The information and communications technology (ICT) industry has a broad impact on our economy and society due to the widespread use of ICT services empowered by large-scale social networks. Eco-friendly ICT services are, however, underrepresented. Consequently, ICT is currently viewed as a polluter because of its ever-increasing greenhouse gas (GHG) emissions. The current approach to dealing with the green ICT problem focuses on reducing energy consumption at the micro level. Unfortunately, an unconstrained energy-efficiency approach at this level will most likely lead to an overall increase in energy consumption at the macro level, according to Jevon’s paradox.\textsuperscript{1} Energy-aware technology is thus becoming one of the most exigent research realms for sustainable ICT.

Moreover, the renewable energy industry has recently matured to become a utility power generation technology. More than half the total energy generated in Northern Europe comes from renewable sources. However, selling electricity to the power grid can result in waste owing to generation, transmission, and distribution losses. In the US, this waste accounted for more than two thirds of the energy produced in 2008.\textsuperscript{2} Thus, maximizing onsite renewable power usage — for example, by building ICT facilities close to renewable sources — is a cost-effective solution.

Although recent research has considered powering ICT services via renewable energy, experimental models or realizations of energy awareness are rare for wide-area testbeds.
Embedding power-management techniques into the ICT environment hasn’t matured enough to be commercialized, so corporations aren’t yet willing to risk investment in this area. Although recent high-speed research networks, such as the Global Environment for Network Innovations (GENI) in the US and the GÉANT network in Europe, are delivering high-performance computing services, they weren’t built with smart power control or environmentally aware features. Consequently, researchers lack resources for holistically analyzing the ICT carbon footprint and green strategies.

In this context, the GreenStar Network (GSN) project (http://greenstarnetwork.com) is the first wide-area testbed to realize a green ICT initiative based on the “follow the wind, follow the sun” paradigm. Made with nodes powered almost entirely by renewable energy, the GSN combines local energy efficiency and global power optimization. It virtually migrates data centers between geographically distributed nodes according to the availability of renewable energy. Here, we address some fundamental issues we faced when developing this green testbed. We examine how the GSN produces and provisions renewable energy for data centers, and describe the infrastructure underlying a large-scale green testbed network and how service is provided through user slices. We also explain the need for a carbon quantification protocol for ICT with calculation methods. We implemented several techniques and algorithms to maximize green energy usage and network sustainability. Additionally, although the ISO 14064 standard is widely used to measure GHG emissions in traditionally high-polluting industries, specifying it to ICT will require synergistic solutions with regard to power and performance measurement, as well as network and system operation. In particular, the standard doesn’t involve mobility techniques that can effectively reduce ICT’s carbon footprint.

Testbed Infrastructure and Services

Canada’s high-speed Canarie network (www.canarie.ca/en/network/overview) is the cornerstone of our GSN solution. Relocating an entire virtual data center to harvest renewable energy in different geographical locations requires seamlessly transmitting a large volume of data stored in virtual machine (VM) memory to end users. Additional requirements for the network include **elasticity**, **programmability**, and **abstraction**. Elasticity lets us reorganize the network flexibly when a node is relocated. Programmability refers to network operators’ ability to implement new algorithms to adapt network behavior to intermittent renewable energy sources. Finally, abstraction enables unified resource management. We chose virtual network management to build the GSN, because this approach allows different network architectures to coexist and lets us create on-demand independent logical networks on top of different infrastructures.

Network virtualization divides traditional ISPs into two independent entities: the infrastructure provider (InP) manages the physical infrastructure, and the service provider (SP) creates virtual networks by aggregating resources from multiple InPs and offers end-to-end services. Each SP leases resources from one or more InPs to create virtual networks and deploys customized protocols and services, considering each infrastructure’s performance, topology, and cost. Recent research testbeds such as GENI or the Federated E-infrastructure Dedicated to European Researchers Innovating in Computing Network Architectures (FEDERICA) also adopt the virtualization approach.

