Low-Emissions Routing for Cloud Computing in IP-over-WDM Networks with Data Centers

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I. Introduction

INFORMATION and Communication Technology (ICT) industry is rapidly developing worldwide, and this growth is inevitably associated to an increase of its carbon emissions. Ref. [2] estimates that the ICT industry is responsible for 2% of the world's CO_2 emission and, based on 2009 data, ICT consumes about 8% of total electricity worldwide. ICT has been recognized as the key to a low-carbon economy and it has been estimated that ICT could reduce CO_2 emissions in other sectors of approximately five times as much as the ICT's own emissions and deliver about 1/3 of the expected total abatements in 2020 [3].

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Energy consumption of telecom networks, which represent a significant part of the overall ICT energy consumption, is also growing due to the current sustained traffic increase. In particular, the power consumption of *Data Centers* (DCs) is rapidly increasing, fueled by the growth of video distribution, and other data-intensive applications such as medical informatics, genomic, financial, and, more generically, *Cloud Computing* (CC) services. There is a growing consensus in our society to consider energy conservation and CO_2 reduction as a primary design target for telecom networks and data centers.

Recently, significant research efforts have addressed the reduction of energy consumption of telecommunications networks, and specifically optical core networks which are the major focus of this work (see, e.g., [4], [5]). Only few works so far have directly addressed the issue of directly minimizing CO_2 emissions (which is a different target than minimizing overall energy consumption, especially when renewable energies come to play) in the design and operation of an optical network. Some research projects in the last years have been investigating how to utilize renewable energies in the network infrastructure. One of the most relevant is the GreenStar Network (GSN) project [6]; GSN is a green cyber-infrastructure testbed designed to maximize the utilization of renewable energies through "follow the wind, follow the sun" networks. Several zero-carbon energy sites have been selected for the location of network and computing resources and the project is aimed at creating technology and standards for reducing the carbon footprint of telecom network.

Similarly, in this paper we consider a scenario of an IP-over-WDM network interconnecting a set of geographically distributed DCs (also called DC federation). DCs can be either *brown-powered* (i.e., powered by energy produced through fossil fuels) or *green co-powered*, (i.e., DC is co-located with a renewable energy plant which provides green energy to the DC). Since the production of renewable energy is variable in time, the green DCs are also provided with brown energy supply to be used when green energy is not available.

The goal of this paper is to devise novel routing algorithms that allow us to reduce the CO_2 emissions of the DCs connected to IP-over-WDM networks, or, in other words, that allow to minimize the utilization of brown energies in the DCs. This means that routing should be performed such that utilization of green co-powered DCs is maximized in those periods when they have availability of green energy.

As a first contribution and preliminary analysis for the rest of the paper, we model the various terms of power consumption of an IP-over-WDM network interconnecting DCs. We provide: i) an approximated formula to estimate the energy consumption of a specific case of a cloud-computing service, called Processing as a Service; ii) a case-study dimensioning of the size and capacity of renewable energy plants (wind and solar) to power an entire DC subject to a certain traffic; iii) a set of formulas to capture the energy consumption of different IP-over-WDM transport network architectures. We also perform an analysis on regular networks to evaluate how some important network parameters can affect our work. The objective of this preliminary phase is to evaluate how convenient is to transport bits to remotely located green DCs, instead of routing data to brown DCs closer to users.

Then, as a main contribution of the paper, we propose and evaluate two new routing strategies, designed to route optical connections supporting (aggregation of) CC service requests, that are able to follow the current availability of renewable energy and consequently to reduce the CO_2 emissions. Note that, in order to move this huge amount of data towards (usually) remote locations, the energy consumption for the data transfer arises and it may neutralize all the savings in terms of CO_2 emissions coming from using renewable energy. So our algorithms are designed to carefully address the trade-off between the energy consumption of data transport and the energy consumption to process the CC requests inside DCs. We consider here a dynamic-traffic scenario where anycast routing is adopted to perform joint assignment of the routing and of the serving data center. Also we consider different options in terms of network transport technology, traffic profile and network topology. Results show that our approach can achieve significant reduction in CO_2 emissions, up to about 30%, with only a limited penalty on other performance metrics such as blocking probability or delay.

The rest of the paper is structured as follows. Section II describes some relevant background works for this study. Section III briefs the energy model for the IP-over-WDM network, the Cloud Computing services and the dimensioning of renewable power plants for the DCs. In Section IV we perform an analytical study to evaluate the effect of some important network parameters on the rerouting of data processing towards green DCs on regular network topologies. The two routing algorithms for CO_2-reduction are introduced in Section V. Simulation results for the proposed algorithms are reported and discussed in Section VI. The conclusion of the paper is drawn in Section VII.

II. Related Works

In this section we discuss some previous studies that are related to our current proposal. An important research line, recently emerged, concerns the reduction of CO_2 emissions generated by telecom networks. Among the first to provide contributions on this topic, authors in [7] and [8] propose an approach to reduce CO_2 emissions in IP over WDM networks (with or without data centers) by using renewable energy sources. They develop a Linear Programming (LP) model for a network design that minimizes CO_2 emissions (low-carbon design) and propose a heuristic to increase renewable energy utilization. A similar problem is addressed in [9], where authors provide the formal problem formulation for several energy-aware static routing and wavelength assignment (RWA) strategies for WDM networks powered either by renewable or by brown energy sources. In [10], authors propose a solution for determining the optimal placement of services in a data-center network, in order to maximize the overall renewable energy usage and minimize the cooling energy consumption. In general, the energy efficiency of integrated DC and optical network infrastructures has been investigated (see. e.g., [11]), but here we focus more on CO_2 reduction aspects of the problem. Ref. [12] provides an overview on two issues related to achieving carbon abatements in ICT: first, some green communications research challenges are discussed; then some methodologies that accurately quantify the carbon abatement potential of ICT are described. The utilization of renewable sources in ICT is also discussed in [13].

The more general theme of anycast routing is also very relevant for our proposed algorithms. Recently, due to the application of anycast routing for CC traffic, the topic has revived. For example in [14], authors propose anycast routing methods to improve the performance of reconfigurable WDM networks under the variations in the IP traffic. In [15], authors show that the anycast routing problem can be reduced to unicast routing. Since in our proposed algorithms we apply also some degree of load balancing, some other relevant references are [5] and [16]. In [5], the author proposes a novel energy-efficient dynamic provisioning scheme by using an intelligent load control mechanism and an auxiliary graph model. In [16], a new algorithm for dynamic traffic grooming is introduced aiming at load-balancing among existing lightpaths to avoid the generation of bottlenecks.

III. Services and Energy Models

In this section, i) we describe the model evaluating the energy consumption of a specific CC service, ii) we perform a simple dimensioning for wind and solar power plants in order to show that a plant of practical dimension can power a data center, and iii) we provide energy models for the transport network. All the three models will be useful for our numerical considerations in Section VI.

