Hybrid Renewable Energy Routing for ISP Networks

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***Abstract*—The ICT industry has come under criticism as being one of the major energy consumers to exacerbate high global carbon emissions. Meanwhile, using renewable energy to power ICT infrastructure is becoming an attractive solution and is gaining its momentum due to the recent breakthroughs of converting solar and wind energies as power sources at competitive costs. Although significant amounts of fossil fuel based-energy can be saved by allowing network devices (e.g., routers and line-cards) to be set to sleep, this optimization approach comes at a price of degrading routing performance, i.e., the quality of service.**

This paper addresses the problem of minimizing fossil fuel consumption in large Internet Service Provider (ISP) networks, by utilizing a novel gradient-based routing protocol, which favors forwarding packets along routers powered by the highest quantity of renewable energies. Besides favoring renewable energy, the proposed routing protocol can support putting routers to sleep in order to optimize energy consumption while ensuring a minimum degradation in routing performance.

Through our evaluation utilizing real meteorological data, our proposed solution has demonstrated a massive reduction of fossil fuel usage by the network ($> 70\%$) while maintaining the routing performance to a similar level when no energy optimization is applied.

***Index Terms*—renewable energy, wind energy, solar energy, energy-aware routing**

I. Introduction

The current global energy depletion is a widely debated topic. Paralleled to the pressing problem of energy depletion, is the increase in CO_2 emissions [1] which has affected the environment in the form of global warming. These problems have largely been attributed to the poor planning process and short-term goals that we as humans have taken in utilizing natural resources, over the years. We are now witnessing a closer relationship between ICT and its influence in the energy sector [2], [3]. In particular, the growth of the Internet is slowly moving up the ranks as a major source for energy consumption (10% of the world global energy consumption [4]), which is close to other established industries (e.g., the airline industry).

This new landscape has shifted ICT researchers towards developing solutions that can improve the energy consumption of communication networks, and at the same time minimize CO_2 emissions. In particular, as we witness increasing developments in renewable energy infrastructure, ICT researchers are pursuing new solutions where clean energy could be used as alternative energy sources for the Internet infrastructure (e.g., designing energy-efficient networks). While new technologies have been continually proposed to increase the use of renewable energy in data center networks [5], very few of them are available at the ISP network scale.

In this paper, we propose a novel energy-aware routing protocol that aims to forward packets to routers powered by high quantities of *hybrid renewable energy* (we assume that each router is powered by renewable energy infrastructure, which will be a combination of wind turbines and solar panels). The routing protocol is aware of the distributed and hybrid renewable energy infrastructure of a realistic ISP network and is self-adaptive to dynamic network loads and weather pattern changes. Additionally, the routing protocol allows unused routers to be put to sleep in order to minimize the use of fossil fuel energy, also referred to as *brown energy* in this paper.

Nonetheless, optimizing energy consumption by simply turning off devices in ISP networks may result in non-negligible degradation of routing performance, because it creates congestion hot-spots due to a reduced number of network paths. The novelty of our work lies in its protocol design which is able to minimize the use of fossil fuel in ISP networks, without detriment to the routing performance. We conduct thorough evaluations which use real weather data to simulate the performance of the proposed routing protocol. Our key findings are:

- Our energy-aware routing protocol is very effective at decreasing the amount of brown energy consumed by the intra-domain network (by up to 72%) without generating topological instability.
- We show the conflicting objectives of energy optimization and routing performance, but we present a solution for this issue.

The remainder of this paper is organized as follows: Section II presents the related work. Section III clearly defines the objectives of our solution, and this is followed by Section IV which describes our proposed approach. Section V describes the meteorological dataset used for our work (including the mechanisms of converting renewable energy to consumable power), and the evaluation of our proposed solution. Finally, Section VI summarizes the paper.

II. Related work

Developing a greener Internet has been investigated for a number of years [6]. The green strategies that can be used for reducing the energy consumption of ICT infrastructures includes (i) resources consolidation [7], (ii) selected connectedness [8], (iii) virtualization [9] and (iv) proportional computing [10]. [11] surveys different strategies and discusses their mechanisms in details.

In this study, we focus primarily on techniques based on resources consolidation and selected connectedness. Various solutions have been proposed to reduce the global energy consumption of ISP networks, taking into account the large over-provisioning of these networks (i.e., high redundancy of resources) and the numerous under-utilized resources, such as routers and line-cards.

For instance, Cianfrani *et al.* [8] proposed a simple modification of the Open Shortest Path First (OSPF) protocol to minimize the connectivity of routers, resulting in an energy gain by powering-off more than 60% of the network's links. Unfortunately, their proposed solution may lead to overload links when their optimization technique is applied. As a result, the authors suggest to trigger the optimization only during low traffic periods.

More sophisticated solutions have been proposed to take traffic in consideration when performing energy optimization. For example, Chiaraviglio *et al.* [4] formulated the optimization problem of minimizing energy consumption without disrupting traffic using Integer Linear Programming (ILP). Such problems are generally NP-complete and the prior work mostly rely on a centralized solver which prevents it from large-scale use. However, the authors also proposed an heuristic to reduce the computational complexity.

A different approach was taken by Mineraud *et al.* [7], who proposed a fully adaptive routing protocol that reacts to traffic congestion to increase or decrease the number of resources to cope with dynamic traffic. The routing protocol was able to save up to 45% in electricity consumption for the network.