Figure 1a illustrates the GSN’s physical connections. The underlying 100-Gbps network is all-optical and has recently achieved a world record for high-speed networks. It comprises two layers — a reconfigurable optical add-drop multiplexer (ROADM) and synchronous optical networking (Sonet) — and provides lightpaths with user-controlled capability. On top of the Canarie network (InP), the GSN (SP) deploys six lightpaths to link distributed data centers. Connection to the US and Europe occurs via the StarLight, GÉANT, and NetherLight networks. The Canadian section has the largest node deployment (six), linked at layer 2 by optical cross-connects. This section is connected to nodes in Ireland, Iceland, Spain, Belgium, the Netherlands, and the US. Two nodes in China and Egypt are connected on a sporadic basis.

Network virtualization tools — namely Argia, Ether, and Manticore — establish connections between Canadian nodes, as described elsewhere. We achieve federation with international nodes at layer 3 via virtual routers, each of which provides a lightpath tunnel.
Figure 1. Physical infrastructure of the GreenStar Network (GSN) and its user slices. We can see (a) the physical network connection of nodes on top of the Canarie network and (b) network slices controlled by OpenFlow in the GSN.
All servers in the GSN are virtualized using hypervisors, and users rent computing power through VMs. The GSN network slice service lets users actively create and manage their VM networks (Figure 1b). Companies such as Amazon (http://aws.amazon.com/vpc) have recently offered a similar concept, called the virtual private cloud (VPC), in the commercial market. However, links in a VPC are fixed when it’s created, whereas a slice in the GSN is scalable and flexible thanks to a software-defined network (SDN) architecture that uses OpenFlow technology. With clouds, the hypervisor directly links VMs to a physical network interface card (NIC) of the server, which then connects to a physical data center switch. Each server in the GSN, on the other hand, is equipped with a built-in, software-based virtual smart switch (called a vSwitch). Thus, VMs are connected to their vSwitch before they’re connected to the physical switch. This vSwitch lets the network isolate or group VMs running on a server according to user demand.

A software-based OpenFlow controller running on a dedicated VM handles the entire network’s control plane. It controls the vSwitch’s flow tables in such a way that all VMs belonging to a user slice will be put in a virtual LAN (VLAN), which could span multiple vSwitches. Users configure their slices through a Web-based graphical interface (see http://greenstarnetwork.com) that translates and then relays user requests to the controller through the GSN cloud middleware. When a VM is moved among servers (the migration process is described elsewhere), the controller dynamically reconfigures vSwitches so that the VM network slice remains unchanged (for example, in Figure 1b, slice 1 is added to the vSwitch in host 3 after a migration). A VM migration takes roughly two minutes on a 10-Gbps connection with no traffic loss. Virtual routers can configure dynamic tunnels when moving VMs between Canadian and international nodes. We also developed flow-classification algorithms for the controller to provide quality-of-service (QoS) levels to different user categories.

**Power and Environmental Control**

Physically, a GSN green node (see Figure 2a) consists of the following special-purpose equipment:

- a layer-2 switch,
- servers based on the Intel E5500 with virtualization capability,
• a power distribution unit (PDU) with associated temperature and humidity sensors, and
• a solar-powered system (SPS) or wind-powered system (WPS).

The SPS includes solar panels, a charge controller, an inverter, and battery banks. In the WPS, the solar panels are replaced with a wind turbine. Remote control and monitoring is required for both SPS and WPS. The Outback MATE communications device controls the solar battery and the inverter — for example, it switches between solar power and the power grid. The Perle IOLAN server connects serial ports to Ethernet ports, letting computerized applications control power devices. Both MATE and IOLAN are software-virtualized and exported as cloud resources in this project.

A node’s logical architecture comprises three planes: the power plane deals with power generation and provisioning, the data plane provides data transfer and hosting services, and the control plane includes monitoring, reporting, and signaling functions. We use cloud middleware to manage these planes in a unified fashion.