A. The Cloud services Energy Model

In our simplified model for CC services, every connection request coming from users is a Cloud request. Various cloud services could be considered, e.g., Storage as a Service (S_taaS), Processing as a Service (PaaS) or Software as a Service (SaaS) [17]; in the following, as a case study, we focus on the PaaS case, for which we calculate the power consumption necessary to process the request inside a data center for every single connection at 10 Gbit/s, deriving our analysis from [17].

In the cloud, DCs are used to serve cloud tasks such as PaaS tasks. Data are uploaded to a cloud DC, and the completed output is returned to the user. As an example of a computationally-intensive PaaS task, we model the task of converting and compressing a video file. To start, we model the power consumption of a computational server, whose per-user energy consumption (Watt-hours) E_{proc} of the processing service is:

$$E_{proc} = 1.5 \cdot T_{proc} \cdot P_{ps,SR} \qquad (1)$$

where $P_{ps,SR}$ is the power consumption of the server (355 W, as in the HP DL380 G5 [17]), and T_{proc} is the average number of hours it takes to perform one video file encoding. A factor of 1.5 is included to account for the energy consumed to cool the computation servers, as well as other overheads. Let us now consider the processing of a 2.5-h DVD-sized video stored in MPEG-2 (8.54 GByte, i.e., 68.32 Gbit) and encoding it into the H.264 (MPEG-4 Part 10) format. According to the measurements in [17], the encoding performed by a server of such a 68.32 Gbit video file takes 1.25 h. We can say that encoding 10 Gbit (i.e., the amount of data delivered in one second by a 10 Gbit/s lightpath, as in our following simulations) would take 0.183 h. Substituting the values in eqn. (1) we obtain $E_{proc} = 97.4$ Watt-hour ≈ 100 Watt-hour and then multiplied for connection's holding time will give the total energy consumption. Note that it is implicitly assumed here that the $Eproc$ value is valid across all data centers and all tasks in a specific time interval are run in parallel.

Given this Cloud service power model and the amount of data delivered at a DC in a certain interval of time, we can calculate how many servers at full load are needed to support a certain load, and so their overall energy consumption. We assume here that the DC is enabled with some green server management, such that only the servers that are needed to process data in a specific period of time are kept awake and used (many proposals to implement such strategies of server/rack consolidation have been already discussed and demonstrated, see, e.g., [18]). Based on this assumption, we can consider as negligible the load proportionality of the server energy consumption.

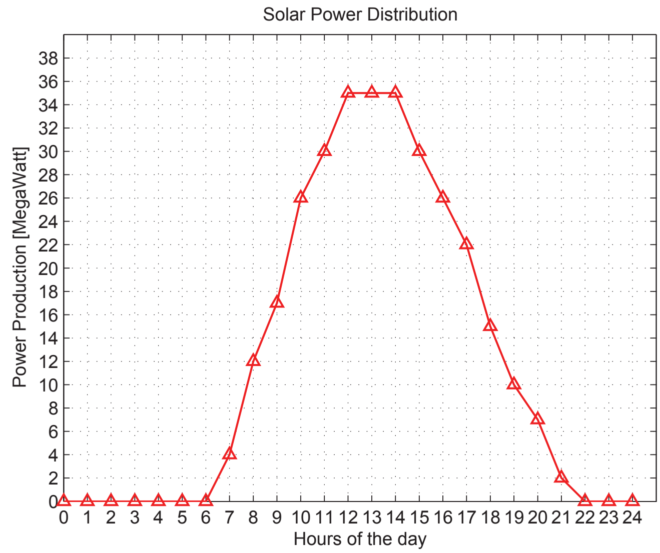
B. The Renewable Energy Model

Another important aspect of our study is the dimensioning of renewable energy sources. We need to power some of the DCs in the IP-over-WDM network by using renewable energy in order to reduce the CO_2 emissions. The main problem of renewable energy is that its generation is subject to relevant variability during the day (and along the seasons) depending mainly on weather conditions.

A possible profile of the solar energy power availability is shown in Fig. 1(a) as in [7]. The solar energy output is non-zero from 6:00 to 22:00 and the maximum output power occurs at 12:00. A possible profile of the wind power available to a data center is shown in Fig. 1(b), extrapolated from data in [19]. Wind presents more variability compared with the sun and it is quite difficult to predict. So the wind-intensity profile used in our numerical experiments follows an arbitrary profile. In practice this profile would differ according to seasons, geographical position, weather conditions, etc. As geographical location of data centers has impact on the generated renewable energy, we have also considered that different DCs can be located in different time zones. Note that this is one possible (and realistic) wind and solar distribution used to test our algorithms, but our algorithm can work with any power distribution.

C. Transport Energy Model

We consider in our study three different IP-over-WDM network architectures: *IP basic*, *IP-over-WDM Opaque* and



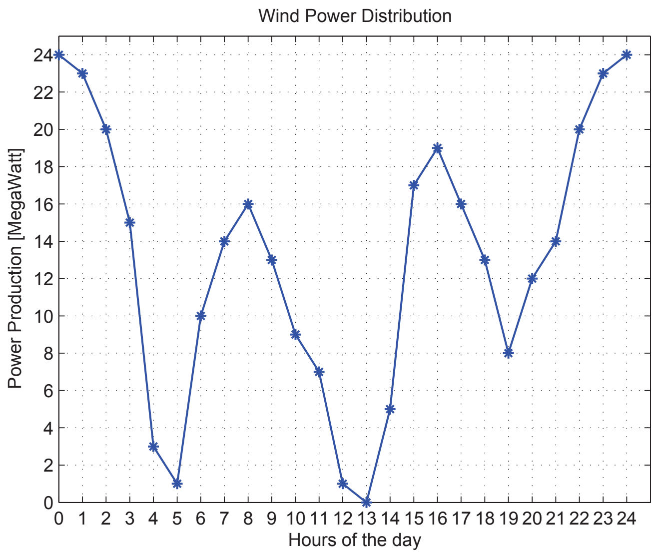


Fig. 1. Solar (a) and Wind (b) Power Distribution

IP-over-SDH-over-WDM according to the models presented in [20]. Each of them has a different power contribution for connection transport and switching.

IP basic: in the IP basic architecture, the IP routers are interconnected by point-to-point optical fiber links; both switching and grooming of traffic are accomplished in the electronic domain, thus all traffic flows are electronically processed in every node. Therefore, in this architecture, we can neglect the optical switching power contribution. The transport power for this architecture is calculated as follows:

$$P_{T,IP} = 2 \cdot H \cdot P_{tr1} + (H - 1) \cdot P_{IP}$$

where H is the hop number (number of links crossed), P_{tr1} and P_{IP} represent the power of transponders and electronic processing. Electronic processing accounts for the router line and switching cards power contribution, according to the energy consumption modeling proposed in [20]. Note that in

TABLE I
POWER CONTRIBUTIONS OF NETWORK ELEMENTS [20]

Network Equipment	Power [W]
Transponder P_{tr1}	34.5
Transponder P_{tr2}	16.25
Short-Reach interface P_{SR}	16.25
Optical Switching P_O	1.5
Digital Cross Connect P_{SDH}	18.75
Electronic Processing P_{IP}	145

case of H=1, the power P_{IP} contribution is set to zero, as there is no intermediate IP router along the path.

