

System and Methods for Data Center Cooling and Power Generation Using Liquefied Natural Gas

[0001] The present patent application claims priority from two US provisional patent applications, Serial Nos. 61/603,992, filed February 28, 2012, and 61/657,079, filed June 8, 2012, both of which are incorporated herein by reference in their entireties.

Technical Field

[0002] The present invention relates to cryogenic cooling of heat transfer fluids by liquefied natural gas (LNG) for purposes of cooling process air or heat transfer fluid and, more particularly to the application of cooling the process air or heat transfer fluid used to cool data center equipment.

Background Art

[0003] For high density data computing, telecommunications and storage needs, computer system equipment is typically installed in open or enclosed equipment racks located in data centers, also known as “server farms,” where the environment can be controlled to maintain the proper operating temperature range, relative humidity range, and cleanliness from particulate matter.

[0004] Industry analysts estimate the number of data centers in the U.S. alone at almost 3 million. Most of these data centers are small or medium sized and serve the internal needs of companies. More recently, “cloud” and online service providers have created a step change in the way digital information is handled by providing more capacity to process, transfer, and store data in remote data centers rather than users’ computers. This exponential increase in demand for data computing and storage as a function of time has resulted in a need for many new data centers, each with large capacity and correspondingly high electrical demand.

[0005] Worldwide electricity demand for data centers increased by an estimated 56% between 2005 and 2010 and now represents a total global electricity demand of between 1.1

to 1.5% of electricity used, or about 30 billion Watts, as described by Glantz, *Power, Pollution and the Internet*, *The New York Times*, (September 22, 2012), which is available at http://www.nytimes.com/2012/09/23/technology/data-centers-waste-vast-amounts-of-energy-belying-industry-image.html?pagewanted=all&_r=0, and is incorporated herein by reference.

[0006] According to Toomey, *Growth in Data Center Electricity Use 2005 to 2010*, <http://www.analyticpress.com/datacenters.html>, incorporated herein by reference, the U.S. data center electricity demand was between 1.7 to 2.2% of the total electrical power produced in 2010. Based on 2009 US EPA emission factors, this represents approximately 61.8 million metric tons/year of CO₂ emissions in the U.S. that can be attributed to the power demands of data centers.

[0007] The electrical energy used by the computers, memory storage, and ancillary equipment such as lighting, fans, pumps, etc. in data centers is converted to thermal energy causing the temperature of the equipment to increase. Computer system components are subject to failure if they exceed their maximum design temperatures. The components are maintained in a safe operating temperature range by circulating refrigerated air through the equipment, by cooling the rack enclosures, or by directly cooling the computer components with a heat transfer fluid, or any combination thereof. The American Society of Heating, Refrigerating, and Air Conditioning Engineers (ASHRAE) develops and publishes data center cooling standards which provide industry experts' consensus best practices for data center cooling.

[0008] The most common method for cooling the air or heat transfer fluid used to cool equipment in a data center is by means of electrically driven, reverse Rankine cycle, compressed vapor chillers to chill air, water, or heat transfer fluid which subsequently chills the process air used to cool the equipment.

[0009] Compressed vapor chillers may be used for cooling any data center. The Green Grid (<http://www.thegreengrid.org/>) has defined a metric to measure data center cooling efficiency named Power Usage Effectiveness (PUE): It is determined by dividing the total facility power by the IT equipment power. The average PUE in 2010 was 1.8, but may,

in some cases, be as high as 2.5. This average includes some large new data centers that use alternative cooling methods, so the PUE for data centers using compressed vapor chillers ranges from about 2 to 2.5. (See, *Uptime Institute Announces Results of Second Annual Data Center Industry Survey* (July 11, 2012), (http://www.uptimeinstitute.com/images/stories/NewsPress/July11.12_Uptime_2012_Survey_Press_Release_FINAL.pdf))

