GREEN DATA CENTER COMPUTING:
A DEMONSTRATION PROJECT

NYSERDA Agreement # 22899

Period of this report: Jan 26 – April 27 2012

Introduction:

The project aim is to demonstrate the feasibility of deploying a network of Performance Optimized Datacenters (PODs), geographically distributed to exploit the availability of renewable energy for their operation. Such a distributed system has the potential to significantly enhance the energy efficiency, reliability, security, and overall performance of the data center by several means, including optimizing the utilization of the available renewable power for computing by intelligently redistributing computational load depending on the availability of renewable energy and minimizing losses associated with power transmission by placing the PODs near the power source. This concept provides data center operators the means to avoid performing expensive utility upgrades as the availability of wind power through New York State and other states grows, keeping the infrastructure and Transmission & Distribution (T&D) costs low, thus making it possible to use the wind power that is currently stranded, i.e. not-delivered to the grid due to the T&D constraints.

a. Progress of project to-date

TASK 1 - Progress to Date

From an electric and control stand point, this project will be divided into seven major tasks. Selecting the subsystem architecture and topology capable of providing high quality electricity to servers that are co-located is the first major undertake (task 1.1). A description of different strategies of monitoring the available power, from different intermittent sources of power will be considered (task 1.2). In addition, the robustness of the selected architecture will be verified (task 1.3). On the other hand, shifting data from one server to another with both servers under sufficient power availability conditions and subjected to willful electric defaults will be considered (task 1.4). As a result, the system should demonstrate its ability to overcome electric failures and ensure transparent data shifting. Then, unpredictable events due to real-world weather constraints will be gradually introduce to the system (task 1.5). For instance, the system has to provide a fast response to an eventual lack of solar power, wind power, and other sources of energy. A nonstop run of the system will be monitored in order to detect eventual anomalies (task 1.6). Data from different seasons will be used for a period to be determined. Finally, a scaling up design in order to implement a field test will be developed (task 1.7).

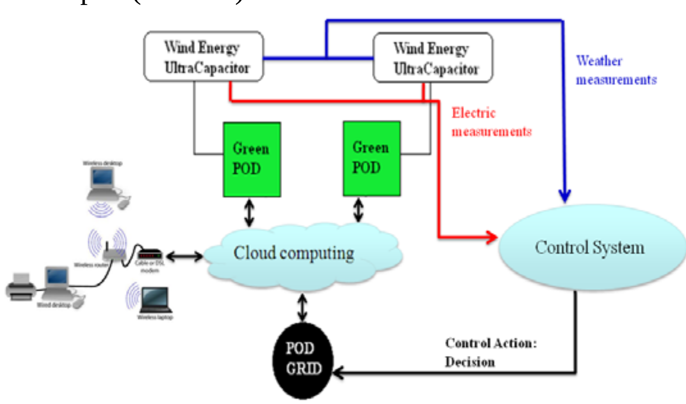


Figure 1 – GDC Architecture

1. Description

A system emulator will be used to simulate the behavior of real renewable energy sources. A short description of additional components is given below:

a. RES: Renewable Energy Sources: wind turbines and solar panels will be used to respectively transform kinetic motion and light intensity to electricity (respectively 3 phases AC voltage and one DC voltage line);
b. CC: Charge Controller is the device responsible for rectifying the AC voltage and providing continuous DC voltage. It is also responsible for controlling the output DC intensity current to avoid electric components failure (including servers and other subsystems);
c. EMU: Energy Management Unit is managing and monitoring energy input/output, state of charge of the storage unit. It is also responsible for managing energy resources in peak times and other critical periods of the day;
d. SCU: Signal Conditioning Units are a series of power electronic devices such as rectifiers, inverters and UPS. Generally, these components cannot be all used at the same time, however, if the application is critical, they can be combined;
e. PDU: Power Distribution Unit is responsible for intelligently distributing the power available at the source to the servers based on their computing needs and efficient operations.
f. Load: The HP ProLiant DL385 G7 servers are currently being selected for this application. It has multi-core processors (4/8/16 μP), each server is dedicated for highly mission critical applications; this server includes 12-core AMD Opteron 6100 Series.

2. Datacenters Architectures

In this section, a comparison between datacenters architectures based AC and DC voltage is performed according to a study presented by "The Data Center Journal" published in March 2007. Also, an evolution of these architectures is proved in immediately after the comparison.

a. Architecture for AC servers

The architecture of the AC voltage transmission for AC servers is given below.

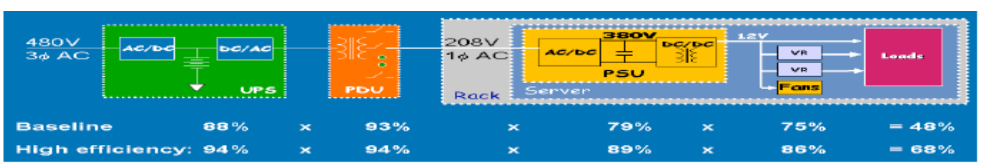


Figure 2 - AC Servers Architecture

The maximum energy efficiency that an AC voltage transmission can reach is 48% for a baseline and 68% for high efficiency architecture. Both transmission configurations are mid-range efficiency.

b. Architecture for DC servers

The architecture of the DC voltage transmission for DC servers is given below.