IP-over-SDH-over-WDM: in this architecture, IP flows are mapped into SDH frames (i.e., virtual circuits, or VCs) and then the electronic signals are transferred into the WDM channels through transponders. Optical circuits are terminated at each node where OE conversions are performed. The Digital Cross Connect (DXC) provides for switching VCs without performing neither grooming nor degrooming of traffic flows, which are aggregated, when needed, at the IP layer. The transport power is calculated as follows:

$$P_{T,SDH} = 2 \cdot H \cdot P_{tr2} + (H+1) \cdot P_{SDH} + 4 \cdot P_{SR}$$

where H is the hop number, P_{tr2}, P_{SDH} and P_{SR} are the power contributions due to transponders, Digital Cross Connect and short-reach interfaces (the interfaces interconnecting the IP router and the SDH DXC).

IP-over-WDM Opaque: in Opaque configurations transponders perform OEO conversion and signal regeneration, in each node an OXC is connected to the IP router via short-reach interfaces. Electronic processing is performed only if grooming of traffic is needed. So transport power becomes:

$$P_{T,OP} = 2 \cdot H \cdot P_{tr2} + (H+1) \cdot P_0 + 2 \cdot P_{SR}$$

where H is the hop number, P_{tr2}, P_0 and P_{SR} are the power contributions due to transponders, optical switching and short-reach interfaces (only at the source and destination nodes). Tab. I shows the power contributions of transport and switching network elements considering a 10 Gbit/s lighpath.

IV. REGULAR NETWORKS ANALYSIS

Before we illustrate our routing algorithms, we analytically study which are the network parameters that mostly affect the routing towards DCs powered by renewable energy. We compare the amount of brown energy (i.e., the amount of emissions) consumed by a shortest-path-based routing strategy which chooses the closest DC (which we assume to be brown-powered) vs. a renewable-energy-aware routing strategy, which takes a longer route (incurring in larger transport energy), but it delivers data in a green-powered DC. So, we devise some analytical formulas that capture the trade-off between the two algorithms as a function of network parameters.

The objective is to derive under which condition one strategy is more effective that the other one in terms of total CO_2 emissions. In formulas, such condition can be expressed by this simple equation $p_G - p_{SP} < p_p$ where p_G is the transport power consumption for renewable energy-aware (Green) algorithm and p_{SP} is the transport power consumption for shortest path algorithm; p_p is the brown processing power consumption. We expect p_G to be larger than p_{SP} as the route is typically longer. Expanding the terms of the equation below with, for example, the power transport contributions for an opaque configuration (see subsection III-C), we obtain:

$$2 \cdot H_G \cdot P_{tr} + (H_G+1) \cdot P_O + 2 \cdot P_{SR} - 2 \cdot H_{SP} \cdot P_{tr} + \\ -(H_{SP}+1) \cdot P_O - 2 \cdot P_{SR} < p_p$$

and then:

$$H_G - H_{SP} < \frac{p_p}{2 \cdot P_{tr} + P_O}$$

where the term H_{SP} represents the number of links to reach the nearest data center through the shortest path, and H_G is the number of network links needed to reach a data center with renewable energy. The last step shows that the performance of a renewable energy-aware algorithm is strictly dependent on the path hop difference $\Delta H = H_G - H_{SP}$. In a real network, ΔH depends on various network parameters, namely: the number K of data centers (out of which K_g are powered by renewable energy), the number of network nodes N, the average inter-data centers distance D (with D_{max} and D_{min} maximum and minimum distance) and nodal degree R. In the following we provide a analytical study where the relation of ΔH as a function of (K, N, D, R) are captured in closed-form expressions. To derive these formulas we assume regular networks with varying number of nodes (i.e., $N = 8, 12, 16$), nodal degree $R = 2, 3, 5, N-1$ ($N-1$ varies according to the topology, and it corresponds to the case of full-mesh topology) and number of data centers $K = 2, 3, 4$. Due to space limitations, we show in Fig. 2 the regular networks in the case of $N = 12$ and $R = 2, 3, 5$ (DCs are indicated with a circle around the node, and the circle is darker for brown-energy powered DCs and lighter if powered by renewable energies). To obtain the topologies in the case of $N = 8$ and $N = 16$, consider that each side of the squares in Fig. 2 is composed of 3 and 5 nodes, respectively, instead of 4.

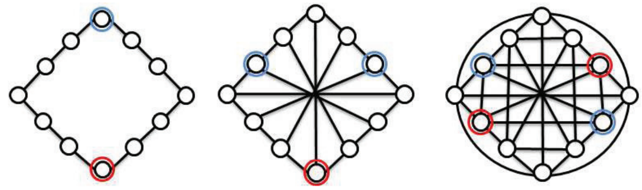


Fig. 2. Example of regular network topologies with data centers

In the case of network configurations with 2, 3[1], or 4 DCs, we obtain the following formulas, shown in Tab. II, for varying network nodes number N and nodal degree R (symbol "-" means that no closed-form formula has been found).

In the upper graph of Fig. IV, we plot the metric ΔH as a function of the connectivity index I, defined as the fraction between nodal degree and the number of network nodes, $I = R/N$. We report results only for N= 16. The largest

[1]In order to calculate H_{SP} with 3 data centers (see Table II), if D_{max} is odd, then $D_{max}/2$ is rounded to the lower integer and the term $D_{max}/2$ inside the brackets is not subtracted.

TABLE II
EXPLICIT FORMULAS FOR H_{SP} AND H_G WITH K=2,3,4 DATA CENTERS.

K=2	R=2	R=3	R=5	N-1
H_{SP}	$\frac{\sum_{n=1}^{N/4} n + \sum_{n=1}^{N/4-1} n}{N/2}$	$\frac{\sum_{n=1}^{N/4} n + \sum_{n=1}^{N/4-1} n}{N/2}$	$\frac{N-G}{N/2}$	$\frac{N-K}{N}$
H_G	$\frac{2 \cdot \sum_{n=1}^{D_{max}} n - D_{max}}{N}$	$\frac{4 \cdot \sum_{n=1}^{N/4} n - D_{max}}{N}$	-	$\frac{N-K_g}{N}$

K=3	R=2	N-1
H_{SP}	$\frac{2 \cdot (2 \cdot \sum_{n=1}^{D_{max}/2} n - D_{max}/2) + 2 \cdot \sum_{n=1}^{D_{min}/2} n - D_{min}/2}{N}$	$\frac{N-K}{N}$
H_G	$\frac{2 \cdot \sum_{n=1}^{D_{max}} n - D_{max} + 2 \cdot \sum_{n=1}^{D_{min}/2} n - D_{min}/2}{N}$	$\frac{N-K_g}{N}$

