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Environmentally opportunistic computing: A distributed waste heat reutilization approach to energy-efficient buildings and data centers

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ABSTRACT

With building energy consumption rising in industrial nations, new approaches for energy efficiency are required. Similarly, the data centers that house information and communications technology continue to consume significant amounts of energy, especially for cooling the equipment, which in turn produces vast amounts of waste heat. A new strategy to overcome these challenges is called environmentally opportunistic computing (EOC), which conceptualizes the data center as a series of distributed heat providers (nodes) for other-purposed buildings that use the waste heat from the data center nodes to offset their own heating costs. In this paper, a general framework for evaluating the deployment of EOC is developed and select model cases are analyzed. The results show that by redefining a centralized data center as distributed nodes across multiple buildings, the overall energy consumption of an organization decreases significantly. The advantages of applying EOC to buildings that require constant water heat as opposed to seasonal space heat are explained, and the method of distributing the computational load among data center nodes is evaluated.

1. Introduction

It is well known that energy consumption by commercial and residential buildings continues to rise worldwide in developed nations, with most of the energy going to heating, ventilation, air conditioning (HVAC), and water heating [1]. For example, a 2011 report by the United States (U.S.) Department of Energy showed that building energy consumption accounts for approximately 40% of the energy consumption in the U.S. today, or nearly 11.61 trillion kW-h/yr [2]. Further, nearly all of this energy is generated by non-renewable energy resources (*e.g.*, petroleum, natural gas), thus presenting a challenge to develop both more energy-efficient buildings and buildings that integrate renewable energy sources. For this reason, a number of studies have explored ways to reduce energy consumption in buildings, such as optimizing the control strategy for the building management system [3] and incorporating novel construction practices and materials [4]. Alternatively, a variety of renewable energy concepts, utilizing, for example, solar energy [5,6] or wind energy [7], have begun to emerge at the single building scale. However, given the magnitude of the problem, more aggressive, scalable solutions and alternative routes to energy efficiency need to be developed.

Congruently, data centers, which house the information and communications technology (ICT) that supports our economic, government, and social infrastructure, consume a significant amount of electricity. Recent estimates place data center consumption at nearly 198.8 billion kW-h/yr and rising or ∼1.3% of all electricity use world wide (and ∼2% of electricity use in the U.S.) [8]. Further, this usage is widely spread among many data centers and organizations. For example, one of the largest web-based presences, Google Inc., was estimated to account for less than 1% of all data center electricity consumption worldwide. One main concern is that not all of this electricity goes to operate the ICT equipment; a significant amount goes to facility operation, especially cooling the data center. Because nearly all of the ICT electricity consumption is manifested as heat, and overheating directly impacts reliability and performance, data centers cool and condition their ICT equipment continuously in order to meet customer demand for consistent availability and uptime. Recent studies have suggested that on average ∼40% of the electricity consumed in a data center powers equipment required to maintain operating conditions within the facility, and nearly all of this is for thermal management.

One perspective on sustainable development is to address both of these challenges symbiotically by using the heat generated by data centers as space and/or water heat for commercial, residential,

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Nomenclature

Symbol

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P_b	total power consumed by building without EOC implemented [kW]
P_{dc}	total power consumed by data center without EOC implemented [kW]
P_{org}	total power consumed by organization without EOC implemented [kW]
$P_{b,EOC}$	total power required by building with EOC implemented [kW]
$P_{dc,EOC}$	total power consumed by data center with EOC implemented [kW]
$P_{n,EOC}$	total power consumed by EOC node [kW]
$P_{org,EOC}$	total power consumed by organization with EOC implemented [kW]
$P_{org,ICT}$	total computational power for an organization [kW]
$P_{n,ICT}$	computational power in an EOC node [kW]
$P_{dc,ICT}$	computational power in the data center [kW]
$P_{dc,facility}$	facility power consumed by data center [kW]
$P_{n,facility}$	facility power consumed by EOC node [kW]
$P_{w,deliver}$	power required to deliver waste heat from EOC node to building [kW]
$P_{w,utilize}$	power required to increase waste heat to useable temperatures [kW]
PUE_{dc}	power usage effectiveness of data center
PUE_n	power usage effectiveness of EOC node
$q_{b,req}$	heating power requirement for a building [kW]
q_w	heating power provided by EOC waste heat [kW]
ε_{bldg}	building effectiveness
ε_{org}	organization effectiveness
η_{bldg}	efficiency of the native building heating system and envelope
η_{loss}	percentage of waste heat due lost to heat transfer inefficiency

