Abstract—To reduce the GHG emissions of IP over WDM networks, we introduce renewable energy usage at each network node and design the networks considering the state of renewable energy available at each node location. Results indicate that the designed network can save up to 50% or more non-renewable energy consumption in the example scenarios considered here compared with the design method which simply minimizes the total energy consumption.

Keywords—follow the sun, follow the wind; green network design; renewable energy; MILP model

I. INTRODUCTION

Current ICT technologies produce Green House Gas (GHG) which contributes to around 2%-3% of global emissions. This is primarily through the consumption of electricity at coal fired power stations and is all the more worrying as this ICT contribution is expected to double in the next 4-6 years [1]. Moreover, the rate of growth of ICT is expected to further accelerate because its increasing usage, especially in smart grid scenarios, is also seen as a powerful tool to reduce GHG emissions in other sectors of society [2]. This would be clearly unsustainable and therefore reducing GHG emissions has become an urgent and challenging area of research. The current approach of dealing with the network GHG problem is to improve the overall energy efficiency [3, 4, 5], i.e., by reducing the total energy consumption of network by employing energy-minimized design [6, 7, 8] or turning off network devices [9] in order to reduce GHG emissions. However, merely increasing efficiency will not be sufficient to counterbalance the expected growth in equipment usage and services arising from higher Internet traffic demand [10].

Using renewable energy such as solar or wind energy has long been a recognized goal of the ICT industry [10, 11, 12]. However, designing a robust IP over WDM network with renewable energy sources such as solar and wind power is a challenge, as these are far less reliable than hydro-electric or traditional fossil fuel power plants [11]. The solar and wind power available at any given location changes dynamically depend on the local weather conditions, i.e., changing sunlight and wind speeds. However, it is also possible to reasonably predict the solar and wind energy generation during a period (e.g., a day) based on the weather forecast [13, 14]. This implies that the amount of renewable energy available at a network node in a certain period is a known parameter. This can be used in designing an IP over WDM network which aims to consume the least amount non-renewable energy (i.e., minimize the GHG emissions) by following the available state of renewable energy. In a subsequent period (e.g., next day), the network can be reconfigured based on the availability states of solar and wind power in that period. Such networks are often referred to as “follow the sun, follow the wind” IP over WDM networks.

In this paper, we focus on reducing the GHG emissions of backbone IP over WDM networks by employing renewable energy sources (i.e., solar and wind energy). To minimize the non-renewable energy consumption, a mixed integer linear programming (MILP) optimal model for “hybrid-power” IP over WDM networks is developed. The rest of the paper is organized as follows. In Section II, we introduce the network model and the mechanism of “follow the sun, follow the wind.” In Section III, we present the MILP model for minimizing the non-renewable energy. In Section IV, we elaborate on the way that we estimate the renewable energy and the test conditions of the study. We present and discuss the simulation results for the study in Section V. The paper is finally concluded in Section VI.

II. NETWORK MODEL AND “FOLLOW THE SUN, FOLLOW THE WIND” APPROACH

A. Network model

We consider a transparent IP over WDM optical network [15] as shown in Fig. 1, in which IP traffic can be groomed in the electronic domain by routers and directly switched in the optical domain by intermediate OXCs, i.e., IP flows can directly bypass intermediate routers along an end-to-end lightpath (optical channel) to reach their destinations. These end-to-end optical channels form a virtual topology for the upper IP layer. Such network configuration is also referred to as lightpath bypass.

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A hybrid-power IP over WDM network architecture uses power from a mix of non-renewable energy and renewable energy [16]. A non-renewable energy source is needed as a backup if the amount of renewable energy available at the node is not sufficient for operation; this is expected to happen because of the unreliable nature of the renewable energy sources. In this case, the total GHG emissions of an IP over WDM network will reduce if a portion of the non-renewable energy consumption or even all of it is replaced by renewable energy. Therefore, the problem of reducing the GHG emissions of IP over WDM networks becomes one of minimizing the total energy consumption of non-renewable energy sources in the networks.

B. Mechanism of “follow the sun, follow the wind”

Fig. 2 demonstrates the mechanism of “follow the sun, follow the wind” IP over WDM networks with the example network of Fig. 2 (a) which has three nodes connected to each other through fiber links. We assume that each of the node pairs (N0, N2) and (N1, N2) has 20-Gb/s IP traffic between the nodes and that the capacity of each wavelength is 40 Gb/s.

