Green Computing

Toward a Zero-Carbon Network: Converging Cloud Computing and Network Virtualization

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Reducing greenhouse gas (GHG) emissions is one of the most challenging research topics in ICT because of people’s overwhelming use of electronic devices. Current solutions focus mainly on efficient power consumption at the micro level; few consider large-scale energy-management strategies. The low-carbon, nationwide GreenStar Network in Canada uses network and server virtualization techniques to migrate data center services among network nodes according to renewable energy availability. The network deploys a “follow the sun, follow the wind” optimization policy as a virtual infrastructure-management technique.

Over the past 10 years, global warming has caused annual mean temperature increases and sea-level rise and transition. Most research agrees that the main reason for such climate changes is the greenhouse effect caused by greenhouse gases (GHGs), in which carbon dioxide is a key factor. This issue not only jeopardizes the planet’s sustainability but also poses significant, long-term threats to the global economy. Among the main power consumption industries, information and communication technologies (ICT), with an annual growth rate of 9 percent, contributes approximately 2 percent to global GHG emissions—an amount that will nearly double by 2020.

The current approach to this problem is to improve energy efficiency—that is, reduce energy consumption at the micro level. Numerous research projects focus on microprocessor and computer design, power-on-demand architectures, and virtual machine consolidation techniques. However, a micro-level energy-efficiency approach will likely lead to an overall increase in energy consumption due to the Khazzoom–Brookes postulate (also known as Jevon’s paradox), which states that energy-efficiency improvements that, on the broadest considerations, are economically justified at
the micro level lead to higher energy consumption at the macro level. Such approaches would consequently increase GHG emissions. This has led some researchers to conclude that energy efficiency is an irrelevant network design approach and that the objective should be to make networks carbon neutral.

The SMART 2020 report showed that ICT's unique ability to monitor and maximize energy efficiency both within and outside of its own sector can lead to emission reductions five times the size of the sector's own footprint. This represents a savings of 7.8 giga-tons of CO₂ equivalent by 2020 — greater than the current annual emissions of either the US or China. Using new network and distributed computing architectures to reduce or eliminate indirect GHG emissions from ICT through zero-carbon data centers is one of the most promising ICT strategies to mitigate global warming progression.

Canada's GreenStar Network (GSN; http://greenstarnetwork.com) is one of the first nationwide networks powered entirely by green energy. The project is motivated by a previously proposed carbon-neutral approach, along with the emerging need for a green energy distribution wide-area network model that can establish a standard carbon protocol for the ICT industry. The project aims to create a pilot and a testbed environment from which to derive best practices and guidelines that ICT providers can follow when building low-carbon networks. Although the ISO 14064 standard — used to measure GHG emissions in traditionally high-polluting industries and on which the GSN protocol is based — is straightforward, specifying it to ICT will require synergistic solutions relating to power and performance measurement, as well as network and system operation. Thus, the GSN project focuses on two principal activities: creating an ISO 14064-compliant protocol and enacting a GHG reduction project based on using green data centers; and developing management and technical policies that leverage virtualization's mobility to facilitate the use of renewable energy, such as solar and wind, within the GSN.

A Zero-Carbon Network

As data centers increasingly provide ICT as a service — including evolving forms such as cloud, grid, and utility computing, storage, and networking — the urgent need to reduce GHG emissions will affect both providers and customers. Cap-and-trade or carbon taxes will increase service provision costs because most data center activities are carbon-dependent. This explains why large ICT companies such as Microsoft — which consumes up to 27 megawatts (MW) of electricity at any given time — have built their data centers near renewable power sources. Unfortunately, many other computing centers aren't so close to these sources. Thus, one emerging research area is renewable-energy distributed networks and how we can relate them to current grid systems using smart grid technologies. A key assumption is that losses incurred in energy transmission over power utility infrastructures are much higher than those caused by data transmission, which makes relocating a data center near a renewable energy (or green energy) source a more efficient solution than trying to bring the energy to an existing location. Other types of energy that aren't renewable, such as nuclear, aren't considered green.

