Wind Blows, Traffic Flows: Green Internet Routing under Renewable Energy

Yuan Yang*, Dan Wang†, Dawei Pan‡, Mingwei Xu*
*Tsinghua National Laboratory for Information Science and Technology (TNList)
Department of Computer Science and Technology, Tsinghua University
†Hong Kong Polytechnic University ‡Harbin Engineering University
yyang@csnet1.cs.tsinghua.edu.cn, csdwang@comp.polyu.edu.hk, pandawei@hrbeu.edu.cn, xmw@cernet.edu.cn

***Abstract*—We present a study on minimizing non-renewable energy for the Internet. The classification of renewable and non-renewable energy brings in several challenges. First, it is necessary to understand how the routing system can distinguish the two types of energy in the power supply. Second, the routing problem changes due to renewable energy; and so do the algorithm designs and analysis. We first clarify the model of how routers can distinguish renewable and non-renewable energy supporting their power supply. This cannot be determined by the routing system alone, and involves modeling the energy generation and supply of the grid. We then present the router power consumption model, which has a fixed startup power and a dynamic traffic-dependent power. We formulate a minimum non-renewable energy routing problem, and two special cases representing either the startup power dominates or the traffic-dependent power dominates. We analyze the complexity of these problems, develop optimal and sub-optimal algorithms, and jointly consider QoS requirements such as path stretch. We evaluate our algorithms using real data from both National and European centers. As compared to the algorithms minimizing the total energy, our algorithms can reduce the non-renewable energy consumption for more than 20% under realistic assumptions.**

I. Introduction

Developing a greener and sustainable world has become a worldwide concern nowadays. The Internet is a major energy consumer. As a consequence, how to save energy has become an important issue and there are many works in energy conservation of the Internet [3][1]. It should be noted that the energy usage itself may not be environmentally damaging. Renewable energy such as wind and solar are highly advocated. It is the usage of non-renewable energy, leading to the burning of fossil fuels and the CO_2 emission, that is harmful to our planet. As such, it would be more meaningful to conserve non-renewable energy, as against to conserve the total energy. Though there exists studies that minimize non-renewable energy in different domains [14][13][8], in this paper, we present a first study on minimizing non-renewable energy consumption in the context of the Internet.

In the Internet, routers are the dominating energy consumers. For example, a Cisco CRS-1 router can draw about one MegaWatt under full configuration, 10,000 times more than a PC. By 2010, 5000 Cisco CRS-1 routers were deployed and this number is increasing rapidly.[1] Many recent works focus on energy efficient routing. These studies try to find appropriate angles to switch nodes or links into the sleep mode. They minimize energy consumption while maintaining various levels of routing services. All these studies, however, consider minimizing the total energy consumption.

The classification of renewable and non-renewable energy brings in several challenges. First, if we only minimize the total energy, we can focus on the routing system alone. With multiple type of energy sources, we need to look into the power supply system. The renewable and non-renewable energy generation and supply are determined by the grid, not the routing systems. As a matter of fact, a routing device does not distinguish whether its power supply is from renewable or non-renewable sources when it runs. It is, however, important for the routers to know what portion of the energy supporting its power supply is from renewable or non-renewable sources, so as to make routing decisions that can minimize the non-renewable energy. Second, the routing problem greatly changes when we have both renewable and non-renewable energy. For example, if we only have one type of energy, the routing decision may not turn-off a router to minimize the total energy because, without this router, the network connectivity may be broken. With two type of energy sources, the routing decision can turn-off the non-renewable energy of this router to minimize the non-renewable energy, when there exists enough renewable energy to support the routing services. As such, directly applying past algorithms by assuming "non-renewable" energy as the "total" energy will not lead to the best solution. We thus need new formulation on the routing problem, and also new algorithm designs and analysis.

In this paper, we overcome the aforementioned challenges: 1) We present a model of how the routers collect renewable and non-renewable energy information. This requires clarification of a set of energy generation models for the grid and on-site power supply. 2) We present a power consumption model for the routers and we formulate a minimum non-renewable routing (MIN-NRE) problem. In the router power consumption model, a router has a fixed startup power and a dynamic traffic-dependent power. As each of these has certain practical importance, we further investigate two special cases of MIN-NRE. We define a proportion-powered network where the traffic-dependent power dominates the power consumption of the routers in the network; and we define a fix-powered network where the fixed startup power dominates the power

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[1] http://newsroom.cisco.com/dlls/2010/prod_030910.html

consumption of the routers in the network. We study MIN-NRE under these two context. 3) We analyze the complexity of the MIN-NRE problems. We develop optimal and sub-optimal algorithms using graph transformations for the two special cases. We then develop a solution for the general MIN-NRE problem. 4) We further develop an advanced algorithm in joint consideration of important QoS requirements such as path stretch.

We systematically evaluate our algorithms through simulations. We obtain two real data sets from the National Renewable Energy Laboratory, and the European Tracer EXperiment (ETEX). We fit these data into our renewable energy generation and supply models. We use real Internet topologies and traffic traces. Our evaluation shows that our algorithms can reduce non-renewable energy consumption by more than 20% under realistic assumptions, as compared to the algorithms minimizing the total energy.

The following part of the paper is organized as follows. We discuss the related work in Section II. In Section III, we present an overview of green Internet routing with renewable and non-renewable energy, and we develop the power supply models. In Section IV, we develop the router power consumption model, present the MIN-NRE problem, analyze its complexity and its two special cases. Section V is dedicated to a full set of algorithm development. We evaluate our algorithms in Section VI and we conclude the paper in Section VII.

II. Related Work

Energy conservation in the Internet: There are three broad classes of research in green Internet, focusing on routers, routing, and upper layer protocols.

First, there are studies on saving energy from the routers' point of view. They primarily develop new structures for the most power consuming components of a router, such as TCAMs. For example, there are studies to develop a packet pre-classifier so as to save energy from TCAMs [15].

Second, there are studies on energy conservation of the Internet from upper layers' point of view. For example, Energy Efficient TCP [7] is proposed to perform congestion control with dynamic bandwidth adjustment. Such an energy saving will be finally realized by the energy saving of routers.

Third, there are studies to save energy from a network routing point of view. GreenTE [22] is proposed to aggregate traffic using MPLS tunnels, so as to switch the underutilized network components into sleep mode and thus save energy. REsPoNse [19] is proposed to identify energy-critical and on-demand paths offline. The packets are delivered online with the objective to effectively aggregate traffic and switch more network components into sleep mode. There are a set of other works [5][2] with various considerations. These studies prune the network topology. A recent work [21] shows that different traffic volumes lead to different energy consumption. This means that without pruning the network topology, energy can be saved by better managing the traffic flows. Hop-by-hop algorithms are developed to explore this opportunity [21].

Our work falls into the third category, yet we differ from all the aforementioned schemes as we for the first time set an objective to save the non-renewable energy in the Internet.