![Fig. 2: An example of virtual topology establishment with renewable energy: (a) physical topology; (b) virtual topology with no renewable energy; (c) virtual topology with sufficient renewable energy at node N0; (d) virtual topology with sufficient renewable energy at node N1.](image)

To serve the IP traffic, direct lightpaths (N0, N2) and (N1, N2) are established to form the virtual topology in the IP layer as shown in Fig. 2 (b). This minimizes the total energy consumption and thus reduces the GHG emissions when no renewable energy is available in the network. However, assume that location at node N0 has a very sunny and windy day and has sufficient renewable energy available on that day at the node. At that time, to reduce the consumption of non-renewable energy, we can establish lightpath (N0, N2) and (N0, N1) in the IP layer as shown in Fig. 2 (c). IP traffic between node pair (N0, N2) is served by lightpath (N0, N2) and IP traffic between node pair (N1, N2) is carried through lightpath (N0, N2) and (N0, N1). Note that the two traffic flows can be groomed at a common lightpath (N0, N2). Here, although the number of lightpaths in the network does not decrease, the consumption of non-renewable energy reduces. This is because just two router ports at nodes N1 and N2 consume non-renewable energy in Fig. 2 (c) compared to the three router ports at those nodes consuming non-renewable energy as in Fig. 2 (b). For the same reason, when location at node N1 has a sunny and windy day and the others do not, we can establish the virtual topology of Fig. 2 (d) to reduce the consumption of non-renewable energy. When this approach is followed, IP over WDM networks which establish virtual topologies according to the state of sun and wind so as to minimize the consumption of non-renewable energy, are referred as “follow the sun, follow the wind” networks.

III. MILP OPTIMIZATION MODEL

As discussed earlier, in order to reduce non-renewable energy consumption, different virtual topologies in the IP layer are established at different time slots according to the state of renewable energy available at each node of the network. The problem of forming an optimal virtual topology which minimizes the non-renewable energy consumption of an IP over WDM network with dual energy sources (i.e., renewable and non-renewable energy) can be formulated as an MILP model. The sets and parameters of the MILP model are defined as follows.

A. Sets and parameters

\( \mathcal{N} \) sets of network nodes.
\( \mathcal{A}_{\text{td}} \) traffic demand between node pair \((s, d)\).
\( \mathcal{B} \) capacity of each wavelength channel in Gb/s.
\( E_r \) total energy consumption of each router port in a day.
\( E_t \) total energy consumption of each transponder in a day. Note that a router port corresponds to a transponder in the transparent IP over WDM networks and the capacity of each router port and transponder are also \( B \).

\( ES_i \) amount of renewable energy (sum of solar and wind energy) available in a day at node \( i \). We assume that the parameter \( ES_i \) can be predicted based on the weather report (i.e., the state of sun and wind on that day).

B. Variables

\( \mathcal{A}_{\text{td}} \) traffic demand between node pair \((s, d)\) that traverses virtual link \((i, j)\) (real).
\( v_{ij} \) number of lightpaths (i.e., optical channels) between virtual link \((i, j)\) (integer).
\( tr_i \) number of router ports or transponders at node \( i \) (integer).

\( ENS_i \) non-renewable energy consumption at node \( i \) in a day (real). Note that the minimum value of non-renewable energy consumption at node \( i \) in a certain day can be zero if the renewable energy sources can supply entire energy needed at that node without consuming any non-renewable energy.

C. Objective

Minimize \( \sum_{i \in \mathcal{N}} ENS_i \) (Minimize the total non-renewable energy consumption of the network in a day)
D. Constraints

\[
\sum_{i \in N} \sum_{d=1}^{D} \lambda_{ij}^{sd} - \sum_{j \in N} \sum_{i=1}^{D} \lambda_{ij}^{sd} = \begin{cases} 
\lambda_{ij}^{sd} & i = s \\
-\lambda_{ij}^{sd} & i = d \\
0 & \text{otherwise} 
\end{cases}
\]  
\forall s,d,i \in N: s \neq d 
\tag{1}

\[
\sum_{i,j \in N} \sum_{d=1}^{D} \lambda_{ij}^{sd} \leq B \cdot v_{ij} 
\forall i,j \in N: i \neq j 
\tag{2}
\]

\[
\lambda_{ij}^{sd} = \lambda_{js}^{di} 
\forall i,j,s,d \in N: i \neq j, s \neq d 
\tag{3}
\]

\[
v_{ij} = v_{ji} 
\forall i,j \in N: i \neq j 
\tag{4}
\]

\[
\sum_{i \in N} v_{ij} = tr_t 
\forall i \in N 
\tag{5}
\]

\[
ENS_i + ES_i \geq tr_t \cdot (E_r + E_e) 
\forall i \in N 
\tag{6}
\]

Constraint (1) is the flow conservation constraint in the IP layer. Constraint (2) ensures that each virtual link has sufficient capacity to carry the traffic flows. Constraint (3) says that traffic flows are bi-directional in the network and constraint (4) ensures that the virtual links in the IP layer are bi-directional. Constraint (5) counts the total number of router ports or transponders at each node. The last constraint ensures that the total energy supply including renewable energy and non-renewable energy at each node can satisfy the total energy consumption of the network node. Note that in this paper, we measure the energy consumption of only the two most energy-hungry devices (i.e., router port and transponder) [3] as the total energy consumption of the transparent IP over WDM networks.

