Data Center Cooling System Integrated with Low-Temperature Desalination and Intelligent Energy-Aware Control

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November 15, 2018

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***Abstract*—Data centers consume enormous energy, presently reported up to 2% of the world's electricity, with most of this energy then rejected into the atmosphere as waste heat. Meanwhile there is a global scarcity of safe drinking water. The UN states that 20% of the world's population lives in regions affected by scarcity of drinking water. In this paper, we discuss an on-going research initiative that investigates the reuse of "free" waste heat energy from data centers in coastal cities and island countries, and in modular data centers that are deployed in coastal regions, through a low-pressure desalination process that converts sea water into safe drinking and irrigation water supplies, while significantly improving the Power Utilization Efficiency (PUE) for the data centers. In this paper, we discuss a work-in-progress experimental setup with the purpose of demonstrating that heat removed via common fluid-cooled rack heat exchangers in modern data centers can be re-used via a controlled-low-pressure desalination technique to turn salt water into drinking water at zero added carbon cost for the desalination, and significantly reduced carbon cost for the data center operations.**

***Index Terms*—data centers; energy efficiency; heat extraction; waste heat; desalination; sustainability;**

I. INTRODUCTION

Data centers consume enormous electrical energy and contribute significantly to atmospheric carbon burden. In 2010, the global electricity consumption of data centers exceeded 70GWatts [1] and continues to rise significantly. This energy consumption is mainly used (i) for active IT compute tasks and (ii) to extract heat from the data center IT components. Most of the heat extracted from cooling the electronics is rejected to the atmosphere as waste [6]. There is significant work done in reducing the energy consumption in data centers - ranging from server virtualization, intelligent work scheduling, advances in cooling techniques, etc. Nevertheless, data centers consume energy simply to function (i.e. execute compute and storage tasks), and dissipate the waste energy as heat back to the atmosphere.

UN report [5] cites that scarcity of safe water supplies affects a large percent of the world population, and affects populations in both developing and developed nations. For example, for four of the last five years southern California has been under drought conditions and people have been affected by high costs associated with the lack of potable water. Nations can benefit from reusing or reclaiming water resources as an alternative to their pressing water demands [16]. There are many large data centers in coastal cities that consume 100s of GWh energy, but with an essentially infinite supply of cold salt water nearby.

For data centers in the future that are located near large salt water bodies, the new eco-efficiency innovation reported here exploits low-cost desalination of cold sea water using the "free" waste heat from the servers (in data centers) in an optimal multivariate control scheme to produce drinking and irrigation water as a byproduct. In this paper, we present an IT telemetry-controlled bivariate workload-scheduling and fluid-flow control technique that allows continuously-optimal efficiency by which the waste heat from the servers to be recycled efficiently to desalinate sea water at low pressure. The output is a zero carbon footprint irrigation/ drinkable water. The concept reported here integrates Oracle's Intelligent Power Monitoring (IPM) technology for energy-aware job scheduling and intelligent fluid-flow control and a new low-temperature desalination technique [11] that turns salt water into drinking water at zero added carbon cost. This sustainability solution leverages re-using waste energy/ energy recovery from the data center. With advances in the field of data center waste energy recovery, further techniques can be developed to address the global challenge in an environmentally benign way.

This paper we present a work-in-progress sustainability solution to addresses two issues: (i) The energy crisis for many nations is exacerbated by the fact that data centers now consume 2% of the world's electricity (over 70 GWatts) globally, with approximately 40% of that electricity used for cooling, and with most of the energy being dumped as waste heat into the atmosphere; and (ii) the latest UN reports are that a large percent of the world's population lives in regions affected by scarcity of safe water supplies.

The rest of the paper is organized as follows. Section II lays the groundwork with technical discussions and explains the foundation for our intelligent multivariant control design/ solution. In section III we present the integrated architecture and overall solution comprising a symbiotic integration of three proven techniques. Section IV presents our preliminary studies, theoretical underpinnings, and our preliminary studies, theoretical underpinnings, our experimental setup and expected results. Section IV presents our preliminary studies, theoretical underpinnings, our experimental setup and expected results. Section V presents related work. Finally, section VI concludes this paper and discusses our future directions.