The renewable and non-renewable energy models: The proportion of the power supply sources is not determined by the routing system, but by the power grid. Past modeling on the respective proportion of the renewable and non-renewable energy can be classified into three broad categories.

First, there are models for on-site renewable energy. Battery is used when extra renewable energy can be stored. When there is not enough power supply from the on-site renewable energy and the battery, the equipments will be supported by the power grid. For example, Li et al. [11] propose iSwitch, a load power balancing scheme in data centers to conduct intelligent and real-time switch between different power supply sources. Note however, that they do not consider that the power grid also has renewable and non-renewable energy sources. As a matter of fact, the power grid nowadays draw large amount of energy from wind or solar farms. Second, Gao et al. [8] model different power sources of a power grid (in terms of the carbon footprint of different power sources), such as hydro, nuclear, wind, etc., and the modeling is location specific. We see that the first category is suitable for the scenario where the amount of power needed is limited as the on-site renewable energy is commonly assumed to be insufficient to provide an all-time supply. The second category is suitable when there is large power demand.

In this paper, we develop a model considering both on-site renewable energy and the renewable energy from the power grid. One important characteristics of a network is that though a network can have thousands of routers, these routers are located in hundreds of locations. Thus, there are only a handful of routers in each location. As a consequence, on-site renewable energy can provide a significant portion of the power supply in one location. On the other hand, due to the large number of locations of a network, we cannot ignore the power supply of a network by the power grid. Even some locations may have a decent amount of on-site renewable energy at one time or another, a combination of the routers of a network still need to draw significant power from the power grid. It is therefore necessary to model the proportion of the renewable and non-renewable energy in the power grid as well.

There is a third category on modeling the microgrid. A microgrid targets on a local electricity distribution at a scale of a campus environment or a data center. It has renewable and non-renewable energy as well. Due to its scale, the power generation of microgrid is usually influenced by the demands of its consumers. There are studies on modeling and co-design of microgrid and data centers [12]. As said, there is a big difference between the Internet and data centers. A data center has tens of thousands of servers, yet these servers are located in only a handful of locations. In one location, there are thousands of computers with reasonable power demands to make a local microgrid meaningful. A microgrid is not suitable in the Internet context.

In this paper, our contribution is to clarify the suitable modeling and associate details for differentiating the renewable and non-renewable energy supply in the Internet context; so that the routers can have the information to minimize non-renewable energy. We do borrow models from past works, e.g., from the first and second category [11][8]. Yet, none of these models can be used directly for the Internet.

III. Internet Routing with Multiple Energy Sources: An Overview and Power Supply Models

A. An Overview

From a high level point of view, each router needs the knowledge of 1) the network topology and the traffic matrix, 2) the power consumption of this router, which is related to the traffic load on each link adjacent to the router, and 3) the percentage of the renewable and non-renewable energy supporting the power supply, even though the router does not distinguish whether the electricity is from renewable or non-renewable resources at runtime.

All these information can be distributed, in an OSPF manner, to all routers. Specifically, the topology information uses OSPF. The traffic volume information can be gathered through the Traffic Engineering Link State Advertisement (TE-LSA) [10]. The power consumption of the routers can be distributed once for all. This is because the fixed startup power will not change, and the traffic dependent power can be computed with the traffic information from TE-LSA. The information of renewable and non-renewable energy is less dynamic than the traffic data. It is thus possible to advertise such information by extending TE-LSA.

The routers then compute the routing paths that minimize the non-renewable energy consumption of the whole network. Finally, the computed paths can be realized by MPLS. We emphasize that in this paper, our work is confined to intra-domain routing. Further, we suggest centralized computing with MPLS, which is widely used in Internet backbones, especially tier-1.

In this regard, we need to develop 1) the power supply models to compute the renewable and non-renewable energy split in a router. We discuss the details in Section III-B, 2) power consumption model of a router. We discuss the details in Section IV-A, and 3) the routing algorithms for minimizing the non-renewable energy consumption of the network. We discuss the details in Section IV-B and Section V respectively.

B. The Power Supply Models

Our objective is to know what percentage of power a router consumed is from renewable or non-renewable resources.

There are two ways to power a router: 1) through the grid, and 2) through the on-site power generation. The on-site power generation usually uses renewable resources. However, the fluctuation of the on-site renewable power generation may make the power supply intermittent. As such, a common solution is a joint usage of the grid and the on-site power with an electricity switching device.

We next discuss the grid power supply model and the on-site power supply model separately.

1) The Grid Power Supply Model: The grid power supply is from both renewable and non-renewable resources. The electricity from renewable resources can be generated in a large centralized facility, such as a wind farm or solar farm, or it can be generated dispersedly, i.e., from many small energy sources. Either way, the renewable energy can be connected to the grid, and used by all the electricity consumers. The grid also has to online track the fluctuation in customer loads, referred as *load following*. As renewable resources have a limited electricity generation capacity at present, the load following is always compensated by non-renewable resources such as fossil fuels.

Note that the routers are highly distributed in hundreds of locations (this is in sharp contrast to the data centers, where thousands of servers are aggregated in a handful of locations). This means that the total electricity generated by a grid, even from renewable resources, can easily cover the power demands of its local routers. However, it is commonly accepted that it is impossible for the renewable energy to cover the demands of the entire market.[2] We thus make an assumption that the proportion of the renewable energy that the routers can consume, to their total energy consumption, is the same as the proportion of the renewable energy generation to the total energy generation of the grid. As an example, assume that the proportion of the renewable energy to the non-renewable energy in the grid is 14% to 86%, and a router demands 100 units of energy. The total renewable energy that this router can expect is 14 units, though the entire renewable energy within the grid is many orders beyond 14 units. This assumption provides a linkage between the split of renewable and non-renewable energy a router consumes and the macro view of renewable and non-renewable energy in the grid. In other words, if we can have the information of the renewable and non-renewable energy of a grid, we know the energy consumption split of the routers at that region.

Formally, let $P_c(v)$ be the total power consumption of a router v, and $P_{re}(v)$ and $P_{non}(v)$ denote the renewable and non-renewable energy drawn by v, respectively. We have, $P_c(v) = P_{re}(v) + P_{non}(v)$. Note that we can know the total power consumption of the router $P_c(v)$, which we will model it in Section IV.A. We need to know its split $P_{re}(v)$ and $P_{non}(v)$.

Let $\rho_{re}(v) = \frac{P_{re}(v)}{P_c(v)}$. If we can compute $\rho_{re}(v)$, we will have

$$P_{non}(v) = (1 - \rho_{re}(v)) \times P_c(v) \quad (1)$$

As said, we can obtain $\rho_{re}(v)$ of v by modeling the renewable energy availability in the power grid. We abuse the notations a little by using $\rho_{re}(v)$ to denote the ratio of the electricity from renewable resources to the total electricity in the region where v locates.

