat island effect, forcing office air conditioning systems to work harder. It has been estimated that if Beijing had switched from fossil fuel to electric vehicles – which produce 80% less heat **-** during the summer in 2012, temperatures in the city would have been reduced by 1°C. This in turn would have cut electricity consumption by 14.4 GWh and emissions by 11,800 tonnes of CO_2 per day. Moreover, vehicle air conditioning increasingly contributes to the heat island effect: in hot countries, installing air conditioning on a bus raises its diesel consumption by almost 100%. Electric buses are currently not a proper solution, since heating or cooling loads drain the battery and severely restrict the vehicle’s range.

Thus, developing a new thermal approach to provide cold to both buildings and vehicles with near zero carbon emissions and avoiding the drawbacks of batteries is compelling.

A recent opportunity is represented by liquid air or liquid nitrogen. Liquid air and liquid nitrogen store energy as cold and power, rather than electrons alone, making it a highly efficient and zero-emission means for cooling in both buildings and vehicles. Air turns to liquid when refrigerated to around -196 °C and can be conveniently stored in insulated but unpressurised vessels. Exposure to heat - even at ambient temperatures - causes rapid re-gasification and a 700-fold expansion in volume, which can be used to drive a turbine or piston engine. Regasification also gives off large amounts of valuable cold, which makes liquid air an excellent way of storing energy whenever cold and power are required simultaneously.

Liquefied Natural Gas (LNG) is produced when natural gas is cooled to -160°C below its boiling point, turning it into liquid suitable for transportation or storage. LNG can then be regasified and delivered into the distribution pipelines to different end-users or power generation stations. Natural gas in liquid form holds a large amount of exergy (due to the very low temperature at which is stored), which is released during the regasification process (LNG cold energy).

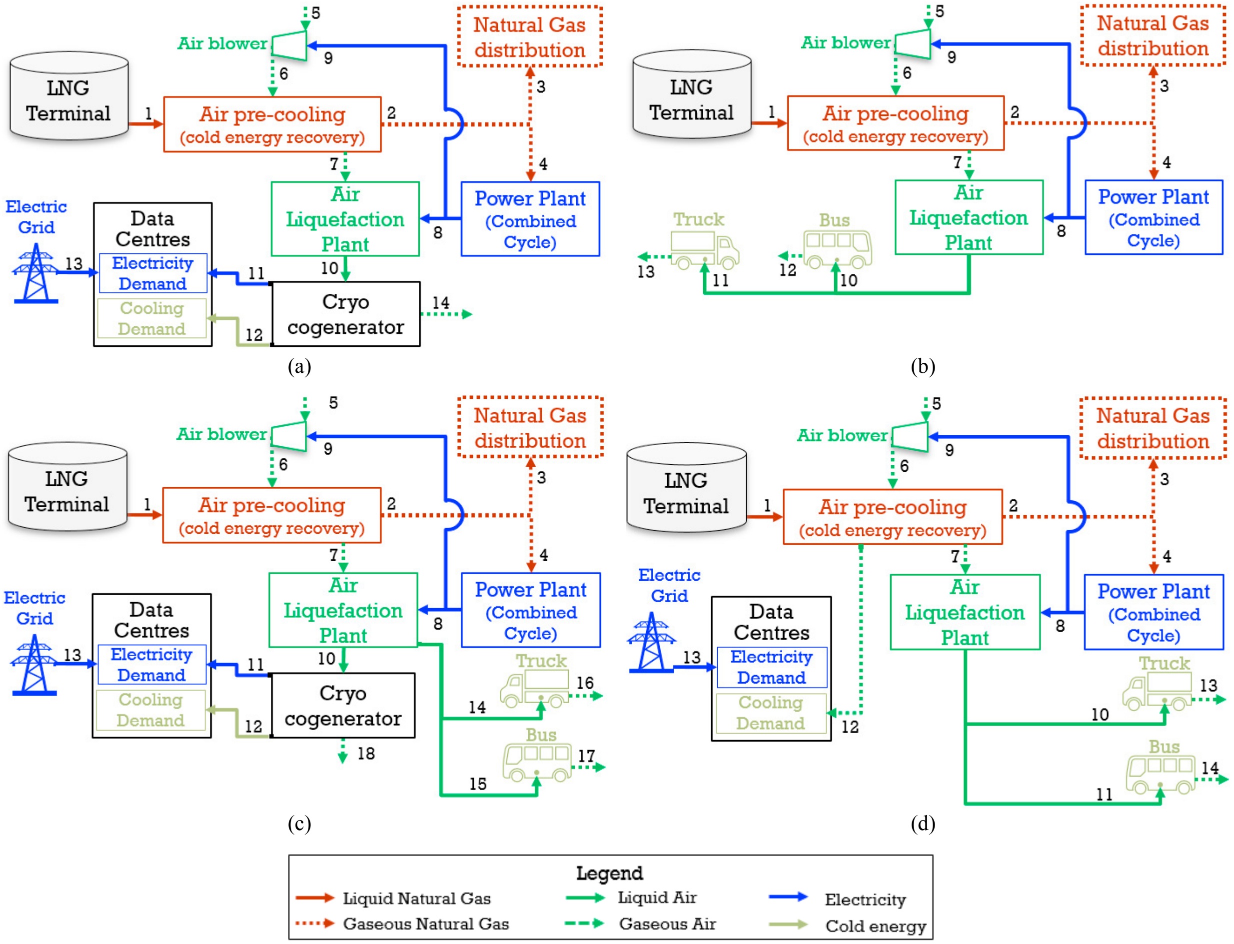
The proposed paper aims to assess alternative utilizations of LNG cold energy by involving liquid air and looking at road vehicles and data centres applications. The paper is structured as follows: in section 2 alternatives solutions are explored, while in section 3 results from the case study of Singapore are analysed. Finally, conclusions are derived in sect. 4.