II. DESIGN TECHNIQUES

Our design techniques are based on simple proven methodologies and technologies as as discussed in the sections below and enumerated here: Oracle's Intelligent Power Management (IPM) telemetry from executing IT systems in datacenters is mature methodology that has evolved over the last 15 years. The bivariate control algorithm that manages workload scheduling queues and fluid flow rates is based upon Oracle's Multivariate State Estimation Technique2 (MSET2), which is very mature advanced pattern recognition technology that is already operating in business-critical enterprise and cloud data centers. And the low-pressure desalination concept which uses gravity to create a vacuum and requires only a source of low-grade heat as its energy source is well proven in its own field of use. The innovation reported in this paper is bringing these three technologies together and leveraging very high thermal flux levels from free (i.e. already paid for) waste heat from data center IT assets. We combine these three elements with additional technology/ strategies into an overarching solution to achieve dual-sustainability results in a conventional data center. We start with a quick introduction to these techniques and show how they combine to form our overall design. It is important to point out here that Oracle's IPM telemetry requires no hardware or firmware modifications to any IT systems in the data center. IPM telemetry operates passively on the standard board-management-control (BMC) processor, also called the Integrated Lights-Out Manager (ILOM), on all modern enterprise computing systems and does not use any CPU cycles from the end-customer data center IT assets. IPM imposes no overhead compute cost on any end-customer CPU-intensive, memory-intensive, or IO-intensive workloads since IPM runs passively on the BMC/ILOM processors in enterprise servers.

A. Data center workloads v. CPU temperatures

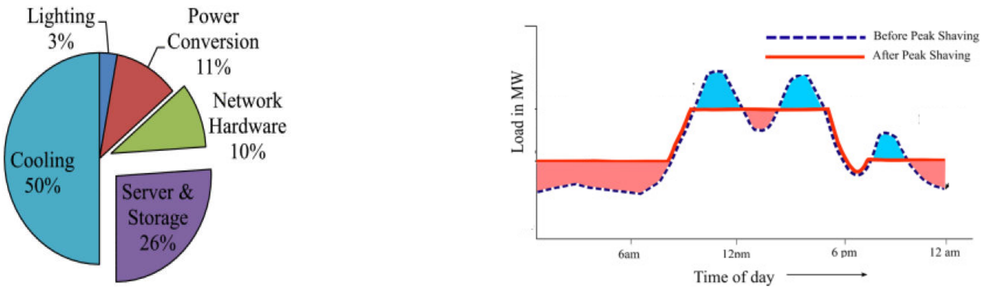
It has been well established over the last few decades that CPU thermal dissipation in computers is directly proportional to the work done (switching energy) in the chip, and exponentially proportional to the much smaller leakage energy in the chip. All enterprise computing CPUs use real-time Dynamic Voltage and Frequency Scaling (DVFS) to adjust the frequency and voltage of the CPUs to avoid wasteful "leakage power" in the CPUs. Leakage power is exponentially driven by CPU temperatures, so that DVFS "slows down" the operating frequency of CPUs when the CPU temperatures are warmer, and "speeds up" the operating frequency when the CPU temperatures are cooler. Consequently, there is an increase in computational performance and throughput when the CPUs are cooler, and a performance penalty when the CPUs are warmer. Because of this relationship between CPU temperatures [13] (which are measured for every CPU and every core in all of the IT systems) and workload execution, we get a direct and monitorable three-way nonlinear relationship between compute-work executed, CPU-core-junction temperature, and heat dissipated. Our work uses this continuously monitorable (via IPM) thermal dissipation from CPUs as a heat source for low-pressure desalination, while leveraging the cold incoming saline water as the transport medium for the free waste heat to the desal module and as the means to continuously keep wasteful leakage power at an absolute minimum.

B. Fluid Cooling in Data Centers

The US Dept. of Energy reported that in 2016 data centers consumed 2% of the electricity generated in the USA [8], approximately 40% of that energy is used for cooling. Data center energy consumption and categorical breakdown of the energy components is well studied [6](Fig. 1(a)). Air cooling of data centers has nearly reached the limits allowed by the laws of physics [3]. Advancements toward fluid cooling of data center servers try to address the climb in heat densities. Fluid cooling is substantially more efficient for heat removal, such that thermal experts predict that data centers of the future will be fluid cooled [14]. All modern data centers are already hybrid fluid-air data centers that still have fans inside servers, but then extracts the intense heat of the IT system exhaust air with a large, efficient water-cooled heat-exchange system (the so-called glacier doors that use cold water to cool the very hot air exiting the backs of the racks of IT servers). Data centers that use air-fluid heat exchangers to directly extract heat from the high power density IT systems have a lot of potential for waste-heat-reuse [22]. This extracted heat lays the first foundation for our research.