Many factors affect $\rho_{re}(v)$ in the region. First, the renewable energy production fluctuates according to the climate condition. Second, $\rho_{re}(v)$ is affected by the total energy consumption of the region. This is because a power grid needs to guarantee load following. As renewable resources have a limited electricity generation capacity and customer loads always change, the increase or decrease of the electricity generated by non-renewable resources such as fossil fuels leads to the change of $\rho_{re}(v)$. In reality, we can import $\rho_{re}(v)$ from the grid in real-time.

2) The On-site Power Supply Model: The on-site renewable power supply depends on the condition at each individual region. The two commonly available renewable resources are

[2]The total renewable energy consists of 14% of the energy supply in the US, and the US sets a target to increase the renewable energy supply to 25% by 2025. The target of the European Union is 20% from renewable resources by 2020.

solar and wind. They heavily depends on the climate at their location. Specifically, given the rated output power, the realtime power generation of a wind turbine is a function of wind velocity, while the power generation of a solar panel is a function of solar irradiance and temperature [17].

3) The Overall Power Supply Model: The on-site renewable energy is first used to power a network component directly. The grid compensates when the renewable energy is not enough. Let $PO_{re}(v)$ be the power production of the on-site renewable energy generation system. Recall that $\rho_{re}(v)$ is the renewable energy ratio in the grid. Following what was developed in Section III-B1, we have

$$P_{non}(v) = \begin{cases} 0, & PO_{re}(v) \geq P_c(v) \\ (1-\rho_{re}(v))(P_c(v) - PO_{re}(v)), & PO_{re}(v) < P_c(v) \end{cases} \tag{2}$$

Note that Eq. (1) is a special case of Eq. (2) when $PO_{re}(v) = 0$. With these models, we have a concrete $P_{non}(v)$, which we will minimize in the next section. Note that batteries are also often used to store energy when the on-site renewable energy generation produces more electricity than required, and uses during the periods without enough renewable energy. In this paper, we will focus on on-site renewable energy generation and leave the batteries to future work.

IV. Green Routing under Renewable Energy: The Problem and Complexity Analysis

A. Router Power Consumption Model

In previous section, we derived $P_{non}(v)$. We develop $P_c(v)$, i.e., the energy consumption of a router, in this section.

Let $P_l(y_l)$ be the power consumption of link l when the traffic volume is y_l. From [4], we have

$$P_l(y_l) = P_l^0 + \lambda \cdot y_l \tag{3}$$

where P_l^0 is a nonnegative startup link power and λ is a nonnegative constant. In practice, λ usually is in the range of 0.001 to 0.1 Watt/Mbps [20]. We assume that $P_l(0) = 0$, i.e., we can switch link l into sleep mode if it does not carry traffic. Let $P_s(v)$ be the startup power of a router (node v). Then,

$$P_c(v) = \frac{1}{2} \sum_{l \text{ s.t.} v \in l} P_l(y_l) + P_s(v) \tag{4}$$

i.e., there is a startup power and a node share $\frac{1}{2}$ of the link power for each of its links.

B. The Problem and Complexity

Now we formally define our problem. We model a network as $\mathcal{G}(\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ and $\mathcal{E}$ denote the sets of nodes and links, respectively. We have a set of traffic demands $\delta \in \mathcal{V} \times \mathcal{V}$, for each pair of source and destination. Let d^δ be the traffic volume of demand δ. We want to find a path for each traffic demand. Let x_l^δ be the amount of demand δ traversing link l. The minimum non-renewable energy routing problem (MIN-NRE) is

$$\min \sum_{v \in \mathcal{V}} P_{non}(v) \tag{5}$$

$$\text{s.t.} \qquad \text{Eq. (2), Eq. (3), Eq. (4)}, \qquad v \in \mathcal{V}, l \in \mathcal{E}$$

$$y_l = \sum_{\delta} x_l^\delta, \qquad l \in \mathcal{E} \tag{6}$$

$$y_l \leq C_l, \qquad l \in \mathcal{E} \tag{7}$$

$$x_l^\delta : \text{flow conservation}, \qquad l \in \mathcal{E}, \delta \in \mathcal{V} \times \mathcal{V} \tag{8}$$

$$x_l^\delta \in \{0, d^\delta\}, \qquad l \in \mathcal{E}, \delta \in \mathcal{V} \times \mathcal{V} \tag{9}$$

Eq. (2) - Eq. (4) are the energy related constraints we have developed. Eq. (6) - Eq. (9) are traffic maintenance related constraints. Eq. (6) means that y_l equals the total traffic volume on link l. Eq. (7) means that the total traffic volume on link l must not exceed link capacity C_l. Eq. (8) means that the amount of demands entering and leaving a node must be balanced. Eq. (9) means that only integral routing is allowed (no fractional routing).[3] An algorithm should calculate x_l^δ.

Theorem 4.1: The MIN-NRE problem is NP-hard.

Proof: We prove the theorem by reducing the minimum degree spanning tree problem which is NP-hard [9] to the MIN-NRE problem in polynomial time.

The minimum degree spanning tree problem is to construct a spanning tree whose maximal degree k is the smallest among all the spanning trees. For each instance of the minimum degree spanning tree problem, i.e., graph $\mathcal{G}$, we construct an instance of MIN-NRE as follows. Let $d^\delta > 0$ for each $\delta \in \mathcal{V} \times \mathcal{V}$. Let $C_l = \infty$ for each $l \in \mathcal{E}$. Let $P_l(y_l) = P_l^0 > 0$, i.e., $\lambda = 0$. Let $PO_{re}(v)$ can just power on k links for each $v \in \mathcal{V}$ and $\rho_{re}(v) = 0$. In such a case, the minimum non-renewable energy consumption can be achieved by any routing in a subgraph $\tilde{\mathcal{G}}(\tilde{\mathcal{V}}, \tilde{\mathcal{E}})$ of $\mathcal{G}$, where $\tilde{\mathcal{V}} = \mathcal{V}$ and the degree of each $v \in \tilde{\mathcal{V}}$ is less than or equal to k. In such a case, the non-renewable energy consumption is 0 for $\tilde{\mathcal{G}}$, and thus is minimized. The construction of the above instance of MIN-NRE can be done in polynomial time.

We now show that finding the minimum degree spanning tree $\mathcal{T}$ of $\mathcal{G}$ is equivalent to finding $\tilde{\mathcal{G}}$ of $\mathcal{G}$. On one hand, any node in the minimum degree spanning tree $\mathcal{T}$ has a maximum degree that is not larger than k, so for each node v, the links in $\mathcal{T}$ connected to v can be sustained by $PO_{re}(v)$. Thus, $\mathcal{T}$ is a solution of $\tilde{\mathcal{G}}$. On the other hand, if we find $\tilde{\mathcal{G}}$, any node degree in $\tilde{\mathcal{G}}$ is not larger than k, so any spanning tree produced from $\tilde{\mathcal{G}}$ is a solution of $\mathcal{T}$. ■

C. Two Special Scenarios

We define two special networks by relaxing constraint Eq. (3). This provides deeper understanding of the impact of energy constraints to the problem. These cases may also be used when they match special fitted scenarios in practice.