Nodes are hosted on a rack-mount structure in an outdoor, climate-controlled enclosure equipped with an air conditioner for summer and a heater for winter (see Figure 2b). A key issue this enclosure faces is keeping humidity inside the container within acceptable levels. Solutions include an additional ventilation system or occasionally triggering the heater.

To collect power and environmental data, we virtualize each node’s physical device using a software tool and then represent it as a cloud resource. These resource instances communicate with devices through the Telnet, Secure Shell (SSH), and Simple Network Management (SNMP) protocols, parse commands, and decide when to perform appropriate actions. The virtualization approach lets other resources or services use a given resource, enabling auto-management processes.

Although all GSN nodes have power generators, renewable energy wasn’t intended to be their only power source. Indeed, the GSN is predicated on the assumption that renewable power availability will wax and wane in relation to the sun and wind. The GSN achieves continuous data center operation services, despite fluctuating power availability using controlled VM migration between nodes. For example, when solar power dwindles in a node, the network relocates services to other nodes; if, for any reason, this migration fails or occurs too late, the node will switch to the power grid so that these VMs will continue to run normally until they can be migrated.

We implemented automated algorithms to make decisions on dynamically migrating and consolidating VMs among servers within data centers to meet the workload requirements while maximizing renewable energy usage. These algorithms address several key issues, including when to trigger VM migrations and how to select alternative hosts to achieve optimal VM placement and avoid service outages.

Carbon Assessment: Measurements and Reporting

A key challenge green testbeds face is how to accurately quantify and report GHG reductions. The GSN determines reductions resulting from both renewable energy usage and VM relocation by processing data at two levels. The first level, called local fast data acquisition and collection, involves physical, cloud-resource-controlled devices. The GSN collects power consumption data from the PDU using highly accurate power, temperature, and humidity sensors. The MATE device reports power generation from solar panels and wind turbines. Each cloud resource controls a physical device and measures a set of environmental metrics, as Table 1 shows.

Using cloud resources (such as compute resources for the server or network resources for a network element), the GSN can measure and control metrics such as CPU, memory, virtualization capacity, VM metrics, VPN, and bandwidth. Unlike existing middleware in the market — such as OpenNebula or OpenStack, which focus on the IP network — the GSN’s network resources cover metrics at all three network layers.

The second level of data processing calculates power consumption at a lower granularity — namely, VMs and migration traffic. We can derive the power consumption of a VM running on a host from the host’s capacity and power and the VM’s resource requirements, as follows:

\[ P_V = \left( \frac{\alpha \times M_V}{M_H} + \frac{\beta \times U_V}{U_H} + \frac{\gamma \times O_V}{O_H} \right) \times P_H, \]

where \( P_H \) is the host’s maximum power consumption (measured by PDU resource using...
stress tools); $M_V$, $U_V$, and $O_V$ are memory, the number of CPUs, and the VM’s I/O capacity, respectively; $M_H$, $U_H$, and $O_H$ are memory capacity, CPU, and the host’s I/O (given by compute resource), respectively; and $\alpha$, $\beta$, and $\gamma$ are three constants for memory, CPU, and I/O power consumption.\(^7\)

In reality, a server is powered off (on standby) if it doesn’t host any VMs. This action consumes a power $P_{\text{HOff}}$. When the network moves a VM to a server that is off, a power $P_{\text{HOn}}$ is required to restart the server. Both $P_{\text{HOff}}$ and $P_{\text{HOn}}$ are measured by PDU resource and added to each server’s total consumption according to the server’s status. Similarly, when all of a data center’s hosts are off, a power $P_{\text{DOff}}$ is consumed to turn off the data center (including its networking gear and cooling). A power $P_{\text{DOn}}$ is required to restart the data center.

