COVER SHEET FOR PROPOSAL TO THE NATIONAL SCIENCE FOUNDATION

PROGRAM ANNOUNCEMENT/SOLICITATION NO./CLOSING DATE/if not in response to a program announcement/solicitation enter NSF 11-1 **PD 11-7643** **03/03/11**	**FOR NSF USE ONLY** **NSF PROPOSAL NUMBER** **1134152**
FOR CONSIDERATION BY NSF ORGANIZATION UNIT(S) (Indicate the most specific unit known, i.e. program, division, etc.) **CBET - ENVIRONMENTAL SUSTAINABILITY**	

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TITLE OF PROPOSED PROJECT **GOALI - Sustainable Advances in Cyberinfrastructure via Environmentally Opportunistic Computing**

REQUESTED AMOUNT	PROPOSED DURATION (1-60 MONTHS)	REQUESTED STARTING DATE	SHOW RELATED PRELIMINARY PROPOSAL NO. IF APPLICABLE
$ 348,263	36 months	10/01/11	

CHECK APPROPRIATE BOX(ES) IF THIS PROPOSAL INCLUDES ANY OF THE ITEMS LISTED BELOW

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CERTIFICATION PAGE

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The undersigned certifies, to the best of his or her knowledge and belief, that:

(1) No federal appropriated funds have been paid or will be paid, by or on behalf of the undersigned, to any person for influencing or attempting to influence an officer or employee of any agency, a Member of Congress, an officer or employee of Congress, or an employee of a Member of Congress in connection with the awarding of any federal contract, the making of any Federal grant, the making of any Federal loan, the entering into of any cooperative agreement, and the extension, continuation, renewal, amendment, or modification of any Federal contract, grant, loan, or cooperative agreement.

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(2) for other NSF Grants when more than $25,000 has been budgeted in the proposal for repair, alteration or improvement (construction) of a building or facility.

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AUTHORIZED ORGANIZATIONAL REPRESENTATIVE	SIGNATURE	DATE
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* EAGER - EArly-concept Grants for Exploratory Research
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Summary: GOALI - Sustainable Advances in Cyberinfrastructure via Environmentally Opportunistic Computing

This research program aims to establish Environmentally Opportunistic Computing (EOC) as a new approach to creating and maintaining sustainable data centers while improving the design of sustainable buildings in commercial, industrial, governmental, and educational sectors. EOC is based on the philosophy that the heat generated by high performance computing and information and communications technology (ICT) can be treated as a viable energy source and that the cooling required by ICT equipment is an energy waste. Therefore, EOC promotes integrating data center nodes into other-purposed buildings to capitalize on the generated heat for either space or process heating. Further, cooling of the data center can either use free ambient air or symbiotically use the cooling and water assets of the parent facility. While serving as the backbone of America's information economy, traditional data centers represent a major energy drain on the nation; accounting for upwards of \$7B in energy costs and consuming more than 3% of the United States' electricity, with these figures projected to rise in the future. Widespread implementation of EOC will improve not only the sustainability of national ICT infrastructure, but also that of the buildings they serve, providing a timely solution to this critical resource management issue.

Intellectual Merit: This research program will be guided by four technical deliverables: (i) creating an Evaluative Model to assess implementation strategies for EOC frameworks, (ii) establishing an EOC design optimization toolset and integration guidelines using the Evaluative Model, (iii) defining a dynamic national economic impact calculator that will predict the impact of EOC on a national scale under changing energy markets, and (iv) implementing EOC in a prototype through a GOALI collaboration with the City of South Bend, IN. The Evaluative Model will quantify the relative importance of the complex factors that affect successful EOC implementation, including the energy efficiency of the EOC node(s) and parent facility, the efficiency of effective computational load migration, and the impact of EOC technology on building function and efficiency, including usable space and occupant comfort. The Evaluative Model will consolidate these seemingly unrelated quantities into a unified implementation efficiency that characterizes whether EOC will be beneficial to an organization. The team will investigate broad case studies using a Design of Experiments methodology and stochastic optimization simulations based on the Evaluative Model in order to identify a set of integration guidelines that emphasize creating the most benefit for an organization and optimizing the implementation. As part of that study, we will compare EOC to the prevailing data center standard (power usage effectiveness - PUE), and assess the projected performance of EOC. A second tool will calculate the national impact of wide scale EOC implementation, accounting for energy volatility, to predict the long term impact of EOC on the national energy economy. Through a GOALI collaboration with South Bend, we will improve and enhance an existing EOC prototype installation at a local greenhouse. This will be a true demonstration of the viability of EOC for a municipality and university.

Broader Impact: This research will have broad impact in both the sustainable building and data center communities, transforming current philosophies on how to most efficiently design data centers and reduce the negative environmental and energy impacts. Further, the Evaluative Model and integration guidelines can be easily extended to evaluate other sustainable building practices, such as integrating wind, geothermal, or solar energy into a collection of buildings. Beyond the broad impact of the scientific content, this EOC research will form a bridge to the general public with a highly visible prototype in the community and an easily accessible educational website showing current operating conditions. By incorporating this research into specifically-tailored undergraduate courses, we will both educate the next generation of engineers and architects on EOC principles and expose them to interdisciplinary collaboration.

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*Proposers may select any numbering mechanism for the proposal. The entire proposal however, must be paginated. Complete both columns only if the proposal is numbered consecutively.

Description: GOALI-Sustainable Advances in Cyberinfrastructure via Environmentally Opportunistic Computing

1 Introduction

The goal of this research program is to establish Environmentally Opportunistic Computing (EOC) as a new sustainable approach for the design and integration of high performance computing and information communications technology (ICT) infrastructure into the built environment. EOC [1, 2, 3] is the broad concept of integrating data centers with other-purposed buildings so that they can re-utilize the waste heat generated by the ICT equipment and symbiotically reduce ICT cooling power consumption through provision of uncapitalized facility exhaust air. By treating ICT equipment not as a separate entity but an available and useful heat source, EOC will transform current building practices in an information-geared culture and create a paradigm shift where the question will no longer be how to cool data centers but how to most effectively utilize their heat. Our multidisciplinary research team, representing the fields of computer science (Brenner), mechanical engineering (Go), and architecture (Buccellato), is uniquely suited to successfully execute this research proposal. In this endeavor, we will take our prior work on EOC [1, 2, 3] in a new direction, focusing on establishing a modeling framework to best integrate EOC with current building practices in order to accelerate the broad implementation and adoption of this next generation approach to sustainable computing and building design.