Definition 4.1: Network $\mathcal{G}^p(\mathcal{V}, \mathcal{E})$ is said to be *proportion-powered* if $P_l(y_l) = \lambda \cdot y_l$ ($\lambda > 0$) for each link $l \in \mathcal{E}$ in this network.

[3] Note that fractional routing can be supported, e.g., by multi-path routing etc. In this paper, we primarily focus on non-fractional routing, yet we would like to specify that this constraint (Eq. (9)) does not affect the problem complexity, i.e., NP-hardness.

Definition 4.2: Network $\mathcal{G}^f(\mathcal{V},\mathcal{E})$ is said to be *fix-powered* if $P_l(y_l) = P_l^0 > 0$ when $y_l > 0$ and $P_l(y_l) = 0$ when $y_l = 0$ for each link $l \in \mathcal{E}$ in this network.

Note that proportion-powered networks and fix-powered networks show two extremes in power consumption of routers. In current stage, the startup power P_l^0 is still a dominant factor [3]. However, there exist more and more efforts in developing proportion-powered routers [16]. Therefore, we believe that the study of these two cases in details also has certain practical importance. The algorithms developed for these two scenarios will also become subroutines for our algorithm solving the general MIN-NRE.

V. Algorithms

In this section, we first study MIN-NRE in proportion-powered network $\mathcal{G}^p(\mathcal{V},\mathcal{E})$. We will transform it into a multi-commodity flow problem and show that it can be solved optimally when the flows are fractional. We will study the MIN-NRE problem in fix-powered network $\mathcal{G}^f(\mathcal{V},\mathcal{E})$ and derive optimal or sub-optimal solutions under different conditions. Then, we develop an algorithm for the general MIN-NRE. We further develop an algorithm to minimize non-renewable energy with joint consideration of QoS constraints of path stretch.

A. MIN-NRE in Proportion-Powered Networks

We conduct a graph transformation as follows (See illustration in Fig. 1). We construct a virtual directed graph $\mathcal{G}'(\mathcal{V}',\mathcal{E}')$ based on the original graph $\mathcal{G}^p(\mathcal{V},\mathcal{E})$ and the traffic demands. For each node v_j of $\mathcal{V}$, we split it into two nodes v_j^r and v_j^f in $\mathcal{V}'$, representing packet receiving and forwarding respectively. We add a link (v_j^r, v_j^f). We set the capacity of (v_j^r, v_j^f) as $PO_{re}(v_j)/\lambda$ (See the doted arrows in Fig. 1). The intuition is that by such split, we can represent the on-site renewable power capacity of node v_j by the capacity of link (v_j^r, v_j^f). We then add a parallel link for each (v_j^r, v_j^f), and set the capacity to ∞ (See the dashed arrows in Fig. 1). We represent the electricity in the grid by this parallel link, which contains the non-renewable power to be minimized. We add virtual source nodes s_i and virtual sink nodes t_i for nodes $v_i \in \mathcal{V}$. The intuition is that for the traffic demand originated from v_i, s_i will push such traffic demands to t_i. As such, we have a multi-commodity flow problem where sources s_i needs to push traffic to sinks t_i and the power capacity will not be violated.

Formally, let $\mathcal{V}^s = \{s_i | v_i \text{ has traffic demands}\}$, $\mathcal{V}^t = \{t_i | v_i \text{ has traffic demands}\}$, $\mathcal{V}^r = \{v_j^r \big| 0 \le j \le |\mathcal{V}|\}$, and $\mathcal{V}^f = \{v_j^f \big| 0 \le j \le |\mathcal{V}|\}$, then we have $\mathcal{V}' = \mathcal{V}^s \cup \mathcal{V}^t \cup \mathcal{V}^r \cup \mathcal{V}^f$. $\mathcal{E}'$ is defined as the union of five sets. Each set and the corresponding link capacities are defined as follows. 1) $\mathcal{E}_s = \{(s_i, v_i^r) | s_i \in \mathcal{V}^s\}$, and $c(s_i, v_i^r)$ is the sum of the traffic demands that are originated by node v_i; 2) $\mathcal{E}_v = \{(v_j^r, v_j^f) \big| 1 \le j \le |\mathcal{V}|\}$, and $c(v_j^r, v_j^f) = PO_{re}(v_j)/\lambda$; 3) $\mathcal{E}_g = \{l_j | l_j \text{ is a parallel link of } (v_j^r, v_j^f) \in \mathcal{E}_v\}$, and $c(l_j) = \infty$ for $l_j \in \mathcal{E}_g$; 4) $\mathcal{E}_e = \{(v_{j_1}^f, v_{j_2}^r) \big| (v_{j_1}, v_{j_2}) \in \mathcal{E}\}$, and $c(v_{j_1}^f, v_{j_2}^r)$ equals the capacity of link (v_{j_1}, v_{j_2}) in $\mathcal{E}$; and

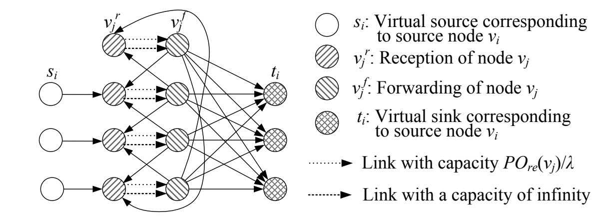

Fig. 1: Graph $\mathcal{G}'(\mathcal{V}',\mathcal{E}')$ and the multi-commodity flow model.

5) $\mathcal{E}_t = \{(v_j^f, t_i) \big| v_j^f \in \mathcal{V}^f \text{ and } t_i \in \mathcal{V}^t\}$, and $c(v_j^f, t_i)$ is the traffic demand from node v_i to node v_j.

The model of $\mathcal{G}'(\mathcal{V}',\mathcal{E}')$ is a multi-commodity flow problem, where each flow of amount $c(s_i, v_i^r)$ need to be delivered from a specific s_i to a specific t_i. An illustrative example is shown in Fig. 1, where the original graph $\mathcal{G}$ has four nodes, and nodes v_2, v_3, v_4 have traffic demands.

We can find the optimal solution by solve the multi-commodity problem in $\mathcal{G}'(\mathcal{V}',\mathcal{E}')$ with the objective of

$$\min \sum_j \lambda \cdot y_{l_j} \cdot (1 - \rho_{re}(v_j)),$$

where y_{l_j} is the traffic volume on link $l_j \in \mathcal{E}_g$. The objective function is a linear function and is equal to the total non-renewable power in network $\mathcal{G}(\mathcal{V},\mathcal{E})$.

Observation 5.1: An optimal solution can be found in polynomial time for the MIN-NRE problem in a proportion-powered network, if the flows can be fractional.

In the rest of the paper, we call this the MNE-PN algorithm. It will also be a subfunction for our general algorithm.

B. MIN-NRE in Fix-Powered Networks

We now consider the MIN-NRE problem for fix-powered networks. In this special case, the problem is still NP-hard.