[0010] Many other methods of cooling have been tried, and each has its advantages and disadvantages. Some are commonly referred to as “free cooling.” Using alternative heat sinks to supplement or replace vapor compression chillers may result in electrical energy savings for the data center. The alternative methods currently in use include air-side economizers (use of lower temperature outside air while rejecting hot air to the environment) and water-side economizers (use of a lower temperature water source or cooling towers to provide evaporative cooling). The extent to which such ambient temperature alternatives are effective in reducing cooling costs depends on the equipment and local climate. With the exception of locations that continuously have cold or low humidity climates, data centers that utilize these methods will need supplemental refrigeration when ambient air or water temperatures and relative humidity are too high. Data centers that operate outside the ASHRAE temperature and humidity limits increase the probability that equipment reliability will be compromised and maintenance costs increased due to damage from excessive temperatures or corrosion. See, Strutt *et al.*, *Data Center Efficiency and IT Equipment Reliability at Wider Operating Temperature and Humidity Ranges*, (The Green Grid, 2012) available from www.thegreengrid.org.

[0011] Another cooling method uses water sprayed onto the air filter medium to create some evaporative cooling of the air. If the moist air is directly used to cool the computing equipment, it may exceed the maximum recommended ASHRAE relative humidity level.

[0012] The cooling methods commonly referred to as “free cooling” are not truly free, however. They use equipment such as fans and pumps in their operation and may require very large capital expenditures to achieve the required capacity. For example, evaporative water cooling towers will become very large even in temperate climates and

require very significant pumping and fan energy. As the outside air or water temperature approaches maximum data center allowable operating temperatures, the volume of outside air or evaporative-cooled water increases exponentially causing large increases in the volume of filtered air flowing through the equipment, as well as cooling fan energy, and pump energy. In some cases, especially for air-side economizers, the cooling capacity may become so limited by the cooling air velocity through the resistance of equipment racks that the computer power load must be reduced or computers shut down to prevent their destruction from excessive heat.

[0013] The amount of thermal energy that can be dissipated in an equipment rack of a given physical size and power density is dependent on several factors that are determined by the computer manufacturer and the data center design. Increasing the cooling capacity within the rack permits the power density to be correspondingly increased, allowing the overall data center size to be reduced. Alternative cooling methods in hot, humid climates are not capable of maintaining operating temperatures cool enough to allow for the high rack power densities that are now being developed and adopted. According to Intel, in 2002, a 3.7 teraflop computing system was typically installed in about 25 racks with a power density of about 5.1 kW electrical (kWe)/rack. By 2008, the same computing capacity could be installed in a single rack with a power density of about 21 kWe occupying 1/25th as much floor space. State of the art rack power density in new data centers in 2008 was about 30 kWe. Patterson *et al.*, *The State of Data Center Cooling* (Intel, 2008) forecast an increase in rack power density to about 37 kWe by 2014, primarily due to rapid increases in memory capacity.

[0014] Rath, *Data Center Site Selection*, (Rath Consulting, http://rath-family.com/rc/DC_Site_Selection.pdf) addresses many factors to be considered in determining new data center locations in addition to the availability of environmental heat sinks and/or low cost electrical power. Siting considerations include: network latency, availability of fiber optic cable connectivity, proximity to the users, political stability, natural disaster potential, censorship, workforce availability, and many others.

[0015] Operational reliability is of utmost importance in the operation of data centers. (See Neudorfer, *The Advent of the Tier 5 Data Center*, Mission Critical Magazine Feb. 5,

2013, <http://www.missioncriticalmagazine.com/articles/85506-the-advent-of-the-tier-5-data-center>.) Data center outages are expensive. According to the 2011 National Study on Data Center Downtime, the mean cost for any type of data center outage, has been cited as \$505,502 per event. Extended outages can be devastating to the data center operator in both expense and reputation.

[0016] In the realm of the cooling requirements, therefore, there is a long-felt, and growing need for a cooling system which is continuously available, capable of cooling high power density equipment, effective in all climates, environmentally neutral or beneficial, and more energy-efficient than that of existing practices.

Summary of Embodiments of the Invention

[0017] In a variety of embodiments, the present invention provides a cooling system for data centers that is continuously available, capable of cooling high power density equipment, effective in all climates, environmentally beneficial, and more energy-efficient than existing practices. That cooling system employs liquefied natural gas (LNG), as described with respect to the following embodiments.