1.1 Motivation

Energy utilization by ICT is a critical resource management issue. The U.S. Environmental Protection Agency (EPA) estimated that the U.S. spent $4.5 billion on electrical power to operate and cool ICT servers and data centers in 2006 and has forecast that the national ICT electrical energy expenditure will nearly double, ballooning to $7.4 billion in 2011 [4]. Energy demand for ICT is already more than 3% of U.S. electricity consumption and places considerable pressure on the domestic power grid: the peak load from ICT is estimated at 7 GW or the equivalent output of 15 base load power plants. In response to the EPA report, the Green Grid's 2008 "Data Center Baseline Study Report" [5] states that "(d)ata center industries will make very significant improvements ... however, given accelerating technology adoption curves, we anticipate total energy consumption by data centers will increase." Similarly, the International Data Corporation [6] reported that half of all surveyed data center administrators "planned to improve their measuring and tracking of energy efficiency ... with little expectation for major advances." Ultimately, the aggressive growth of users and the capability demanded by those users must necessarily be met with new integrated design paradigms. Recognizing that national power resources for data centers are finite, several professional entities within the technology industry are exploring this problem such as the High-Performance Buildings for High Tech Industries Team at Lawrence Berkley National Laboratory [7], the ASHRAE Technical Committee 9.9 for Mission Critical Facilities, Technology Spaces, and Electronic Equipment [8, 9], the Uptime Institute [10], and the Green Grid [11]. At the same time, efforts by corporations, universities, and government labs to reduce their environmental footprint and more effectively manage their energy consumption have resulted in the development of novel waste heat exhaust and free cooling applications, such as the installation of the Barcelona Supercomputing Center, MareNostrum, in an 18th century Gothic masonry church [12], and novel waste heat recirculation applications, such as a centralized data center in Winnipeg that uses re-circulated waste heat to heat the editorial offices of a newspaper directly above [13]. Similar centralized data centers at the U.S. National Renewable Energy Laboratory [14], in Israel [15], and in Paris [16] use recaptured waste heat to condition adjacent office spaces and an on-site arboretum, respectively.

The guiding principle of EOC is that ICT data centers do not need to be isolated entities, but can be integrated with existing buildings and facilities to synergistically share energy needs. Waste heat from high-output ICT can be harvested by the facility (waste heat recovery) and the facility's existing plumbing and air exhaust flow can be used as "free" cooling for the ICT (Fig. 1). Rather than centralizing hardware in single-purpose, isolated data centers, which is the standard approach, EOC promotes distributing ICT infrastructure across a network of buildings to create heat where it is already needed, to exploit cooling where it is already available, to utilize energy when and where it is least expensive, and to minimize the overall energy consumption of an organization [2]. At the University of Notre Dame, we have studied multiple EOC models and constructed an EOC prototype (the Green Cloud) through a unique partnership with the City of South Bend and the South Bend Botanical Conservatory and Greenhouse. This successful EOC prototype is currently used for high performance scientific computing from Notre Dame's campus, delivering waste heat to the Greenhouse to offset heating bills. While this prototype and the aforementioned waste heat re-utilization efforts represent a crucial step in reshaping current data center philosophy, a quantitative and qualitative framework for implementing EOC, both from an engineering and architectural perspective, is required to advance EOC as a pervasive sustainable design model.

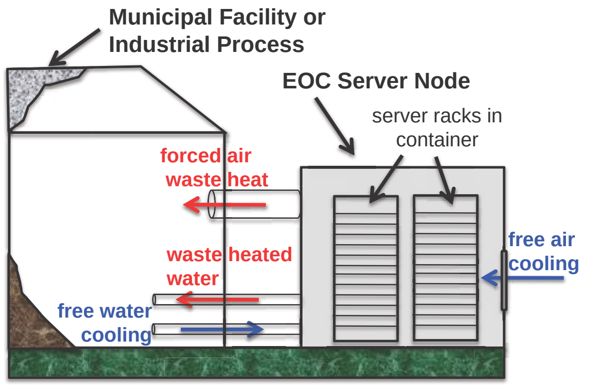


Figure 1: Schematic of an EOC node/facility interface where the node can deliver forced air heat from external air cooling or receive water cooling and deliver heated water to the facility.

1.2 Proposed Research and Deliverables

In this work we propose a new course of EOC research by establishing a greater understanding of the complex, dynamic, multidisciplinary, and multiscale technical, operational, and social component considerations necessary for effective ICT/facility integration. We aim to create a toolset that can be used to evaluate and guide successful implementation of EOC on a broad scale. By doing so, we envision that EOC will be a transformative approach to sustainable engineering, not only making industrial, commercial, and government organizations more energy efficient but also solving the grand challenges facing data center energy consumption. To that end, this research program has four deliverables:

- Create an Evaluative Model for EOC frameworks across multiple public & commercial sectors.
- Establish an EOC design optimization toolset and facility integration guidelines by using the Evaluative Model.
- Define a dynamic national economic impact calculator for EOC implementation that adapts with changing energy markets.
- Implement EOC in an upgraded prototype through a GOALI collaboration with South Bend.

While the outcomes of this research will be practical, the essence of this research is fundamental in nature. Creating an Evaluative Model will require assessing the implications and factors affecting EOC implementation at a fundamental level - how does implementation improve energy usage, what is the impact on the computing user, and how does it affect the occupants of the EOC-enabled building? Determining integration guidelines and identifying optimized implementation points will require Design of Experiments and stochastic optimization. Thus, we will deliver tools that can be used to apply EOC on a wide scale. The PIs are uniquely suited to tackle this challenge, which will require addressing EOC implementation from a number of perspectives. PI Go's expertise in thermodynamics and heat transfer complements PI Buccellato's LEED certification and energy-efficient building insight and experience. PI Brenner's extensive expertise and experience with cloud computing and data center management as associate director for Notre Dame's Center for Research Computing, and as evidenced by his earlier work on Grid Heating [17, 18], is essential for this research program. Finally, Buccellato's recognized experience in architectural practice and education will provide the architectural perspective required to create and study the Evaluative Model. Their existing collaboration on the Green Cloud [2, 3] has demonstrated that they will be able to effectively advance this novel sustainable engineering concept.

2 EOC Fundamentals and Prior Work

Environmentally opportunistic computing, recognizes ICT not as an isolated entity but as a *necessary* and *useful* producer of heat and as a *wasteful* consumer of cooling. Whereas many conventional approaches to sustainable computing focus on optimizing power and cooling usage, consolidating hardware through virtualization, or improvements applied to individual application and hardware components, EOC complements these improvements by emphasizing macro scale sustainability at the facility level. In an ideal scenario, EOC would be implemented across a number of buildings throughout an organization, whether that be a municipality, industrial campus, or university (Fig. 2). The computing load is treated as a mobile entity (where load migration is viable) that is passed from building to building based on which building requires the waste heat, which building has EOC nodes that can provide the necessary computing power, which building can provide free cooling to the hardware, or simply where the energy is cheapest. In this way, EOC capitalizes on the mobility of virtualized services to exploit energy volatility for cost savings and lower environmental impact. EOC takes advantage of current operating system, scheduler, and hardware efficiency improvements [19, 20, 21, 22, 23, 24] and combines these with new sustainable building approaches. Further, EOC opens up the door for establishing new partnerships between institutions (cities, industry, etc.) that could greatly enhance the environmental and economic benefit for all.