K=4	R=2	R=3	R=5	N-1
H_{SP}	$\frac{N/2 + 2 \cdot (N/2 - K)}{N}$	see R=2	see R=2	$\frac{N-K}{N}$
H_G	$\frac{\sum_{n=1}^{N/4} n + \sum_{n=1}^{N/4-1} n}{N/2}$	$\frac{\sum_{n=1}^{N/4} n + \sum_{n=1}^{N/4-1} n}{N/2}$	-	$\frac{N-K_g}{N}$

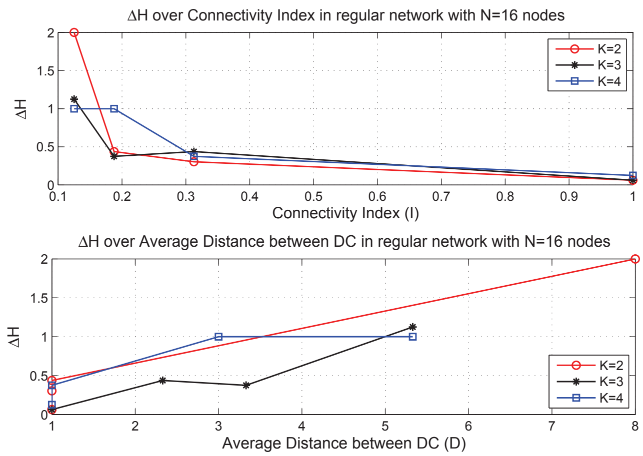


Fig. 3. Analysis of ΔH in function of different network parameters.

gap is obtained with 2 data centers and very low connectivity index; as in this case average node connectivity is very low, the additional hops needed to reach a renewable-energy DCs significantly increase ΔH. Considering 2 renewable-energy-powered DCs, in a configuration with 3-DCs ΔH values are lower than in a 4-DCs configuration. In the lower graph of Fig. 3 ΔH is plotted in function of the average distance between data centers D. The minimum value for ΔH is obtained with a full meshed network (nodal degree $N-1$) and this time ΔH values are always lower than 1.5 for each N and K.

V. ALGORITHMS FOR CO_2 EMISSIONS REDUCTION

A. Problem definition

We consider the problem of routing dynamic connection requests in IP-over-WDM network architectures, considering renewable-energy powered DCs. Each connection request has to be mapped over an optical circuit (or lightpath) and must be served by a DC that has to process the CC-service requests. The problem can be stated as follows:

Given:

- Dynamic connection requests to be established;
- Physical topology;
- Number of wavelength channels per fiber;
- Current network state (information on existing lightpaths, number of used wavelengths);

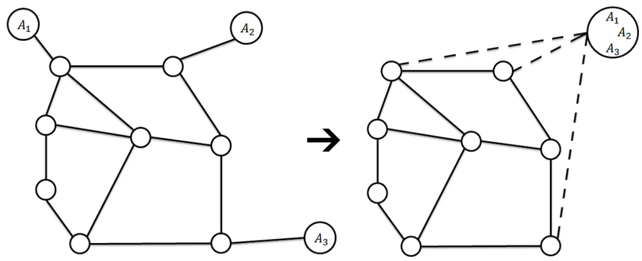


Fig. 4. Physical network graph VS Auxiliary graph.

- Number of data centers k, their position and their daily renewable-energy availability;
- Power consumption parameters: p_p processing power ,P_k current available renewable energy, P_t transport power.

The goal is to determine:

- The route that minimizes the CO_2 emissions (promoting renewable-energy utilization);
- The data center chosen to process the user's request.

Under the following constraints:

- each connection request should be originated at its source node and terminated in one of the DCs;
- traffic on a link should be limited by link capacity.

Physical topology is described by a graph $G = (V, E, C, \lambda)$, where V is a the set of nodes, E the set of edges, C is the wavelength-channel capacity and λ is number of wavelengths on the link; the connection requests follow a given traffic profile and for each connection $c = \langle s, B, t_h \rangle$, s is the starting time, B is the requested bandwidth and t_h is the holding time.

Note that power consumption comes from: 1. transport power, needed to move traffic, 2. processing power at the DCs. While transport energy is always from not renewable sources (i.e., "brown" energy), processing energy can be either green (when renewable energy sources are active) or brown (when renewable sources are either inactive or not present).

B. Anycast Routing

In an IP-over-WDM network with DCs supporting CC services, each node is a possible source of a CC request and each DC is a possible destination where the connection can be processed, i.e. we assume that the contents that users want to access are replicated inside all the DCs. Consequently, an *Anycast Routing* [14] problem arises. In fact, in a Cloud scenario, a user's interest typically lies in successful job execution subject to certain predetermined requirements, but, since multiple processing locations exist in the network, the exact location and network route used is of less importance to the end user. Anycast routing specifically enables users to transmit data for processing and service delivery, without assigning an explicit destination. The destination can be anyone among a set of nodes associated to the DCs. To solve the anycast routing problem and transform it into an unicast routing problem we introduce in our work an anycast abstraction of the topology. From a routing perspective, all the network nodes A_j that host a DC are connected to an additional virtual anycast node A, called *Dummy Node*, as depicted in Fig. 4. Each user will then route towards the Dummy Node, i.e. the virtual destination, while the actual destination will be the last DC traversed before reaching the dummy node. In the following, the graph originating from the combination of the original graph, the dummy node and the so called anycast links (that connect DCs to the dummy node) will be referred to as "auxiliary graph". Note that the capacity of anycast links is set to a value large enough not to enforce any actual capacity constraint on the number of connections supported over them.

C. SWEAR

The first proposed algorithm is called SWEAR, Sun-And-Wind Energy-Aware Routing. SWEAR is designed to promote the choice of a renewable-energy powered DC (end-node) based on its current renewable-energy availability; it also attempts to perform load balancing [16] on network links. In brief, the algorithm compares two candidate paths: the one with lowest transport-power consumption (i.e., minimal power needed to transport the data) and the one with maximum usage of renewable energy. If the increase in transport power of the second option is compensated by the utilization of renewable energy, the second option is chosen. The detailed metacode for algorithm SWEAR is shown in Tab. III. Note that SWEAR besides the input parameters defined in Subsection 5.1, requires an additional parameter, the threshold T.

Let us discuss a brief example to explain how SWEAR works and how it routes each connection. We suppose that a connection request $c_1 = \langle 1, 10Gbps, 1\rangle$ (i.e., connection c_1 is originated at node 1, requires a 10Gbps bandwidth, and has duration $t_h = 1s$) arrives at time t_1. A possible way to route the connection c_1 with SWEAR is shown in Fig. 5a. c_1 can be routed towards any of the data centers in the network, i.e., DC_1, DC_2 or DC_3. SWEAR first evaluates the renewable energy availability in each DC: in our example DC_1 has only non renewable energy, DC_2 has solar renewable energy and DC_3 has wind renewable energy. Let us assume that DC_2 has higher availability of renewable energy than DC_3, so lighpath l_{g1} is routed to DC_2 thorough the route $1-4-3-DC_2$, requiring overall 110 Watt for transport and switching (and 0 Watt of brown energy at DC_2). This lightpath is compared with lightpath l_{s1}, obtained with a simple shortest-path algorithm, which leads the connection request to be processed by DC_1 through the path $1-2-DC_1$. Path l_{s1} consumes 72 Watt for data transport and switching (less than l_{g1}), but it requires 100 W at DC_1 for data processing (more than l_{g1}). So, considering the total CO_2 emissions, the best path is l_{g1}, which uses renewable power but it does not exceed in transport power.