Theorem 5.1: The MIN-NRE problem is NP-hard for fix-power networks.

The theorem can be proved also by a polynomial time reduction from the minimum degree spanning tree problem which is NP-hard. We omit the details due to page limit. We again consider a special case where there is no on-site renewable energy available for any node. We then have

Theorem 5.2: There is a polynomial time algorithm that can minimize the non-renewable energy consumption, if $PO_{re}(v) = 0$ for each node $v \in \mathcal{V}$, $d^\delta > 0$ for each $\delta \in \mathcal{V} \times \mathcal{V}$, and $C_l = \infty$ for each $l \in \mathcal{E}$.

Proof: We prove the theorem by showing that a minimum spanning tree can achieve the minimum non-renewable energy consumption. We assign each link $(v_i, v_j) \in \mathcal{E}$ with a cost of $P^0_{(v_i,v_j)} \cdot (2 - \rho_{re}(v_i) - \rho_{re}(v_j))$, which is the non-renewable power of the link. As $d^\delta > 0$ for each traffic demand δ, each node has to be able to reach any other nodes. Thus, the minimum spanning tree has the minimum non-renewable power and guarantees all traffic demands to be delivered. ■

Definition 5.1: Let link set $\mathcal{L}_k(v) \subseteq \{l | v \in l\}$ satisfies $|\mathcal{L}_k(v)| \le k$. A fix-powered network $\mathcal{G}^f(\mathcal{V},\mathcal{E})$ is said to be *k-sustainable*, $k \geq 0$, if for each node $v \in \mathcal{V}$ and for each $\mathcal{L}_k(v)$, $PO_{re}(v) \geq \sum_{l \in \mathcal{L}_k(v)} P_l^0$.

Intuitively, a k-sustainable fix-powered network is a network that on-site renewable power $PO_{re}(v)$ can power on at least k links for each $v \in \mathcal{V}$. If k is large enough such that all the links can be powered on by renewable energy, the minimum non-renewable energy is achieved, i.e., 0. We now show the conditions under which a polynomial time algorithm exists to compute optimal solutions for k-sustainable fix-powered networks.

Lemma 5.1: For a k-sustainable network, there is a polynomial time algorithm which approximates the minimum non-renewable energy consumption within at most one link's startup power for each node, if there exists a spanning tree with the maximum degree of k, $d^\delta > 0$ for each $\delta \in \mathcal{V} \times \mathcal{V}$ and $C_l = \infty$ for each $l \in \mathcal{E}$.

Proof: The lemma can be deduced from the theorem in [6]: There is a polynomial time approximation algorithm for the minimum degree spanning tree problem which produces a spanning tree of degree at most $k+1$, where k is the maximum degree of the minimum degree spanning tree. Thus, the spanning tree produced by the algorithm in [6] has a degree of at most $k+1$, so due to the definition of k-sustainable, the non-renewable power required for each node is at most one link's startup power. ∎

Theorem 5.3: For a k-sustainable network, there is a polynomial time algorithm that can minimize the non-renewable energy consumption, if there exists a spanning tree with the maximum degree of $k' < k$, $d^\delta > 0$ for each $\delta \in \mathcal{V} \times \mathcal{V}$ and $C_l = \infty$ for each $l \in \mathcal{E}$.

Proof: The theorem can be deduced from Lemma 5.1. Because $k' < k$ and the network is k-sustainable, the network is also k'-sustainable. Due to Lemma 5.1, there is a polynomial time algorithm that approximates the minimum non-renewable energy consumption within at most one link's startup power for each node. This one link's startup power in fact can also be sustained by renewable power because $k' < k$. ∎

We next study the general case of MIN-NRE in a fix-powered network. Note the difference is that the on-site renewable energy can be arbitrary. We develop a heuristic MNET. With the understanding of k-sustainable fix-powered network, we also follow the minimum degree spanning tree algorithm. A good approximation algorithm for the minimum degree spanning tree problem is developed in [6] with an approximation ratio of $(k+1)/k$.

We start from an arbitrary spanning tree $\mathcal{T}^*$ of G. In each round, we update $\mathcal{T}^*$ to increase the residual renewable power for some node (we call this an improvement). When no improvement can be found, the algorithm terminates. Specifically, let $\mathcal{R}(v)$ be the residual renewable power capacity of node v, which is calculated as $PO_{re}(v) - \sum_{v \in l \text{ and } l \in \mathcal{T}^*} P_l^0$. We scale $\mathcal{R}(v)$ by $1 - \rho_{re}(v)$ if $\mathcal{R}(v) < 0$. Then, in each round we find links l and l', and update $\mathcal{T}^*$ by adding link l' to, and deleting link l from $\mathcal{T}^*$, pursuing the increment of $\min_{v \in l \text{ or } v \in l'} \mathcal{R}(v)$.

In algorithm MNET(), in order to make a "good" improvement, we find l' and l in a way similar to [6]. If node v_i with the smallest value of $\mathcal{R}(v_i)$ can split $\mathcal{T}^*$ into a forest $\mathcal{F}$, and there is a link $l \in \mathcal{E} - \mathcal{T}^*$ which can connect two components of F (Steps 6, 7 and 8), then l is "good" to take place of some l' that is adjacent to node v_i (Steps 9 to 11).

Algorithm 1 MNET()

Input: $\mathcal{G}(\mathcal{V}, \mathcal{E})$, P_l^0, $PO_{re}(v)$, $\rho_{re}(v)$ for $l \in \mathcal{E}$, $v \in \mathcal{V}$;
Output: spanning tree $\mathcal{T}^*$ of $\mathcal{G}$ which approximates the minimum non-renewable power consumption for P_l^0;

```
1: T* ← the spanning tree created by BFS from the
       node with the largest value of PO_re(v);
2: for each node v ∈ V
3:     R(v) ← PO_re(v) − Σ_{v∈l and l∈T*} P_l^0;
4:     if R(v) < 0
5:         R(v) ← R(v) · (1 − ρ_re(v));
6: for each node v_i ∈ V in increasing order of R(v_i)
7:     F ← the forest created by T* − {v_i};
8:     for each link l ∈ E − T* and l connects two
         components in F
9:         C ← the unique circle generated when l is
               added to T*;
10:        for each link l' ∈ C
11:            if v_i ∈ l' and min_{v∈l or v∈l'} R(v) increases
                 when adding l to, and deleting l' from T*
12:                T* ← T* ∪ {l} − {l'};
13:                update R(v) for v ∈ l and v ∈ l';
14:                goto step 6;
15: return T*;
```

C. MIN-NRE in the General Case

We now consider the MIN-NRE problem for general link power model $P_l(y_l) = P_l^0 + \lambda \cdot y_l$, where $P_l^0 > 0$ and $\lambda > 0$.