The authors have evolved toward the EOC concept based on a number of related smaller scale research prototypes. Our first model framework, called Grid Heating [25], specifically focused on controlling the heat exhausted by servers to achieve thermal targets in a functional office space. We were able to successfully demonstrate the dynamic migration of computational loads to different servers based on energy-need (i.e., more load produces higher exhaust temperatures) or in response to environmental stimuli such as an increase in air temperature [17]. The Grid Heating work suggested that a container-based collection of servers (e.g., Fig. 1) could be used to generate appreciable waste heat while the jobs could be migrated to and from servers to prevent overheating. We then focused on energy utilization at the CPU core level using benchmark loads in order to shape our macro scale migration policies [18].

2.1 The Green Cloud Prototype

Most recently we have constructed the Green Cloud prototype, which represents a heterogeneous, geographically distributed, multi-institutional data center infrastructure that utilizes waste heat for an existing facility (the South Bend Greenhouse) and provides a production environment for

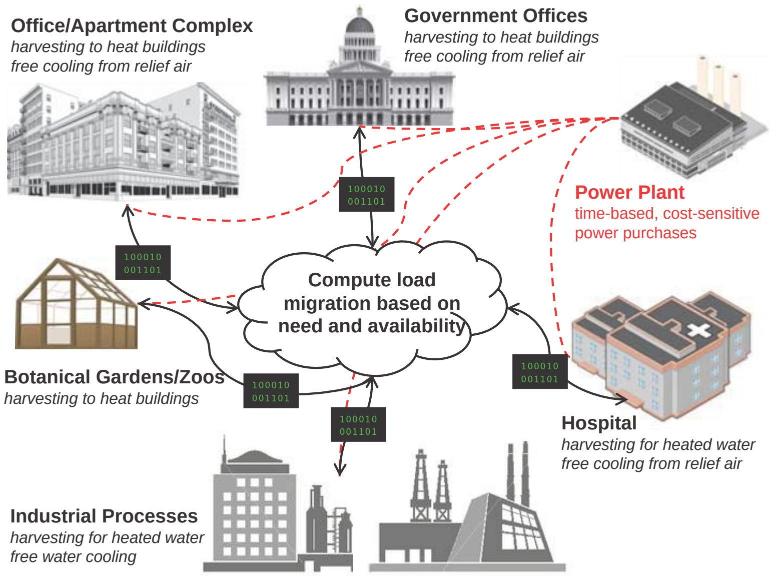


Figure 2: Grand concept for EOC implemented across multiple buildings in a community.

computing load migration research. The Notre Dame Center for Research Computing (CRC) and South Bend collaborated to install the container-scale data center at the local Greenhouse [1] (Fig. 3). This distributed data center is networked to the primary, centralized CRC data center and utilizes Condor [26] protocol to run a wide variety of high throughput research computing jobs. These jobs can migrate from personal workstations on campus to the centralized CRC data center or the Green Cloud data center at the Greenhouse with no apparent difference to the end user. The Green Cloud prototype was designed to minimize capital cost while still providing a suitably secure facility for use outdoors in a publicly accessible venue. The container is 20ft long by 8ft wide and houses three racks of servers. In this application, the servers are cooled by outside ambient air drawn by three fans through a louver (or return air from the Greenhouse), precluding the need for an energy consuming air conditioning system. During the summer, the heat is expelled to the ambient but during the fall, winter, and spring, the exhaust heat is expelled into the Greenhouse through two insulated ducts, helping to offset boiler heating costs which can approach \$15K/month during peak winter months. One focus of this prototype is to push the servers beyond ASHRAE [8, 9] and industry specified limits for the air temperature and condition (humidity and particulate), in order to evaluate realistic performance and mean time to failure in this harsher, but more energy efficient, configuration. Further, by allowing the servers to endure a larger window of thermal fluctuation, we can provide variable exhaust heat densities to the Greenhouse. Because of its public location in the largest park area in South Bend, the prototype is highly visible and provides a wonderful tool for both outreach to the community and for undergraduate students. A number of undergraduates have been able to make measurements at the Greenhouse and work directly with the Green Cloud prototype, and local media coverage has been very positive. (Additional details on the specifics of the prototype can be found in Ref. [25].)

2.1.1 Green Cloud Controls

Critical to the operation of the Green Cloud prototype is managing the computing load to generate the greatest amount of waste heat for the Greenhouse. The Condor-based control handles

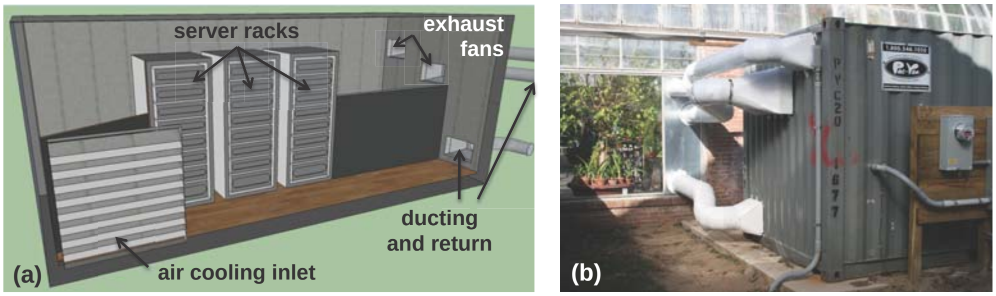


Figure 3: (a) Schematic of container-based EOC node. (b) Photograph of physical implementation at the Greenhouse.

the compute load management for the Green Cloud servers, allowing them to accept or reject jobs based on their system temperatures. An additional control level using xCAT continuously monitors the server's system vitals in real time by interfacing with the server's processor Intelligent Platform Management Interface (IPMI). A management code we call Environmentally-Aware GC Manager (GCM) interfaces Condor and xCAT, and is designed to maintain each server within its safe operating temperatures or shutting them down to prevent damage. At the same time, the GCM attempts to maximize the number of servers available for computing, therefore maximizing the temperature of the exhaust air that is used for Greenhouse heating. For example, as the outside air temperature warms up in the afternoon, servers can idle or migrate jobs in order to keep their system temperatures below a specified limit. The jobs can then return in the evening and early morning when the environment is more suitable, and a greater amount of waste heat can be generated. By incorporating smart controls that allow each server to respond not only to the local air temperature but also to the temperature of its neighbor servers, we were able to increase the average heat production by 13.7% [27]. To complement these controls, we post dynamic, real time machine utilization and temperatures on the GC website, as shown in Fig. 4, allowing the general public to visualize in real time the amount of heat harvested for the Greenhouse.