[0018] In accordance with various embodiments of the present invention, methods are provided for chilling air or a heat transfer fluid, also referred to variously herein as a “working fluid”, “transfer fluid” or “refrigerant.” The heated air or heat transfer fluid from a data center transfers heat to liquefied natural gas either increasing the temperature of the subcooled liquefied natural gas or vaporizing at least a portion of the liquefied natural gas and producing subsequently recovered natural gas in the process. Processes for transferring heat from the air or transfer fluid to the liquefied natural gas include heat transfer to a refrigerant that subsequently transfers heat to liquefied natural gas, and heat transfer to a first refrigerant that transfers heat to a second refrigerant that transfers heat to liquefied natural gas. It is conceivable that some high efficiency systems could require an embodiment of a cascade of multiple heat transfers to multiple working fluids.

[0019] In accordance with a further embodiment, a method is provided for using the cooled refrigerant(s) to remove heat from air or heat transfer fluids that are subsequently

utilized to maintain computing equipment at a data center in the desired operating temperature range.

[0020] In accordance with a further embodiment, a method is provided for using the temperature gradient between LNG and heat from the data center to drive an expansion engine or prime mover to create work, generate electricity, or drive a cooling system to provide data center cooling.

[0021] In accordance with yet another embodiment, a method is provided for using the cooled refrigerant(s) in combination with an electrical cogeneration facility that produces waste heat which can be used to drive an absorption chiller to provide data center cooling.

[0022] In accordance with another aspect of the invention, a system is provided for cooling data center computer equipment. The system has a heat transfer loop for receiving heat from a data center and a refrigerant impelled for circulation within the heat transfer loop for transferring heat from the data center to a heat sink, wherein the heat sink is provided by extraction of heat used to heat or vaporize liquefied natural gas. The system may also have a heat engine for extracting work from a thermal gradient between the data center and the thermal sink.

Brief Description of the Figures

[0023] The foregoing features of the invention will be more readily understood by reference to the following detailed description, taken with reference to the accompanying figures, in which:

[0024] Fig. 1 shows a process overview for using LNG to provide cooling to computer data centers in accordance with preferred embodiments of the present invention.

[0025] Fig. 2 schematically depicts an embodiment of the present invention using a second refrigerant to transfer heat generated in the data center to the liquefied natural gas vaporizer.

[0026] Fig. 3 schematically depicts an embodiment of the present invention to generate electrical power.

[0027] Fig. 4 schematically depicts an embodiment of the present invention to provide supplemental cooling to the data center.

Detailed Description of Embodiments of the Invention

[0028] In accordance with embodiments of the present invention, as now described in detail, data center cooling requirements are met by collocation between a data center and an LNG regasification plant (otherwise referred to herein as a vaporization plant or terminal). The particular requirements described above make the application of LNG cooling capacity to cooling of data centers and attendant electrical energy generation appealing for cost and resource conservation purposes and other advantages described herein, even if surprising and unprecedented.

[0029] Standard ‘free cooling’ technologies for data center cooling use much warmer temperature heat sinks, such as ambient air or sea water, than cryogenic temperature LNG. Use of the colder temperature provided by an LNG-based heat sink advantageously results in vastly larger temperature gradients for heat transfer, and, thus, highly efficient cooling. Indeed, processes in accordance with embodiments of the invention described below entail “thermal-to-thermal” heat exchange, which can be accomplished at efficiencies approaching 100%.