C. Desalination under Low Temperature/Low Pressure

Of the many techniques used for desalination of sea water, clean water production by the condensation of evaporated salt water under vacuum is a commonly applied technique [2]. Low-pressure desalination is based upon a very simple principle: If one fills a horizontal pipe with water, seals one end of the pipe and then raises the sealed end vertically (with the uncapped end still under the surface of the water), low pressure is created at the sealed top of the pipe, simply from gravity (the weight of the vertical column of water in the pipe). The degree of vacuum at the top of the pipe is proportional to the height of the water column. Under low pressure or vacuum conditions, desalination can be achieved at a high efficiency and relatively low temperatures by reducing the saturation temperature of saline water through vacuum [17, 19]. This forms the basis for our desalination step in our sustainability solution.



(a) Data center energy consumed [6]

(b) Load Smoothing Effect

Fig. 1. Breakdown of energy consumption & Load smoothing

D. A Heat Source

The desalination process needs heat energy. The GWatt-hours per year of thermal energy that is presently being rejected to the atmosphere in present generation data centers II-A forms the basis of our heat source. To cite an example, one of Oracle's customers with a data center in Virginia uses 360 MWe of electrical power, fed by six regional power plants, and essentially all of this energy is degraded to heat and discarded to the atmosphere. There are tens of thousands of data centers around the world, many in coastal areas/ cities with unlimited volumes of salt water within reasonable pumping distances. For modern data centers, fluid-air heat exchanges enable the waste heat from data center IT systems to be efficiently extracted, concentrated, and channeled into a single heat stream. This continuous heat stream, at approximately 50°C, is our final step towards 'fueling' our desalination process.

So far, we have shown the foundation steps that forms the basis of our solution. Next, we present the detailed architecture and solution that encapsulates the above proven techniques into an overall solution.

III. INTEGRATED ARCHITECTURE

Our research integrates the above three elements into an overall engineering methodology that achieves efficient cooling of data centers while turning sea water into reusable/ drinking water. We put together these elements to form an overarching solution, as below.

A. Intelligent Power Monitoring Telemetry

Intelligent Power Monitoring Telemetry (IPM) [20] software monitors the real-time temperatures, voltages, currents, power metrics, and fan speeds inside the enterprise servers and storage systems in a data center. IPM telemetry allows real-time assessment of the dynamic power level, thermal dissipation, and thermal headroom margins (difference between real-time temperature when systems are under load and a maximum thermtrip threshold above which reliability issues could arise, for enterprise computer servers and storage technology throughout a data center. We use the data harnessed by this system to efficiently manage the workload dynamics and (through an intelligent bi-variate controller) the flow rate through the air-fluid heat exchanger doors so that we maintain a relatively steady stream of heat source to fuel our apparatus.