2.1.2 Thermal Measurements and Analysis

The prototype was outfitted with networked temperature sensors in the cold aisle (upstream of the servers), hot aisle (downstream of the servers), and at the container exit. In this way, local temperature and heat recovery could be estimated and directly correlated to server usage and activity. We treated the container as a single control volume, and analyzed it using a standard conservation of energy approach. We were able to estimate the energy harvested for the Greenhouse based on the temperature rise across the servers. That is, $q_{harvest} = \dot{m}c_p(T_{\text{hot aisle}} - T_{\text{cold aisle}}) - q_{loss}$, where $\dot{m}$ is the mass flow rate through the fans as measured by a velocimeter, c_p is the specific heat of air, T is the measured temperature, and q_{loss} was estimated based on a conduction analysis. Figure 5a shows a representative plot of the temperature measurements from the various sensors and one of the servers over a 48-hour period in July 2010. The plot illustrates three significant points. The temperature at the exit is significantly hotter than that of ambient air, exemplifying the vast amount of waste heat that is generated in data centers, and, though the single hardware temperature varies significantly because of dynamic computational loads, overall the temperatures are fairly constant because the total number of active servers stays fairly constant. Finally, the average server inlet temperatures (T_{HPC}) range from 21-38°C, which exceeds current recommended hardware operating ranges. One aspect of the EOC philosophy is that certain ITC applications can be operated beyond current general limits, and the data demonstrate server operation at temperatures greatly exceeding standards. Figure 5b shows the amount of waste heat harvested for the same 48-hour period. On average, nearly 9.39 kW was extracted from the data servers for this period of time, for a total energy recovery of 450.7 kW-h. Though this value is limited by approximations for the heat loss and simple bulk temperature measurements, it was consistent with the energy consumed by the container according to energy bills during the same period.

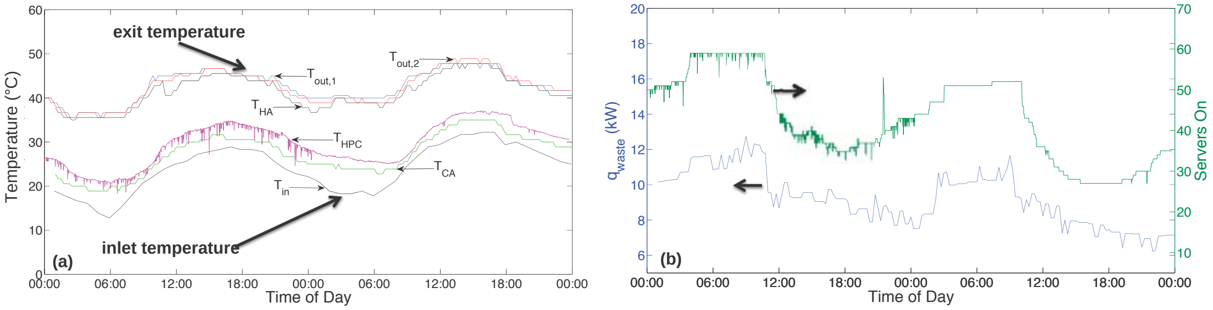
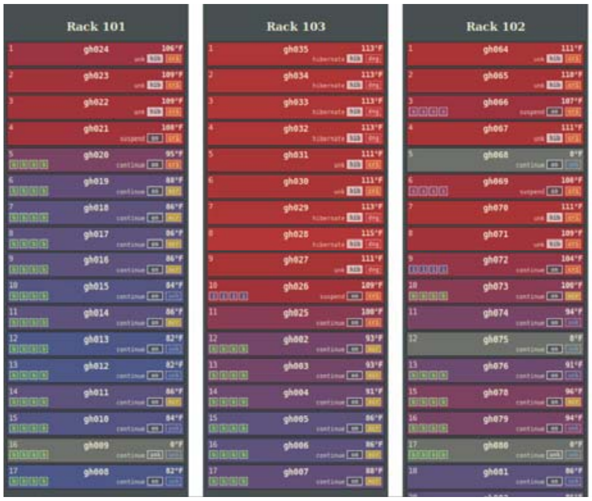


Figure 5: (a) Temperature measurements from Green cloud prototype. (b) Calculated waste heat recovered and number of active servers.

2.2 Remaining Challenges and Motivation for Proposed Research Program

The Green Cloud prototype represented a pivotal step in proving the concept of EOC in a production environment. However, there are significant scientific questions that remain to be answered. For instance, the servers in a single EOC node form a complex thermal system and the thermal interactions between servers can be functions of time (season/time of day), location, and computational load. To fully optimize the control of a single data center node would require extensive understanding of each of these interactions. Further, in a more practical implementation, such as placing an EOC node at a industrial plant, the control of the EOC node would need to be closely coordinated with the environmental or process control for the facility. Additionally, optimization and improvement of the mechanical systems involved is required. All of these are ongoing areas of development. But from a broader perspective, a general evaluative model is necessary so that engineers, architects, and ICT managers can effectively implement EOC on a wider scale. Such a model needs to consider not only the technical computational and mechanical components, but also the building integration and social/economic components as well. The aim of this research program is to fill the void by making a translational contribution to EOC development to accelerate broad implementation and adoption.



Rack 101	Rack 103	Rack 102
1 gh024 106°F	1 gh035 113°F	1 gh064 111°F
2 gh023 109°F	2 gh034 113°F	2 gh065 110°F
3 gh022 109°F	3 gh033 113°F	3 gh066 107°F
4 gh021 108°F	4 gh032 113°F	4 gh067 111°F
5 gh020 95°F	5 gh031 111°F	5 gh068 0°F
6 gh019 88°F	6 gh030 111°F	6 gh069 100°F
7 gh018 86°F	7 gh029 113°F	7 gh070 111°F
8 gh017 86°F	8 gh028 115°F	8 gh071 109°F
9 gh016 86°F	9 gh027 111°F	9 gh072 104°F
10 gh015 84°F	10 gh026 109°F	10 gh073 100°F
11 gh014 86°F	11 gh025 100°F	11 gh074 94°F
12 gh013 82°F	12 gh002 93°F	12 gh075 0°F
13 gh012 82°F	13 gh003 93°F	13 gh076 91°F
14 gh011 86°F	14 gh004 91°F	15 gh078 96°F
15 gh010 84°F	15 gh005 86°F	16 gh079 94°F
16 gh009 0°F	16 gh006 86°F	17 gh080 0°F
17 gh008 82°F	17 gh007 88°F	18 gh081 86°F

Figure 4: Screen capture of Green Cloud website showing server temperature in the three racks.