2. Alternative solutions for LNG cold energy exploitation

Four different solutions can be developed to exploit the available cold energy from LNG regasification, as reported in Fig. 1. In all the configurations, the available cold energy is firstly recovered by pre-cooling ambient air (see the red contour blocks in Fig. 1).

Then, the cooled air can be sent to an air liquefaction plant (ALP) for liquid air production in order to further satisfy different energy requirements (see green blocks and connectors in Fig. 1a, 1b, 1c) or also directly feed Data Centres to fulfil their cooling demand (see Fig. 1d). Moreover, all the configurations adopt a combined cycle fed by the regasified natural gas from the LNG terminal to supply energy to the ALP and to the air blower used to recover the LNG cold energy (see blue blocks and connectors).

In the first solution of Fig. 1a, the cooled air is entirely sent to the ALP for liquid air production. The liquid air is then used in a cryo-cogenerator to supply both electric and cold energy to Data Centres. Since the cryo-cogenerator is thermal-load-driven (i.e. it follows the cooling demand), Data Centres can withdraw electricity from the grid when required.



(a) (b) (c) (d)

Fig. 1. Studied configurations: liquid air production to feed cryo-cogenerator supplying energy to (a) Data Center only, (b) diesel vehicles only, (c) Data Center and diesel vehicles, (d) diesel vehicles and direct cold energy recovery to cool Data Centers

In the second solution (Fig. 1b), the produced liquid air is used, instead, to feed a fleet of hybrid buses and trucks thanks to the adoption of Dearman Engines (DEs). The DE is a novel cryogenic engine concept driven by the vaporisation and expansion of liquid air to produce high pressure gas that can generate clean cold and power [2].

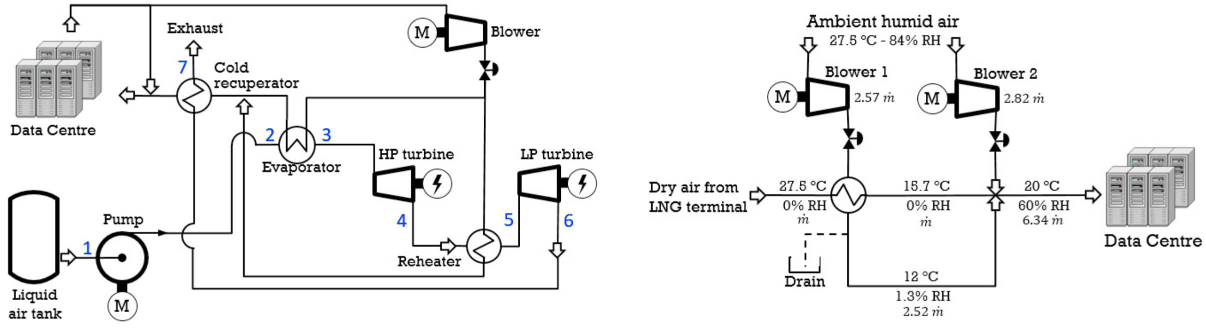
The DE cycle requires the use of a heat transfer fluid inside the cylinder of the engine as a source of heat in order to augment the efficiency of the liquid air expansion by resembling a nearly isothermal process.