A Canadian consortium of industry, universities, and government agencies initiated the GSN project with the common goal of reducing GHG emissions arising from ICT services. The project focuses on the relationship between networks and green data centers to provide green ICT services. The idea is that a carbon-neutral network must consist of data centers built near clean power sources, and that user applications will move to such data centers for execution. Such a network must allow for the migration of entire virtual machines to alternate data center locations. The GSN goes a step further than prior research that focuses on allocating physical data centers close to cheap energy sources; rather, we're actively and dynamically migrating virtual data centers to green nodes while maintaining user services. A high-speed optical layer with up to 1,000 Gbps of bandwidth capacity supports this migration. Compared to electronic equipment such as routers and aggregators, optical networks have a modest increase in power consumption — especially with new 100G and 1,000G waves. The GSN includes small- and medium-size data centers, so the network's construction can be flexible and cost-effective. Small data centers can be relocated in a timely manner, which is appropriate for online services. The advantages of small or even tiny data centers over large-scale data centers in terms of energy consumption and management are discussed elsewhere.
Here, we focus on the GSN’s design and management. The GSN uses no special hardware, so we don’t consider the cost of producing and maintaining network elements, such as routers and servers. The only difference between a regular network and the GSN is that the latter can transport ICT services to green-energy-powered data centers. The network implements this feature at a software level, as we describe.

Figure 1 shows the core GSN built in Canada, which includes six nodes powered by sun, wind, and hydroelectricity. Cybera (Calgary, Alberta) and CRC (Ottawa, Ontario) use solar power, whereas BastionHost (Truro, Nova Scotia) uses wind power. Three nodes at Rackforce (Kelowna, British Columbia) and ETS-UQAM (Montreal, Quebec) are hydro-energy-powered. The British Columbia and Quebec provinces have a large capacity of hydroelectricity, so service interruption in the network owing to power outages is unlikely. However, using renewable energy such as wind and solar is considered a higher priority because hydroelectricity isn’t necessarily a renewable energy source. The network thus requires applications to run in solar- and wind-powered nodes whenever possible.

Figure 2 illustrates the architectures of a hydroelectricity-powered node and two green nodes (one solar- and one wind-powered). The solar panels are grouped in bundles of nine or 10, and each panel generates 220–230 W. The wind turbine system generates 15 kW. After accumulating in a battery bank, electrical energy is treated with an inverter/charger to produce an appropriate output current for electrical devices. User applications run on multiple Dell PowerEdge R710 systems, hosted by a rack-mount structure in an outdoor, climate-controlled enclosure. At solar and wind nodes, air conditioning and heating elements are powered by green energy; at hydro nodes, they’re connected to the regular power grid. Power distribution units (PDUs) provided with power-monitoring features control electrical current and voltage. A local network links servers within each node and is connected to a core network through GbE transceivers. Data flows between GSN nodes over nine optical core switches in Canada’s Canarie network (http://canarie.ca).

The GSN node in Montreal acts as a manager (or hub node) that opportunistically sets up required layer-1 and layer-2 connectivity using dynamic services, then pushes VMs or software-based virtual routers from the hub to sun and wind nodes (spoke nodes) when power is available. The hub node pulls VMs back when power dwindles. In such cases, the spoke nodes can switch to grid power to run other services as needed. However, GSN services are entirely green-energy-powered. The VMs run user applications, particularly high-performance computing services. Using this testbed network, researchers can perform experiments that target cloud management algorithms and the optimization of intermittently available renewable energy sources. The GSN is also incorporating green nodes in Ireland (HeaNET), Belgium (IBBT), Spain (i2Cat), China (WiCo), Egypt (Smart-Village), and the US (ESNet).

Cloud Management and Data Center Migration

Converging server and network virtualization techniques, the GSN environment consists of a set of clouds, each one representing a data center along with that center's power and network accessories. Thus, the key challenge is managing, connecting, and coordinating elements within the environment to achieve specific tasks, while maintaining the required power level and minimizing GHG emissions. Our Web-based management solution lets cloud users transport their services over the network to green energy sources.

Cloud Management

Our cloud-management solution, the IaaS Framework, is based on the infrastructure-as-a-service (IaaS) concept, which deals primarily with delivering computing infrastructure. IaaS lets clients fully outsource services such as servers, software, data center space, or network equipment without needing to purchase physical resources or deal with the difficulties equipment owners face. The key notion behind IaaS is cloud architecture, which addresses difficulties inherent to large-scale data processing.

Figure 3 compares the GSN’s layered architecture to a typical four-layer cloud architecture. The GSN data plane corresponds to the general system level, and encompasses massive physical resources such as storage and application servers linked by controlled lightpaths. The platform control plane corresponds to the core middleware layer, and implements platform-level
Figure 1. The GreenStar Network. The core network includes six nodes powered by sun, wind, and hydroelectricity.
services to provide GSN services with a running environment that enables cloud computing and networking capabilities. The cloud middleware plane corresponds to the user-level middleware, providing platform-as-a-service capabilities based on IaaS Framework components. The top management plane or user level focuses on application services, building on those services that the lower layers provide.