We develop our algorithm based on MNE-PN and MNET. The observation for linking these two is that, we should switch appropriate links into sleep mode. If too few links are switched into sleep mode, the startup power P_l^0 of many links cannot be saved, and these may need to come from the non-renewable energy. On the other hand, if too many links are switched into sleep mode, many end-to-end paths may be stretched, which increases the power of $\lambda \cdot y_l$ and also increases the non-renewable energy consumption of the whole network. The optimal solution is related to the value of P_l^0, λ, and the traffic demands. Note that the same observation also exists for networks without renewable energy.

Based on this observation, we design a heuristic algorithm GreenNRE. The basic idea is a greedy search by running MNE-PN repeatedly on a subgraph of $\mathcal{G}$. We first constructs subgraph $\mathcal{T}'$ by calling MNET, and computes routing X_0 by running MNE-PN on $\mathcal{T}'$. Then in the h-th round ($h > 0$), we add to $\mathcal{T}'$ the link with the largest residual on-site renewable power, and computes routing X_h by calling MNE-PN. If the total non-renewable power consumption of X_h is less than that of X_{h-1}, we continue adding links. Otherwise, we use X_{h-1} as the final green routing. We also do a randomly round up on X_{h-1} to produce an integral routing. This algorithm can produce a routing that is the same to that of MNE-PN for a proportion-powered network, and can produce a routing that is the same to that of MNET for a fix-powered network.

GreenNRE calls MNET once, and calls MNE-PN for at most $|\mathcal{E}| - |\mathcal{V}| + 2$ times.

D. MIN-NRE with QoS Requirements

We now study the balance between non-renewable energy conservation and normal QoS requirements for the routing

TABLE I: Summary on Algorithms

Router Power Consumption Model		Complexity	Algorithms	Optimality
MIN-NRE in proportion-powered networks		P	MNE-PN()	optimal (fractional routing) / sub-optimal (integral routing)
MIN-NRE in fix-powered networks	no on-site renewable energy	P	minimum spanning tree	optimal
	k-sustainable and $k >$ the degree of the minimum degree spanning tree	P	[6]	optimal
	general cases	NP-hard	MNET()+MNE-PN()	
MIN-NRE in the general case		NP-hard	GreenNRE()	
MIN-NRE with QoS requirements		NP-hard	GreenNRE-shortest()	

Algorithm 2 GreenNRE()

Input: $\mathcal{G}(\mathcal{V},\mathcal{E})$, λ, P_l^0 for $l \in \mathcal{E}$, $PO_{re}(v)$ and $\rho_{re}(v)$ for $v \in \mathcal{V}$, d^δ for each $\delta \in \mathcal{V} \times \mathcal{V}$;
Output: green routing $X = \{x_l^\delta | \delta \in \mathcal{V} \times \mathcal{V}, l \in \mathcal{E}\}$;
1: $\mathcal{T}' \leftarrow$ call **MNET**();
2: $h \leftarrow 0$; $min\_non \leftarrow$ infinity;
3: **for** each node $v \in \mathcal{V}$
4: $\quad PO_{re}(v) \leftarrow PO_{re}(v) - \sum_{v \in l \text{ and } l \in \mathcal{T}'} P_l^0$;
5: $X_h \leftarrow$ call **MNE-PN**();
6: $total\_non \leftarrow$ total non-renewable power using X_h;
7: **if** $total\_non < min\_non$
8: $\quad min\_non \leftarrow total\_non$;
9: $\quad h \leftarrow h + 1$;
10: $\quad$ add link (v_i, v_j) with the largest value of $PO_{re}(v_i) + PO_{re}(v_j)$ to $\mathcal{T}'$;
11: $\quad PO_{re}(v_i) \leftarrow PO_{re}(v_i) - P^0_{(v_i,v_j)}$;
12: $\quad PO_{re}(v_j) \leftarrow PO_{re}(v_j) - P^0_{(v_j,v_i)}$;
13: $\quad$ **goto** step 5;
14: **else**
15: $\quad X_{h-1} \leftarrow$ randomly round up X_{h-1};
16: $\quad$ **return** X_{h-1};

paths. In other words, we want to investigate whether the pursuit of green may sacrifice typical routing metrics such as end-to-end delay; and how a balance can be made.

Specifically, we consider *path stretch ratio*: the ratio of the length of a source-destination path to that of the shortest path between this source-destination pair. Given a path stretch threshold θ, we want to find a routing that minimizes the non-renewable energy consumption, subject to the constraint that the path stretch ratio for each source-destination pair is equal to or less than θ. In the extreme case, $\theta = 1$, then the problem reduces to shortest path routing. Generally, we have $\theta > 1$.

In order to design an algorithm, we make the following observation. If link (v_i, v_j) is switched into sleep mode, the length of the path between v_i and v_j will stretch at least to $len'(v_i, v_j)$, where $len'(v_i, v_j)$ denotes the length of the shortest path from v_i to v_j in $\mathcal{G}^*(\mathcal{V}, \mathcal{E} - \{(v_i, v_j)\})$, i.e., the second shortest path from v_i to v_j in $\mathcal{G}(\mathcal{V},\mathcal{E})$. Thus, to meet the path stretch ratio requirement, we should power on the links that are in a second shortest path, if this second shortest path induces the path stretch to exceed threshold θ. We do this based on the result subgraph computed by the GreenNRE algorithm, and call this algorithm GreenNRE-shortest.

In summary, the problems and the corresponding algorithms developed in this section are shown in Table I.

VI. Evaluation

A. Simulation Setup

We evaluate our scheme through simulations. We first present the network configuration, energy generation, and traffic traces of our simulation and then our evaluation criteria.

1) Network Configuration: We evaluate our algorithms using real topologies. We obtained two real topologies: 1) the Internet2 backbone with 12 nodes and 15 two-directional links,[4] and 2) the pan-European Research and Education Network (Geant) backbone, which has 23 nodes and 37 two-directional links.

For each link, the power consumption per unit traffic volume (λ) is set as a constant 0.004, referring to the measurement results given by [3]. The startup power consumption (P_l^0) of different link operation rates is calculated using the maximum power[5] and λ, shown in Table II.

TABLE II: Power consumption of line cards

line card (1-Port)	operation rate (Mbps)	maximum power (Watt)	calculated P_l^0 (Watt)
OC3	155.52	60	59.4
OC12	622.08	80	77.5
OC48	2488.32	140	130.0
OC192	9953.28	174	134.2

2) Renewable Energy Generation: We evaluate energy saving when either wind power or solar power is used. We use the meteorological data from the Measurement and Instrumentation Data Center (MIDC) of the National Renewable Energy Laboratory,[6] and the European Tracer EXperiment (ETEX).[7] MIDC data includes wind velocity, irradiance, and temperature from 32 stations in the US, reported every 60 seconds. ETEX data includes wind velocity from 168 stations in the Europe, reported every 3 hours. For each node in Internet2 and Geant, we use the data from the meteorological station that is nearest to that node. In particular, the maximum distance between a network node and the corresponding data collection point is 449.08 km for Internet2 and 282.0 km for Geant; and the average distance is 148.79 km for Internet2 and 71.13 km for Geant. We consider the meteorology to be similar in such a range. However, there are some network nodes (4 in Internet2 and 7 in Geant) far from the data collection points. We assume that these nodes have no on-site renewable energy.