The third solution (Fig. 1c) can be considered as a combination of the first and second configurations, meaning that part of the liquid air is used to feed a fleet of hybrid buses and trucks and the rest is used in the cryo-cogenerator to supply electric and cold energy to data centres.

In the last solution (Fig. 1d), a portion of the cooled air is directly sent to data centres in order to fulfil their cooling demand, while the remaining part is used to produce liquid air to feed DEs in hybrid trucks and buses.

2.1. The Cryogenic Cogenerator

Fig. 2a describes the layout of the cryogenic energy system leading to the combined generation of cooling and power for data centres under a thermal-load-driven control strategy (see Fig. 1a and 1c). The proposed cryo-cogenerator is a multistage system where the heat transfer is performed over two pressure levels and the thermoelectric conversion by two expansion stages. Throughout an open cycle, the liquid air at ultra-low sub-zero temperature is sequentially compressed (1 → 2), gasified by transferring cold flux to the Data Centre air loop (2 → 3), expanded through a high-pressure turbine (3 → 4), reheated (4 → 5), then re-expanded through a low-pressure turbine (5 → 6). At the low-pressure turbine outlet, the residual cold energy at sub-zero temperature is fully transferred to the Data Centre air loop through a cold recuperator (6 → 7), hence allowing a reduction of the liquid air consumption. Since the cryo-cogenerator is used to fully cooling and partially powering a Data Centre, the traditional chiller is by-passed.



(a) (b)

Fig. 2. Process Flow Diagram of the a) cryo-cogenerator and b) direct energy recovery system

2.2. Direct cold energy recovery

Unlike the cryo-cogenerator, the direct cold energy recovery system exploits the cold energy potential from the LNG plant without any liquefaction requirement. Fig. 2b shows the related Process Flow Diagram with temperature and humidity values to satisfy the recommended inlet air conditions according to the ASHRAE guidelines for data processing environments [1].

3. Results and discussion

The four proposed solutions for LNG cold energy exploitation have been applied to the case study of Singapore, where an expected cold energy potential of 735 GWh/year can be recovered by the LNG terminal capacity in 2020.

When adopting the first solution, the cryo-cogenerator can supply 70% of the electricity demand of a data centre, while the remaining 30% is withdrawn from the electric grid. The total expected liquid air production of 10,892,088 t/year could supply 30% of the data centres in Singapore. Table 1 compares the CO_2 emissions and net running cost of traditional data centres, whose energy demand is entirely satisfied by withdrawing electricity from the grid, to those gained by adopting the proposed first configuration of Fig. 1a for energy supply. The use of liquid air produced by recovering the LNG cold energy allows a reduction of the running cost of the data centres of about 7%. Nevertheless, the consumption of liquid air in the cryo-cogenerator leads to a strong increase of CO_2 emissions, equal to 210% of those related to the current national mix.

Table 1. CO_2 emissions and net running cost of data centre in Configuration 1

Data centre configuration	Net running cost (SGD/y)	Running cost variation	CO_2 emissions (t_{CO2}/y)	CO_2 emissions variation
Traditional	340,737,189	- 6.5 %	647,164	+ 210%
Cryo Cogenerator-based	318,506,017		2,008,199	

The main results for the second configuration of Fig. 1b are reported in Table 2. Given the quite limited potential number of hybrid trucks and buses, only 16% of the available cold energy can be recovered, for a total production of liquid air equal to 1,730,474 t/year. Hybrid buses can absorb up to 70% of the produced liquid air, while the remaining 30% can be employed by the hybrid trucks. In this configuration, the use of liquid air allows a strong reduction of both running costs and CO_2 emissions. Running costs, in facts, are reduced by 83.3%, while the reduction of CO_2 emission achieves 45.8% for a total saving of 252,921 t_{CO2}/year, due to substitution of fossil fuel.