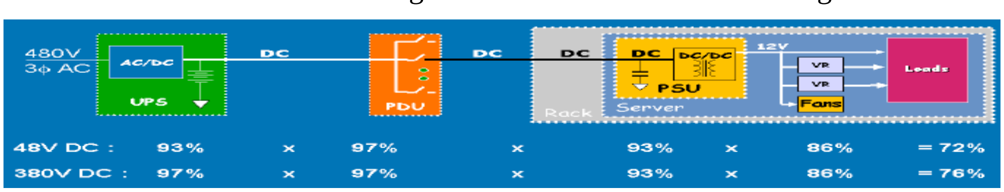


Figure 3 - DC Servers Architecture

The maximum energy efficiency that a DC voltage transmission can reach is 72% for a 48 VDC line and 76% for high voltage DC. The performance is largely better than the one given by AC transmission.

c. Comparison:

According to Pratt and Kumar "*Evaluation of Direct Current Distribution in Data Centers to Improve Energy Efficiency*", using DC servers can increase the energy efficiency of the system due to the reduction of conversion loss by suppressing one stage of conversion. However, the efficiency of electronic converters has increased among last years. Hence, power loss due to conversion was reduced, which has a positive influence on power efficiency enhancement. The following architectures are based on the architectures given previously but with current converters.

d. Proposed DC server (based on HP server architecture)

The efficiency of a 48 DC voltage server is shown in figure 4. Compared to the efficiency described for the DC servers above, it is clear that the efficiency has increased and reached 77% of power efficiency.

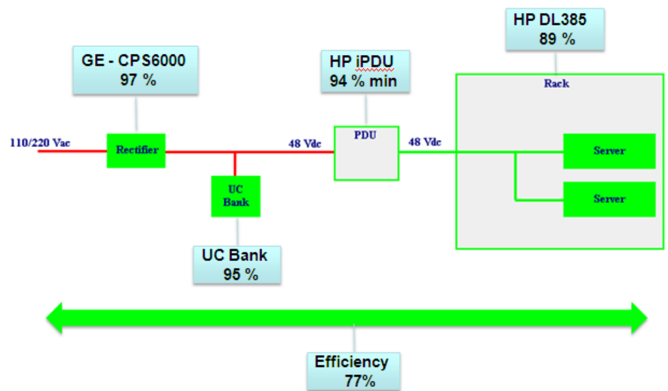


Figure 4 - Proposed DC Architecture

e. Proposed AC server (based on HP server architecture)

The efficiency of a 240 AC voltage server is shown in figure 5. Compared to the efficiency of the AC servers given by Pratt and Kumar, the power efficiency has increased from 48% to reach 86%.

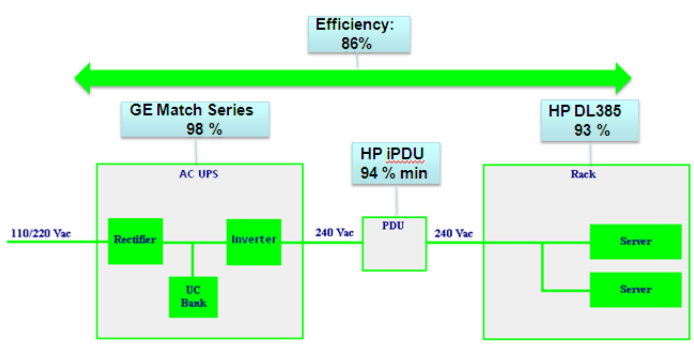


Figure 5 - Proposed AC Architecture

It has to be noted that the DC architecture can be made more efficient, up to 88%, if a 380VDC architecture is used and server components are properly selected to support this voltage. However, HP currently does not have commercial servers that support 380VDC architectures. We intend to work with HP to evaluate the possibility of using some experimental servers, it might be selected for a phase 2 field test operation.

f. Comparison between HP based AC and DC architectures

Power efficiency estimation of the proposed architectures favors the use of AC servers (86%) instead of DC servers (77%). Hence, currently the use of AC server is the best solution to increase the energy efficiency of the system because of the high efficiency components available in the market. However, DC servers also have their advantages. For instance, voltage control is made easier. In addition, backup storage can directly be connected to the PDU without any conversion ensuring faster response. Hence DC server will also be studied in due course.

3. Renewable Energy Emulator

As shown in the figure below, a database of wind speed and solar intensity will be used to emulate the real-world weather conditions.

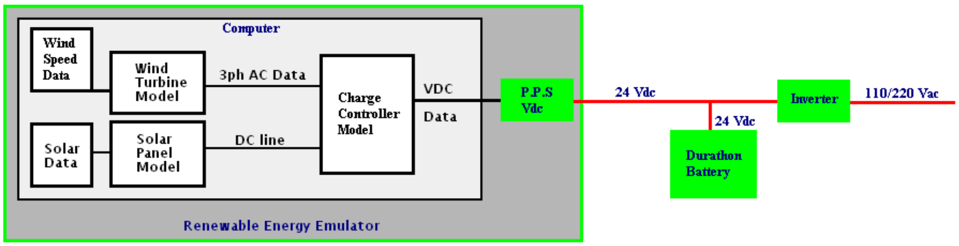


Figure 6 - Renewable Energy Emulator Architecture

Data from a weather database will be accessed in order to generate the appropriate voltage profile corresponding to the real AC voltage and DC voltage respectively coming out of wind turbines and solar panels. This generated voltage database will be fed into a Programmable Power Supply (PPS), then the real voltage coming out of the renewable energy emulator will be used to supply the proposed architectures given in part "2.d" and "2.e" .