B. Continuous System Telemetry Harness

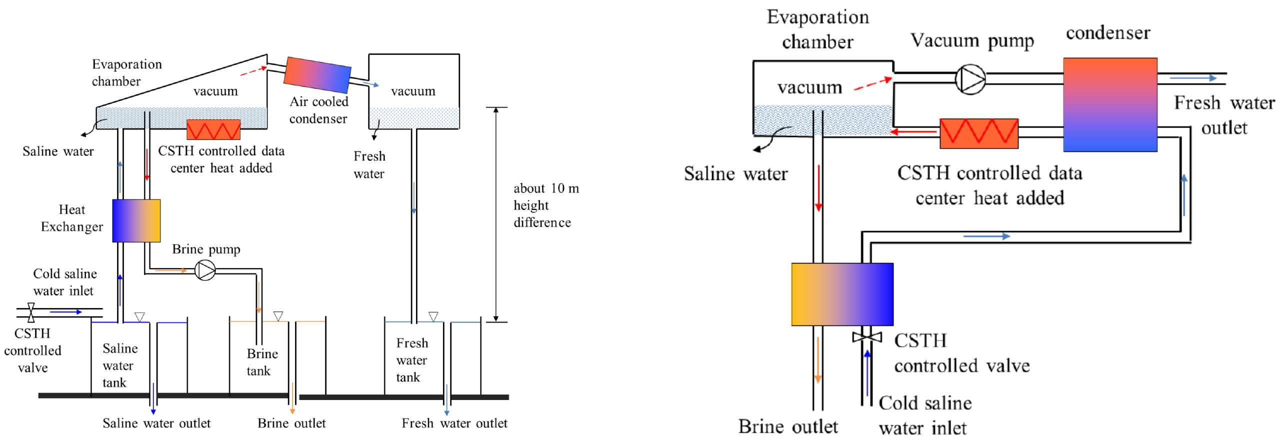
The Continuous System Telemetry Harness (CSTH) is a software application that enables energy-aware job scheduling to maintain a relatively flat aggregate thermal load for the data center. This relatively flat thermal load Fig. 1(b) is desired to optimize the efficiency of the heat source that is required for low pressure salt-water/fresh-water conversion. Our machine-learning Multivariate State Estimation Technique-2 (MSET2)[10] control algorithm allows the end customer to ”turn a knob” to either achieve maximum computational throughput with some trade-off in desalination efficiency, or achieve maximum desalination efficiency with some trade-off in completion times for low and medium priority workloads. Workload scheduling methodologies, including Oracle's power-aware scheduling, leverage (now standard) virtual-machine workload mobility to ensure that the peaks and valleys of the workload are smoothed to give a quasi-uniform average power load (and hence constant/ average thermal output) as in Fig. 1(b).

C. Low Temperature Desalination

Low-temperature, low-pressure desalination processes are proven, well established and readily available [12]. The approach is to create a vacuum at the top of the evaporation chamber, since sea water vaporizes readily at relatively low temperatures when under vacuum [11]. Under such vacuum or low pressure conditions, we need a heat source at only 40°C-50°C to get good desalination conversion efficiencies. To create the vacuum (or low pressure), our design utilizes two candidate systems: one is 'passive' (Fig. 2(a)) in that it uses gravity to create the vacuum, and the other one is 'active' (Fig. 2(b)) that uses a vacuum pump. The passive system only needs a good source of free waste heat, while the active system needs additional electrical energy for the vacuum pump (trade-offs in overall energy and desalination efficiencies are being evaluated as part of this ongoing sustainability research initiative). Our design uses the waste energy (Fig. 1(a)) from data center IT systems as the main heat source for the desalination process.

D. Maintaining a steady heat source

We control energy and desalination efficiencies of the system using real time telemetry of the saline inlet temperature



(a) Passive System [11]

(b) Active System

Fig. 2. Passive & Active Desalination Techniques

and machine language (ML) control the saline water flow rate with an Oracles advanced pattern recognition algorithm MSET2. To optimize the efficiency for salt-water/sea-water conversion, it is best to have a uniform heat flux to the saline water so that the saline temperature in the evaporation chamber is nearly invariant. However, many data center workloads are quite dynamic with time. We address and smooth out these dynamics with a novel power-aware Intelligent Job Scheduler detailed in Fig 3.

Low priority jobs typically include long-running simulations, batch numerical analysis workloads, background database builds, operating system housecleaning utilities, etc. Medium priority jobs typically comprise those where a human eventually wants to access and manually interact with the results, but does not need/expect the results in seconds or minutes. Top priority jobs that are business critical, or that involve direct human-interactive processes (searching, spreadsheet manipulation, database sorting/mining, etc).

High priority jobs are always dispatched as soon as possible at the instant that compute assets are available. One aspect of this research is that the real-time power flux (monitored via IPM) from the distributed compute elements is input into the Intelligent Power-Aware Job Scheduler, which inserts small delays in dispatching of the Medium Priority jobs, and larger delays in dispatching of the Low Priority jobs, thereby using the Low and Medium priority jobs to ”fill in” the troughs in overall thermal flux for a much more balanced and stable aggregate workload (hence, more stable thermal flux to the desalination system). To the extent there are still overall variations in aggregate thermal flux (e.g. if there are sustained periods with low utilization such as in the middle of the night or weekend), we control the saline water flow to maintain the desired uniform saline temperature in the evaporation chamber for the integrated low-temperature/low-pressure desalination system (See Fig 2(a)).