Despite the recent achievements in reducing the energy consumption of ISP networks, solutions taking advantages of the available renewable energies are still missing. Currently, the use of renewable and green energies has only been used to improve the energy efficiency of data centers [5].

For instance, Liu *et al.* [12] proposed the use of renewable energy for powering data-centers, including an optimal mix of renewable sources of energy, using a $30kW$ wind turbine and a $4kW$ solar panel[1]. The authors found the optimal energy proportion to be 80% wind and 20% solar, which is mainly due to the extra power than can be generated by a $30kW$ wind turbine compared to a $4kW$ solar panel.

Unlike [12], our work does not focus on a single location but rather on taking advantage of a distributed network of renewable infrastructures [13]. We propose a novel routing protocol that is aware of the local renewable energy infrastructure (i.e., one-hop knowledge) and aims to reduce the network's energy consumption, such as in [4] and [7], in an extremely dynamic environment (i.e., weather conditions).

[1]A $4kW$ solar panel is roughly the size of an house rooftop

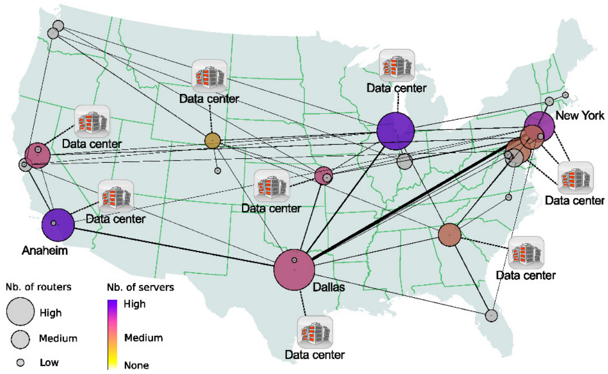


Fig. 1: **Sprintlink USA mainland network [14].** *The ISP network used in the evaluation of our proposed solution. The size of the bubbles indicates the size of the POP. The placement of data centers is explained in Section V-A.*

III. Problem statement

We now present our problem statement and our energy consumption model of the routers. We consider an ISP network as presented in Fig.1, where nodes are powered partially by renewable energy and partially by traditional fossil fuel-based energy. We refer to fossil fuel energy as brown energy and renewable energy as green energy in the rest of the paper. The green energy could be a combination multiple renewable energy sources, such as hydraulic, but we consider only wind and solar sources in this paper. The ISP network connects the geographically distributed data centers (data sources) and the user access networks (data sinks) with routers. An verbal description of the design problem is:

[**Given**] (i) an ISP network consisting of routers and links and (ii) a decentralized infrastructure harvesting hybrid renewable energies.

[**Objective**] is to reduce the global brown energy consumption of the network by enabling green routing and powering off unused devices, without degrading routing performance.

We extend the energy consumption model in [15], where Chabarek *et al.* empirically measured the energy consumption of chassis and line-cards in *Cisco GSR*, to incorporate renewable energies. Due to various hardware models and vendors, network devices, such as routers and line-cards, usually consume energies in different ways, i.e., having different energy consumption models. For each router, we use a non-negative integer vector $X \in \mathbb{N}^m$ which contains the categorical values to specify the types of m devices installed within the router, e.g., *OC-48* line-card for the *GSR*. X can be viewed as the configuration of a specific router. Hence, we use X and a router's configuration interchangeably in the following discussion.

Function $PC : \mathbb{N}^m \rightarrow \mathbb{R}^+$ maps a router to its corresponding energy consumption given its internal devices specified by the configuration X, as below.

$$PC(X) = CC(X_0) + \sum_{i=1}^{N}(TP(X_i) + LCC(X_i)) \quad (1)$$

As we can see, for a router, its energy consumption $PC(X)$ can be further decomposed into three components: one is from the chassis, one is from the installed line-cards, and one is from processing the passing-by traffic. Specifically, $CC(X_0)$ and $LCC(X_i)$ represent the energy consumption for chassis and line-card i respectively, N is the number of line-cards in router X. $TP(X_i)$ represents the energy consumption due to the traffic on line-card i. However, Chabarek *et al.* [15] show that the impact of the traffic load is marginal, therefore $TP(X_i)$ can be safely dropped in Eq. 1, leading to:

$$PC(X) = CC(X_0) + \sum_{i=1}^{N} LCC(X_i) \quad (2)$$

To save energy, we assume that we can switch the network devices to sleep mode or even off when they are not used then quickly wake them up to work whenever needed [11]. We refer to the aforementioned energy saving mode as `green` mode for convenience. Obviously, the power consumption is not static but a function of time, where we introduce time t as another variable in the model. The power consumption at time t is

$$PC(X,t) = x_{0,t} \cdot CC(X_0) + \sum_{i=1}^{N} x_{i,t} \cdot LCC(X_i) \quad (3)$$

subject to

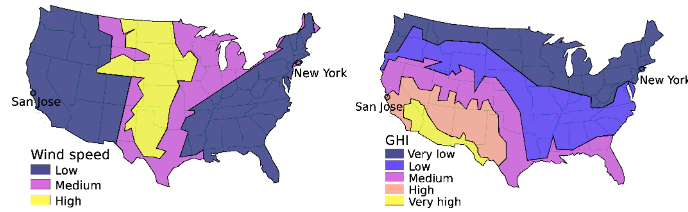
$$x_{i,t}, (i > 0) = \begin{cases} 0 & \text{if } X_i \text{ in green mode at time } t \\ 1 & \text{if } X_i \text{ in normal mode at time } t \end{cases} \quad (4)$$

$$x_{i,t}, (i = 0) = \begin{cases} 0 & \text{if } \sum_{i=1}^{N}(x_{i,t}) = 0 \\ 1 & \text{otherwise} \end{cases} \quad (5)$$