4. Short Term Storage

In the case of a deficiency in available power in one location, data has to be shifted to another location with surplus power before driving the POD of first location to a safe shutdown or standby. This is not feasible without a storage unit integrated in the architecture. A short term storage unit has been designed based on ultracapacitors that are environment friendly. The elementary cell used in our design is a 3000F IOXUS ultra-capacitor. The elementary cell used in our design is a 3000F IOXUS ultra-capacitor. Parameters related to our design are provided in Exhibit B. The final architecture assembled in a rack is given in the figure below:

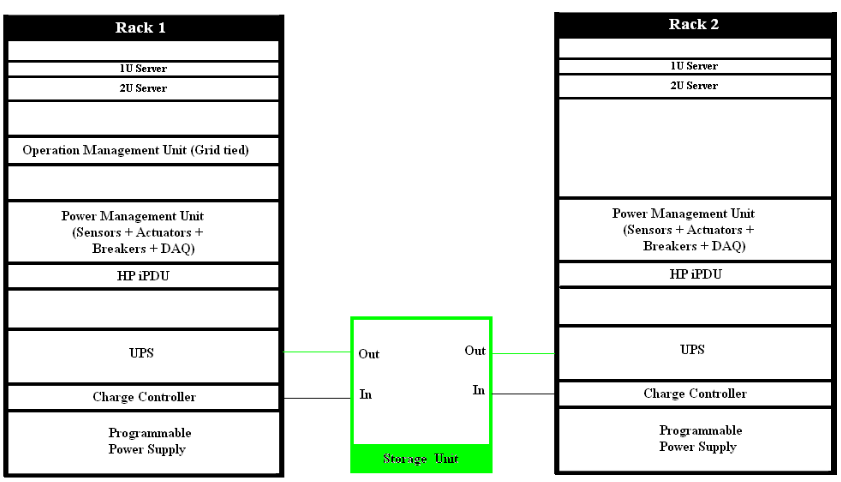


Figure 7 - Racks organization

Summary TASK 1 Progress

Two different architectures are under evaluation in order to realize the desired application. Energy efficiencies have been estimated for the two configurations and it appears that the AC architecture can provide satisfactory performance compared to the DC architecture, considering the current HP server technologies available in the market. Hence, it is highly recommended to use AC servers for similar applications. In addition, a renewable energy emulator is under development. The emulator can provide realistic profiles of intermittent power simulating power produced from wind turbine and solar panels. A wide range of output voltage and current can be simulated by the emulator. Hence, a larger number of wind turbines and solar panels can be simulated in addition to other sources of energy. The design of a storage unit for providing power temporarily during the event of shifting data from one location to another, in order to permit smooth shifting of data, has been proposed. Finally, the team has been experimenting with currently available 1U and 2U server racks. This initial lab experimental setup is providing valuable insights into various aspects of setting up the actual lab demonstration.

TASK 4 - Progress to Date

Task 4 focuses on the migration of workloads into and out of a POD datacenter.

1. Virtual Machine Migration

The first set of subtasks we have identified involves conducting a series of quantitative experiments of virtual machine migration. Most of the popular server class hypervisor/ virtualization technologies including VMware, Xen, and KVM offer a form of virtual machine migration. However, in many instances, it is assumed that the migration will take place between machines in the same datacenter and possibly even on the same network switch. In many cases, the machine initiating the migration must have access to the same network attached storage device (NAS) as the machine accepting the migrated VM.

Our first task is to perform a thorough evaluation of these migration technologies in a wide range of environments – between two machines in the same rack sharing a NAS, between two machines in the same rack not sharing a NAS, between two machines located in two different labs on campus with and without NAS and finally between an on-campus machine and an off-campus machine with and without NAS.

We plan to collect a variety of interesting measurements of virtual machine migration including the total time to accomplish the migration (from start to finish), the total time the virtual machine is unresponsive during migration (typically during at least the last stage of migration), the total amount of data transferred to accomplish the migration and the total power required on the transmitting side to complete the migration.

We will also collect these same measurements of two extreme configurations – "cold" migration and a high-availability pair. In cold migration, the VM is suspended, the files transferred to other side and the VM resumed. This represents a worst case for the amount of time a VM will be unresponsive but makes the fewest assumptions about the environment (no NAS required for example). In a high-availability pair, VMs run constantly on both machines so full VM migration is never required. In some cases, data will be shipped from one VM to another to keep the two VMs in sync. The only thing that changes is where requests are sent (to both VMs if available, to just one, etc.).

a. Progress to Date

- Surveyed advertised features/requirements of several major hypervisors and cloud orchestration tools, and added this information into a master spreadsheet

- Set aside several physical servers in one rack in the Applied C.S. Labs for building a testbed;

- Set up a similar rack of servers in one of the labs in CAMP which can, in part, be used for testing cross-campus migration

b. Next Steps

- Begin quantitative testing of virtual machine migration with VMware, Xen and KVM in each of the configurations we have identified.

2. Workload Characterization

The second set of subtasks in this portion of the project relates to workload characterization towards the goal of identifying a wide range of techniques that can be used to enable different workloads to run effectively in a distributed POD environment. Virtual machine migration as discussed in the previous section is one very powerful tool, but there are some workloads for which other techniques may be more effective including high-available pairs (both hot-hot pairs and hot-cold pairs) and workload summarization (e.g. caching the most popular results or providing a smaller summary when the full dataset or service is not available).

We plan to characterize workloads according to a variety of characteristics including size of data set required, rate of change in dataset, tolerance for inconsistency, tolerance for downtime, etc and use these characteristics to suggest a range of techniques to make the distributed POD environment effective.

a. Progress to Date

- Identified a set of workload characteristics to collect/record about important data center workloads

- Identified a set of workload modification techniques that may be applied including VM migration, high availability pairs, workload summarization, predictive downtime and request queuing.

b. Next Steps

- Identify a concrete set of representative workloads that we can use as the targets for our workload characterization and modification techniques (e.g. SpecWeb to represent web server workloads).

- Develop a set of VMs that represent each of these workloads.

- Identify a set of tests and measurements that we can use to evaluate the effectiveness of our workload modification techniques

3. Note on Staffing

For the majority of the project, we expect to have two graduate students working on this portion of the project. Each graduate student will TA one semester a year and work as an RA on the project full time during the other semester and during the summer. When serving as a TA, the student will continue to attend meetings and contribute to the project but not as intensely.

This semester one PhD student was supported as TA, and partially engaged in the research, one Masters student who was interested in becoming more involved in the project and one undergraduate. One PhD student who was finishing up a co-op position also followed the project and attended meetings by phone. Over the summer, we will have at least one full time Ph.D. student and two full time Masters students, using some of the funds that we did not use during this first semester.