3 Research Plan

Given the requirement for novel solutions to ensure a sustainable growth of national ICT infrastructure, and building on the fundamentals established with our successful EOC Green Cloud prototype, we propose a new course of EOC research to develop a greater understanding of the complex, dynamic, multidisciplinary, and multiscale technical, operational, and social component considerations necessary for effective ICT and facility integration. This study's discoveries will provide a spectrum of design and implementation insights guiding key impact personnel including data center administrators, facility managers, architectural and engineering (A&E) firms, chief financial officers, and national policy makers.

3.1 Objective 1: Evaluative Model

The purpose of Objective 1 is to establish an Evaluative Model that can be used for a wide variety of EOC frameworks in order to characteristically quantify the benefit(s) or detriment(s) of EOC implementation. Because potential implementation applications range from industrial and commercial sectors to public and educational organizations, the emphasis of this model will be global. That is, unique design considerations for a specific implementation will not be the focus, but rather, the model will center on those general forces which either impact or are impacted by EOC. The output from this Evaluative Model can then be used to guide decisions by engineers, architects, and management on how to best implement EOC in their organization.

3.1.1 Balance of Forces

At its surface, EOC is a very simple concept – to utilize the waste heat from ICT hardware to offset a building's heating costs and to utilize the utilities of a building (relief air/process water) to offset the cooling costs of ICT hardware. However, there are many more multidisciplinary issues that must be considered before EOC can be truly implemented on a scale larger than the Green Cloud prototype. Table 1 summarizes the numerous issues that must be addressed. We consider these as market forces, some of which are in direct competition with each other and must be balanced in order for EOC to be successful. For example, thermal optimizations benefit from computational mobility, but that is constrained by data locality, security, and consistency issues. Thermally-triggered computational process migration from one EOC node to another that introduces response latency or saturates the network bandwidth would not be an acceptable balance. Or consider the Green Cloud prototype that currently produces forced air heat that is comparable to that produced by a 93,000 Btu furnace to heat a 2000 ft^2 home in South Bend, IN. However, the prototype has a volume that is 23× greater than a standard furnace, such that implementing EOC on a single-family home in this capacity is unrealistic. As such, a number of possible scenarios can be imagined where the balance of forces becomes either fairly simple or, alternatively, too difficult to manage. The purpose of this Evaluative Model is to attempt to quantify many of these forces so that optimization algorithms can be used to help guide decision-making.

3.1.2 Building the Evaluative Model

Our approach to building the Evaluative Model will be to establish some quantitative metric that characterizes any proposed implementation of EOC. Here we present a simplified model to clarify how we will approach building the Evaluative Model. In most engineering systems, the performance of the system can be quantified by an efficiency η. If the total system consists of a number of subsystems each with its own efficiency η_i, the total system efficiency will be some function quantity of the subsystem efficiencies,

$$\eta_{tot} = f(\eta_1, \eta_2, \eta_3, ...). \tag{1}$$

Computational Infrastructure and User Forces
– User demand for computational capacity
– Mobility of computational capability and related security concerns
– Computational hardware thermal and environmental limits
Facility Integration Forces
– Existing HVAC and/or renewable energy systems
– Renovation versus new build
– Building thermal performance (materials, orientation, size, location of openings, etc.)
– Impact of ICT on footprint, size, and space
Facility Occupant Forces
– Occupant thermal and environmental control (comfort expectations and ASHRAE/LEED standards and guidelines)
– Environmental air quality (ASHRAE/EHSO standards)
– Occupant perception of heat source (radiant, forced air, etc.)
– Impact of ICT hardware on occupant space (reduced space, lighting, windows, etc.)
External Forces
– Weather and air temperature variation (seasonal, daily)
– Local climate trends (long winters, humid summers, etc.)
Economic Forces
– Return on investment and total cost of ownership
– Energy cost volatility and carbon footprint reduction

Table 1: Relevant Market Forces for Integrating ICT into the Built Environment

This function could be a weighted product, an average, or some other form depending on the application and subsystems being considered. Our approach is to treat each of the market forces outlined in Table 1 as a subsystem of a particular EOC implementation and to assign each of these subsystems an efficiency, which we simply define as a characteristic performance parameter. We will then identify the proper total efficiency function η_{tot} that can be used across the global spectrum of EOC implementations. In some cases, the subsystem efficiency can be determined quantitatively, such as the absolute thermal performance of a building with and without an EOC node or the capacity of ICT hardware to meet user demand. For other market forces, the efficiency will need to be treated qualitatively or characteristically. For instance, it may not be possible to quantitatively characterize the occupant's perception of an EOC node. However, through case studies, we will be able to assign some quantitative measure such as $\eta = 1.0$ (positive perception), $\eta = 0.5$ (neutral perception), and $\eta = 0.1$ (negative perception). Similarly, the local climate efficiency may be treated as the percentage of the year where outside air temperature exceeds 90°F when external air cooling of an EOC node is not feasible. Initially, we will consider a simplified weighted product as the η_{tot} function and use this uniformly for every application. For instance, building thermal efficiency and total cost of ownership efficiencies may be weighted heavily compared to process water integration efficiency. However, as we begin to exercise this Evaluative Model in different scenarios (Section 3.2), we may find that different applications (municipal vs. commercial vs. industry) may require different functional relationships. We will then adapt our model accordingly.

3.1.3 Defining Efficiencies

In creating the Evaluative Model, it will be necessary to create a database of efficiency definitions and values. We will seek to define most efficiencies in a similar manner where $\eta_i = 1$ is qualitatively ideal performance, and all real performance will be $\eta_i < 1$. For thermal and energy related efficiency, we will use standard models and approaches. Section 2.1.2 used a simplified energy conservation model that is a representative example, but we will expand this model using techniques such as those outlined in Trost and Choudhury [28] or prevailing parametric building information modeling (BIM) that is used to analyze and anticipate building performance [29, 30, 31]. We will incorporate ASHRAE [8, 9] and LEED [32] standards, where applicable, and make the model as general as possible. It may be that current components of BIM models are sufficiently comprehensive to utilize without further adaption, and, since developing a comprehensive building efficiency predictor is not the focus of this program, we will adopt and adapt these existing models as needed.

For computational efficiency, we will extend our earlier studies on Grid Heating [17, 18] with a focus on the suitability of migrating computational loads. Computational load migration is both an active and mature area of distributed computing research with foundations in utility computing [33], grid computing [34], and most recently cloud computing [35]. For the purposes of this research we will focus on those components of the technology that would either enable or prevent migration of computational load to the most energetically favorable locations. Efficiencies in this regard range from quantitative estimations of performance degradation to qualitative approximations of security and ownership concerns. For example a corporation might have four data centers distributed nationally in a "private cloud" and choose to migrate portions of the compute load from data center 3 in Houston, TX to data center 4 in Chicago, IL throughout the year based on seasonal availability of free cooling and fluctuations in energy pricing. This capability would yield a higher total annual data center efficiency $\eta_{\text{no migration}} < \eta_{\text{migration DC3-DC4}}$; however the respective data storage, network bandwidth, and user-experienced performance latency costs might outweigh the efficiency gains and make this impractical. In the multi-institution case it might be both economically and environmentally beneficial for an industry to migrate excess load into a commercial cloud service during its highest points of annual demand. However, concerns regarding data security and software licensing may prevent such migration in both quantitative and qualitative ways.