If a neighbor router is in `green` mode, the line-card connecting the two routers is also switched to `green` mode accordingly. We assume that the router X is equipped with an hybrid renewable energy source, such as a combination of hydraulic, solar and wind, which is able to provide $rePC(X,t)$ (*re* - renewable) amount of energy at time t. In this paper, we consider only wind and solar energy sources, resulting in the following equation:

$$rePC(X,t) = P_w(X,t) + P_s(X,t). \quad (6)$$

$P_w(X,t)$ and $P_s(X,t)$ are the power from wind turbines and solar panels respectively. Equation 6 can be easily extended whenever new energy sources are incorporated in the model. In our work, $rePC(X,t)$ is derived from the renewable energy infrastructure available to the router (see Section V-A2 for more details) using the meteorological data which is



(a) Windspeed (b) GHI

Fig. 2: **Average annual wind speed and Global Horizontal Irradiance in U.S.** *Weather conditions differ greatly depending on the location. A distributed renewable energy infrastructure requires a locally optimized energy source combination. Brighter colors indicate higher availability.*

publicly available from the *National Renewable Energy Laboratory*.[2] The dataset includes: (i) *Global Horizontal Irradiance* (*GHI*), a widely used metric to estimate how much power could be generated by photovoltaic solar panels; (ii) wind speeds for every hour in a year. Fig. 2 shows that the average annual wind speed and GHI in U.S. according to our dataset. As we can see, the available energy differs greatly depending on the locations. Constraint 4 indicates the current mode that a node is in, i.e., `green` or `normal`, while constraint 5 means that a node can be powered off completely if all the line cards are in the `green` mode.

By subtracting $rePC(X,t)$ from $PC(X,t)$, we obtain $brPC(X,t)$ which is the brown energy consumed by router X at time t.

$$\begin{aligned} &brPC(X,t) = PC(X,t) - rePC(X,t) \\ &\quad \text{with } brPC(X,t) = 0, \text{ if } rePC(X,t) \geq PC(X,t) \end{aligned} \quad (7)$$

To measure the efficacy of our energy saving solution, we compare the energy consumption of the network where every single device always works in `normal` mode with the energy consumption where underutilized devices can be switched to `green`. We name this metric *brown energy saving*, or σ_n, which is calculated as followed:

$$\sigma_n = 1 - \frac{\sum_{\forall X}\sum_{\forall t} brPC(X,t)}{\sum_{\forall X}\sum_{\forall t} brPC(X',t)} \quad (8)$$

where $brPC(X',t)$ is the brown energy consumption of a router (when none of its internal devices are in `green` mode).

IV. Renewable energy-aware routing protocol

The proposed *hybrid Renewable Energy Routing* protocol (*rePGBR*) is a fully distributed routing protocol. *rePGBR* is inspired by the work of Mineraud et al. [7]. As in [7], *rePGBR* generates a gradient field to modify the route discoveries and

[2]The national solar radiation database collected between 1991 and 2005 has been processed to represent an average year in the U.S. The dataset includes hourly values of meteorological conditions for 1020 locations in the U.S., and is available at this URL: http://rredc.nrel.gov/solar/old_data/nsrdb/

adapt to the local environment. In *rePGBR*, a packet traverses from node to node along the path with the highest gradient, as described below, until it reaches the destination.

A. Gradient equation

Specifically, the gradient $G_i^d(j,t)$ of the link $i \rightarrow j$ for destination d at time t is defined by the following equation:

$$G_i^d(j,t) = \alpha g_i(j) + (1-\alpha) h_i^d(j), \quad 0 \leq \alpha \leq 1 \qquad (9)$$

where $g_i(j,t)$ (Eq. 11) is the greenness ratio of neighbor j of node i at time t, and $h_i^d(j)$ is the normalized hop count of neighbor j of node i for destination d, as shown in Eq. 10. $\alpha \in [0,1]$ is the weighting parameter between greenness and number of hops.

Regarding the normalized hop count $h_i^d(j)$, ideally, the neighbor that is the closest to the destination should have value $h_i^d(j) = 1$, while the one that is the furthest has value 0. Consequently, we defined the hop count metric as below

$$h_i^d(j) = \frac{\max(w_i^d(k)) - w_i^d(j)}{\max(w_i^d(k)) - \min(w_i^d(k))}, \quad \forall k \text{ neighbors of } i \qquad (10)$$

where $w_i^d(k)$ is the number of hops for the shortest path between nodes u and v.

In the same vein, we define another metric referred to as *greenness ratio* to identify the greenest neighbor. In calculating greenness ratio, we replace the hop counts with the amount of available renewable energy at each router. More precisely, the greenness ratio $g_i(j,t)$ of a neighbor j is calculated as

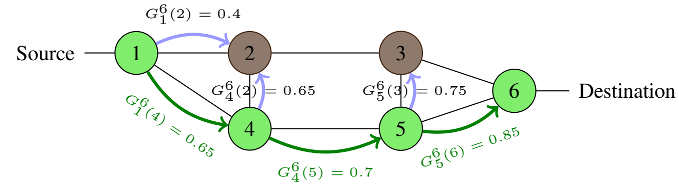
$$g_i(j,t) = \frac{\max(rePC(k,t)) - rePC(j,t)}{\max(rePC(k,t)) - \min(rePC(k,t))}, \quad \forall k \text{ neighbors of } i \qquad (11)$$

The greenness ratio $g_i(j,t)$ counterintuitively favors neighbors with highest renewable energy over neighbors with least brown energy to the optimized brown energy needs of the network. Using a greenness ratio favoring least brown energy, our routing protocol favored nodes with low energy needs (i.e., node with low connectivity) which limited their ability to switch to `green` mode. However, with the greenness ratio of Eq. 11, our routing protocol favors green nodes with high connectivity. This increases the probability to switch a high number of underutilized devices to `green` mode.

