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A ‘System’ Integration for Energy Recovery within Data Centres Using Combined Cooling and Power Technology

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Abstract

Data Centres (DCs) are emerging as a large industrial sector, consuming about three percent of the global electricity supply, contributing for about two percent of total greenhouse gas emissions and the amount of energy used by DCs is doubling every four years. Despite the innovations in energy management system in DC that incorporate renewable energy solutions to reduce energy consumption and cap their carbon footprint, as much as half of electricity is used for cooling purposes and is ultimately wasted as heat. An innovative system is presented here which integrates a DC cooling process with a zero-emissions power and cooling utilising a novel cryogenic engine technology. The integration enables DCs to take advantage of opportunities for thermal management, rather than electrical power, to control peak temperature environments and electricity price mitigation through cryogenic energy storage. Substantial improvement in DC energy efficiency together with reduction in greenhouse gas emission has been discussed.

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Keywords: Energy efficiency, Heat recovery, Liquid-air engine, Process integration, Energy storage, Carbon footprint reduction;

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1. Introduction

With the rapid advances in computer and electronic technology, dramatic growth rate in the demand for digital information management, such as data processing, data storage, digital communications, have been observed during the past two decades. As a result, Data Centres (DCs) are of paramount importance responsible for information

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management and communication functions in nearly every sector of the economy. In 2009, energy statistics revealed that an estimated 330 terawatt-hours of energy (equivalent to about 2% of the global electricity production) was consumed to operate DCs worldwide [1,2]. In 2014, the DC sector in United States was estimated to have consumed 70 terawatt-hours of energy [3], representing 2% of the country's total energy consumption. This is a 4% increase in total DC energy consumption from 2010 to 2014. The ongoing growth of the DC sector coupled with the development of higher power density server components, it is expected that the US DC energy consumption will grow by 4% between now and 2020, reaching about 73 terawatt-hours [4].

Despite increased energy demand by the DCs, typically about 44% of the electrical power is used directly to support IT equipment, while the remaining are attributed to cooling and indirect uses such as building management, lighting, etc. (Fig. 1)[5]. DCs must be adequately cooled as almost all the energy supplied to the server is dissipated into heat, requiring the use of large scale cooling systems to keep the server rack temperature in a safe operational range [6]. This problem addressed by this paper is how the "next generation combined cooling and power" technology can be utilised to provide energy efficient operation of DCs.

Currently there are around 8 million private and commercial DCs globally. With the digital world projected to grow 44 times from 2009 to 2020, the industry is experiencing an exponential growth in DC deployment. Indeed, International Data Corporation (IDC) reports that global DC capacity will grow to 1.94 billion square feet by 2018 from around 1.6 billion today. Another 600,000 DCs will be built in the coming years; 450,000 of which are anticipated to be in the Asia-Pacific region with Malaysia alone seeing 8,600 new DCs. However, despite these substantial growth figures, DC services and products are largely seen today as commodity products owing to the fact that there is very little differentiation between quality, type and price of offerings. DC operators are grappling with high energy costs, space scarcity, energy security, sustainability compliance and a lack of unique selling propositions (USPs). There is a great need to tackle these challenges and create the basis for a commercial USP offering energy cost reduction and increased energy security while simultaneously adding sustainability credentials through greenhouse gas emissions reduction and abatement of air pollution. These outcomes could be achieved by a substantial reduction in DC energy consumption and emissions through the innovative integration of DC cooling process with zero-emissions power and cooling utilising the novel cryogenic engine technology. This integration will enable DC operators to take advantage of opportunities for thermal, rather than electrical, control of peak temperature environments and electricity price mitigation through cryogenic energy storage.