One unique feature of our efficiencies approach will be a quantitative assessment of "architectural quality" that extends beyond the energy performance of the building. Use of space, form, and function are essential considerations that define the character of a building. However, implementing EOC presents a new challenge to how heat sources are incorporated into buildings, whether in new construction or retrofits. An EOC node will have much lower energy density than a conventional heating source, such as a boiler or furnace, and thus requires much more physical space to generate comparable usable heat. Further, since the heat is fairly low grade (that is, it is low temperature $\sim 100\ ^{o}$F), it cannot be stored or transported long distances, therefore the EOC node must be integrated with the conventional heating system it supplements. Though forced air heating, as in the Green Cloud prototype, is one possible approach, other implementations are possible including water-based heating and as a radiant heat source. To address these concerns, we will consider case studies that can be used to reveal architectural qualities (such as open floor space) that are affected by potential EOC nodes. From these case studies, we will begin to assign architectural efficiency values, providing some level of quantification to the relative merits of various design decisions. As the research progresses and a more diverse set of case studies are considered, we will be able to compile a library of quantified values that can be used in the Evaluative Model.

The final feature of the Evaluative Model will be to incorporate economic variables, such as the dynamic cost of resources and carbon footprint of the EOC implementation. We will use historical and projected consumption and pricing data from the U.S. Energy Information Administration [36] in order to create a cost efficiency model that accounts for the local cost of energy (electric and natural gas) and projects the consumption. We will also use the Department of Energy's Federal Greenhouse Gas Accounting and Reporting [37] tools to estimate projected carbon footprints of an organization with and without EOC. By exercising these data, we will be able to establish characteristic efficiencies that account for critical economic factors.

3.2 Objective 2: EOC Design Optimization Toolset and Integration Guidelines

The purpose of Objective 2 is to exercise the Evaluative Model in order to establish a software toolset for design optimization decision-making and develop facility integration guidelines. We will approach this in two ways, by evaluating a number of representative, characteristic case studies and by using a stochastic optimization approach.

3.2.1 Design Optimization Toolset

We propose to develop a software-based optimization toolset to facilitate rapid "what if?" analysis of complex EOC systems as necessary for large-scale efficiency optimizations in the early stages of the facility funding, specification, and design process. This toolset will have capabilities beyond simple manual selection of market force efficiency values that lead to an overall efficiency calculation. It will allow multivariate optimization calculations across all model variables (subsystem efficiencies) in relation to those variables that are known to have a fixed value (if any). As the number of variables with unknown value becomes large, stochastic optimizations will be employed. This provides not only a tool for designers but also a means to globally evaluate fundamental EOC possibilities and limitations.

The basic principle behind stochastic optimization [38] is to use Monte Carlo simulations to evaluate a large number of possible implementations within their statistical probability. We can then identify the statistically most effective or "optimized" implementation strategy, and we can tailor it within specified design constraints to support policy and decision making. The principle behind Monte Carlo simulations is to run a function, in this case the Evaluative Model, through a large number of scenarios but allowing the proposed variables (efficiencies) to fluctuate statistically. These statistical fluctuations may be physically based, such as the energy efficiency as a function of physical dimensions or local climate, or they may be based on other factors such as the building usage efficiency fluctuating with occupants throughout the year.

The software development of the design optimization toolset will take place in three phases and include multiple application platforms to enhance usability, accessibility, and extend the useful life cycle. All software components will be open source and available both on the public project website and in public code repositories where applicable. In year one, the toolset will be developed within Microsoft Excel; while this arguably limits global accessibility, it greatly improves usability and initial adoption based on the broad utilization of Microsoft Excel in the U.S. In year two, the EOC spreadsheet tools will be updated while the feature set is ported into a stand alone EOC design application to improve performance for complex stochastic optimization calculations and remove the dependency on the proprietary Microsoft software. The application will be accessible via the project's website for remote computations of limited size and duration. Development in year three will focus on portability and integration of the feature set into larger peer public and (where licensing permits) commercial software applications such as the DOE's Data Center Energy Profiler (DCPro) [39] and APC's TradeOff Tools [40], respectively.

3.2.2 Facility Integration Guidelines and Best Practices

In line with our research and development of the Evaluative Model and optimization toolset, a series of facility integration guidelines and best practices will necessarily evolve out of the rigorous analysis and testing of EOC efficiencies. Using the design optimization toolset, we will conduct a broad series of case studies of both as-built integrations and new building designs to arrive at a portable set of implementation guidelines that would 1) assist engineers and architects in the selection of EOC as a viable and competitive integrated building system, and 2) serve as a resource, along with the optimization tool, to guide the design and implementation of EOC in a building or network of buildings. These guidelines will allow decision makers, such as architects and engineers, to assess the applicability of the technology at the outset of a design process that involves EOC as part of a comprehensive sustainable design solution. The integration guidelines will also serve to facilitate and accelerate recognition of both the EOC approach and the Evaluative Model as an assessment tool for sustainable energy source integration by organizations that establish and maintain prevailing energy standards, design guidelines, and sustainable building practices such as ASHRAE's Standard for the Design of High Performance Buildings 189.1 [9], the ICC's International Energy Conservation Code [41], and the U.S. Green Building Council's LEED building accreditation program [32]. In order to increase the accessibility of the Evaluation Model, design optimization toolset, and guidelines we will develop them to dovetail with prevailing whole building energy modeling software programs (Energy 10 [42], DOE2, Visual DOE4.0, etc.) and also building life cycle cost analysis programs such as SimaPro [43].

One set of case studies currently underway explores EOC integration with a new experimental research and education facility, the St. Patrick's Experimental Ecology Center. The facility is currently being designed as an extension of Notre Dame's Environmental Change Initiative program. We will explore how best to implement EOC within this research facility, allowing us to both identify architectural efficiencies and exercise the Evaluative Model, while also enabling the University to capitalize on EOC's core vision. We will reference data from the Green Cloud prototype and observations generated from paper-based design studies being conducted in PI Buccellato's undergraduate architecture design course Environmental Stewardship through Interdisciplinary Research and Design. This "new build" case study will not only provide valuable data for the Evaluative Model, but also position the Ecology Center to become the first EOC-enabled facility of its kind. A second set of case studies will be coordinated with the City of South Bend through a GOALI. We will consider utilizing EOC to offset heating costs at a water treatment facility, using a retrofit approach. As opposed to space heating, an EOC node could provide process heat, whether that be air or water heat, to improve the efficiency of the plant. An initial analysis has suggested this is a highly appropriate application for EOC. As an industrial plant, it will provide a completely different challenge for identifying building impact qualities. As a retrofit, it will introduce a different set of architectural constraints.