Now we consider another connection request $c_2 = \langle 1, 10Gbps, 1\rangle$ arriving at time $t_2 > t_1$. We suppose that DC_2 has ran out of renewable energy, instead in DC_3 renewable energy is still available. The path selected for lighpath l_{g2} is, for example, $1-4-5-6-7-DC_3$ and requires a transport power of 186 Watt. Note that there is a load balancing phase that promote the choice of low-loaded links: in particular, link 1-5 has overcome the load threshold so it is not used. This lightpath is compared with lightpath l_{s2}, obtained with a simple shortest-path algorithm, which leads the connection request to be processed by DC_1 through the path $1-2-DC_1$ consuming 72 Watt. Now we evaluate the power gap between l_{g2} and l_{s2}: this time we obtain 114 Watt, which is bigger than the connection processing power (100 W), so, considering the total CO_2 emissions, the choice of a renewable energy data center is not the optimum and the path l_{s2}, which does not use renewable power but it has a much lower transport power consumption, is chosen.

TABLE III
SWEAR METACODE

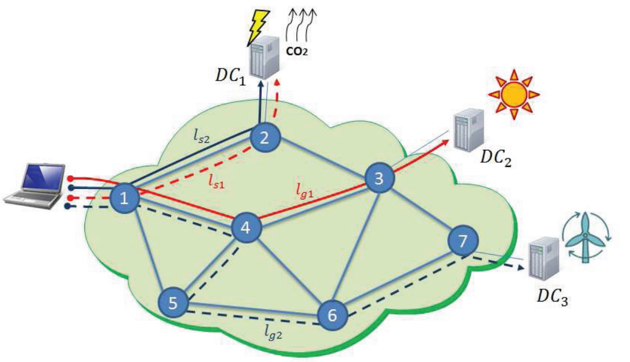
Algorithm 1 - SWEAR

Input: $G = (V, E, C, \lambda)$, $c = \langle s, B, t_h\rangle$, k, P_k, T, p_p
Output: Path with maximum usage of renewable energy considering a trade-off with transport energy. The data center chosen to process the user's request.

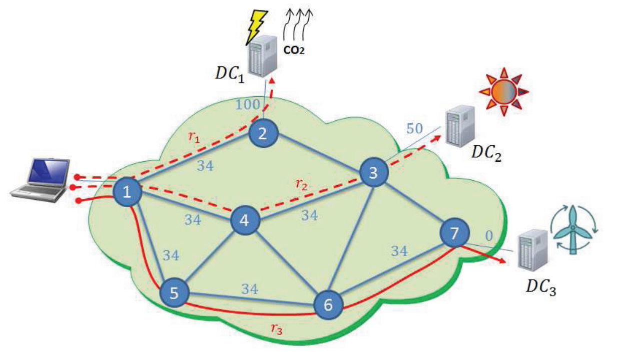
1) Build auxiliary graph $G' = (V, E)$ with transport links and anycast links.
2) Weight assignment for transport links: check the load on transport links (Load Balancing phase):
   a. for every transport link, calculate $L_{xy} = \dfrac{(\lambda - \lambda_{xy})}{\lambda}$, where λ_{xy} is the number of free wavelengths;
   b. if $L_{xy} > T$, then the weight assigned to transport link is $c_{xy} = L_{xy}$;
   c. else: the weight assigned to the link is $c_{xy} = 1$.
3) Weight assignment for anycast links: verify which DC among the K DCs has enough renewable energy to process the connection and assign weights consequently:
   a. calculate the threshold S, as the product of the holding time t_h and the processing energy consumption of the connection p_p, hence $S = p_p \cdot t_h$;
   b. if $P_k < S$ then the weight of the anycast link is $d_{kd} = M \cdot p_p$, with M is large number (large enough to discourage, but not impede, the utilization of the link);
   c. else: assign the weight $d_{kd} = \dfrac{(P_k^h - P_k)}{P_k^h}$, i.e., the energy utilized by the DC, normalized to the starting available energy at hour h.
4) Once weights have been assigned according to step 2 and 3:
   a. calculate the shortest path l_g;
   b. for path l_g, calculate the transport energy cost t_g for the connection.
5) Assign value 1 to all the weights in G':
   a. $c_{xy} = 1$ and $d_{kd} = 1$ for all the links;
   b. calculate the shortest path l_s;
   c. for path l_g, calculate the energy cost t_s to transport the connection.
6) Compare the two paths:
   a. calculate $\Delta_t = t_g - t_s$, as the difference between the two transport energy cost;
   b. if Δ_t is lower than the threshold S, choose path l_g;
   c. else: choose path l_s.
7) If at least one path exists, then allocate resources, set up the new lightpath and update network's status. Else block the connection and exit.

D. GEAR

The second proposed algorithm is called GEAR, Green-Energy-Aware Routing. The aim of GEAR is to directly find the path with the lowest non-renewable (brown) energy consumption. GEAR assigns as weights of a transport link the transport power, and as weight of the anycast link the current brown power of the DC connected to the network by that anycast link. In this case, it is enough to apply the shortest



(a) Connection provisioning with SWEAR.



(b) Connection provisioning with GEAR.

Fig. 5. Example of connection provisioning with SWEAR and GEAR.

TABLE IV
GEAR METACODE

Algorithm 2 - GEAR

Input: $G = (V, E, C, \lambda)$, $c = \langle s, B, t_h \rangle$, k, P_k, p_p, P_t
Output: Path with lowest non-renewable (brown) energy consumption. The data center chosen to process the user's request.

1) Build auxiliary graph $G' = (V, E)$.
2) Weight assignment for transport links: link weight is equal to transport power P_t.
3) Weight assignment for anycast links: verify which DC k among the K DCs has enough renewable energy to process the connection and assign weights consequently:
   a. if renewable energy is enough to process the connection request, then assign zero weight ($d_k d$=0);
   b. if renewable energy is not enough to process the connection request, then assign to link cost $d_k d = (p_p - P_k) \cdot t_h$ which is the amount of non-renewable energy used to process the connection request;
   c. if no renewable energy is present, then assign to link cost $d_k d = p_p \cdot t_h$, which is the non-renewable energy used to process the connection request.
4) Once weights are assigned as defined at step 2 and 3, calculate the shortest path.
5) If the chosen path exists, then allocate resources, set up the new lightpath and update network status. Else block the connection and exit.

path routing algorithm to obtain the "minimum brown power" path. The metacode for GEAR is proposed in Tab. IV.