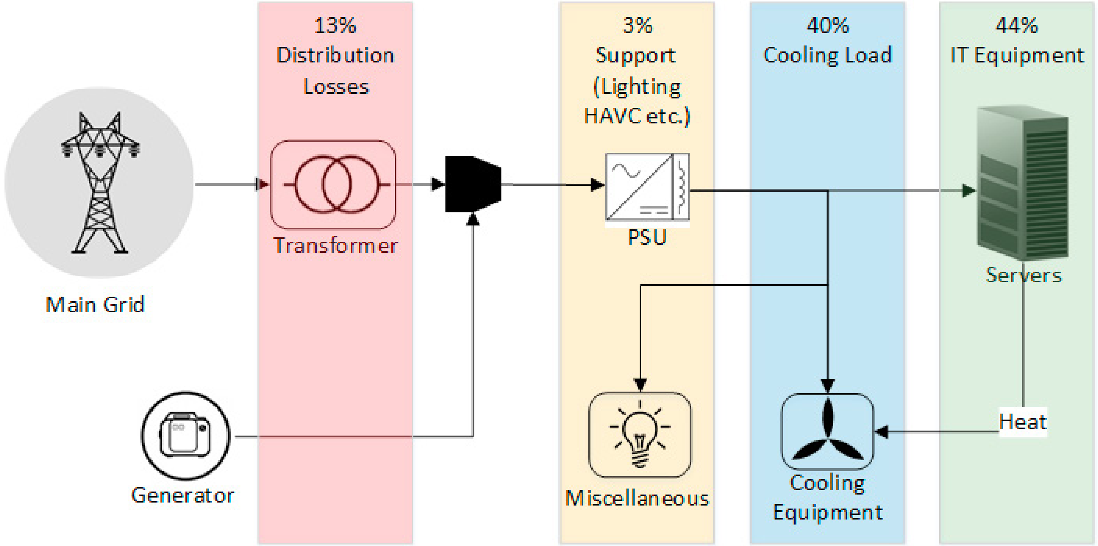

Fig. 1. DC energy attributes, adapted from [5]

2. Research methodology

DC operators are taking proactive approaches to manage energy consumption by their servers. Studies indicated that the majority of servers operate at or below 20% of their maximum capacity most of the time however still, 60-100% of the maximum power is consumed even when the system is idle [1,2]. Development of dynamic need-based resource allocation system as one way to reduce heat dissipated by DCs has been prioritised research effort in recent years [3,4].

2.1. The energy lifecycle approach

For DCs to improve environmental performance through increased energy efficiency there are two major approaches: (i) the use of renewable energy and (ii) the reduction of energy consumption [5]. The development of renewable energy technologies has been relatively slow compared to the growth in DCs [6]. The supply of renewable energy also falls short of the current workload management as the systems are not designed to accommodate the time variations in renewable energy availability. Although on-site energy storage technologies, such as flywheels, batteries, and other systems, can be used to store energy generated from renewable sources for delayed and smooth delivery of power for DCs, each technology has its costs. Energy storage is still expensive and there is power loss associated with energy conversion and charge/discharge [7].

A more cost effective solution would be to reduce energy demand, which can be further divided into three opportunities: (1) reduction in the growth of DCs, (2) energy management to minimise cooling requirement [8,9] and (3) recovery and reuse of waste energy within DCs. A reduction in the growth of DCs is not an ideal solution as DC activities are mostly driven by continuously raising demand for data handling and would thus impact company profitability. Research activities have focused on improving cooling management for DCs through CFD modelling [10], but have had limited success. There has also been research into energy recovery yet it may be considered to be the least developed option of the three.

Despite the effort in optimising energy consumption by DCs, heat dissipation is inevitable and demand for cooling and associated operational costs is ever increasing. Hence, the recovery and reutilisation of waste heat energy has the potential to improve energy efficiency and significantly reduce DCs' operational costs [11]. The main challenge to the implementation of waste heat recovery and reutilisation systems into operational DCs is that the heat is of relative low grade. Although plentiful, the low grade waste heat makes it difficult and inefficient to provide power through conventional thermodynamic cycles [12].

There are several perspectives to efficient energy management within a DC, as depicted in Fig. 2. These include energy supplies from multiple sources, for example brown energy or renewable energy, energy consumption by the IT equipment and waste heat recovery. These three areas do not stand in isolation, but are inherently connected. It has been observed that increased demand for energy from DCs drives supply, but due to the intermittent nature of most renewable energy, more emphasis is placed on the ability to recover waste heat energy. The next generation combined cooling and power technology delivers cooling and electricity supply to the DC.

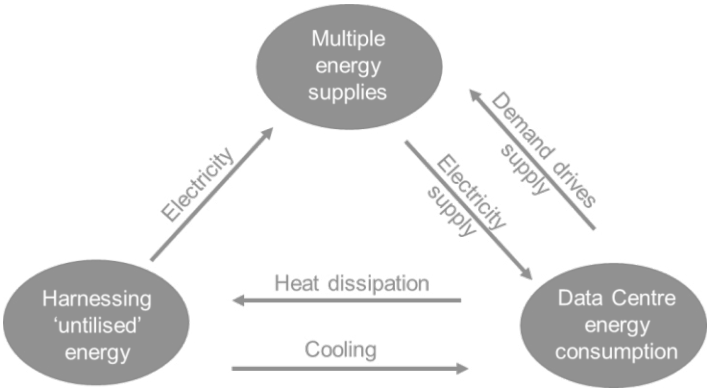

Fig. 2. Three perspectives of energy lifecycle in next generation data centres.