We will use a Design of Experiments approach [44] to exercise the Evaluative Model in order to analyze a broad series of case studies. Since there will be a large number of variables that feed the Evaluative Model and subsequent design optimization toolset, it is not feasible to explore every possible situation in order to identify a set of best practices. If there are 100 variable efficiencies and each variable efficiency can only take two values (e.g., $\eta_i = 0.1$ or 1), then 2^{100} Evaluative Model simulations would need to be run in order to assess the impact of each of these variables on η_{tot}. While two values may bracket continuous variables, such as energy efficiency, other variables, such as occupant perception may take discrete values and more than two of these must be considered - increasing the number of runs. However, a factorial design reduces the number of variations for each variable that needs to be assessed, allowing us to *statistically* identify the variables that most influence η_{tot} as well as interactions between the various market forces and their efficiencies that may not be obvious. Because the Evaluative Model and toolset are simulation-based, we will be able to not only explore 1st order interactions but 2nd order and higher interactions as well, while still running a reasonable set of simulations. This will give us a high level of understanding of which factors most influence a positive outcome from the Evaluative Model.

3.3 Objective 3: EOC National Economic Impact Calculator

The purpose of Objective 3 is to consider and calculate the national implications of expanding EOC on a nationwide scale. The target audience in this regard includes senior policy makers and the general public with a goal to provide education as to the practical possibilities of EOC to improve both the sustainability of the ICT industry and those sectors of the built environment well mapped into EOC. To do this the PIs will perform a high level analysis of national thermal energy requirements, their associated economic costs, their carbon footprint, and their suitability for EOC integration based on the findings of the Evaluative Model. We will then cross reference the national thermal requirements with best fit EOC frameworks to calculate total national EOC impact benefits given various levels of adoption.

For the analysis of national thermal energy requirements we will reference those detailed by the U.S. Energy Information Administration, which show \$200 billion in energy consumption by residential buildings in 2005 [45], \$84 billion in commercial building consumption in 2003 [46], and \$136 billion in manufacturing energy consumption in 2006 [47]. Further, according to the EPA, the building sector accounts for nearly 40 percent of U.S. energy consumption [48]. Similar data from the DOE and studies by the National Institute of Building Sciences reveal that, on average, 85 percent of the energy/carbon impact of buildings is tied to operating energy or energy used for heating, cooling, and ventilation [48, 30]. The building energy demands are thus sufficiently large and various that we propose a significant portion of the 3% ICT component of national electrical energy demand should integrate via EOC into the larger set. Our calculator will then take into account the major differences in energy types (gas, electricity, oil, etc.) with respect to their economic costs (regional and seasonal) and environmental costs (carbon footprint).

The impact calculator will bridge the national energy requirement quantifications with the energy savings made available through appropriate fit EOC models as identified by the Evaluative Model and optimization toolset. To make the impact calculation as relevant as possible, the calculations will be conducted in conjunction and comparison with conventional ICT efficiency improvement impacts as estimated by the application of various Power Usage Effectiveness (PUE) [49] values to the national ICT energy demand. PUE has become a standard metric for evaluating the energy efficiency of a data center. It is defined as the ratio of total power consumption by a data center facility to the ITC equipment power, or

$$PUE = \frac{\text{Total Facility Power}}{\text{ICT Equipment Power}}. \tag{2}$$

The PUE value by definition does not consider heat reuse (PUE values less than 1). The Green Grid however has recently proposed a new Energy Reuse Factor metric ERE [50] where

$$ERE = \frac{\text{Data Center Energy Reused}}{\text{Total Energy Input to the Data Center}}. \tag{3}$$

For purposes of estimating EOC impact in line with developing industry standards, we will evaluate if EOC energy savings can be formulated in conjunction with the ERE metric to compare and contrast with PUE improvement impacts alone.

3.4 Objective 4: Prototype Implementation and GOALI Collaboration

The purpose of Objective 4 is to expand the current Green Cloud prototype through a GOALI collaboration with South Bend. The current Green Cloud prototype, while demonstrating the concept of an EOC node, is neither optimally designed nor adequately instrumented to show the real, viable capacity of an EOC node. When originally implemented, it was limited by its budget and available personnel. However, this research program will increase the instrumentation on the Green Cloud node in order to validate the thermal and computational subsystem models. Further, the relationship with the City of South Bend will be greatly enhanced by an Undergraduate Student Industrial Traineeship, where an undergraduate student will liaise between Notre Dame and South Bend to ensure that the Green Cloud prototype fulfills its promise.

3.4.1 Instrumentation and Measurements

One weaknesses of the current prototype is that it is not sufficiently instrumented to accurately calculate the energy harvested from the servers. Though a preliminary set of measurements have led to estimates of the harvest energy that are in line with usage statements from the local power utility (e.g., Fig. 5b), a more exact quantification is required not only to fully understand the operation of the prototype, but also to validate the models used to estimate thermal and computational migration efficiencies. This research program will therefore upgrade the number of sensors measuring not only temperature and humidity, but also power consumption.

The primary effort will be to refine our energy model to more accurately account for all energy consumption and generation (including lighting, fans, and accessories) and to coordinate with the local power utility to ensure that our measurements of energy consumption, loss, and delivery are in line with conservation laws. We will purchase intelligent power distribution and power monitoring units (APC Switched Rack PDU) that will not only allow us to remotely control the power to each server but also to monitor power usage. We will also expand our collection of environmental monitoring units that measure temperature and humidity (APC Model AP9512) so that we can get a more accurate spatial distribution of the air temperature at the inlet to the container, upstream and downstream of the servers, and at the ducted exit into the Greenhouse. Since all of these sensors will be networked and monitored in real time, we will be able to calculate the time constant of the entire system and relate it to computational migration in order to more effectively control how jobs are accepted and distributed to the servers. Additionally, we will add actuators to the inlet louvers and variable transformers to the fan system, to give us greater control over of the mass flow through the container and into the Greenhouse. This will provide another control variable to increase the waste heat and provide us greater ability to push the thermal limits of the hardware to discover new operating points for enhanced energy efficiency.