[0030] The use of regasifying LNG (vaporization) for various cooling applications has been suggested in the literature. Some of these cooling applications include those as diverse as: deep-freezing food, separation of air constituents by liquefying gases such as nitrogen, argon, and oxygen, cryogenic grinding of elastomers such as rubber, and power generation and power generation efficiency improvements using various technologies. Continuous cooling operation is not critical, however, to any of these prior art applications. Surprisingly, LNG regasification may also be applied in a critical application such as the cooling of a data center, where loss of cooling would cause infrastructural disruption on a massive scale. Thus, a data center is a better match and a more consistent source of heat than prior applications. Similar to the LNG regasification terminal, the data center is typically a “mission critical” operation which runs 365 days/year and therefore its continuously rejected heat is always available to the LNG terminal and therefore well-suited to the regasification

terminal's continuous need to vaporize LNG. In prior art applications noted above, the source of heat provided by a collocated industry is not consistent, and must be supplemented more frequently by heat from seawater or the combusting of natural gas which are methods typically used for vaporizing LNG. Moreover, if the LNG terminal does not have continuous natural gas pipeline send-out, non-critical data centers may still be collocated for mutual advantage. Some data centers exist solely for backup purposes and can be dispatched when the LNG terminal is sending out gas and has the refrigeration available to provide the cooling to the data center for temporary use as a backup facility.

[0031] Publications, including published patents, patent applications, websites, company names, and scientific literature referred to herein, establish the knowledge that is available to those with skill in the art and are hereby incorporated by reference in their entireties to the same extent as if each was specifically and individually indicated to be incorporated by reference in its entirety. Any conflict between any reference cited herein and the specific teachings of this specification shall be resolved in favor of the latter.

Definitions

[0032] As used in this description and the accompanying claims, the following terms shall have the meanings indicated, unless the context otherwise requires:

[0033] The term “data center” (or, equivalently, “server farm”) shall denote any facility, comprising one or more structures specifically intended to house computer equipment.

[0034] The term “cloud service provider” shall refer to any entity which provides data and/or computing capacity via the internet to one or more parties, which may include the provider entity authorized to access the data and/or computing capacity via any connected device.

[0035] The term “connected,” as used herein, shall be used to describe the relationship between or among two or more devices or functionalities, whether the coupling is physical or virtual, to enable transfer of matter, energy or information between the devices or functionalities, or some subset thereof.

[0036] The term “heat transfer fluid” (also referred to herein as a “refrigerant” and “working fluid”), is a fluid that serves for conveying heat by virtue of motion of the fluid. A heat transfer fluid may be a liquid or a gas, or, may be employed, as described herein, in more than one phase or state of matter.

[0037] The term “heat engine” shall refer, without limitation, to any modality for extracting the available thermal energy of a system and for converting it to mechanical work that may subsequently be harnessed for mechanical use or converted into energy in any form, whether electrical, thermal, or mechanical.

[0038] “Process air” shall refer to air, or any other gas, that is integral to an industrial process such as cooling electrical equipment. Process air may serve as a heat transfer fluid for purposes described in accordance with embodiments of the invention described herein.

[0039] A general overview of concepts involved in the practice of the present invention is first provided with reference to Fig. 1. In accordance with embodiments of the present invention, a source of refrigeration, designated generally by numeral **100**, is provided for a data center **101**. Data center **101** includes computers (not shown) as indicated by the definition of data center provided above. At the same time as refrigeration source **100** cools data center **101**, heat produced by computers comprising the data center **101** is recovered and used to heat and vaporize liquefied natural gas (LNG) **102**. The refrigeration resulting from the process depicted in Fig. 1 can be used to chill the air or a heat transfer fluid in a data center conduit **111** used by the data center to keep equipment within a safe operating range of temperatures.

[0040] A facility where LNG **102** is converted to a gas (designated as natural gas NG) is referred to herein as an “LNG regasification plant,” designated generally by numeral **112**. LNG **102** is delivered to a regasification plant **112** at -162°C , but must be vaporized and heated to ambient temperature prior to distribution (also referred to as “send-out”) into natural gas pipelines. Many LNG regasification plants combust natural gas as a fuel to vaporize LNG. This process on average consumes approximately 1.8% of the total received LNG in order to vaporize and warm the natural gas. And many LNG terminals use heat from

seawater to vaporize LNG. In accordance with the present invention, the LNG regasification plant **112** may benefit by using waste heat from data center **101** to vaporize LNG **102** and to heat natural gas **NG** to ambient temperature for delivery to end users. The present invention reduces negative environmental impacts of these conventional heat sources by reducing emissions and cost from burning NG and/or reducing electricity demand for pumping seawater and water quality issues due to use of biocides, impingement and entrainment of fish and larvae and impacts from the rapid change of temperature on biota. Moreover, the collocated data center **101** also realizes lower costs and secondary environmental benefits. Thus, the present invention simultaneously reduces the costs and energy required for both vaporizing liquefied natural gas and cooling the data center computing equipment.