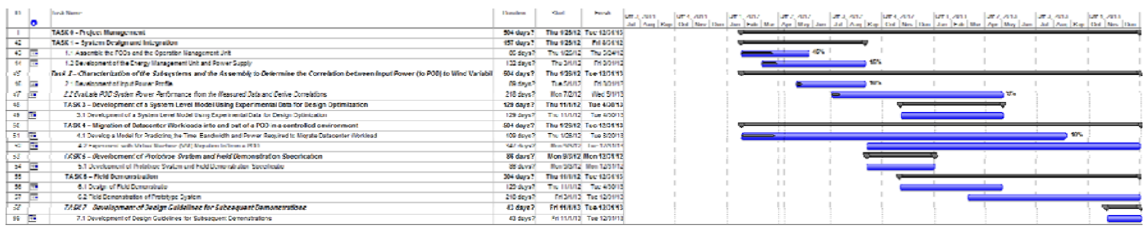
b. Identification of problems & Planned Solutions.

Task 1 and Task 4 are on schedule.

c. Ability to meet schedule, reasons for slippage in schedule, unforeseen obstacles, promising research directions not originally identified in current SOW

No significant slippage or unforeseen obstacles encountered in the project as of now. Work is going according to the plans.

d. Schedule - percentage completed and projected percentage of completion

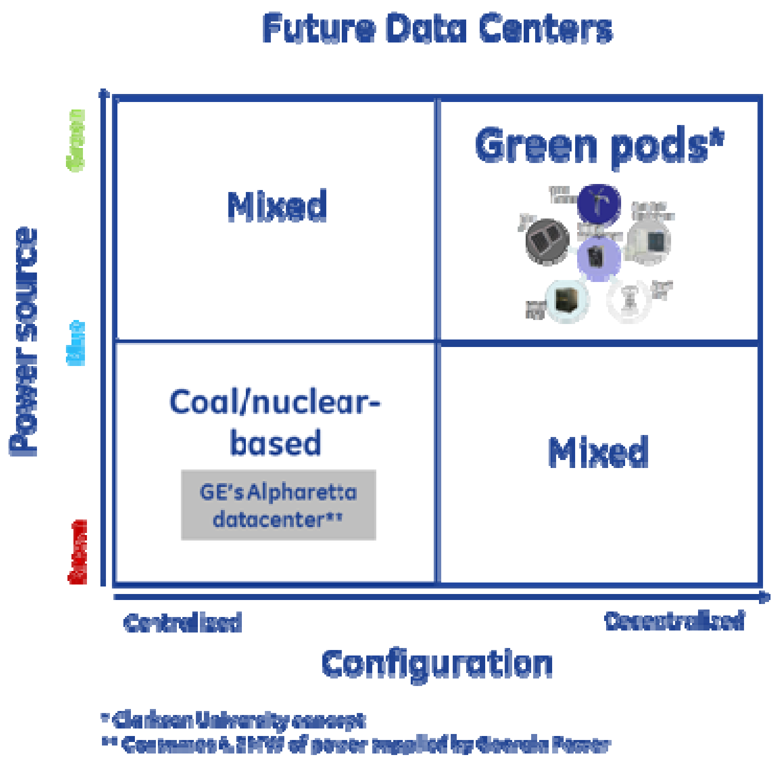


e. Dissemination and Meetings

Green Data Centers Meeting: GE Headquarters, Atlanta

The GDC POD team was represented by P. Marzocca, K. Janoyan, and S. Bird at a meeting at GE in Atlanta on March 22-24. Clarkson director of OIT Kevin Lynch joined the group and continues to have a strong supporting role for the project. J. Matthews and students from Clarkson participated to the meeting via Webex conferencing. Jay Owens from AMD also joined the meetings. It was a joint meeting for two Clarkson University Projects. The first project was discussed in the morning session and involved GE technical support for Clarkson's implementation of a Green Data Center at the "Old Main" campus building. The afternoon session involved presentations concerning the POD project and concept. There were GE presentations throughout the day concerning GE's involvement in datacenters and associated technology. It included a walkthrough of the GE Marietta datacenter.

Response from GE was positive, and GE representatives were highly engaged in the discussion. Peter Evans, Director of Global Energy Strategy for GE Energy, was so taken with the idea that he incorporated the concept of "distributed data centers" into a talk he gave the following week to GE employees. It is below:



Several discussions emerged from the meetings. First, GE voiced concerns for cost feasibility and siting issues for small hydro as a component of green data centers – it is clear that siting and cost issues require more research. Second, they voiced support for the idea of PODs and green data centers in emerging markets (e.g. Africa, South America, Asia). We believe the concept can be developed in New York State as a testbed, and then expanded and exported to other locations. They also particularly liked the conceptual ideas of data as an energy product, and the potential redundancy savings for data centers via Green Data Centers (this is an idea that needs to be examined in greater detail).

The team is also in the process of submitting an ARPA-E Concept paper in response of the Funding opportunity No. DE-FOA-0000670, CFDA Number 81.135 (see Exhibit B).

f. Analysis of actual cost incurred in relation to budget

Total cost incurred up to April 15th: **$8,236.74** (NYSERDA portion)

Student Salary – $5,076.90 (budget allocation - $89,320.00)

Travel expense – $342.00 (budget allocation - $10,000.00)

Indirect cost – $2,817.84 (budget allocation - $88,946.00)

Cost-share – **$27,937.20** (Clarkson)

Student Salary	$6,769.20
Student Tuition	$19,168.00
Travel	$2,000

Cost-share – **$10,000.00** (Partners)

AMD Corporation	$10,000

Exhibit A

Task 1 – System Design and Integration

The Contractor shall complete the engineering design and integration aspects of the project necessary for a renewable-powered POD. This includes; (1) developing the hardware and algorithms necessary to directly power the POD from a renewable energy source (wind turbine), (2) the ability to migrate computational load from one location to another, (3) study of the wind characteristics of the selected location and the inertial response of the turbine to variation in the instantaneous wind power profile, (4) determination of the expected short and long term power variations (based on wind characteristics, and availability and specifications of the UC), (5) the identification, selection and sizing of all the subsystems required for a laboratory and field demonstration.