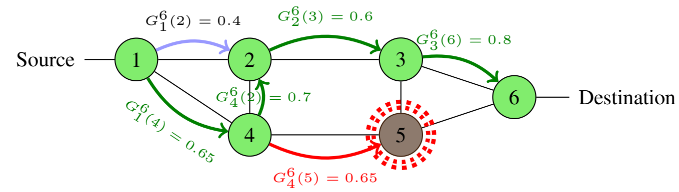
B. Routing protocol

rePGBR, as presented in Algorithm 1, is a routing protocol that discovers a path for each traffic flow. [3] The path is discovered by sending a probe packet that traverses hop-by-hop and selects the link with the highest gradient value. We add an additional parameter ϵ to select the node with the highest connectivity when gradient values are very close (i.e., difference is lower or equal to ϵ). This allows the protocol

[3] A flow is a consecutive sequence of packets with similar 5-tuple headers (destination IP, source IP, destination port, source port, protocol). Refer to [7] for more details.



(a) Discovery of path along gradient field formed by routers with high renewable energy.



(b) Gradient field modification due to changes in renewable energy performance.

Fig. 3: **Route discovery process for *rePGBR*.** *An update of the gradient field automatically modifies the path discovery process by rePGBR.*

to perform additional energy saving, which will be discussed in Section V-B. Algorithm 1 describes how *rePGBR* chooses the next hop during discovery. *rePGBR* stores necessary information in a router to avoid loops (i.e., list of incoming and outgoing neighbors, lines 13 and 14) and performs back-tracking (i.e., line 11) in a distributed manner.

Fig. 3a and Fig. 3b illustrate the discovery process where the path dynamically changes to avoid brown hot-spot areas (e.g., discovery avoids brown node 5 due to the gradient field changes). Once the weather condition changes (updated on an hourly basis), a new discovery packet is issued. During the discovery process, the existing path remains stable until the new one is adopted sequentially as the discovery message backtracks to the source using the local information as Algorithm 1 describes.

Furthermore, the α (in Eq. 9) provides *rePGBR* with a control over the greenness. Low α values generate paths close to the shortest route (more weight is attributed to the hop count) while a large α favors greener routes but may increase the paths stretch. In the next section, we describe the evaluation of the *rePGBR* routing protocol as a function of α.

V. Evaluation

A. Experiment setup

To validate our proposed solution, we have simulated a large scale ISP network spanning across the U.S. We augmented the ISP network with a distributed infrastructure to collect hybrid renewable energy that can be used by routers to cover some of their energy needs.

1) ISP network: The network used in the evaluation is Sprint router-level topology from the Rocketfuel project [14]. The Sprint network consists of 278 routers geographically distributed in 27 cities on the U.S. mainland (meteorological data described in Section V-A2 is available only for the U.S.

Algorithm 1 *rePGBR*'s route discovery

procedure FIND ROUTE(s, d, ϵ) ▷ Path between s and d, $epsilon$ is the aggregation metric
  $n \leftarrow s$
  $p \leftarrow [s]$ ▷ Initialize path
  while $n \neq d$ **do**
    if $V(n) = \emptyset$ **then**
      $V(n) = []$ ▷ Queue of visited nodes
    $m \leftarrow maxGradient(n, d, V(n), \epsilon)$
    if m is $\emptyset$ **then**
      if $empty(V(n))$ **then**
        return $\emptyset$
      $n \leftarrow first(V(n))$ ▷ Back-tracking
    else
      $V(n) \mathrel{+}= m$ ▷ Adding out-node
      $V(m) \mathrel{+}= n$ ▷ Adding in-node
      $n \leftarrow m$
      if $m \in p$ **then**
        Remove loop from p
      else
        $p \mathrel{+}= m$
  return p

procedure MAXGRADIENT($n, d, V(n), \epsilon$)
  $maxG \leftarrow 0$
  $t \leftarrow$ current time
  for all neighbors m of n **do**
    if $m \notin V(n)$ and $G_n^d(m, t) > maxG$ **then**
      $maxG \leftarrow G_n^d(m, t)$
  $next \leftarrow \emptyset$
  for all neighbors m of n **do**
    if $m \notin V(n)$ and $maxG - G_n^d(m, t) <= \epsilon$ **then**
      if $next = \emptyset$ or $|m| > |next|$ **then**
        $next \leftarrow m$
  return $next$

mainland locations). In reality, ISP routers of high connectivity usually locate at PoP (Point of Presence) and process most of the traffic in the network, while routers of low connectivity usually located at the network edge to serve as access network for end-users [14]. We apply this to pick 40 servers and 80 clients in our topology.