We estimate the power consumed by the underlying network for a VM migration between two nodes through bandwidth capacity, the power of core switches between the nodes, and the VM’s size (in memory). Indeed, data centers in the GSN are connected directly to core switches without passing an access network. Assuming that all switches are the same type (that is, the same as those in the Canarie network), we can derive a migration’s power consumption as follows:\(^8\)

$$P_m = \mu \times \left( \sum_{1}^{L} \frac{M_V \times P_S}{B_S} \right), \tag{2}$$

where $L$ is the number of switches between two nodes (determined by the network manager); $M_V$ is the VM’s size (measured by the compute resource); $B_S$ and $P_S$ are bandwidth capacity and a switch’s power (given by the network manager), respectively; and factor $\mu$ accounts for the power requirements for cooling and redundancy, which are provided with switch configurations. Note that current switches aren’t load-proportional, so their consumption is constant even if they run under their full switching capacity.

The carbon footprint of a data center, the network, or a user slice is the product of the power consumption and the energy source’s emission factor (that is, tons of CO₂ per kWh). The emission factor of sources, including the power grid in Canada and worldwide, is available elsewhere.\(^9\) Note that //our?// research focuses only on the project’s operational phase. Footprints also result from the project’s manufacturing and retirement phases, which we’ll consider in future work.

Based on the aforementioned calculations, the Canadian Standards Association built and released the GSN Carbon Measurement Protocol\(^10\) to help in reporting and verifying emission reductions resulting from the delivery of low GHG emissions associated with ICT services. This protocol’s scope involves quantifying emission reductions that ICT services achieve, either by moving to a lower-carbon environment or improving workload efficiency. It defines two types of application ICT project activities. The first type includes activities wherein an ICT facility reduces emissions by changing its environment, such as improving

| Table 1. Environmental metrics (an incomplete set) measured by cloud resources. |
|-----------------|----------------------------------------------------------------------------------|
| Metric name     | Description                                                                      |
| Power distribution unit (PDU) resource |                                                                                   |
| Outlet current  | Electric current of a PDU outlet (consumed by electrical equipment)               |
| Outlet voltage  | Voltage of a PDU outlet                                                           |
| Outlet status   | Status of a PDU outlet (on/off)                                                   |
| Power resource  |                                                                                   |
| AC mode         | Whether the battery is selling or buying electricity to/from the grid            |
| Photovoltaics (PV)/wind current | Generated electric current of the solar PV or wind turbine                       |
| PV/wind voltage | Generated voltage of the solar PV or wind turbine                                 |
| Battery voltage | Solar/wind battery voltage                                                        |
| Climate resource|                                                                                   |
| Temperature     | Temperature in the enclosure (Celsius)                                            |
| Humidity        | Humidity in the enclosure (%)                                                     |
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efficiency or changing the energy source to renewable energy. The second type comprises activities that achieve reductions by improving ICT service delivery — for example, by migrating services from one environment to another.

To illustrate the reporting process, we investigate a use case in which an ICT project reduced emissions from a scientific application, called GeoChronos, from June to September 2011 through an increase in workload efficiency and migration to a green node (type 2). Initially, GeoChronos operated on eight blade servers with 480 Gbytes of RAM and consumed a total power of 500 W/h in the Calgary data center. The GSN achieved real emission reductions by moving the electricity-powered GeoChronos application from the Calgary coal-powered grid to a data center in Kelowna that’s powered by hydroelectricity. According to the protocol, we can estimate emission reductions as the difference between the project and the baseline. The baseline is the hypothetical case in which we assume that the application is running at the initial location (that is, Calgary) during the project period. The protocol requires that we report the following measurements:

- the amount of energy used by equipment at Calgary (using Equation 1),
- the emission factor of electricity from the grid in Calgary,
- the data center’s power usage effectiveness (PUE),
- the emission factor of the power source (hydroelectricity) in Kelowna, and
- the amount of power the underlying network uses between Calgary and Kelowna (using Equation 2).