We propose a brief example to explain how GEAR works and how it routes connections. We suppose that a connection request $c_1 = \langle 1, 10Gbps, 1 \rangle$ arrives at time t_1. Three possible ways to route the connection c_1 are shown in Fig. 5b. The connection request can be routed towards one of the data centers deployed in the network, in our case DC_1, DC_2 or DC_3. GEAR first evaluates the renewable-energy availability in each data center. In our example DC_1 has only non-renewable energy, DC_2 has solar-renewable energy, but not enough to process the entire power requirement associated to the connection (i.e., less than 100 Watt, let's say, e.g., 50W) and DC_3 has enough wind-renewable energy to process the connection (i.e, greater or equal than 100 Watt). On transport links, weights are assigned considering the power needed to transport and switch the connection, calculated according to the chosen IP-over-WDM network architecture (see III-C). On anycast links, weights are assigned considering the renewable energy availability of the data center: so link from node 2 to DC_1 has a weight equal to 100, link from node 3 to DC_2 has a weight equal to 50 (as we have supposed that 50W of renewable energy are available) and link from node 7 to DC_3 has a weight equal to 0 because DC_3 has enough renewable energy. The choice is made applying Dijkstra algorithm, so route r_3 is chosen (in our example, note that route $r_1 : 1 - 2 - DC_1$ has cost 134, route $r_2 : 1 - 4 - 3 - DC_2$ has cost 114 and route $r_3 : 1 - 5 - 6 - 7 - DC_3$ has cost 102).

On the efficiency in brown power minimization of GEAR. Even though GEAR minimizes greedily (i.e., independently for each connection) the brown power consumption to support the requested CC service, GEAR has not knowledge about possible changes in the availability of renewable energies in the future. For sake of comparison, and to provide a lower bound in terms of brown energy consumption to GEAR, we introduce here a modified version of GEAR called Duration-Aware GEAR (DA-GEAR). This enhanced version can exploit the knowledge of future events, and specifically DA-GEAR assumes that each incoming connection has a knowledge of the instant of connection departures (or, in other words, a knowledge of the duration of the current connections in the network) and a knowledge of the renewable energy availability in DCs during its whole holding time. Based on this additional information, DA-GEAR can use the knowledge of connection duration t_h and, if the connection duration covers multiple time periods (expressed, e.g., in hours), characterized by a different amount of renewable energy, the weights d_{kd} of the anycast links for the DCs with no renewable energy are multiplied by a penalty factor $F = 1 + \delta_H$, where δ_H is the difference between the initial and the final time slot. We remark here that this feature cannot be usually assumed for online dynamic algorithms, but it is introduce here in order to provide a lower bound to the performance of GEAR.

E. BGD

The last algorithm we propose is called BGD, Best Green Data Center. This algorithm follows a simple routing strategy and has a comparison purpose only. The first step is the

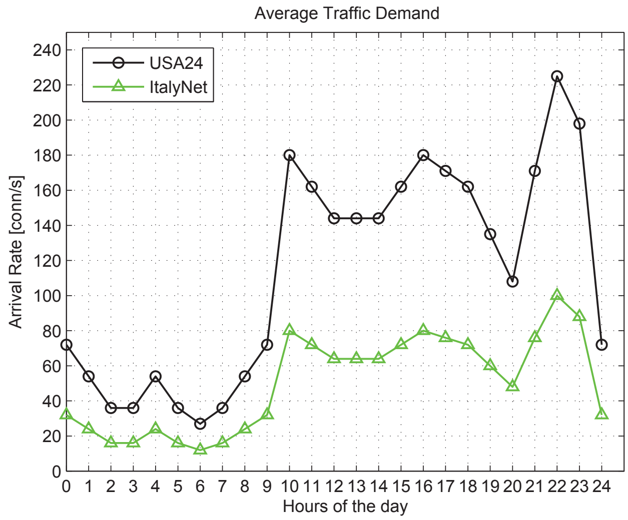


Fig. 6. Traffic profile.

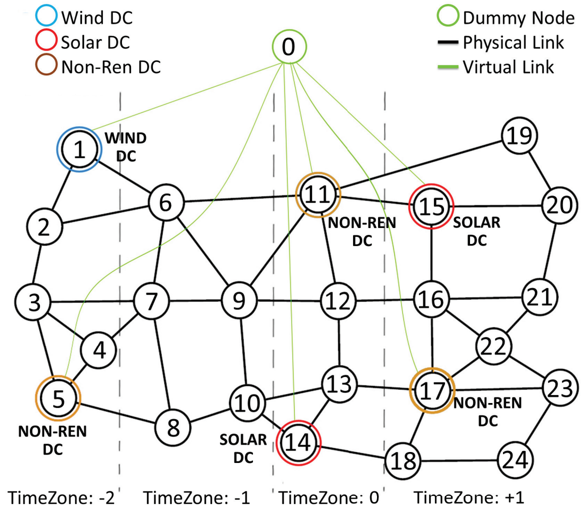


Fig. 7. USNet network topology.

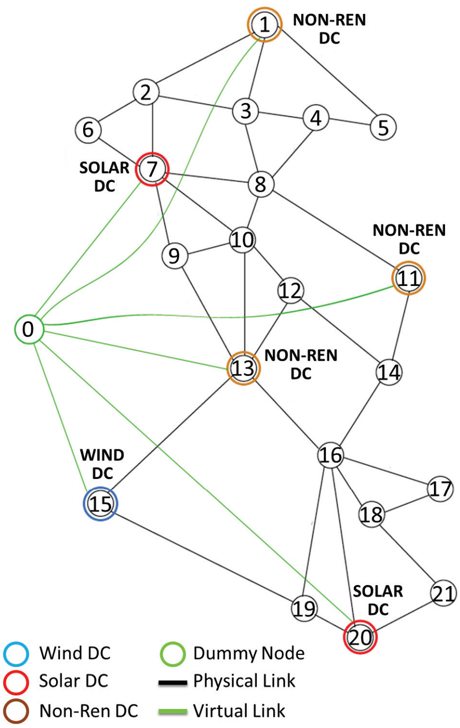


Fig. 8. ItalyNet network topology.