Table 2. CO_2 emissions and running cost variation of hybrid vehicles in Configuration 2

Vehicle	Diesel saving (t/y)	Running cost saving (SGD/y)	Running cost variation	CO_2 emissions (t_{CO2}/y)	CO_2 emissions variation
Bus	121,545	141,736,576	- 83.3%	210,580	- 45.8%
Truck	51,502	60,058,214		89,229	

When adopting the third solution (see Fig. 1c), 84.1% of the produced liquid air is expected to be employed in data centres, 4.7% is used in hybrid refrigerated trucks and the remaining 11.2% is consumed by hybrid buses. Table 3 shows CO_2 emissions and running cost variation for the involved end-users. It can be observed that the running costs are always reduced, while the variation of CO_2 emissions is increased in the case of data centres and decreased when liquid air is used in hybrid vehicles. The CO_2 emissions saving achievable by the hybrid vehicles cannot compensate the increased CO2 emissions due to the use of liquid air in data centres.

Table 3. CO_2 emissions and running cost variation of hybrid vehicles and data centre in Configuration 3

	Diesel saving (t/y)	Running cost saving (SGD/y)	Running cost variation	CO_2 emissions (t_{CO2}/y)	CO_2 emissions variation
Data Centres	n.a.	18,699,207	- 6.5 %	1,587,277	+ 210 %
Buses	121,545	141,736,576	- 83.3%	210,580	- 45.8%
Trucks	51,502	60,058,214		89,229	

Concerning the last configuration in Fig. 1d, 84.1% of the cooled air from cold recovery is directly sent to data centres in order to satisfy their cooling demand. The remaining 15.9% is employed for the production of liquid air to be used in hybrid vehicles, shared between hybrid buses (70%) and trucks (30%). Table 4 shows the related CO_2 emissions and running cost variations. It is worth noting that the direct use of cooled air to cover data centre cooling requirements allows a reduction of 32.6% of both running costs and CO_2 emissions.

Table 4. CO_2 emissions and running cost variation of hybrid vehicles and data centre in Configuration 4

	Diesel saving (t/y)	Running cost saving (SGD/y)	Running cost variation	CO_2 emissions (t_{CO2}/y)	CO_2 emissions variation
Data Centre	n.a.	23,849,195	- 32.6 %	93,626	-32.6 %
Bus	121,545	141,736,576	- 83.3%	210,580	- 45.8%
Truck	51,502	60,058,214		89,229	

Table 5 compares the total variation of running cost savings and CO_2 emissions among the different analysed solutions. It can be observed that the best scenario is related to configuration 4, which leads to a reduction of the total running cost equal to 225,643,985 SGD/y. The total CO_2 emissions is reduced by 298,218 t/year. The worst scenario is related to configuration 1, in which there is a slight reduction of running cost but a remarkable increase of CO_2 emissions.

Table 5. Comparison of running cost and CO_2 emissions savings for the proposed configurations

	Total running cost savings (SGD/year)	Total CO2 emission variation (t_{CO2}/year)
Configuration 1 (Fig. 1a)	- 22,231,172	+ 1,361,035
Configuration 2 (Fig. 1b)	- 201,794,790	- 252,921
Configuration 3 (Fig. 1c)	- 220,493,998	+ 891,880
Configuration 4 (Fig. 1d)	- 225,643,985	- 298,218

4. Conclusions

The paper presents alternative solutions for LNG cold energy recovery by means of air liquefaction. The utilization of the liquid air has been considered for Dearman Engines adoptable in road vehicles (i.e. Refrigerated Trucks and Public Buses) and a cryogenic system for data centres. Four different configurations have been analysed: the first, in which all the liquid air is used for data centres cooling and power; the second in which the liquid air is used for road vehicles only, the third in which liquid air is shared amongst road vehicle and data centres, the fourth in which cooled air from LNG cold recovery is directly sent to data centres in order to satisfy their cooling demand. The analysis showed that the fourth configuration is the most advantageous scenario in terms of running cost savings (more than 200 million SGD/year) and CO_2 emissions reductions (≈ 300,000 t_{CO2}/y). In general, the substitution of fossil fuel of road vehicles with a cheaper and cleaner energy source is essential to gain significant results from the environmental point of view. The exploitation of cold energy in data centres by the cryogenic system, in fact, while leading to cost savings, leads also to increase GHG emissions, which should be counterbalanced by vehicles performance for an overall positive result. As future developments, the authors intend to carry out a sensitivity analysis which aims to offer a more comprehensive understanding of the available solutions.

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