By feeding cold back into the cooling system from which it is extracted, or by supplying electrical power directly into the main factory supply, this low grade heat can be harness. The research presented in this paper examines how waste heat energy recovery can play a part in energy efficient DC.

3. Process integration for next generation DCs

The process integration consists of three stages that aim to define a system for the identification and matching of waste heat source and available sink within a DC facility.

3.1. Waste heat survey

Waste heat survey, targeted at the identification of sources of waste heat within a DC environment, is carried out using either invasive techniques i.e. Resistor Temperature Detectors (RTDs), thermometers and thermistors, as well as non-invasive devices (infrared thermography). Flow rates of the hot medium are measured using a range of flowmeters and flow sensors can be setup according to the types of hot stream media involved. The results from this survey highlights a number of opportunities to recover and reuse large quantities of waste heat within a DC using a number of specific parameters such as:

- Th_{in}, Th_{out}, T_{amb} (inlet and outlet hot medium and ambient temperature respectively) and the flow rate (m^3/s) for the source(s).
- Tc_{in}, Tc_{out}, (inlet and outlet cold medium temperature respectively) and flow rate (m^3/s) for the sink(s).

The output generated by this survey is used for the quantitative and qualitative assessment of DC waste heat and selection of appropriate cryogenic engine power rating to recover this energy.

3.2. Quantitative and qualitative assessment of waste heat

In order to quantitatively evaluate waste heat in a DC environment, the following parameters are utilised:

i) Temperature

Clearly, the heat transfer and recovery can only be achieved if a temperature difference between a waste heat source and a heat sink is observed. Hence, the magnitude of the temperature difference is an important determinant of the quality of waste heat, along with the heat transfer rate per surface area unit, and the theoretical efficiency of converting thermal energy from the heat source to another form of energy, i.e., mechanical or electrical.

ii) Exergy

The exergy is that part of energy which is convertible into all other forms of energy. Most common energy analysis methods ignore the degradation of energy quality, and hence exergy analysis is required to distinguish between recoverable and non-recoverable energy. The exergy can be calculated as outlined in publication by Taheri *et al.* [13] and formulated in the Equation 1.

$$Exergy = m\, c_p\, \Delta T(1 - T_{amb}/T) \tag{1}$$

Where m is the mass flow rate (kg/s), cp is the stream specific heat capacity (kJ/kgK), ΔT is the temperature difference between the hot and the cold streams, T_{amb} is the ambient temperature and finally T is the measured temperature.

Similarly, qualitative assessment of waste heat is carried out taking into account, the following parameters:

i) Carrying medium of waste heat sources and sinks

Waste heat medium can be in the form of liquid, gas or solid. The physical nature of the stream media can strongly influence the compatibility between the sources, sinks and the heat recovery equipment, its installation cost and other requirements.

ii) Spatial availability

The need of a spatial availability assessment is important to evaluate possible constraints in the area where the heat recovery equipment needs to be installed. This assessment must take into account the following factors:

- Accessibility to the units for installation and maintenance
- Positioning, i.e. underground or over ground pipework, for health and safety reasons
- Locality of the waste heat sources and sinks to minimise the heat transportation costs and maximise the recovery

iii) Risk of contamination.

Fouling and corrosion are the main causes of degraded performance or failure in heat recovery units [14]. Contamination can occur through medium leakages in the equipment highlighting the need of a very careful selection of the construction materials, in order to ensure their compatibility with the working fluids and to avoid other mechanical and chemical failure.

These qualitative and quantitative attributes of the available waste heat energy are used to compare potential heat recovery solutions with the available sources.

3.3. Overview of ‘cold and power’ process integration

The parameters described in the previous sections can be used to assess the conditions which ‘cold and power’ technology can be applied for meeting the DCs cooling and power demand. In order to achieve the desired heat recovery, cooling and power generation, a liquid nitrogen (LiN) engine will be needed.

Operating as a high efficiency “Rankine Cycle” expander, the engine uses a novel expander technology driven by the expansion of LiN – heat is sourced from the environment or the data centre waste heat stream to boil LiN which expands about 700 times between liquid and gas phase. The LiN engine will be used to provide electrical power, reducing the DC’s energy costs and providing reserve services to the grid – while also offering DC operators access to zero emission cooling as shown in Fig. 3. It will operate utilising a high efficiency, multi cylinder LiN engine that harnesses the expansion of liquid nitrogen to produce zero-emission power. As well as producing shaft power, the system will also be able to provide ‘free’ cooling, removing further electrical load during times when electricity is valuable or expensive. The system’s efficiency can also be enhanced using waste heat generated onsite, further reducing costs and environmental impact.