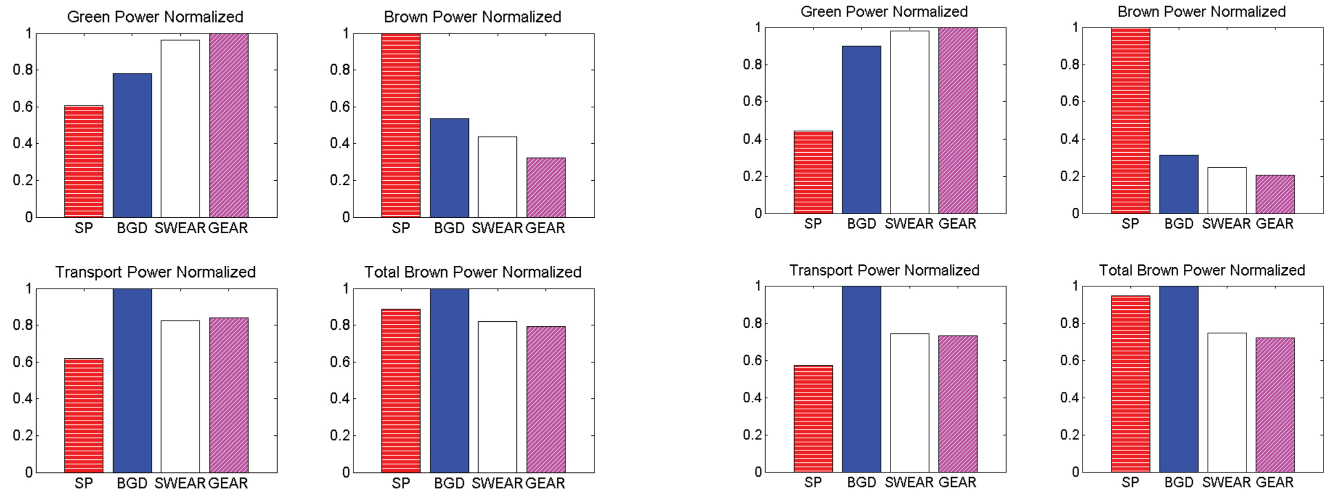
choice of the DC with highest renewable energy availability, then the connection is routed by a shortest-path algorithm to that DC, such that utilization of renewable energy sources is maximized, but, in return, the chosen path may have an excessive number of hops, leading to an increase in total transport and switching power consumption which overcomes the CO_2 reduction coming from the renewable source.

Finally, note that for all the three proposed algorithms we assume that information regarding current available renewable power at the end-nodes is always available for the routing algorithms. This information can be carried by a routing protocol, e.g., a modified version of Open Shortest Path First - Traffic Engineering (OSPF-TE), or it can be periodically collected in an centralized computing element, such as a Path Computation Element (PCE).

VI. Illustrative Numerical Results

In this section we describe our case study and we show some illustrative numerical results. We consider two network topologies, the *USA24* (Fig. 7) and the *ItalyNet* (Fig. 8), consisting of nodes interconnected by bidirectional links each carrying data at a rate of 10 Gbits/s and 16 WDM channels. Both networks host 6 DCs (see again Figs. 7 and 8), 3 co-powered by renewable energies (i.e., renewable energies are used when available, when not we assume an alternative source of brown energy is also available) and 3 powered only by brown energies. Connection arrivals follow a Poisson process with an arrival rate that varies according to the time of the day according to the profile in Fig. 6 [7], [21]. Peak traffic is 220 arrival per second for the *USA24* and 100 arrival per second for *ItalyNet*. Connection durations are exponentially distributed with average 1. Tab. V reports the main parameters of the considered network topologies.

We validate our proposed algorithms by using a dynamic discrete-event based simulator (developed in C++). We contrast our proposed algorithms SWEAR and GEAR to a basic Shortest Path (SP) and the Best Green Data Center (BGD) algorithm, which always routes towards the DC with maximum renewable energy availability. For each algorithm we consider four energy metrics: *Green Power* (P_G) and *Brown Power* (P_B) are the renewable energy and non-renewable power used for processing connections inside a DC, *Transport Power* (P_T) is the power used during the transport and switching of the lightpath and *Total Brown Power* (P_{TOT}) is the total non-renewable power consumption, coming from the sum of *Brown Power* and *Transport Power*. Besides, we consider *blocking probability*, p_b, as metric to evaluate the network performance under dynamic traffic. The results on power consumption are cumulative results obtained simulating a day (24 hours) with varying traffic intensity as in Fig. 6.



(a) Results for USA24 network topology.

(b) Results for ItalyNet network topology.

Fig. 9. Normalized power contributions for the two different network topologies.

TABLE V
NETWORK PARAMETERS FOR *USA24* AND *ItalyNet*.

	USA24	ItalyNet
Nodes	24	21
Links	48	36
Connectivity Index (links/nodes)	2	1.7
Average Nodal Degree	3.6	3.3
Diameter [Hop]	8	6
Diameter [Km]	6900	970
Renewable DC	3	3
Non-Renewable DC	3	3

TABLE VI
POWER CONSUMPTIONS AND CO_2 EMISSIONS FOR USA TOPOLOGY.

	SP	BGD	GEAR	SWEAR
P_G *[MW]*	476.247	612.42	785.607	757.133
P_B *[MW]*	516.243	275.735	166.315	224.753
P_T*[MW]*	628.806	1014.67	854.073	834.909
P_{TOT} *[MW]*	1145.049	1290.405	1020.388	1059.662
E_p *[tCO_2]*	117.703	62.867	37.919	51.243
E_T *[tCO_2]*	143.367	231.344	194.712	190.357
E_{Tot} *[tCO_2]*	261.071	294.211	232.648	241.452
H_{av}	0.88	2.17	1.55	1.43

TABLE VII
POWER CONSUMPTIONS AND CO_2 EMISSIONS FOR ITALYNET TOPOLOGY.

	SP	BGD	GEAR	SWEAR
P_G *[MW]*	170.039	343.402	382.746	374.919
P_B *[MW]*	271.181	85.3445	55.2976	66.3121
P_T *[MW]*	289.321	506.678	371.119	375.962
P_{TOT} *[MW]*	560.502	592.02	426.416	442.27
E_p *[tCO_2]*	61.83	19.458	12.606	15.12
E_T *[tCO_2]*	65.967	115.522	84.615	85.719
E_{Tot} *[tCO_2]*	127.79	134.98	97.222	100.83
H_{av}	0.95	2.27	1.41	1.43

In Fig. 9a and 9b we draw the normalized power consumption in the two topologies considering the four power contributions described above. We observe that SWEAR and GEAR can reduce P_{TOT} (and, in turn, the CO_2 emission) up to 11% and 20% compared with SP in USA24 and up to 24% and 27% in ItalyNet network topology. These results come from two combined effects: i) our algorithms induce an increase of about 40% and 20% in P_G, compared to SP and BGD respectively for USA24 network and 55% and 10% in ItalyNet; ii) on the other hand, SWEAR and GEAR reduce P_B of 56% and 67% compared to SP and 25% compared to BGD in USA24 topology; in ItalyNet we have a reduction of about 75% and 16% respectively. Also, as expected, P_T increases for our algorithms compared to SP that routes with the shortest path and so the minimum transport power (we note an increase of about 35% in USA24 and 21% in ItalyNet). Note that BGD, that routes directly connections to Green DCs without any concern about increasing transport energy, pays off an extremely high transport power, and it results in a very high Total Brown Power. The absolute numerical values are shown in Tab. VI and Tab. VII, where E_p, E_T and E_{TOT} are respectively the CO_2 Processing Emissions, CO_2 Transport Emissions and the CO_2 Total Emissions and H_{av} is the average hop number of a connection. Emissions are calculated in tons of CO_2 (tCO_2) considering that for each kWatt-hour of non renewable energy 228 g of CO_2 are released in the atmosphere (note that this number may vary depending on circumstances such as the fossil fuel used to produce the brown energy).