IV. RENEWABLE ENERGY AND TEST CONDITIONS

We assume that each network node can configure solar panels and wind turbines to generate renewable energy when the weather conditions permit [17]. The metrics of sky cover (i.e., cloud cover) and wind speed are considered as the most important factors in the energy harvested from solar panels and wind turbines, respectively [18].

Typically, a one square meter silicon solar cell can produce about 0.28 kW of power on a completely sunny day (i.e., sky cover equal to 0%) [16], and generates no solar power on a completely cloudy day (i.e., sky cover equal to 100%). Using this, we assume that the solar energy harvested in a day is proportional to the sky cover conditions on that day (i.e., $P = 0.28 \times (1 - \text{sky cover})$). For example, if the sky cover is 30%, then one square meter silicon solar cell will produce $0.28 \times (1 - 0.30) = 0.196$ kW energy in a day. The wind power harvested is given by $P = \frac{1}{2} \rho A \nu^3$, where $A$ is the effective windward area, $\rho$ is the density of air and $\nu$ is wind speed [14].

We assume that the area of silicon solar panels and the effective windward area configured at each node are 100 square meters. Therefore, according to the weather reports for sky cover and wind speed available at the location of each network node from National Weather Service (NWS) forecasts [19], we can estimate the solar and wind energy that would be available at each node on that day (i.e., parameter $ES_i$).

The 14-node 21-link NSFNET network and 24-node 43-link US backbone network (USNET) are considered as the test networks in this paper and shown in Fig. 3. Table I shows the weather conditions (i.e., sky cover and wind speed) and the renewable energy outputs (i.e., sum of the solar and wind energy) on May 1st, 2013 at each node location of the NSFNET network. Table II shows the case of the USNET network on May 7th, 2013. From these tables, we can see that the outputs of solar and wind energy in a day are different for different nodes due to different weather conditions at each node location. Table III shows the weather conditions and renewable energy outputs from May 1st to May 7th, 2013 at node N1 of NSFNET network (i.e., Seattle, WA). It indicates that the outputs of solar and wind energy vary across different days due to the weather change.
The traffic demand between each node pair is a uniformly distributed random variable over a given range, i.e., centered at its average as in [6]. For example, given an average demand intensity \( X = 40 \) Gb/s, the actual demand between each node pair is generated by a random function uniformly distributed with the range \([10, 2X-10]\), i.e., \([10, 70]\) Gb/s for \( X = 40 \). The average demand intensity is set as \( X = 40 \) Gb/s for NSFNET network and \( X = 20 \) Gb/s for USNET network in this paper. The capacity of each wavelength is assumed to be 40 Gb/s (i.e., \( B = 40 \)). According to the Cisco CRS-1 carrier routing system [20], the power consumption of a 40-Gb/s router port is about 600 W and its energy consumption in a day is 14.4 kW (i.e., \( E_r = 14.4 \)). The power consumption of a 40 Gb/s transponder is assumed to be 125 W [21] and its energy consumption in a day is 3 kW (i.e., \( E_t = 3 \)).

### V. Numerical Results

Fig. 4 (a) shows the total non-renewable energy consumption in the network from May 1st to May 7th of the NSFNET network. The “Follow” in the legend means the design method of “follow the sun, follow the wind” and the “Energy-min” is the design approach of minimizing the total energy consumption in the entire network [6]. Note that the two approaches measure the non-renewable energy in the same way, i.e., the total non-renewable energy consumption in the network is the sum of the non-renewable energy consumption at each node and the minimum value of non-renewable energy consumption at each node is zero if the node can provide sufficient renewable energy. From Fig. 4 (a), we can see that the “Energy-min” approach always consumes more non-renewable energy than the “follow the sun, follow the wind” approach as the latter follows the state of renewable energy available at the nodes (as for the example network of Fig. 2). As shown in Fig. 5 (a), this latter approach can save up to 50% non-renewable energy consumption on a given day compared to the “Energy-min” method. In addition, we can see that total non-renewable energy consumption and the percentages of non-renewable energy saving at different days vary greatly due to the changing output of renewable energy at different nodes on different days.