Fig. 1 shows the resulting topology where routers located in the same city are grouped (i.e., the size of the city increases with the number of routers). For instance, Anaheim, Chicago, New York and Dallas are the cities with the highest number of routers. The color of the cities, on the other hand, represents the number of servers (e.g., nodes which have the highest connectivity). A total of 10 cities have servers resulting in 10 data centers that are interconnected through the ISP network. Once again, Anaheim, Chicago and New York are the three cities with the highest number of servers.

The remaining routers are used as intermediate nodes for the routing algorithm. The clients continuously request data from the servers, the request rate depends on the traffic pattern. We designed the traffic matrix to provide constant traffic between clients and servers. The objective of the traffic matrix is to maximize resource usage (i.e., maximize average link load) using OSPF without generating overload. As a result, OSPF is able to successfully process at all times the traffic between clients and servers. The aim for the traffic matrix design is to highlight the negative consequences on the routing performance when optimizing the network's energy consumption.

The power requirements of every router has been set using the measurements of a Cisco 7507 model [15]: the basic chassis requiring 210W and each line-card an additional 70W (i.e. a router with 4 line-cards consumes $210+4*70 = 490W$).

2) Distributed renewable energy infrastructure: We previously described the characteristics of the ISP network used in our experiments. However, a requirement for the experiments is to put in place a realistic renewable energy infrastructure to power, at least partially, the routers of the ISP network. We planned our distributed renewable energy infrastructure to supply at most c times the energy required by the router. The constraint is defined as:

$$max(rePC(X, t)) = c \times PC(X'), \forall t \tag{12}$$

where $PC(X')$ is the energy required by the router when all its components are not in `green` mode. The c parameter, referred to as capacity is assigned randomly, but biased by the degree of the router. Routers that have a degree d are assigned a capacity c based on the following constraint:

$$c = \begin{cases} rand(0, 2) & \text{if } 0 \leq d \leq 2, \\ rand(1, 3) & \text{if } 3 \leq d \leq 5, \\ rand(2, 4) & \text{if } 6 \leq d \leq 10, \\ rand(3, 5) & \text{if } 11 \leq d \leq 20, \\ rand(4, 6) & \text{if } 21 \leq d. \end{cases} \tag{13}$$

We assumed that highly connected nodes are more susceptible to have access to a larger renewable energy infrastructure, because it would result in more advantageous economical gains [11]. The proportion of wind and solar power is then designed to maximize the average value of $rePC(X, t)$ during the whole year.

In [12], Liu *et al.* used $30kW$ wind turbines to generate renewable energy. However, the average wind speed in the U.S. does not enable these wind turbines to achieve optimal performance when distributed in various locations, as planned in our solution. In fact, the authors used wind energy to power data centers and thus, the location of the data center can be selected based on the average wind speed at this location. In our solution, locations are defined by the Sprintlink network, and can not be modified. Consequently, we also tested $5kW$ wind turbines which have the advantage to generate more power at lower wind speeds, as shown in Fig. 4.

The proportion of wind and solar energies have been calculated separately for each router X in order to maximize the yearly average of $rePC(X)$ while satisfying the constraint on

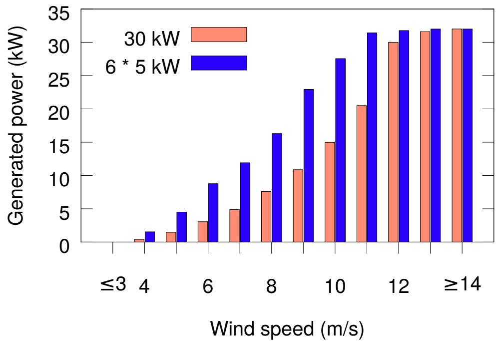


Fig. 4: **Wind speed to power conversion** *Using smaller wind turbines for the distributed renewable infrastructure is more advantageous than their larger counterparts. The wind speed to power conversion is obtained from [16].*

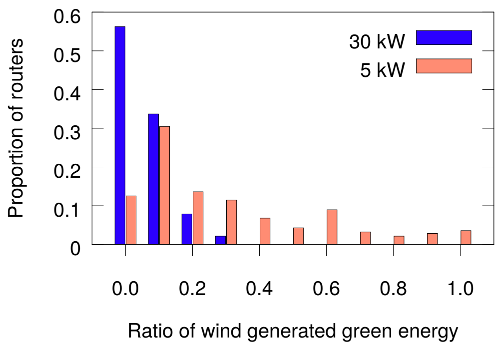
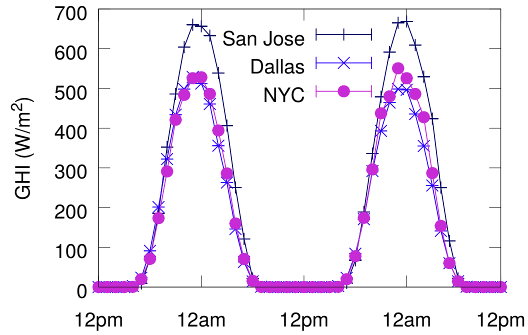
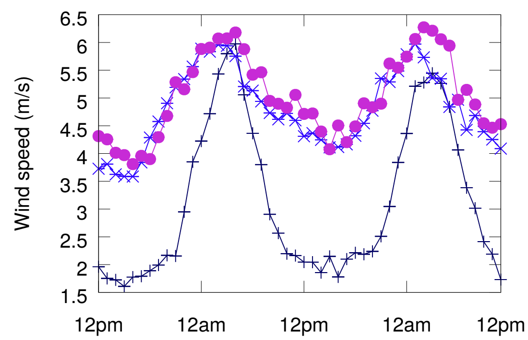