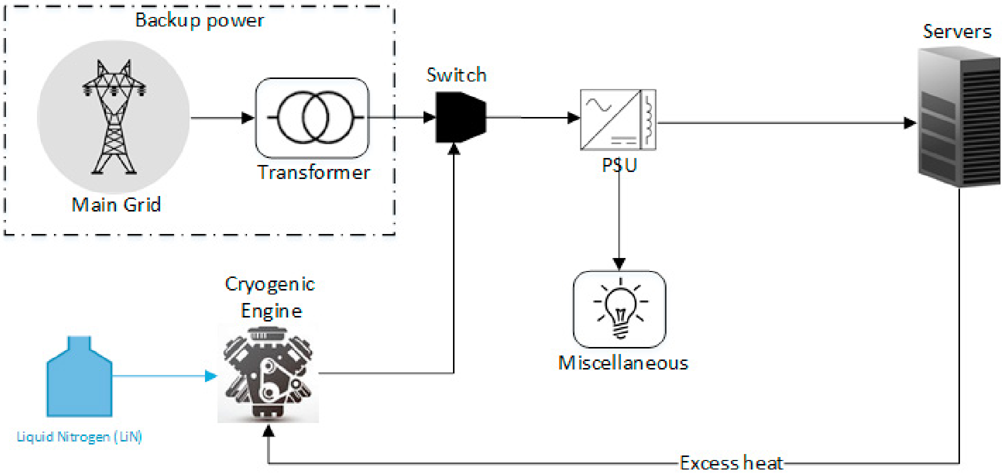

Fig. 3. Integration of LiN engine and data centres

The integration enables DC operators to take advantages of opportunities for thermal, rather than electrical, control of peak temperature environments. With sufficient electrical power generation, DCs are also more resilient to the event of power failure. As exemplified in Table.1, the implementation of combined cooling and power technology enables the DC to achieve power usage effectiveness (PUE) of 1.36, indicating that large proportion of energy is used to power IT equipment and hence improved energy efficiency within the facility.

Incorporating these considerations into a system model enables DC operators to gain information on waste heat recovery, cooling and power generation performances and their ramification, and as a result a selection of the most sustainable solution to manage process energy can be made. Consequently, the system integration model is envisaged to be used by management staff in DCs or members of staff with similar roles and duties in the low-grade waste heat industrial sector.

4. Conclusions

The research presents a process integration opportunity to recover low-grade waste heat energy to produce electrical power and cooling for DCs. A terminology and closed loop energy management approach has been defined, which includes the identification of necessary parameters and variables to model the process integration. The applicability of the model has been discussed, and the practicality of the approach has been tested through industrial applications. Further work includes the identification of additional attributes which can be relevant to the process integration and the incorporation of their computational interrelationships into the model. In addition, the model will also assess the environmental, economic and social impacts and inform the user of the most optimised solution to improve energy efficiency and management in DCs.

Beyond the scope of the current research, there are a number of scenarios where this process integration approach can be utilised to improve overall facility energy efficiency:

- Retrofitting of LiN engine within legacy DC where energy efficiency is still limited by the mechanical cooling system;
- Implementing the integrated system within a reconfigurable DC or modular system;
- Design stage of new DCs within waste heat recovery and combined cooling and power consideration.

It is envisaged that this methodical approach to implementing waste heat recovery with liquid nitrogen engine within DCs will form part of a standard practice for new and old facilities striving to reduce overall energy demand.

Table 1. Examples of performance comparison between traditional and next generation data centres

Parameter	**Traditional data centre**	**Next generation data centre**
Electricity supply	Electrical Grid	Cryogenic engine
Cooling load	2.0 MW	
IT Load	2.2 MW	2.2 MW
Infrastructure Load	0.8 MW	0.8 MW
Typical DC power demand	5.0 MW	3.0 MW
PUE (Power usage effectiveness)	2.27	1.36
Waste stream	Hot air dissipated into environment	Recovered as energy input for cryogenic engine
Cooling effectiveness	Heat exchange low $\Delta T \approx 20K$	Heat exchange high $\Delta T \approx 220K$
Cooling control	Electrical	Thermal
Breakdown of energy demand	• IT load at 44% • Cooling system take up 40% of total input • Other energy users at 16%	• IT load at 73.3%, energy supplied by LiN engine • liquid nitrogen cooling • Other energy users at 26.7%

Acknowledgements

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