**Data Center Migration**

The GSN project seeks to move virtual data centers from one node to another. This migration is required for large-scale applications running on multiple servers with a high-density connection local network. Migration involves four steps:

- setting up a new environment (that is, a new data center) for hosting the application with the required configurations;
- configuring the network connection;
- moving VMs and their running-state information through this high-speed connection to the new location; and
- turning off computing resources at the original node.

Many existing ICT operators offer solutions for migrating simple applications. However, to move large-scale data centers, they must arbitrarily set up their complex working environments, resulting in the reconfiguration of numerous servers and network devices.

In our experiments with the online interactive application GeoChronos, each VM migration requires 32 Mbps of bandwidth to keep the service live during the migration. Thus, a 10-Gbps link between two data centers can transport 312 VMs in parallel. Given that each VM occupies one processor and that each server has up to 16 processors,
the GSN can move 20 servers in parallel. If each VM consumes 4 Gbytes of memory, the time required for such a migration is 1,000 seconds.

Currently, the GSN runs a simple energy-distribution algorithm:

When a green energy source is available at a spoke site, perform data processing; otherwise, run applications at the hub.

Each site contains computing and storage resources. Each spoke site is associated with an energy broker that monitors power and triggers migration events. Our future work will consider other energy-distribution strategies, such as maximizing the use of renewable energy sources or sharing supported devices among users and data centers.

The migration of data centers among GSN nodes relies on cloud management support. We can view the whole network as a set of computing resource clouds that’s managed using the IaaS Framework, which includes four main components: The engine creates model and device interaction abstractions; the resource helps build Web service interfaces for manageable resources; the service acts as a broker to control and assign tasks to each VM; and the tool provides various tools and utilities that the three previous components can use (see Figure 4).

The engine is at the lowest level of the architecture and maintains interfaces with physical devices. It uses protocol- and transport-layer-provided services to achieve communication.

Figure 3. Cloud architectures. We can compare (a) the layered GreenStar Network and (b) a typical cloud computing architecture.

Figure 4. IaaS Framework architecture. The engine creates model and device interaction abstractions; the resource helps build Web service interfaces for manageable resources; the service acts as a broker to control and assign tasks to each VM; and the tool provides various tools and utilities that the other three components can use.
Each engine has a state machine that parses commands and determines when to perform appropriate actions. Three engine types achieve GSN management: the computing engine manages VMs, the power engine handles power monitoring and control, and the network engine controls network devices. These engines let GSN users quantify their service’s power consumption. To notify upper layers, engines trigger events. The resource component serves as an intermediate layer between the engine and the service. It provides the service with different capabilities, which can contribute to a resource’s business, presentation, or data access tiers. The tool component provides additional services, such as persistence shared by other components.

Based on the Java Platform Enterprise Edition/Open Services Gateway Initiative (J2EE/OSGi) platform, the IaaS Framework’s modular design lets us use each module independently of the others. OSGi is a Java framework for remotely deployed service applications that provides high reliability, collaboration, large-scale distribution, and a wide range of device usage. With an IaaS Framework-based solution, we can easily extend the GSN to cover different layers and technologies.

Through Web interfaces, users can determine GHG emission boundaries based on information provided about VM power and energy sources, and then take action to reduce GHG emissions. The project is thus ISO 14064-compliant. Indeed, cloud management isn’t a new topic; however, we developed the IaaS Framework for the GSN because the project requires an open platform that supports both server and network virtualizations. Whereas most commercial cloud management solutions focus on computing resources, IaaS Framework components let GSN developers build network-based virtualized tools, letting them flexibly set up dataflows among data centers. The IaaS Framework also lets us incorporate third-party power control components.

The GSN is built on top of the Canarie network and links multiple data centers with different network architectures and paradigms, such as IP, Ethernet, Multiprotocol Label Switching (MPLS), and optical. As the GSN grows, new protocols and architectures will need to be deployed independently without disruption. Network virtualization is thus an appropriate solution because it lets different network architectures, including legacy systems, coexist.