Fig. 5: **Optimal mix distribution** $5kW$ *wind turbines allows a wider use of wind energy in our distributed renewable infrastructure.*



(a) Global Horizontal Radiance (GHI) for solar energy



(b) Wind speed for wind energy

Fig. 6: **Weather profiles for San Jose (CA), Dallas (TX) and New York City (NY).** *Weather profiles greatly influence the composition of the renewable infrastructure. San Jose relies solely on solar, NYC on wind, while Dallas uses both wind and solar energies.*

the maximum capacity (see Eq. 12). As shown in Fig. 5, $5kW$ wind turbines increase the popularity of using wind energy. For example, when using $30kW$ wind turbines only 2.15% of the routers have a $rePC$ composed of at least 30% of wind energy, while the proportion increases to 43.37% with $5kW$. Consequently, in our experiments, the $5kW$ wind turbines have been preferred to $30kW$ wind turbines.

Fig. 6 pictures the weather profiles (solar on top and wind at the bottom) for two consecutive days in the year for each season at three locations. In San Jose, the provision of solar energy is much higher than wind energy, thus the optimization of the proportion between wind and solar energies has resulted in a renewable infrastructure entirely composed of solar panels. On the other hand for New York City, the infrastructure is only composed of wind turbines, as the availability of fast winds is much more frequent. Finally, Dallas presents intermediate characteristics and has an infrastructure equally shared between wind and solar energy sources. Additionally, we would like to note that, in Fig. 6b, the average windspeed at each hour rarely goes above $6m.s^{-1}$, a speed at which the $5kW$ wind turbines outperform their $30kW$ counterparts. This confirms our preference towards the $5kW$ wind turbines to build our renewable energy infrastructure.

B. Minimizing fossil fuel usage

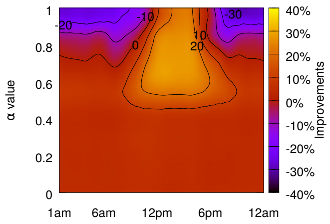
Our objective with *rePGBR* is to reduce the global fossil fuel need of ISP networks. Nevertheless, this energy optimization should not come at the cost of degrading routing performance or creating instability. Hence, we propose the following metrics to evaluate our proposed solution:

[**Brown energy saving**] The amount of brown energy that has been saved by turning on devices to `green` mode. The brown energy saving is calculated using Eq. 8.

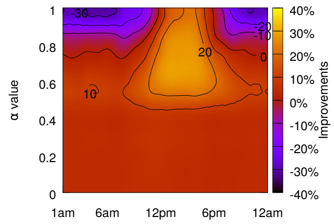
[**Stability**] The number of times routers needs to change their mode between `green` and `normal`. This metric is important to show the stability of the proposed protocol.

[**Overload**] The ratio of links which are overloaded. Ideally the ratio should be nil as with shortest path.

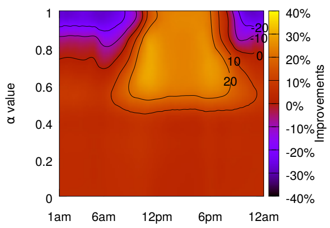
Fig. 7 depicts the performances of *rePGBR* in terms of saving fossil fuel energies in comparison to shortest path (i.e., OSPF). To be fair, the unused links and routers by OSPF have also been put in `green` mode in order to show the direct improvement of a renewable energy-aware routing protocol over a purely performance-driven protocol. The results presented in



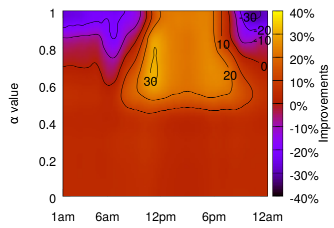
(a) Fall



(b) Winter



(c) Spring



(d) Summer

Fig. 7: **Improvements of brown energy saving over shortest path (OSPF)** *rePGBR exhibits between -40% and 40% energy saving improvements when compared to using only shortest path. The values of α resulting in high improvements are numerous and predictable.*

this heat map are calculated as follows:

$$\frac{\sigma(rePGBR)}{\sigma(OSPF)} \times 100. \quad (14)$$

In these experiments, the value of α remained static over the full year. As shown in Fig. 7, *rePGBR* is able to outperform shortest path at any hour of the day, by at least 3%, even when α is equal to 0 (i.e., should behave like shortest path). This is due to a mechanism in Algorithm 1 (lines 29-30) that aggregates traffic on nodes with the highest number of neighbors if the gradient values are relatively close (i.e., the difference is lower than ϵ). We observe that the brown energy performance of *rePGBR* for different values of α depend greatly on the time of the day. This is due to the diurnal solar pattern which dramatically increases the greenness of the whole infrastructure during the sunny hours of the day. As a result, *rePGBR* is allowed to use more resources in the network without increasing the amount of fossil fuel used. During the darkest hours of the day, high values of α (i.e., $\alpha \geq 0.8$) impact negatively the performances of our routing protocol. This is due to a higher number of links and nodes being used and not powered by renewable energies; their greenness value is high enough (see Eq. 11) to overcome the hop count value of other neighbors (see Eq. 10).

An interesting observation is that the seasonal changes only impact on the duration span of the sunny hours. It allows *rePGBR* to use higher values of α, and for a longer time. In conclusion, it makes the choice of α values for *rePGBR* predictable to achieve high energy saving.