3.4.2 GOALI Undergraduate Student Industrial Traineeship

In order to enhance the relationship between the PIs and South Bend, an undergraduate student will serve as a liaison under the direction of PI Brenner and Mr. Gary Gilot, Director of the Department of Public Works. The undergraduate liaison will have a number of responsibilities, including supporting the acquisition and analysis of experimental data, maintaining the instrumentation, and managing interactions with Greenhouse personnel. The student will also work closely with South Bend's engineers to quantify the benefit the Green Cloud brings to the Greenhouse and the impact on the Department of Public Works. Additionally, the student will assist in the EOC industrial process case study focusing on water treatment facilities. The student will assist in calculations supporting practical integration, cost analysis, and benefit projections. In this way, the student will be exposed to the role and function of Public Works engineers and obtain experience applying engineering fundamentals outside a classroom setting.

4 Collaboration and Management Plan

4.1 Personnel and Available Resources

The EOC team will consist of the three PIs, an engineering graduate student who will be co-advised by PIs Buccellato and Go, and two undergraduate researchers. The team will contribute to weekly internal progress summaries via email and meet monthly to synchronize efforts on model enhancement, experimentation, toolset development, and knowledge dissemination. The lead PI Brenner will coordinate these activities along with direct reporting to the program manager.

In addition to those resources provided by the NSF to support this research, the PIs have access to a large number of education and research resources at Notre Dame. The multidisciplinary nature of the team will allow us to leverage resources associated with our respective colleges and departments. PI Brenner is associate director of Notre Dame's Center for Research Computing (CRC), which operates a state-of-the-art high performance computing data center providing advanced computing support to researchers and teachers within Notre Dame, the local community, and industry. The CRC systems have a wide range of software applications, supporting research across campus. At present there are more than 1000 researchers from Notre Dame making use of the CRC's resources for demanding scientific computation, storage, and visualization tasks. The CRC has extensive experience in software development and performance profiling with numerous professional programmers on staff. As the primary provider of computing and data center services for this EOC research, the CRC is the perfect partner with broad software development expertise and extensive experience managing large-scale ICT hardware.

4.2 Project Milestones

- Year One
  1. Develop the first Evaluative Model schematic to include critical efficiency subsets.
  2. Implement the spreadsheet based optimization toolset and outline the case studies.
  3. Outline the major built environment energy consumers & the requisite energy sources.
  4. Specify, acquire, and install new Green Cloud sensors, actuators, and transformers.
- Year Two
  1. Refine the Evaluative Model with new efficiencies and more specificity.
  2. Implement the optimization toolset application for use in analysis of case studies.
  3. Define equations & assumptions for integrating EOC with national energy consumption.
  4. Utilize enhanced Green Cloud sensors & controls to study new efficiency opportunities.
- Year Three
  1. Analyze and enhance the Evaluative Model through global variate optimizations.
  2. Integrate toolset & design guides into peer applications & design standards.
  3. Add PUE efficiency improvement comparisons into the EOC national impact calculator.
  4. Grow the Green Cloud prototype or implement a new partnership prototype.

5 Broader Impact, Education, and Outreach

5.1 Integration into Outreach and Education

The PIs will continue to incorporate EOC research into important outreach and educational initiatives on campus including (i) computer science opportunities for high school students, (ii) interdisciplinary undergraduate courses, and (iii) a public and web presence promoting our collaboration with the South Bend municipality. PI Brenner coordinates the Notre Dame CRC's two-week Research Computing Bootcamp for high school students. This camp gives high-level direction in a breadth of areas in research computing. In years two and three of the grant period the high-school students will participate in a segment of the bootcamp dedicated to measuring ITC power requirements and formulating novel methods to reduce and reuse related energy components. The program is configured to provide special admittance consideration for students from struggling school districts (those with test scores and graduation rates below national averages). Alyssia Coates of Upward Bound, a college prep program at Notre Dame for low-income minority students, has agreed to help recruit students. The CRC is also a Research Experiences for Undergraduates (REU) site, and PI Brenner leads the sustainable computing research thrust. Through this program and additional REU requests, the PIs will incorporate REU involvement with special consideration given for students from Minority Serving Institutions as facilitated by Notre Dame's REU program.

Two undergraduate courses currently being taught by the PIs are both well-aligned with this research and will be expanded to incorporate facets of it. PI Buccellato's Environmental Stewardship through Interdisciplinary Research and Design course requires upper-level architecture students to integrate EOC technology into their design of a state-of-the-art experimental research facility, the St. Patrick's Experimental Ecology Center. PI Buccellato's course will serve as a "design lab" for exploring the essential architectural considerations that must be made in EOC design. The students will study ways of integrating EOC with current building practices while simultaneously weighing various design considerations, including building performance, occupant expectation, and the potential impacts of the technology on architectural form and spatial dynamics. As part of this course, PI Go has given a special guest lecture introducing the EOC concept from an engineering and national need perspective. PI Brenner's Student Engineers Reaching Out interdisciplinary engineering course emphasizes applying engineering skills to socially important non-profit projects. Students from this course have assessed sources of energy inefficiency in the Greenhouse to aid early development of the Green Cloud prototype. All of the PIs have worked (and published) with undergraduate researchers on the EOC project. PI Go also advises a graduate student in Notre Dame's Engineering, Science, and Technology Entrepreneurship Excellence Masters program who is exploring EOC business applications.

Our close EOC partnership with South Bend and the Greenhouse enables us to give this research a visible public presence for educating the public about sustainable engineering and buildings and energy-efficient data centers. The public location of the Green Cloud in the city's most prominent park has already drawn positive coverage from the local media. We will continue to promote this work to the public through various venues throughout the city and in public talks. Additionally, the Green Cloud website (greencloud.crc.nd.edu) acts as a portal to the greater community and industry. This web site not only contains information on EOC and the Green Cloud prototype, but also real-time measurement readings. The PIs plan to further enhance this site with dynamic status updates including real-time estimates of heat currently being harvested and a graphic of which server (and its location in the prototype) is currently hosting the web site, giving the viewer a sense for how sustainable computing can be implemented.

5.2 Broader Impact on Sustainable Engineering

EOC research has significant potential to broadly impact standard approaches to sustainable design. While these evaluation and design tools are primarily focused on EOC design, they can be readily expanded and applied to other existing and new sustainable energy resources. By demonstrating that harvesting heat from complex ITC infrastructure can be successfully implemented into a broader sustainable design vision, this research will open the window for holistic sustainable design and integration in other industries where energy recovery is possible, such as food services. To that end, the implications of our EOC results can be used to evaluate design criteria and critical approaches across a number of facility design applications. To facilitate reaching such a diverse audience, we will continue to seek opportunities to present at conferences that cut across traditional discipline boundaries such as PI Brenner's (a computer scientist) presentation to mechanical engineers at the 2011 ASHRAE Winter Conference. A wide variety of venues are open for us to present the findings of this research – electronics cooling, distributed computing, and architectural education among these – and we will broadly disseminate our findings.

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