Subtask 1.1: Assemble the PODs and the Operation Management Unit

The Contractor shall assemble two PODs and the Operation Management Unit (OMU) in preparation for demonstration. Each POD will consist of either 10HP ProLiant DL165 G7 Servers (1U rack-mount) with 8-AMD Opteron™ 6100 Series processors or a Configurable-HP BladeSystem c-Class c3000, two programmable DC power supplies, to be specified as a part of the proposed work to meet the needs for the laboratory demonstration.

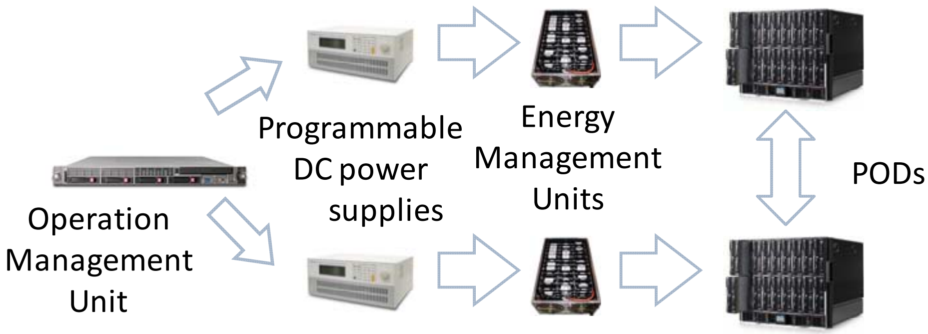
The HP/AMD system will include sensors and power management techniques which enables real-time monitoring and management of power consumption. Examples include the AMD-P technology, a suite of advanced features that can help to significantly reduce energy usage; Dual Dynamic Power Management which helps redue idle processor power consumption; the C1E Power State, which turns off memory controllers, AMD PowerNow! technology which dynamically manages power utilization across processor cores; and the AMD CoolCore technology which enables reduced power consumption within individual cores. In addition the AMD CoolSpeed technology enables precision thermal monitoring and the Enhanced APML technology enables precise digital readouts of CPU thermals to closely monitor cooling impacts in APML-enabled platforms. All these features and sensors will be monitored to evaluate the performance of the system real-time.

One of the 1U rack-mount servers will act as the OMU, the "master" node, which is configured to boot from a single hard disk, and will be controlling the operation of the two PODs.

Subtask 1.2: Development of the Energy Management Unit and Power Supply

The Contractor shall build an experimental setup which will enable characterization and adjustment of the system components under controlled laboratory conditions by simulating the power provided by a wind turbine. This shall be accomplished by using two programmable DC power supplies (PPS), to be controlled by the OMU, which will provide input power profiles to each POD typical of a 5 – 10 kW wind turbine during normal daily operation. The Energy Management Units (EMU) will include short-term power storage components (UCs) and will be controlled, by the OMU, to ensure continuous operation of the PODs. When the PPS power falls below the level necessary for operation of a POD, the capacitor bank will discharge to provide ride-through capability. When the input power is more than the desired value, the capacitor will be charged. The two PODs will be connected through a fiber optic cable in order to demonstrate the ability to shift computational load from one POD to another based on the available (or lack thereof) of renewable energy.

The experimental setup is show below:



Demonstration setup: Consisting of one master node functioning as Operation Management Unit, two programmable DC power supplies, two Energy Management Units based on ultra-capacitors and two interconnected POD testing units.

Additional sensors to measure power at the server and POD level will be installed and monitored. These sensors will provide the ability to see how power use correlates with workload and other operational factors.

Deliverables:

a) *Specification of the PODs and OMU to be assembled*

Assembled Demonstration System

Task 4: Migration of Datacenter Workloads into and out of a POD in a controlled environment

The Contractor shall identify the parameters necessary for migration of computational load from one POD to another and then test that migration in a controlled environment. The objective of this task is to demonstrate the ability of the system to automatically migrate workloads based on the availability and cost of power. This will require the ability to predict and react to the availability of power and/or storing a sufficient amount of power to enable the workload to be fully migrated. This task will characterize a representative workload in order to predict the time, bandwidth and power required for the migration.

Subtask 4.1: Develop a Model for Predicting the Time, Bandwidth and Power Required to Migrate Datacenter workloads

The time, bandwidth and power required to transfer a workload from one datacenter to another can vary substantially with characteristics of the workload and with the configuration of the system and therefore sufficient power must be reserved by the system in order to complete the migration. The Contractor shall develop a model for predicting those parameters required to migrate a workload based on attributes such as:

(1) The total size of the data set. This should include active data elements such as VMs and passive data elements such as files and databases. The larger the dataset the more important it may be to keep additional copies in other PODs in preparation for migration. Disk space is comparatively inexpensive and storing a second copy uses no additional power if the disks are spun down when not active. In the worst case, the entire data set may need to be transferred when migrating the data.

(2) The degree of redundancy in the data placement for high availability. It is advantageous to maintain copies of a workload's data set in multiple PODs to enable efficient operations and redundancy.

(3) The percentage of the total data that is changed per unit time. If a period of low power is predicted, then most recently changed data must be transferred to the new location in preparation for migration.

(4) Tolerance for inconsistency. It may not be necessary to transfer all the most recently changed data in order to migrate a workload to a new POD. For some workloads, a computation or query based on all but the last hour's data may be acceptable.