Many scholarly articles [9, 15] address workload scheduling, load smoothing, job migrations etc. These techniques including Oracle’s approach, work towards moving the peaks & valleys of workload (and in turn heat variations) into a smoothed pattern as shown in Fig. 1(b). This approach ensures that our desalination process/ plant always has access to a steady stream of heat source.

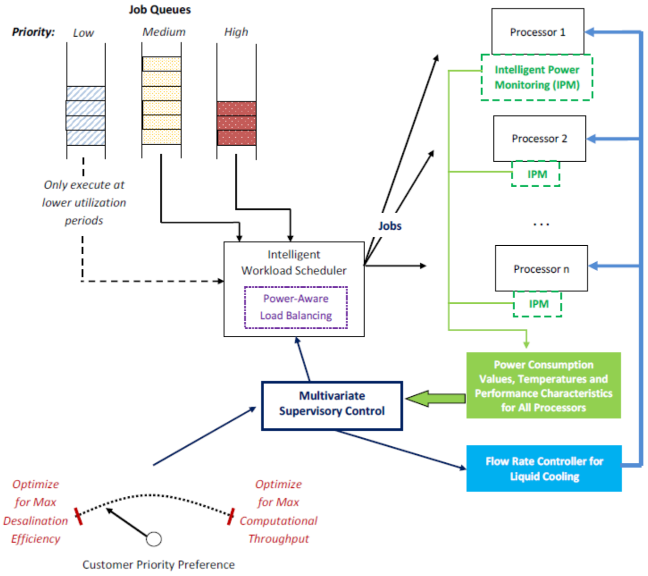


Fig. 3. Job scheduler

IV. EXPERIMENT SETUP

We present initial partial results and basis of our future implementation. Fig. 2 shows two schematic layouts for the low temperature desalination applications. The passive system in Fig 2(a) uses gravity to create a vacuum in the evaporation chamber. The evaporation chamber, condenser and fresh water chamber is located around 10 m above the saline water, brine and fresh water tanks. It is proven [2, 19] that for locations above 10 m above the saline water inlet, preheating

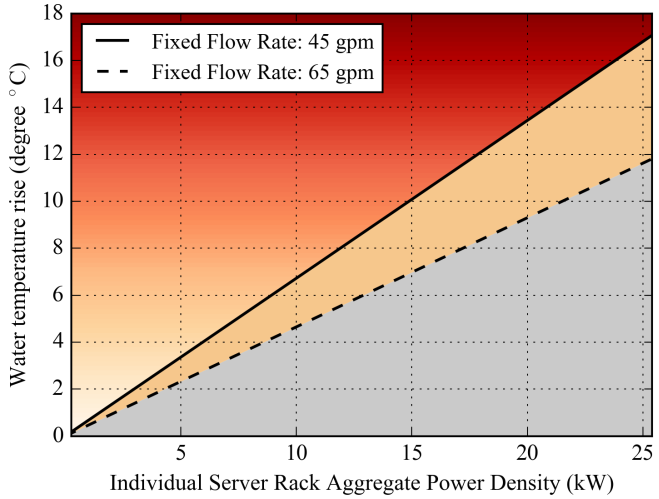


Fig. 4. Water-temp vs. Server Power Heat Map

the saline water in the condenser are not practical. On the other hand, the active system in Fig 2(b) uses a vacuum pump to create the vacuum in the evaporation chamber that all equipment can be located at the same height. Though the vacuum pump consumes electric power, the active system has fewer components thus easier to build.

During the span of this research, we plan to conduct experiments and compare the energy desalination efficiencies of the two systems. We control energy and desalination efficiencies of the system using real-time telemetry of the saline inlet temperature and machine learning control the saline water flow rate with an advanced pattern recognition algorithm called MSET. To optimize the efficiency for sea-water conversion, we have a uniform heat flux to the saline water so that the saline temperature in the evaporation chamber is nearly invariant.