[0041] In accordance with certain embodiments of the invention, a slipstream - a portion or all of the LNG **102** from LNG facility **112** - is heated, resulting in reduction of subcooling (below the boiling point) or, alternatively, the LNG may be vaporized. As used herein and in any appended claims, the term “subcooling” refers to cooling below the temperature of condensation at a given pressure. The vaporized natural gas remains in the facility’s existing natural gas distribution infrastructure. This method is analogous to traditional cogeneration utilized at electric power stations where a portion of the steam energy remaining after expansion is used for heating instead of being wasted during condensation. In this case, the cooling capability of the LNG is harnessed instead of being wasted when the LNG is vaporized prior to distribution of the natural gas to customers.

[0042] Referring further to Fig. 1, LNG **102** travels through inlet conduit **103** to a first heat exchanger **104** (also referred to herein as the “LNG heat exchanger”) and, from there, in liquid or gaseous form, through outlet conduit **106**. An intermediary heat exchange loop **108** carries a heat transfer fluid (or “refrigerant,” not shown), that may be a liquid or a gas, and may change phase upon passing through one or both of the first and second heat exchangers **104** and **114**, respectively.

[0043] Heat exchange fluids that may be used in a heat exchange loop (e.g., intermediary heat exchange loop **108** in Fig. 1) include, without limitation, single component hydrocarbons such as propane and methane, or multicomponent heat transfer fluids. A heat transfer fluid may exist in a liquid or a gas phase, and may change phases within a heat

exchange loop. In some embodiments, a heat transfer fluid will condense from a gas to a liquid over the range of operating temperatures. Accordingly, in some embodiments, propane, pressurized methane, or a multicomponent heat transfer fluid are preferred because of their gas/liquid phase transition within the range of operating temperatures and pressures and because they condense, but do not freeze, over the range of operating temperatures. Any other refrigerants or heat transfer fluids currently known, or developed in the future, may be used as a heat transfer fluid within the scope of the present invention. The heat transfer fluid is circulated within the intermediary heat exchange loop **108** by a pump **110**. Since pump **110** pumps fluid at a cryogenic temperature, it may be a centrifugal pump, which may be obtained from Cryostar SAS of Hesingue, France, and further suitable pumps may be selected by persons of ordinary skill in the art.

[0044] The rate of heat transfer via intermediary heat exchange loop **108** corresponds to the total cooling requirements of data center **101**, or to a portion thereof. Operating temperatures on the high side of heat exchanger **114** are typically in the range of -50°C to 30°C , while operating temperatures at the low side of heat exchanger **104** are typically at or near -162°C . The foregoing values are provided by way of example, and without limitation. Design of the volume and flux of refrigerant required to provide for heat transfer in accordance with the foregoing ranges of operation is well within the skill of a person of even ordinary skill in the thermal engineering arts and need not be further elaborated here.

[0045] The design of an LNG heat exchanger **104** to provide requisite heat transfer capacity is well-known in the art. The design of second heat exchanger **114**, operating at the temperature of intermediary heat exchange loop **108**, is similarly, well within the skill of a person of even ordinary skill in the thermal engineering arts and needs no further elaboration here. Second heat exchanger **114** transfers heat from a heat transfer fluid circulating within data center conduit **111**, which serves to meet the cooling requirements of equipment within data center **101**. Examples of data centers that use a flow of water to meet cooling needs is provided by Miller, *Equinix is Latest to Adapt Ground Water for Cooling*, (Data Knowledge Center, October 26, 2012), (<http://www.datacenterknowledge.com/archives/2012/10/26/equinix-adapts-ground-water-cooling/>), which is incorporated herein by reference.