Subtask 4.2: Experiment with Virtual Machine (VM) Migration to/from a POD.

The Contractor shall, in the context of the physical prototype system described in Task 1, experiment with migrating VMs from the POD to another datacenter and from another datacenter back into the POD. A variety of VMs will be constructed representing common datacenter workloads and experiments will be conducted migrating these VMs to and from the prototype POD. Existing commercial VM migration products such as VMware's vMotion will be used and reports on their effectiveness for this purpose will be created. Experimental data including the total time for migration and the responsiveness of the VM before/during/after migration will be collected. The responsiveness of the server from the perspective of external clients will be evaluated. In order to obtain controlled and repeatable results, representative workloads will be used during the experiments such as SPECweb. The following characteristics will be tested and used to establish the overall system specification:

(1) The time required to migrate various workloads from one POD to another given a drop on available power

(2) The power required to migrate various workloads from one location to another

(3) The responsiveness of the server from the perspective of external clients.

Deliverables:

a) *Description of data migration model*

b) *Data migration test results using developed mode*

Exhibit B – Ultracapacitor short term storage

Rated voltage (V)	48				
V_{max} (V) / V_{min} (V)	54 / 38				
Power (W) / I (A)	2400 / 54.5				
Discharge Time Td	10 (s)	1 (min)	3 (min)	5 (min)	10 (min)
# series cells	20				
# parallel cells	1	3	7	12	23
Capacitor	150	450	1050	1800	3450
Resistor	0.0520	0.0174	0.0075	0.0044	0.0023
UC voltage Drop	6.47	8.21	9.75	9.32	9.60
UC remaining voltage	41.53	39.79	38.25	38.68	38.40
UC Bank level	76.91%	73.69%	70.83%	71.63%	71.11%
UC zone danger	55.30%	37.90%	22.50%	26.80%	24.00%

Table 1 – Ultracapacitor short term storage

The servers used in this project are compatible with 36 VDC architectures. The ultra-capacitor's design proposed previously ensures at least 38VDC as a voltage lower bound.

Designs presented in table 1 are given in the figure below.

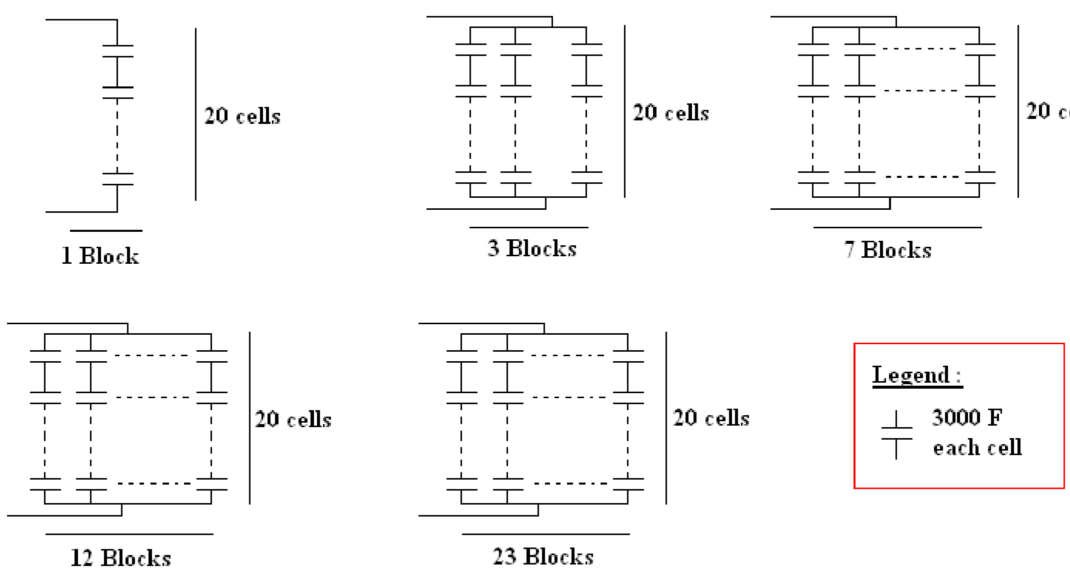


Figure 8 - UC Short term storage

Exhibit C – Bill of Material

The BOM (parts list) is given in the two table below.

Architecture	Product	Brand	Model	Specifications	Efficiency	Quantity
48VDC	DC PPS	Chroma	62000H	5KW (100A-100V)		2
	Rectifier	GE	CPS6000 OSP Shelf	8.8A/150-275Vac to 25/30A (42/58 VDC)	97%	2
	Management Software		EasyView			1
	PDU	HP	HP iPDU		94%	2
	Server 2U			28A/-48VDC		4

Table 2 - Parts list of the DC Architecture

Architecture	Product	Brand	Model	Specifications	Efficiency	Quantity
240 VAC	AC PPS	Quadtech	31000 AC PPS	300 V- 32A		2
		Chroma	61505 Series	150/300 V - 32/20 A		2
	3KVA UPS	GE	GE Match Series	140-305Vac range to 220/230/240 VAC	98%	2
	Management Software		GEDE			1
	PDU	HP	HP iPDU		94%	2
	Server 1U			4A/240V/60Hz		2
	Server 2U			3.5A/240V/60Hz		2

Table 3 - Parts list of the AC Architecture

Note: Only one of the proposed AC PPS models will be used. Needed inverters will be selected to match the final components and will not be used in the current emulator design.

Exhibit D – ARPA-E submission

I. TECHNOLOGY DESCRIPTION

Data Center energy costs are increasing rapidly, raising concerns about their impacts on the nation's overall energy consumption, environment, and security. Concurrently, power transmission constraints limit the use of renewable power sources that are often located far away from the load centers where conventional data centers are usually located. To address these issues, a proof-of-concept demonstration of a disruptive technology that co-locates self-contained modular computational pod/containers with intermittent renewable power sources such as solar and wind power is proposed. This concept has the potential to help the energy sector overcome its challenge of integrating intermittent renewables while also solving the IT sector's challenge of overcoming expensive and unreliable energy.