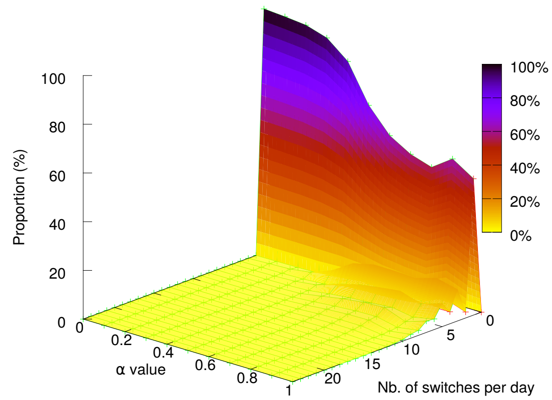


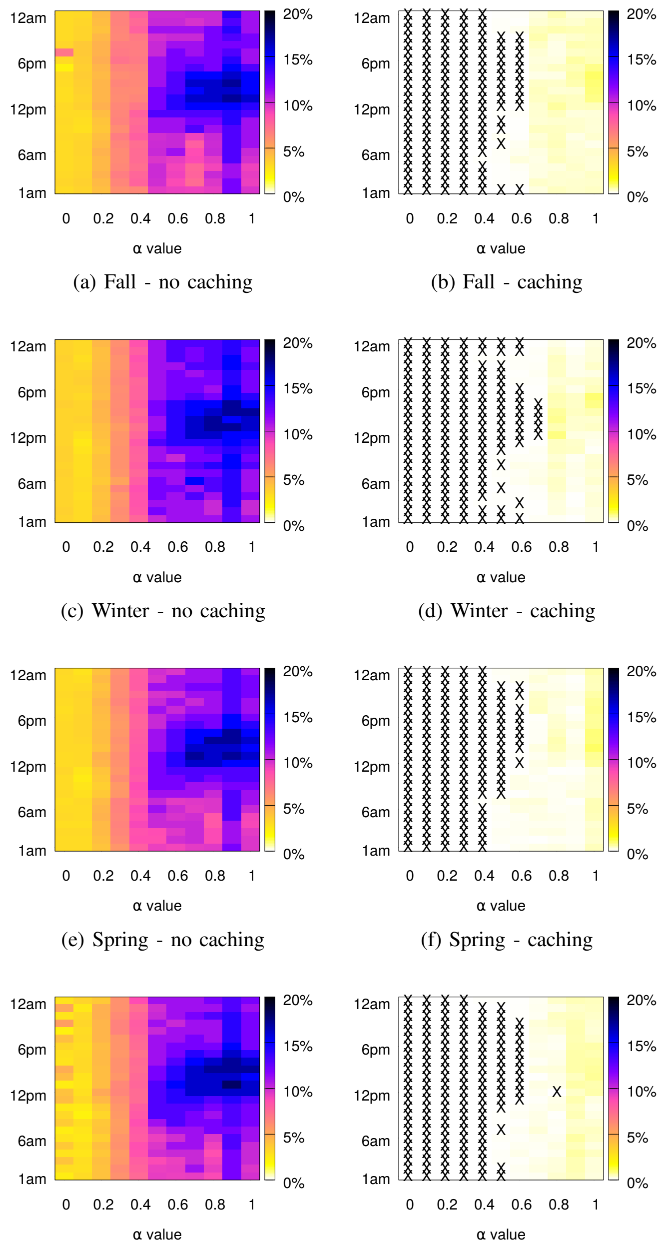
Fig. 8: **Proportion of routers switching mode within a day in function of α.** *Enabling energy optimization with rePGBR does not create instability in the network topology. Routers usually switch mode at most two times per day (averaged over the full calendar year).*

C. Topological stability

Essentially, *rePGBR* saves energy by dynamically switching routers between `normal` and `green` modes. However, in reality, a major concern is how such a switching operation impacts the stability of a network. Especially, considering some routers may take dozens of seconds or even up to minutes to switch between modes and get ready to serve the requests, frequent switching inevitably degrades the quality of services and robustness of a network. To investigate how *rePGBR* affects network stability, we ran the *rePGBR* algorithm over the whole year data and checked the switching frequency of all routers. Meanwhile, we also vary α between 0 and 1 to understand how it changes *rePGBR*'s behavior.

Fig. 8 is a three-dimensional plot of our experiment results. The x axis represents various α values, the y axis represents the frequency of switching between `normal` and `green` modes. The z axis represents the percentage of nodes given an α and number of switches. As we can see in Fig. 8, the subset topology selected by *rePGBR* is rather stable. Most of the routers never change their mode during the whole year period. As reflected in the figure, most of the percentage of nodes concentrates on $y = 0$ with respect to all α values. Thus, the routers that are always used by the routing protocol can be considered as part of the core topology. The core topology is always composed of more than 55% of the topology (worst case scenario: $\alpha = 0.8$). The α value obviously plays a significant role in stabilizing the network. As we increase the α from 0.0 to 0.8, we observe a drastic drop in the number of routers which remain unchanged for the whole year.

This demonstrates that our protocol provides sufficient stability to ensure high performance, as we do not constantly change the status of routers, but rather modify gradually our topology to cope with changing weather conditions.