In Fig. 10 we show the blocking probability p_b during the 24 hours of the day for all implemented algorithms in ItalyNet network topology; we note that BGD, since it always forces the routing towards the "greenest" data center, tends to create capacity bottlenecks that raise the p_b values. We observe the lowest blocking with Shortest Path algorithm (as expected since SP used the lowest amount of network resources), but SWEAR and GEAR return very satisfactory blocking performance, especially in the case of SWEAR, that benefits of its load balancing phase. Blocking probability is calculated hour by hour. The number of offered connections

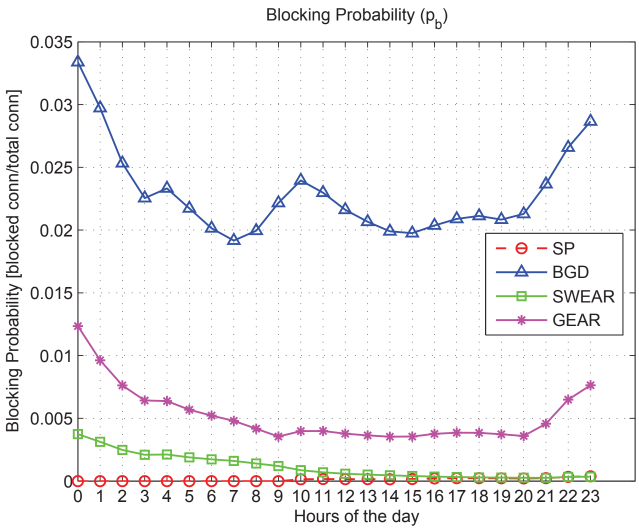


Fig. 10. Blocking Probability during the 24 hours of the day for ItalyNet.

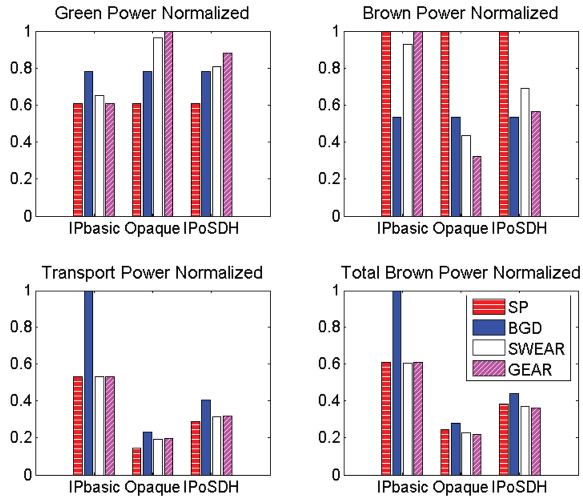


Fig. 11. Comparison of power consumptions among different IP over WDM architectures.

in each hour interval (typically in the order of hundreds of thousands of connections) ensures good statistical confidence of the plotted results.

In summary, GEAR and SWEAR provide a valuable trade-off in terms of total brown power minimization (which is significantly lower than SP and BGD) and blocking probability (which is only slightly higher than SP). Comparing GEAR and SWEAR, we can notice that GEAR has a lower total brown power consumption than SWEAR, because GEAR greedily minimizes brown power, while SWEAR has lower blocking than GEAR, as SWEAR incorporates some degree of load balancing that GEAR does not take into account. As for blocking probability, we can consider SP as the lower bound. DA-GEAR provides the lower bound values for the Total Brown Power. For this reason we performed a comparison in terms of total brown power between GEAR and DA-GEAR for increasing values of average connection duration (graphs are not reported for space limitations). We found that the knowledge of future departures and future renewable energy availability allows DA-GEAR to consume less total brown power. This reduction is quite limited confirming that GEAR provides already good performance. Note that for short-duration connections ($t_h < 1200s$) there is basically no difference in total brown power consumption, while for longer durations the difference increases (it increases almost linearly starting from 0.1% at $t_h < 1200s$ and reaching up to 3.5% with $t_h = 3000s$) as the knowledge of future renewable power availability becomes more important.

We also perform an analysis of different IP over WDM network architectures, as described in Section III-C in Fig. 11. First we consider an opaque configuration: our algorithms SWEAR and GEAR achieve a reduction in CO_2 emissions up to 8% and 10% respectively compared with SP; instead the reductions can reach 17.8% and 21% compared with BGD. Then we consider an IP-over-SDH-over-WDM architecture and we note that performances get worse, achieving a emissions reduction of 2.7% and and 5% compared with SP and 15.3% and 17.5% compared with BGD. In the end we consider an IP basic architecture, which has an elevate power consumption in transport phase due to electronic processing; so GEAR doesn't achieve any significant CO_2 emissions reductions, instead SWEAR can achieve only 1% of reduction, while the percentage of emissions reduction compared with BGD arises up to a 40%. As expected, we can conclude that in network architectures that require higher energy consumption for data transport, such as IP basic and IP-over-SDH-over-WDM compared to the opaque case, routing algorithms are less incentivized to take decisions involving longer routes to send data towards greener data centers.

In fact, if we focus our attention on switching and transport network element power consumption (see transport power normalized in Fig. 11, SP increases its power requirements of 100% moving from IP-over-WDM Opaque architecture to IP-over-SDH-over-WDM and up to 120% moving from IP-over-SDH-over-WDM to IP basic; similarly for BGD; GEAR and SWEAR have smaller increases, of 64% and 30% moving from IP-over-WDM Opaque architecture to IP-over-SDH-over-WDM and an increase of 100% and 70% switching from IP-over-SDH-over-WDM to IP basic, respectively. Results show that the IP-over-WDM Opaque configuration can achieve the best performances in CO_2 emissions reduction using our algorithms SWEAR and GEAR.

In conclusion, fostering utilization of renewable resources through renewable-energy-aware routing is desirable, but care must be taken in avoiding an excessive increase of the average length of paths, especially if power-hungry transport network architectures are used. The algorithms proposed in the paper have been demonstrated to properly address such trade-off.

VII. Conclusion

We have proposed two routing algorithms, SWEAR and GEAR, to perform low-carbon routing of dynamic connections in IP-over-WDM architecture with data centers equipped with renewable energy plants. Simulation results show in our case study that compared to the Shortest Path and Best Green

Data Center, our algorithms SWEAR and GEAR have reduced the CO_2 emission to serve traffic and process data by 25%-27% while maintaining blocking probability at an acceptable level. We have also compared different IP over WDM network architectures to evaluate how the benefit by our algorithms. As expected, configurations with larger transport energy requirements (such as IP basic and IP-over-SDH) benefit less from renewable-energy-aware algorithms.

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