We calculate the emission reductions to be 2,412.63 kg of CO₂ over the 13-week project, which is lower than our initial estimation, probably because of the data center’s high PUE (> 2).

Simulations and Experiments

Researchers conducted simulations and real experiments to demonstrate effective carbon reductions as regards the algorithms on the testbed, the feasibility of a renewable-energy-powered testbed, and the “follow the wind, follow the sun” paradigm.

Figure 3a illustrates a simulation scenario with 13 data centers located in seven cities around the world, hosting VMs under sun movement and under the random movement of several wind streams (see http://greenstarnetwork.com). The simulation imported renewable power-generation patterns from data collected in GSN nodes. The GSN team formulated the carbon-reduction problem for local data center consolidation and global network optimization. We propose genetic and best-fit-decreasing algorithms to solve the problem, which is proven NP-hard with multiple metrics. Simulations point out that the migration-based WAN optimization gives a 59 percent greater carbon reduction compared to local data center consolidation. Together with the use case presented in the previous section, our simulations and calculations show significant emission reductions thanks to the testbed.

We also performed real-time experiments to demonstrate that data center service can be entirely powered by renewable energy for up to three months. Figure 3b shows the electricity generated by a solar photovoltaic (PV) system in Ottawa during the experimental period. Figure 3c shows service states if no relocation occurs. The “ON” state indicates that service is powered by solar energy, while the “OFF” state means that it takes electricity from the grid. As the figure illustrates, the service must frequently switch from the solar PV to the grid during winter. Figure 3d shows service states when VMs are relocated (using a best-fit-decreasing algorithm). Because the virtual data center has migrated to alternate nodes when solar energy dwindles in Ottawa, the period that service is powered by renewable energy increases significantly compared to Figure 3c. However, the power grid is still needed during the second half of January. This suggests that using only solar PV isn’t relevant during the winter. A better solution would be to use solar-wind mixed generators. Such an experiment shows the potential for powering data center service permanently via renewable energy.

We also conducted an intensive experiment in a one-month period (March 2012) with three nodes in the Canadian section of the GSN to validate the “follow the sun” paradigm. Results show that daily migrations usually trigger at about 10 p.m. to move VMs from Ottawa to Calgary (both powered by solar energy), and then at midnight to Montreal (powered by hydroelectricity). VMs move back from Montreal to
Figure 3. Power and data center state from October 2010 to January 2011. We can see (a) our live simulation; (b) the electrical current generated by the solar photovoltaics (PV) at the Ottawa node; (c) the data center service without relocation; and (d) the data center service with relocation (ON: solar energy used; OFF: power grid used).
Ottawa at around 9 a.m. This almost coincides with the difference between the three time zones, if we consider the battery’s charging and discharging time. According to Environment Canada, in March, sunset is at roughly 7 p.m., but electricity in the battery still keeps a data center functional for three hours (until 10 p.m.); sunrise is at about 7 a.m., but we need up to two hours (until 9 a.m.) to get sufficient sunlight power and fully recharge the battery. This experiment thus demonstrates that the “follow the sun” paradigm worked as expected.

Note that, along with greening information and communications technology (ICT) services through data centers, recent research is also interested in greening networks, with respect to energy efficiency in traffic processing. For example, various projects undertaken at Berkeley Labs deal with greening Ethernet by adapting link rates to effective traffic levels because higher data rates require dramatically more power. Europe’s ECONET (low Energy Consumption Networks) project aims to aggressively modulate power consumption in network devices according to actual workloads and service requirements. However, the portion of power that optical core networks consume is smaller than data center consumption (servers, in particular) for the same volume of data processed. At the latest ITU Symposium on ICT, the Environment, and Climate Change, we saw many efforts toward greening data centers; among them, the GSN is the only initiative that addresses a large-scale data center network.

References

we’ll consider the carbon footprint and QoS/quality-of-experience (QoE) models of large-scale applications, such as telecommunications-grade services.

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