At the physical layer, we use Argia, a commercial version of User Controlled LightPaths. Argia is a network virtualizer that lets users (people or applications) treat network resources as software objects and provision and reconfigure optical lightpaths within a single domain or across multiple, independently managed domains. Users can join or divide lightpaths and hand over control and management of their private subnetworks to other users or organizations. With a focus on optical switches, Argia helps virtualize a network that users can reconfigure without interacting with the optical network manager.

GSN achieves layer-2 virtualization with Ether, which is similar in concept to Argia, except designed for LAN environments. With a focus on Ethernet and MPLS networks, Ether lets users acquire ports on an enterprise switch and manage VLANs or MPLS configurations on their own.

At the network layer, GSN deploys a network virtualizer from the Manticore project that can specifically define and configure physical or logical IP networks. It lets infrastructure owners manage their physical as well as logical routers and enables third parties to control them. Manticore also provides tools to help infrastructure users create and manage IP networks using one or more router resources from infrastructure owners.

**GHG Reduction: Estimation and Discussion**

A network’s key power-consuming elements are data centers, the core network, and the access network. Because data centers are connected directly to the core network in the GSN, we didn’t consider the access network in our evaluations. Servers in each GSN node are installed in outdoor enclosures where green energy powers the associated climate control. So, we can ignore GHG emissions from these accessories.

To evaluate GHG emissions, we performed experiments in data centers using the GeoChronos application. This infrastructure enables the Earth observation community to share data and scientific applications, and to collaborate effectively. The application runs on a multiprocessor server system with 48 total cores. Given that a core processor consumes
roughly 78 W, the whole system consumes roughly 32.8 MWh of nonrenewable electricity annually. Prior to the GSN project, the system was powered by Alberta’s power grid, which is fueled mostly by fossil energy and has an electricity emission factor of $930 \times 10^{-6}$ tons/kWh (see http://livclean.ca/PE_offset_calculation.pdf). Thus, the system emits more than 30 tons of CO$_2$ annually. This number doesn’t account for emissions from local switches and routers.

We estimate the core network’s GHG emission when it migrates the data center hosting GeoChronos toward a green energy source as follows. Because the GSN is an optical-based network, we can use a power-consumption model for core routers$^{13}$ with optical links connecting data centers directly to the core network. Assuming the current network with nine core nodes, each core router’s capacity is 640 Gbps, a router’s power is 10.9 kW, each VM’s size is 4 Gbytes (live data), the bandwidth required for each VM migration is 32 Mbps, and a link between two data centers is 10 Gbps. Data centers are migrated on average twice a day, so the power the core network consumes to migrate a single data center is thus 2 kW/day, or equivalent to 0.7 tons of CO$_2$ emissions annually. If core nodes are powered by fossil energy, the carbon credit the GSN saves is $30 - 0.7 = 29.3$. Our result is conservative (that is, underestimated) because an optical switch consumes less energy than a core router. In other words, we might effectively save more carbon credits.

When the network grows, the amount of CO$_2$ emitted during migrations will still be small compared to data centers’ total emissions. According to our calculation model, the GSN might save up to 986 carbon credits when data centers include 1,560 CPUs, assuming that the core network has nine nodes.

The GSN data centers, however, wouldn’t scale up to megasize centers, such as Google’s or Microsoft’s, due to construction and energy provision costs. Moving large-scale data centers is costly in terms of network bandwidth and time. Moreover, leaving a large data center non-operational for some period of time isn’t cost-effective. An appropriate solution addressing large data centers’ carbon footprint is thus two-fold: we must virtualize the data center and then span it across multiple smaller physical data centers, each powered by renewable energy sources. This way, a megascale service could be powered entirely by renewable energy.

As shown throughout the GSN project, having a high-speed optical network is essential for providing neutral carbon services. Because migrations could be required frequently owing to environmental change, the bandwidth that migrations consume would be huge. Thus, highly scalable networking infrastructures, such as Canarie or Internet2, will be necessary, which presents cost considerations. However, a data network is clearly much cheaper than a power transmission network. In addition, energy losses in an optical network are small compared to those in the electrical grid. This makes a neutral carbon network a realistic solution both environmentally and economically, particularly when a carbon tax has been imposed.

With an increase in power consumption for ICT, the GSN is a promising model for dealing with GHG reporting and carbon tax problems, especially for small- and medium-size ICT organizations. We’re working toward large-scale experiments on the GSN with respect to high-quality scientific and industrial services. The GSN protocol is also being internationally standardized.

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**References**


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