or even industrial buildings and facilities. By harvesting the heat produced by data centers for other-purposed buildings, the potential exists to reduce the overall (combined building and data center) energy consumption of an organization. The idea of harvesting the heat produced by a data center has begun to receive more attention as the significant energy costs of data centers continue to rise [9]. For example, adsorption systems that harvest the waste heat to drive the primary cooling system with no additional power input have been suggested by multiple groups [10,11]. Alternatively, a novel use of relatively hot water (~60 °C) to liquid cool a data center rack demonstrated the feasibility of using liquid cooling to generate waste heat that can be directly used for building heating [12]. Practically, a number of groups worldwide have begun to implement waste heat harvesting strategies [13] to the extent that an energy reuse effectiveness (ERE) metric has been proposed to evaluate data centers that reuse waste heat [14]. However, these all use a single centralized data center to service a single other-purposed building immediately adjacent to the data center. A perhaps more effective waste heat utilization philosophy is to decentralize large data centers into smaller data center nodes that are directly integrated into the buildings they serve. This philosophy, which we call environmentally opportunistic computing (EOC) [15], takes the concept of distributed computing and reprioritizes it as distributed heating, where the data centers are treated not only as entities that meet the needs of their computing end-users but also the needs of the buildings they serve as heat sources. Further, if integrated with the buildings' existing HVAC systems, the data center nodes can potentially benefit from cooling provided by the building.

In practice, EOC would consist of distributed "containerized" data center nodes attached to or integrated with other-purposed buildings such as office buildings, apartment complexes, hotels, or university/municipal buildings and facilities. Fig. 1 shows a vision for EOC as a series of nodes implemented across a municipality, community, university, or industrial campus. Buildings throughout the organization would be outfitted with EOC nodes that either provide space or water heat depending on the needs and function of the building. Computational jobs would then be migrated from node to node based on the computational requirements of the job, the availability of servers in the node, and the waste heat required by the integrated building. This, in effect, creates a market place where both the buildings and the end-users act as both consumers and providers – end-users providing heat to the buildings and the buildings providing computational services to the end-users. Further this vision can be extended across multiple communities where local utility availability and cost could also play essential roles in the EOC marketplace. This approach is similar to the concept of the locally integrated energy sector where waste heat and renewable energy sources are integrated and shared across a community to reduce the overall carbon footprint [16], but includes the additional complexity of consumers dictating the production of heat based on their computational demand.

How a single node is integrated into a building would depend on the specific needs of the building (does it require space or water heat), the structure and function of the building, the local climate, as well as numerous other factors that would need to be considered on a case-by-case basis. EOC is built around the concept that each EOC node operates with free cooling to keep the ICT equipment functional and reliable, using either unconditioned ambient air (or return air from the building) for air cooling or the building's existing plumbing for liquid cooling. The four basic EOC node types are then: (1) air cooling to space heat, (2) air cooling to water heat (requiring a heat exchanger), (3) water cooling to space heat (requiring a heat exchanger), and (4) water cooling to water heat (with heat exchanger optional). From this perspective, the energy savings from EOC comes from multiple sources. The other-purposed buildings' energy usage would be reduced by the free heat from the EOC node, and the cost to cool and condition a large, centralized data center would be removed. While there are hurdles to broad EOC adoption [17], such as security concerns, distributed server administration, and coordinating building and EOC node control systems, EOC is a compelling approach to manage energy resources as energy–hungry computing technologies become even more integrated into society.

To demonstrate the concept of EOC, an EOC node has been developed and integrated with a local greenhouse in a collaboration between the University of Notre Dame and the City of South Bend, Indiana, U.S.A. [15]. As shown in Fig. 1b, the EOC node uses free ambient air cooling and exhausts its waste heat directly into the greenhouse as space heat. With three racks of servers connected directly to Notre Dame's research network and actively running computational jobs, the EOC node has been shown to deliver ~15–40 kW of waste heat to offset the space heating needs of the greenhouse during cooler months. During warm months, the waste heat is not reutilized and exhausted directly to ambient.

While this prototype demonstrates a practical implementation of EOC, it does not reveal the benefits of more realistic and broad deployment of EOC. In this work, we take a higher-level perspective to analyze the deployment of EOC for various building sectors – commercial office buildings and apartment buildings or hotels – to understand the benefits of scale. We establish metrics to not only understand performance but also to evaluate the deployment in order to guide future design and implementation decisions.