The rated power of on-site renewable energy generation is set to twice the maximum power consumption of the node. For example, for a router whose maximum power is 1000 Watt, we deploy a wind turbine with a maximum output power of 2000 Watt. With these data, the realtime power generation can be calculated, using wind velocity, solar irradiance and temperature as inputs [17].

[4] Note that we use the old topology because the available real traffic traces are for that time. The same for Geant.

[5] http://www.cisco.com/en/US/docs/ios/12_0s/feature/guide/12spower.html

[6] http://www.nrel.gov/midc/

[7] http://rem.jrc.ec.europa.eu/etex/

As discussed, the electricity in the grid may be from both renewable and non-renewable resources. For the renewable energy ratio $\rho_{re}(v)$, in our simulation, we use the electricity generation data from the U.S. Energy Information Administration's website,[8] and the electricity production and supply statistics reports by the European Commission.[9] These reports summarize the average electricity fuel mix of all the states in the US as well as the EU-27. So we can calculate $\rho_{re}(v)$ for each node in Internet2 and Geant. As an illustration, for the node in Kansas City, $\rho_{re}(v)$ is 15.2%, and for Seattle $\rho_{re}(v)$ is 6.2%. In Europe, $\rho_{re}(v)$ is 17.3% for Germany, and 8.3% for the UK.

3) Traffic Matrix: For the Internet2 network, we use real traffic matrices where one traffic matrix is summarized every five minutes.[10] The traffic volume on an Internet2 link is multi-hundred Mbps and the link utilization ratio is around 10%. For Geant, we use real traces provided by the authors of [18]. One traffic matrix is summarized every fifteen minutes and the link utilization ratio is around 5%.

4) Evaluation Criteria: We evaluate both GreenNRE and GreenNRE-shortest. For comparison purposes, we simulate 1) GreenTE [22], a green Internet routing approach that can achieve near-optimal energy saving but does not differentiate renewable and non-renewable energy; 2) OSPF where the energy injected to the network components contains renewable energy; and 3) ALL-NON. ALL-NON is OSPF in routing, yet it differs from OSPF as it assumes that the energy injected to all the network components are non-renewable energy only. Thus, we can show how much non-renewable energy can be saved by just supplying renewable energy, without changing the routing, by comparing OSPF with ALL-NON; and how much non-renewable energy can be saved by supplying renewable energy and adjusting routing accordingly, by comparing GreenNRE with ALL-NON.

We want to compare the non-renewable energy consumption of different schemes. Thus, we evaluate the ratio of non-renewable energy consumption by GreenNRE to non-renewable energy consumption by other approaches, including GreenTE, OSPF, and ALL-NON. We call this the non-renewable energy consumption ratio. As a variant of non-renewable energy consumption ratio, we also use non-renewable energy saving ratio when it makes the composition clearer. In addition, we evaluate path stretch ratio and link utilization ratio, which are important parameters for the network QoS performance.

B. Results for Solar Power

Fig. 2 shows the non-renewable energy consumption ratio in Internet2. We use the traffic traces from 0:00am, Mar. 8, 2004 to 23:55pm, Mar. 14, 2004, and the solar irradiance traces from 0:00am, Feb. 1, 2013 to 23:55pm, Feb. 7, 2013. Both last for 7 days yet they are not the same period. This is because the traffic traces we have are from March, 2004 to August, 2004, and there are lacks of solar traces for this period. For example, the data sets available on UTPA Solar Radiation Lab are from September 1, 2011 onwards. We cannot find an exact match, yet we tried our best to match them and we select data all from spring.

We can see a diurnal pattern. In the night when no solar power is available, the non-renewable energy consumption of GreenNRE is close to GreenTE. They are about 75% of that of OSPF. This is because both GreenNRE and GreenTE can switch some links into sleep mode. Even no renewable energy is available, they both save the total energy, and thus the non-renewable energy. In the daytime, the non-renewable energy consumption of GreenNRE can be 60% to that of GreenTE, 40% to that of OSPF, and less than 20% to that of ALL-NON. Clearly, GreenNRE takes renewable energy generation into consideration, so that the network components that use more non-renewable energy will be switched into sleep mode preferentially.

Fig. 3 shows the CDF of the non-renewable energy saving ratio in Internet2. We can see that introducing solar power without changing the routing (i.e. OSPF) can save up to 70% non-renewable energy. However, 20% more can be saved by deploying GreenNRE. When the ordinate value is greater than 0.6, GreenNRE has a greater saving ratio than GreenTE, which means that GreenNRE outperforms GreenTE in 40% of the time, while GreenNRE and GreenTE perform similarly in the rest of the time (i.e., the nights).

C. Results for Wind Power

Fig. 4 shows the non-renewable energy consumption ratio in Geant, using the traffic traces from 0:00am, May 6, 2005 to 21:00pm, May 10, 2005, and the wind velocity traces from 0:00am, Nov. 14, 1994 to 21:00pm, Nov. 18, 1994. This is because the traffic traces are from May to August, 2005, and the wind traces are from October to December, 1994.

Unlike Fig. 2, Fig. 4 shows no diurnal pattern, because wind power is more intermittent than solar power. However, we still see that the non-renewable energy consumption of GreenNRE can be as less as 20% to that of ALL-NON, 40% to that of OSPF, and 80% to that of GreenTE.

Fig. 5 shows the CDF of the non-renewable energy saving ratio in Geant. Introducing wind power without change the routing (OSPF) can save 20% to 50% non-renewable energy, while GreenNRE can save 50% to 80%, better than GreenTE. We find that GreenNRE-shortest saves a little less that GreenTE, because more links are powered on to provide a better QoS performance.

Fig. 6 shows the CDF of the path stretch ratio in Geant. We can see that the path stretch of GreenNRE-shortest is less than 1.1 with a probability of 90%, which is much better than GreenTE and GreenNRE. Fig. 7 shows the CDF of the link utilization ratio in Geant. Similarly, GreenNRE-shortest performs good, with a link utilization ratio less than 5% in 95% of the time. The results imply that GreenNRE-shortest can save non-renewable energy that is close to GreenNRE without inducing large path stretches.

VII. Conclusion

In this paper, we presented a study on green Internet routing where we differentiated renewable and non-renewable energy.

[8] http://www.eia.gov/electricity/monthly/index.cfm
[9] http://epp.eurostat.ec.europa.eu
[10] http://www.cs.utexas.edu/%7Eyzhang/research/AbileneTM/

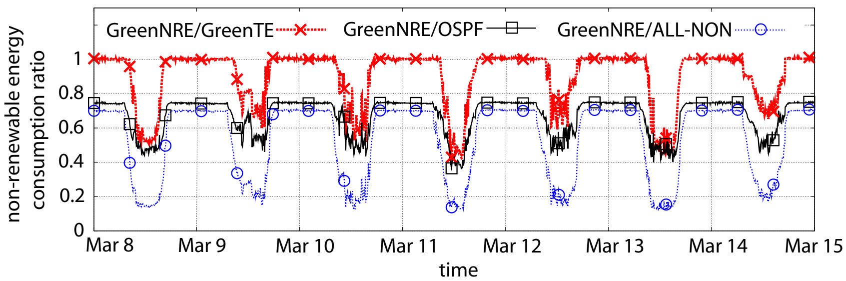

Fig. 2: Non-renewable energy consumption ratio as a function of time (Internet2, solar powered).