[0046] In another embodiment of the present invention, now described with reference to Fig. 2, an additional intermediate heat exchange loop **218** is introduced in the thermal path between the vaporizing LNG **102** and data center **101**. Considerations of thermodynamics, safety, and other properties of available refrigerants might require use of multiple refrigerants, as shown. In Fig. 2, LNG **102** travels through an inlet conduit **103** to a first heat exchanger **104** on the colder side of heat exchanger **104**. From the first heat exchanger **104**, natural gas travels, in liquid or gaseous form, through outlet conduit **106**. A first intermediary heat exchange loop **108** carries a first heat transfer fluid (or “refrigerant”, not shown) which, as discussed above, may be a liquid or a gas, and which may change phase upon passing through one or both of first and second heat exchangers **104** and **114**. The heat transfer fluid is circulated within the first intermediary heat exchange loop **108** by a first pump **110**. Heat is extracted from the first heat transfer fluid within the first intermediary heat exchange loop **108** to heat or vaporize the LNG **102**. Choice of an appropriate refrigerant has been discussed above.

[0047] Second heat exchanger **114** is at the hot side of the first exchange loop **108** and at the cold side of the second intermediary exchange loop **218**. Within the second heat exchanger **114**, heat from the second refrigerant (*i.e.*, the second heat transfer fluid) in the second intermediary exchange loop **218** is heated at heat exchanger **224** by fluid in data center conduit **111**, and, in turn, transfers heat via second heat exchanger **114** at the cold side of the second intermediary exchange loop **218** to the first intermediary heat exchange loop **108**. The second heat transfer fluid is impelled in circulation about the second intermediary heat exchange loop **218** by a second pump **220**. The second pump **220** must handle fluids at the temperature range of the second heat transfer fluid.

[0048] The heated first heat transfer fluid exiting the second heat exchanger **114** is pumped (via the first pump **110** and the first intermediary exchange loop **108**) back to the first heat exchanger **104** to be cooled. Ammonia is preferred as the second heat transfer fluid in some embodiments of the invention because of its high heat of vaporization property.

[0049] The cooled second transfer fluid within the second intermediary exchange loop **218** enters the third heat exchanger **224** where it is heated by the third heat exchanger **224** thereby receiving heat from the heat transfer fluid in a data center conduit **111**. Chilled

water or other heat transfer fluid, or a low-toxicity, non-corrosive, and non-flammable refrigerant, such as R410a, is used, for example, as the transfer fluid in the data center conduit **111** to transfer cooling from the third heat exchanger **224** to the data center.

[0050] The heated second heat transfer fluid exiting the third heat exchanger **224** is pumped (via the second pump **220** and the second intermediary exchange loop **218**) back to the second heat exchanger **114** to be cooled. The cooled third heat transfer fluid exiting the third heat exchanger **224** in data center conduit **111** is then available to cool the data center **101**. At the same time as refrigeration source **100** cools data center **101**, heat produced by computers comprising the data center **101** is recovered and used to heat and vaporize liquefied natural gas (LNG) **102** as it enters the first heat exchanger via the first inlet conduit **103**.

[0051] Typical LNG regasification plants have multiple times the amount of waste refrigeration available needed even for the large cloud and online service provider data centers being constructed today. The capital expense associated with the present invention makes the application to most small and medium size data centers uneconomical. With the advent of large new consolidated data centers being constructed, the thermal balance between the heat source and heat sink is improved, easily justifying adoption of the process here described and generating large operational cost savings. For example, a typical LNG regasification plant with a natural gas send-out volume of one billion cubic feet per day has about 165 MWt (megawatts thermal) of refrigeration available. This is enough refrigeration to provide not only the cooling needed by a large data center but is also sufficient to generate all of the electrical power for a data center with about 40 MWe (megawatts electrical) demand for computing and data storage.