Proposed Technology: A Distributed Green Data Center (DGDC) is a large dispersed interconnected collection of computational pod/containers powered by intermittent renewable sources. A likely embodiment exemplified in Fig. 1 (addendum) involves installing dense computation capability into robust, modular, transportable cabinets or containers, sealed to permit outdoor installation. Such pods are completely self-contained with power input, network connections and, potentially, a connection for cooling and/or waste heat recovery. Component failure within the container is tolerated until overall pod performance degrades to a predetermined level (fail-in-place). The DGDC is designed for resiliency, and operates like a single logical entity irrespective of their physical distribution across a vast region.

Basic Operating Principles: One key design feature is to use the transmission of data over fiber optic cable as a substitute for the transmission of electricity over traditional wires. By coupling data centers to far-flung, intermittent renewable sources, data centers become a form of dispatchable demand for the electrical grid. In that capacity, they improve grid stability while enabling data center access to more affordable electricity. The data centers are distributed over an extensive geographical area, taking advantage of indigenous energy sources and interconnected via a high-speed fiber-optic data highway. Often, renewable power at these locations will be intermittent. Thus the system needs to dynamically adjust applications and databases so they can be shifted to available power within distributed data center network. Because of the partially stochastic nature of the intermittency — as clouds block solar panels in one area, wind power picks up in another — there is generally power available *somewhere* all the time. Distributed computing can be dispatched to match the availability of that power, reducing demand on the electrical grid from data centers, providing a less expensive source of power for computation, and addressing intermittency problems in renewable electricity.

Uniqueness & Innovation: Instead of shipping power to the data center, our approach would distribute computational load as needed to locations where power is surplus. Another novelty of the proposed concept is that it relies heavily on the marriage between two innovative concepts, 1) distribution/decentralization of data centers for cloud computing and 2) distributed renewable power generation, concepts that are each expected to make significant impact in their respective fields. Application of the latter in conventional large data centers is impractical because of the large footprint required from renewable sources. One solution is to have large renewable generation "farms" connected to remote large data centers, but the cost of the necessary transmission lines diminishes the economic competitiveness of this option.

Target Level of Performance: For the demonstration, the team (Clarkson University, UT, NREL, and BNL along with industrial partners) will first consider a system comprised of four small PODs geographically distributed. Power supply and computational load demand scenarios will be studied. This will demonstrate DGDC capability for computational load switching in response to forecasted power and load conditions and also survey power availability, energy storage, efficient cooling, and thermal management. This will include hardware/software development along with system integration and design guidelines, and recommendations for scaling up the system. Evaluations of the inherent energy efficiencies of the small POD will include Power Usage Effectiveness (PUE) and comparisons with traditional Data Centers. PUE will be assessed by contrasting total system power requirement (including switchgear, UPS, battery/ultracapacitor/flywheel back-up, cooling demand, etc) with the power required for the IT equipment (servers, storage, Telco equipment, etc). The target is below 1.251; HP's best recorded value for a large POD container.

Current Readiness Level (TRL): The DGDC is currently at TRL 2; we expect it will be at TRL 6 at the end of the proposed project (36 months).

State-of-the-art: Renewable power such as wind and solar suffer from intermittent production of power, optimum locations for power production that are far from infrastructure and load, losses in electricity transmission, transmission constraints, permitting and regulatory constraints, and high infrastructure costs. With computing, transmission of electricity to the computer involves many stages of AC/DC and sequences that reduce 3-10% of available power at each step (Fig 1). Cloud computing can address many of these concerns. Complexity and cost can be reduced by Software-As-A-Service models in which users do not need to upgrade, patch, or maintain software or hardware. Centralized server farms are expected to grow, increasing challenges for power and cooling.

Advantages and Impact of Proposed Technology**:** This approach will have a significant impact on energy, computation, and the environment. In addition to the higher efficiency of renewable energy use, the research will show that redistribution of computational load can achieve maximum utilization of available power. Wind and solar forecasting, and computational load forecasting, can allow shifts to optimize both energy use and computing output. Computational load transfer will be enabled by advanced chip design, software structures, and POD configuration along a network of fiber optic transmission that can be built at a fraction of traditional electrical Transmission & Distribution (T&D) costs. Successful implementation of this concept will enhance grid performance and reduce transmission losses. Data center operators can avoid expensive utility upgrades as renewable availability increases, and stranded renewable power (i.e. not-delivered to the grid due to transmission constraints) can be optimally used. It will enable customers to reduce costs, energy consumption, and environmental impacts. This can contribute to a paradigm shift in the delivery of cloud computing and data storage.

Key Technical Risk and Issues: Accurately predicting available power from intermittent sources, computational load demands at a specific site simultaneously will be challenging. Second, developing computational load redistribution strategies will also be a concern.

Impact of ARPA-E funding**:** A laboratory scale demonstration is currently progressing with financial support from NYSERDA. Larger scale demonstration of TRL 6 level involves extensive research, design, development and testing, requiring larger financial support.

ADDENDUM

This technology development demonstration and proposal is for 36 months and seeks $4,500,000 under Category 7 (Other) and Technical Subcategory F: Datacenters and Computation.