(a) Fall - no caching (b) Fall - caching

(c) Winter - no caching (d) Winter - caching

(e) Spring - no caching (f) Spring - caching

(g) Summer - no caching (h) Summer - caching

Fig. 9: **Proportion of overloaded link with or without caching** *Optimizing energy consumption may generate congestion. However, traffic reduction mechanisms such as caching can reduce the negative impact of energy optimization. α values which do not generate congestion are marked with an X.*

D. Impact on the routing performance

The direct consequence of enabling `green` mode is to generate potential congestion in the network, which further leads to the degradation of the routing performance. In other words, optimizing energy consumption has conflicting objectives with routing performance [4], [7]. This is due to the limited resources that are made available by the routing protocol to forward packets efficiently. As expected, the brown energy saving impacts negatively on the routing performance. In our experiment setup, we have designed the traffic matrix to emphasize the drawbacks of optimizing energy consumption with regard to the routing performance. The traffic matrix was designed to maximize the network load while using OSPF without generating overload. On the left in Fig. 9, we show the proportion of overloaded links, as a result of congestion. These figures show that all values of α introduce some sort of overload. In the best case scenario, the lowest α values (i.e., $\alpha \leq 0.2$) have just under 5% of overloaded links.

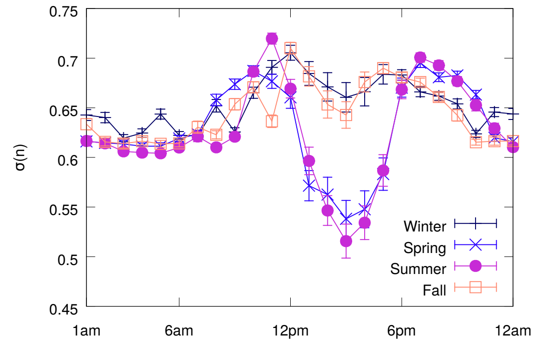


Fig. 10: **Brown energy saving ($\sigma(n)$) for each season and each hour.** *rePGBR saves in average more than 60%, with a maximum of 72%, of the fossil fuel energy needs of the ISP network.*

In order to tackle the overload problem, we decided to apply a network caching mechanism, similar to [17]. In this method, individual routers have an internal cache which they can use to serve requests. For content popularity, we used the realistic *Youtube* trace from Cha *et al.* [18]. We selected *Youtube* Entertainment Category which contains 1,687,506 objects. The trace contains video id, length, number of views, rating, etc. The aggregated video size is $12.87TB$, the average file size is $8.4MB$. The request pattern from the trace roughly follows a Zipf distribution with exponent 0.9, which is also commonly observed in other realistic traces [19]. Our trace requests chunks of content, which are assumed to be independent of each other. We assigned each router with a storage capacity of 4 gigabytes.

The impact of the caching mechanism is depicted on the right in Fig. 9 where the values of α that have no overload are marked with an X. Additionally, the other α values only have limited overload (i.e., under 5% of the topology). Thus, it is possible to overcome the impact of optimizing energy consumption without disrupting routing performance.

E. Balancing between routing and energy saving

In this section, we describe how much brown energy can be saved by our solution without impacting the routing performance (i.e., when the proportion of overloaded links is equal to zero in Fig. 9b to 9h).

The results of this evaluation are shown in Fig.10. In this figure, we observe that our routing protocol is able to save on average always at least 50% of the fossil fuel energy. The error bars represents the 95% confidence interval. During the darkest hour of the day, the performance of *rePGBR* for each season are very similar. However, during the warmest seasons (i.e., Summer and Spring), the performance of *rePGBR* are reduced to just over 50% of brown energy saving. This is due to the global greenness of the network which increases during the sunny hours, thus reducing the amount of fossil fuel energy that can be saved by the energy-aware routing protocol. However, *rePGBR* is able to achieve an average of 63.8% brown energy saving over the whole year, which represents significant economical gains and should overcome by far the cost of installing and maintaining the renewable energy infrastructure.

F. Summary

Our evaluations show that *rePGBR* is able to save more than 60% of brown energy on average without creating instability (i.e., switching network devices between `green` and `normal` modes). This is a very important feature of *rePGBR* since switching modes is a rather costly operation in practice. Unfortunately, we have shown that optimizing energy consumption is possible at the expense of routing performance, which is in our case represented by network overload. Nonetheless, we have shown that using a single parameter α, routing performance degradation can be overcome by a state-of-the-art traffic reduction mechanism. Fortunately, the valid values of α are easily predictable, and are dependent of the time of the day (sunny/dark hours) and the season (duration of the sunny hour period). Safe α values are summarized in Table I.

TABLE I: Safe α values

Season	Maximum α		
	Sunny hours		Dark hours
Fall	(12pm - 9pm)	0.6	0.4
Winter	(12pm - 6pm)	0.6	0.4
Spring	(12pm - 11am)	0.6	0.4
Summer	(12pm - 10am)	0.6	0.4

VI. CONCLUSIONS

The popularity of the Internet today has led to widespread deployment of ICT infrastructures, which is consuming a considerable quantity of energy. In this paper, we propose a hybrid renewable energy-aware routing protocol, taking advantages of intra-domain routers powered directly by wind and/or solar energies. The routing protocol is a novel gradient-based routing algorithm that discovers paths along routers powered by high renewable energy, and automatically adapts to changing weather conditions that may affect energy that is used to power the routers. The results from our experiments, using real meteorological data, have shown the protocol to significantly reduce the brown energy needs of ISP networks. Unfortunately, the cost of optimizing the energy consumption results in a degradation of the routing performance. However, the impact of saving energy was easily compensated by a state-of-the-art traffic reduction mechanism, thus allowing tremendous brown energy savings (up to 72%) while maintaining full performance of the system.

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