[0052] Advantages of collocation between a data center and an LNG regasification facility extend beyond data center cooling and also include providing electrical energy for data center operations. The temperature gradient between cryogenic temperature liquefied natural gas (LNG) (the boiling point of which, at atmospheric pressure, is -162°C) and ambient heat sources can be used as the driving force to generate electrical power using a heat engine. This application may thereby advantageously replace electrical power that might otherwise require generation using non-renewable resources and concomitant negative

environmental impacts. An example of power generation using LNG regasification as a heat sink is provided in (<http://www.ngoafricasummit.com/media/whitepapers/Fluor-LNGRegasificationUtilization.pdf>).

[0053] In accordance with certain embodiments of the present invention, the temperature gradient between LNG and the heat transfer fluid from the data center is used as the thermodynamic driving force to produce work or generate electrical power. In almost all cases, an LNG regasification plant has more waste refrigeration available than is needed for the data center cooling requirements. It is much more efficient to use the waste refrigeration for direct or indirect heat exchange with the data center cooling medium rather than using it to generate electrical power due to the second law of thermodynamics limitations imposed on the cycle, but combining the two processes to take full advantage of the waste refrigeration from the LNG regasification plant provides additional environmental benefits and cost savings to both the data center and regasification plant.

[0054] Fig. 3 depicts one method of using a heat engine to generate electricity. The first or second refrigerant is liquefied by heat exchange with LNG and vaporized cold natural gas. It is pumped to the required process pressure and vaporized by heat exchange, and then used to provide the driving force for an expansion engine. The expansion engine is mechanically coupled to an electrical generator. Many alternative configurations for this method are possible including, but not limited to, multistage heat exchangers, expansion engines, and refrigerants. For example, in Fig. 4, the expansion engine is mechanically coupled to a compressor that is part of a system to provide supplemental cooling. These non-combustion methods of generating electricity or driving a compressor produce zero emissions and eliminate the emissions and fuel cost and resource depletion for the equivalent amount of power that would otherwise be produced for the data center's use. The heat engine itself is not limited to an expansion process; it could conceivably be executed, for example, using solid-state thermoelectric devices.

[0055] In an embodiment of the invention now described with reference to Fig. 3, LNG **102** travels through an inlet conduit **103** to a first heat exchanger **104** on the colder side of the first exchange loop **108**. From the first heat exchanger **104**, LNG **102** exits, in liquid or gaseous form, through outlet conduit **106**. A first intermediary exchange loop **208** carries

the first refrigerant, which condenses upon cooling in first heat exchanger **104**, and is pumped by pump **110** into the second heat exchanger **114**, where it is heated by heat conveyed to the second heat exchanger **114** via heat exchange loop **328**. Upon heating, the first refrigerant expands in expander **315**, and the work performed by the expanding refrigerant powers a generator **317** via a mechanical coupling **316**, to produce electricity. The electricity produced is delivered via electrical path **318** to contribute to the power requirements of the data center **301**, or for other uses such as for the LNG terminal's demand or for export to the electrical grid. Thus, a portion of the electrical energy used to power the data center **301** may come from the electrical power exiting the generator **317** via the generator outlet conduit **318**.

[0056] A refrigeration loop **328** in Fig. 3 allows circulation of a heat transfer fluid from the second heat exchanger **114** (circulated by pump **220**) to the data center **301**, where the second heat transfer fluid is heated by heat dissipated by the data center **301**. In the second heat exchanger **114**, the second heat transfer fluid is cooled by thermal coupling of refrigeration loop **328** to the first intermediary exchange loop **208** carrying the first heat transfer fluid. In the embodiment shown in Fig. 3, refrigeration loop **328** runs through the data center **301** facility itself.

[0057] Yet another embodiment of the invention using energy from the heat conveyed by a first heat transfer fluid in cooling the data center **401** is depicted in Fig. 4. Here, rather than using the expanding refrigerant in loop **208** for generating electricity, or in addition to that application, mechanical power is extracted from the heated refrigerant to run a mechanical cooling loop for additional cooling needs of the data center.

[0058] The additional mechanical cooling loop **421** carries a third refrigerant (not shown) that circulates within the additional cooling loop **421** through the data center **401** by action of a throttle **422**. The third heat transfer fluid within the additional cooling loop **421** is compressed by a compressor **420** that is powered by expansion of the refrigerant in heat-transfer loop **208** via mechanical coupling **419**. The heated third transfer fluid circulates to heat exchanger **423** where heat is shed to the ambient environment. Expanding after throttle **422**, the refrigerant in heat transfer loop **421** cools and is able to absorb heat in data center **401**, thereby providing supplemental cooling .