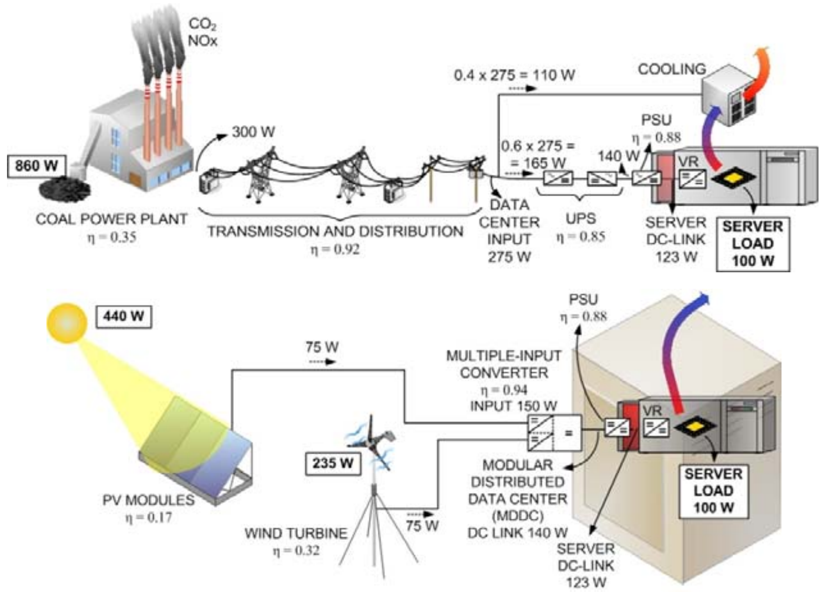


Figure 1 (a) Top: Energy utilization chain in a conventional data center approach; 860 W of equivalent coal power is required for a 100 W server load. (b) Bottom: Proposed approach based on modular distributed data centers (MDDCs); a combined 675 W of equivalent power from carbon-free renewable sources is needed for the same 100 W server load. Thus, the EGC approach requires less energy, smaller infrastructure (fiber optics instead of transmission lines), and potentially emits no carbon. At the same time, the marginal electricity costs for solar and wind power are far lower than the marginal costs for coal power. Moreover most of the difference between necessary equivalent power and load in the MDDC concept is originated in energy that is not harvested in PV modules and wind turbines so power is not lost. On the contrary, in the conventional approach, power differences between the equivalent source of energy (coal) and the load, is power that is lost by dissipating it into the environment, mostly in the form of heat. Because of switching computational loads, the data centers can also be used for firming up the grid through ancillary service markets.

Clarkson investigators bring expertise in modeling, development of wind turbine technologies (Marzocca), sensors and computing system development (Janoyan), system reliability and optimization (Achuthan), data center development and security, networks, and operating systems (Matthews), energy and electricity policy (Bird), and Information Technology (Kevin Lynch). Energy and environment are two signature areas identified for research focus at Clarkson. Similarly, the PIs at UT have extensive credentials in power and energy planning, conversion, and utilization; complementary to Clarkson. Their expertise includes cooling, energy storage, and system modeling (Hebner), energy conversion and control (Kwasinski), and dynamic energy systems modeling and energy policy (Webber). The team will leverage the experience of the industrial partners in the area of computing, data centers, wind turbines and storage, wind and solar power generation, systems integration, and weather forecasting.

Clarkson Investigators have recently started a $770,000 NYSERDA project for initial implementation of the DGDC pods. Clarkson is also a member of the Center for the Evaluation of Clean Energy Technologies (CeCeT) led by Intertek. That consortium has been awarded $4.4M from NYSERDA and is currently working with the other consortium members on associated PV and wind turbine technology testing. A Smart Grid fellowship program, currently funded by GE Energy System, is supporting 12 graduate students. Finally, they are currently developing the North Country's first green data center using IBM technologies under an IBM Shared University Research award of more than $1 million. It includes an IBM Smart Analytics System, BladeCenter servers, storage, networking, and software applications. The new facility will also host the NYSERDA funded hub POD node, which will function as operational management unit for other spoke nodes in the system. The new facility substantially expands the University's capacity to engage in complex computational research and advanced analytics.

UT Austin will leverage extensive energy and computational sciences research portfolios. Energy research exceeds $50 million annually. The Texas Advanced Computing Center (TACC) is a supercomputing facility at UT-Austin that is supported with more than $100 million from the National Science Foundation, DOE, and a wide variety of other high level stakeholders. TACC has a world-leading collection of open-access high-performance computing systems (Lonestar, 302 TFlops; Ranger, 580 TFlops; PECOS, 1.2 Petabytes of storage; and Stampede, 10 PFlops and 14 Petabytes of storage), scientific visualization resources, and data storage/archival systems. The PIs at UT have active research programs relevant to the project. These include energy storage (flywheels, electrochemical, compressed air), renewable power generation, microgrids, smart grids, and energy system integration. The UT team represents the Clean Energy Incubator, TACC, Mechanical Engineering, Electrical & Computer Engineering, and Centers for Electromechanics, and also International Energy and Environmental Policy.

The team is also comprised of government and industry leaders in energy, power systems, information, computational science, electromechanics, and systems integration, with extensive capabilities in analysis, hardware, and software. This includes support by the National Renewable Energy Laboratory (NREL) and DOE's Brookhaven National Laboratory (BNL). This brings experience in energy efficient IT resources, computing, and renewable energy systems. Demonstration site locations will include UT (solar, wind), BNL (solar), Clarkson (hydro, wind), and NREL (wind, solar, and fuel cells). Additional sites are under consideration.

Industrial partners include Advanced Micro Devices (AMD) Corporation, a leading provider for processors in support of cloud computing services, and Hewlett-Packard Product Development, a leader in POD computing and systems. AWS Truepower is an innovator in renewable energy consulting and information services. Intertek is an OSHA accredited Nationally Recognized Testing Lab (NRTL) operating an open air test site for small wind turbines supported by NREL. GE's Global Research Center serves as a hub for rapidly expanding areas and disciplines of science and technology, including wind power and high speed computing. Ballard Power Systems is a world leader in the development and manufacture of hydrogen fuel cells. The project is also supported by the New York State Energy Research and Development Authority (NYSERDA). The Building R&D group at NYSERDA is currently exploring potential parallel support for this ARPA-E submission.