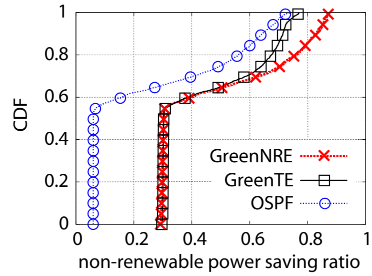

Fig. 3: CDF of non-renewable energy saving ratio (Internet2, solar powered).

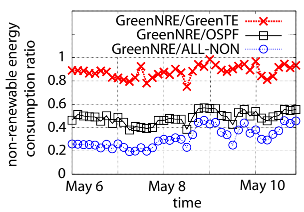

Fig. 4: Non-renewable energy consumption ratio (Geant, wind powered).

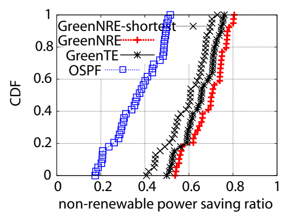

Fig. 5: CDF of non-renewable energy saving ratio (Geant, wind powered).

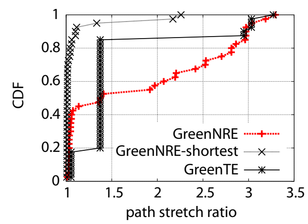

Fig. 6: CDF of path stretch ratio (Geant, wind powered).

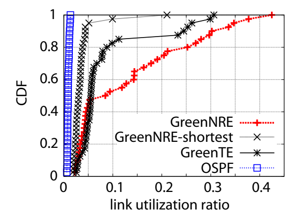

Fig. 7: CDF of link utilization ratio (Geant, wind powered).

We developed an overall model to clarify the working operations to realize minimizing non-renewable energy consumption of the Internet routing. We developed a set of models such that a router can collect the information of what proportion of its power supply is supported by renewable (or non-renewable) energy. We formulated a minimum non-renewable energy routing problem, two special cases with certain academic and practical importance. We analyzed the complexity of the problems and develop optimal and sub-optimal algorithms. Our evaluations on real trace data demonstrated the effectiveness of our algorithms.

References

[1] M. Andrews, A. F. Anta, L. Zhang, and W. Zhao. Routing for Energy Minimization in the Speed Scaling Model. In *Proc. of IEEE INFOCOM*, pages 1–9, 2008.

[2] A. P. Bianzino, L. Chiaraviglio, and M. Mellia. Distributed Algorithms for Green IP Networks. In *IEEE INFOCOM Workshop on Green Networking and Smart Grid*, March 2012.

[3] J. Chabarek, J. Sommers, P. Barford, C. Estan, D. Tsiang, and S. Wright. Power Awareness in Network Design and Routing. In *Proc. of IEEE INFOCOM*, pages 457–465, 2008.

[4] L. Chiaraviglio, D. Ciullo, M. Mellia, and M. Meo. Modeling sleep mode gains in energy-aware networks. *Computer Networks*, 57:3051–3066, October 2013.

[5] A. Cianfrani, V. Eramo, M. Listanti, and M. Polverini. An OSPF enhancement for energy saving in IP networks. In *2011 IEEE Conference on Computer Communications Workshops*, pages 325–330, april 2011.

[6] M. Furer and B. Raghavachari. Approximating the minimum degree spanning tree to within one from the optimal degree. pages 317–324, 1992.

[7] L. Gan, A. Walid, and S. Low. Energy-efficient congestion control. In *ACM SIGMETRICS*, pages 89–100, 2012.

[8] P. X. Gao, A. R. Curtis, B. Wong, and S. Keshav. It's not easy being green. In *Proc. of SIGCOMM*, pages 211–222, 2012.

[9] M. Garey and D. Johnson. *Computers and Intractability: A Guide to the Theory of NP-Completeness*. W.H. Freeman, 1979.

[10] D. Katz, K. Kompella, and D. Yeung. Traffic engineering (te) extensions to ospf version 2, IETF RFC3630, Sep. 2003.

[11] C. Li, A. Qouneh, and T. Li. iSwitch: Coordinating and Optimizing Renewable Energy Powered Server Clusters. In *ISCA*, pages 512–523, 2012.

[12] C. Li, R. Zhou, and T. Li. Enabling distributed generation powered sustainable high-performance data center. pages 35–46, 2013.

[13] Z. Liu, Y. Chen, C. Bash, A. Wierman, D. Gmach, Z. Wang, M. Marwah, and C. Hyser. Renewable and cooling aware workload management for sustainable data centers. In *Proc. of Sigmetrics*, pages 175–186, 2012.

[14] Z. Liu, M. Lin, A. Wierman, S. H. Low, and L. L. H. Andrew. Greening geographical load balancing. In *Proc. of SIGMETRICS*, pages 233–244, 2011.

[15] Y. Ma and S. Banerjee. A smart pre-classifier to reduce power consumption of TCAMs for multi-dimensional packet classification. In *Proc. of ACM SIGCOMM*, 2012.

[16] L. Niccolini, G. Iannaccone, S. Ratnasamy, J. Chandrashekar, and L. Rizzo. Building a power-proportional software router. pages 8–8, 2012.

[17] M. R. Patel. *Wind and Solar Power Systems*. CRC Press, 1st edition, March 1999.

[18] S. Uhlig, B. Quoitin, J. Lepropre, and S. Balon. Providing Public Intradomain Traffic Matrices to the Research Community. *ACM SIGCOMM Computer Communication Review*, 36(1):83–86, 2006.

[19] N. Vasic, P. Bhurat, D. Novakovic, M. Canini, S. Shekhar, and D. Kostic. Identifying and using energy-critical paths. In *Proc. of CoNext'11*, 2011.

[20] W. Vereecken, W. V. Heddeghem, M. Deruyck, B. Puype, B. Lannoo, W. Joseph, D. Colle, L. Martens, and P. Demeester. Power Consumption in Telecommunication Networks: Overview and Reduction Strategies. *IEEE Communications Magazine*, 49(6):62–69, 2011.

[21] Y. Yang, D. Wang, M. Xu, and S. Li. Hop-by-hop Computing for Green Internet Routing. In *IEEE ICNP*, October 2013.

[22] M. Zhang, C. Yi, B. Liu, and B. Zhang. GreenTE: Power-Aware Traffic Engineering. In *Proc. of IEEE ICNP*, pages 21–30, October 2010.