[0059] To minimize interruptions in service, both data centers and LNG regasification plants install redundant equipment, and in some cases, multiple redundant equipment and processes for critical uses. Having similar strategies to assure high reliability makes the two industries very compatible with each other. Cooling and electrical power from the present inventions provide even greater reliability to the data center since they can operate independently of the electrical supply grid and other mechanical backup systems.

[0060] Having thus described various illustrative embodiments of the present invention, some of its advantages and optional features, it will be apparent that such embodiments are presented by way of example only and are not by way of limitation.

[0061] For example, in other embodiments of the invention, the liquefied natural gas may be distributed from an LNG terminal, by tank truck or tank car, to a remote storage tank. The liquefied natural gas from the storage tank may be vaporized and heated to ambient temperature with heat from the data center, and the natural gas may be used as fuel for a cogeneration facility that provides electrical energy for the data center. Some of the waste heat recovered in the cogeneration process may be used to drive absorption chillers and which may not be sufficient alone to meet the data center's cooling requirements. By combining the LNG vaporization and absorption chiller refrigeration sources, heat energy for LNG vaporization and electrical energy for compressed vapor chillers are reduced or eliminated.

[0062] Those skilled in the art could readily devise alterations and improvements on these embodiments, as well as additional embodiments without departing from the spirit and scope of the invention. All such modifications are within the scope of the invention as claimed. The described embodiments of the invention are intended to be merely exemplary and numerous variations and modifications will be apparent to those skilled in the art. All such variations and modifications are intended to be within the scope of the present invention as defined in the appended claims.

What is claimed is:

1. A method for cooling data center computer equipment, the method comprising:
 - a. receiving liquefied natural gas;
 - b. transferring heat from a first refrigerant to the liquefied natural gas, the first refrigerant contained within a heat transfer loop; and
 - c. transferring heat from the data center computer equipment to the first refrigerant, thereby cooling the data center computer equipment.
2. A method according to claim 1, wherein transferring heat from the data center computer equipment to the first refrigerant includes transferring heat via a second refrigerant contained within an intermediate heat exchange loop.
3. A method according to claim 1, wherein transferring heat from a first refrigerant to the liquefied natural gas decreases subcooling of the liquefied natural gas.
4. A method according to claim 1 transferring heat from a first refrigerant to the liquefied natural gas vaporizes at least a portion of the liquefied natural gas.
5. A method according to claim 1, wherein the first refrigerant is characterized by a temperature in a range of from about -165°C to about +30°C.
6. A method according to claim 1, wherein transferring heat from the data center computer equipment includes further comprising chilling a heat transfer fluid in a data center conduit.
7. A method according to claim 1, wherein transferring heat from the first refrigerant to the liquefied natural gas occurs in a heat exchanger.
8. A method according to claim 1, wherein the first refrigerant is a single-component hydrocarbon.
9. A method according to claim 1, wherein the second refrigerant is ammonia.

10. A method according to claim 1, further comprising extracting work from the heat transfer loop.
11. A method according to claim 10, wherein the extracted work is mechanically coupled to an electric generator.
12. A method according to claim 10, wherein the extracted work is mechanically coupled to a refrigeration loop.
13. A method according to claim 12, further comprising providing additional cooling to the data center by means of the refrigeration loop.
14. A system for cooling data center computer equipment, the system comprising:
 - a. a heat transfer loop for receiving heat from a data center; and
 - b. a refrigerant impelled within the heat transfer loop for transferring heat from the data center to a heat sink,wherein the heat sink is provided by extraction of heat used to heat or vaporize liquefied natural gas.
15. A system according to claim 14, further comprising a heat engine for extracting work from a thermal gradient between the data center and the thermal sink.
16. A system according to claim 14, further comprising an intermediate heat exchange loop disposed between the heat transfer loop and the heat sink.