We have demonstrated in experiments with an air-water heat-exchanger cooled modular data center running dynamic workload profiles measured from actual customer datacenters. These modular data center experiments were conducted at University of California San Diego (UCSD) with a modular data center full of racks of the latest generation enterprise servers and storage. These large-scale testbed experiments demonstrate that we have a great deal of control on the exit temperature of coolant as a function of aggregate thermal flux from the servers and storage and coolant flow rate. Fig 4 illustrates this controllability using two distinct flow rates. With this initial experimental proof-of-concept collaborative research between Oracle and UCSD, we have so far established a proven design for our solution. Our initial results have influenced the outcome and selection of different choice of apparatus, workload scheduling algorithmics, and our bivariate control approach I quite robust owing to the fact that to maintain a steady temperature for the brine cooling water stream, it is equally effective to raise/lower workload (which is actually done by time-shifting the low- and medium priority workloads as described above), as it is to raise/lower the cooling-fluid flowrate (from the simple thermodynamic principle that the fluid flowing through the tube-and-shell heat exchangers acquires more heat when flowing at a lower flowrate, and less heat when the flowrate is higher). Future extensions to the research reported here include conducting systematic parametric experiments to collect IPM telemetry data under all permutations/combinations of workload utilization and fluid flowrates. The data collected from these extensions to the research reported here will enable building a high-fidelity simulator, trained with actual empirical telemetry data from a design-of-experiments parametric experimental campaign.

V. RELATED WORK

Many articles [4, 6] cite clear statistical data about energy wasted in data centers. It is well accepted in both academia and industry that a significant percent of energy wasted in a data center can be recovered. In [7] authors provide a review of data center cooling techniques and available heat recovery options. Of the many heat recovery techniques, liquid cooling has a higher potential and efficiency [14]. Any improvement in heat energy recovery reduces the overall carbon foot print [3]. Our experiments in this paper constitute a low-cost and easy-to implement solution towards these goals. Several studies [21] show the relationship between CPU core speeds, DVFS, heat dissipation and workload characteristics. These articles show that heat can be recovered in proportion to the workload. Various articles [15, 18] address techniques to manage data center resources efficiently through workload migration, load scheduling, cooling management (both air and fluid). Our methodology for efficient workload scheduling uses Oracle's intelligent temperature-aware and energy-aware scheduling with a goal of producing a quasi-constant heat source, even during times with highly dynamic workloads, for the desalination process. Research results on low temperature/ low pressure two phase desalination process is presented in [12]. The authors show the economic feasibility of desalination in water and energy scare area, with purchased energy source. Our research uses the free energy source from data centers and hence enhances the economical benefits. Authors in [19] show that in a passive desalination system with vacuum (generated using just 5m of negative head drop) reduces the boiling temperature of water substantially. We use this proven technology, alongside other research [2, 12] and in combination with intelligent thermal-aware workload scheduling and intelligent flowrate control, to desalinate sea water at low temperatures/ low pressure using waste heat energy from data centers.

VI. CONCLUSION

In this on-going research paper, we merge multiple independently studied and isolated technologies - to extract wasted heat energy from data centers. We use the waste energy from data centers to desalinate sea-water at low pressure/ low temperatures. We present a work-in-progress 'data center waste energy' based sustainability solution to address two issues (i) efficient re-use of data center waste energy and (ii) desalination of sea-water. Our overall solution combines the multiple principles of (i) CPU/ core heat generated in data center servers (ii) a fluid cooling technique to extract this heat into a concentrated energy source (iii) use the waste energy as a heat source to desalinate sea-water (iv) desalination under low pressure/ low temperature. To improve the efficiency of the overall system, we integrated a novel bivariate-control scheme (a) An Intelligent Power-Aware Job Scheduling and (b) Intelligent Fluid Flow Control. We show a solution that enables the data-center operator to choose between maximum computational throughput with some trade-off in desalination efficiency, or achieve maximum desalination efficiency with some trade-off in workload completion times. In a future extension to the proof-of-concept experimental results reported herein, we plan to present systematic parametric experimental results that exhaustively step through all combinations of workload utilization metrics and heat-exchanger flowrates, and lessons learned as we conduct this in-depth study at our collaborating facilities at the Univ. of California San Diego. We hope this new eco-efficiency breakthrough will pave way for further research into global sustainability solutions.

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