Similar observations can be made for the larger USNET network as shown in Fig. 4 (b) and Fig. 5 (b). The “follow the sun, follow the wind” approach can save up to 68% non-renewable energy consumption on May 1st compared to the “Energy-min” approach. In addition, according to Fig. 5 (a) and Fig. 5 (b), we can see that there seems no direct association between the percentages of non-renewable energy reduction and network size. The percentages of non-renewable energy saving vary only according to the outputs of renewable energy at different nodes.
Fig. 4: Total non-renewable energy consumption at different days.

Fig. 5: Percentages of non-renewable energy saving at different days.

Fig. 6 (a) shows the relationship between renewable energy available and the number of established lightpaths at each node on May 1st 2013 for the NSFNET network. The plot with the “square” symbol is the amount of renewable energy available at each node. The plots with the “circle” and “triangle” symbols are the number of established lightpaths at each node according to different design approaches, respectively. From this figure, we can see that the “follow the sun, follow the wind” method is able to serve the network traffic according to the renewable energy available, i.e., establish more lightpaths at a node if it has sufficient renewable energy so as to reduce the consumption of non-renewable energy at other nodes. Specially, node N6 is found to have the highest renewable energy and therefore establishes the largest number of lightpaths. Here the nodes with sufficient renewable energy act like the central nodes of the network so as to reduce non-renewable energy consumption at the other nodes. In contract, the “Energy-min” approach does not have this feature and establishes the lightpaths according to the traffic matrix ignoring completely the state of renewable energy available at the nodes of the network. Fig. 6 (b) shows the corresponding results for the USNET network, which are similar to the NSFNET network; here node N11 shows the highest renewable energy and therefore establishes the largest number of lightpaths.

Fig. 7 shows the total renewable energy consumption in the network from May 1st to May 7th. We can see that the “follow the sun, follow the wind” method always consumes more renewable energy than the “Energy-minimized” approach. This implies that the “follow the sun, follow the wind” method can take full advantage of the renewable energy which is generated in a distributed fashion at different nodes around the entire network.
the example scenarios considered here compared with an
method can save up to 50% or more non-renewable energy in
distributed fashion over large geographical networks.
time to implement such energy saving algorithms in a
algorithms to simplify the computation effort and computation
learning. We also plan to introduce effective heuristic
to predict the output of solar energy and wind energy in
designs the IP over WDM networks considering the available
energy-minimized design approach. In our future work, we
introduced at each node location to reduce the GHG emissions
state of renewable energy at each network node location as
A “follow the sun, follow the wind” design approach. This
example scenarios considered here compared with an
energy-minimized design approach. In our future work, we
intend to predict the output of solar energy and wind energy in
a more refined fashion by employing tools such as machine
learning. We also plan to introduce effective heuristic
algorithms to simplify the computation effort and computation
time to implement such energy saving algorithms in a
distributed fashion over large geographical networks.

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REFERENCES
[3] C. Stewart and K. Shen, “Some joules are more precious than others:
managing renewable energy in the datacenter,” in Proc. Proceedings of
Minaoves, A. Pastrama, and W. V. Heddeghem, “Renewable energy
provisioning for ICT services in a future internet,” Lecture Notes in
routing algorithms for cloud computing services in IP-over-WDM
“Power awareness in network design and routing,” in Proc. INFOCOM,
minimized virtual topology design in IP over WDM backbone networks,”
IET optoelectronics. vol. 6, no. 4, pp. 165-172, Aug. 2012.
“Converged optical network infrastructures in support of furture internet
and grid services using IaaS to reduce GHG emissions,” J. Lightw.
Demeester, “Distributed computing for carbon footprint reduction by
exploiting low-footprint energy availability,” Future Generation
efficiency in telecom optical networks,” IEEE Communications Surveys &
generation from weather forecasts using machine learning,” in Proc.
“On the design of energy-efficient mixed-line-rate (MLR) optical
networks employing renewable energy sources,” J. Lightw. Technol.,
vol. 29, no. 1, Jan. 2011.
renewable energy plants functioning in electrical power network,” in Proc.
[18] N. Sharma, J. Gummesson, D. Irwin, and P. Shenoy, “Cloudy computing:
leveraging weather forecasts in energy harvesting sensor system,” in Proc.
Buchali, E. Varvarigos, and I. Tomkos, “Spectrum, cost and energy
efficiency in fixed-grid and flex-grid networks,” in Proc. OFC/NFOEC,