Energy-Aware RWA for WDM Networks with Dual Power Sources

Sergio Ricciardi[1], Davide Careglio[1], Francesco Palmieri[2], Ugo Fiore[3], Germán Santos-Boada[1], Josep Solé-Pareta[1]

[1] Advanced Broadband Communications Center, Universitat Politècnica de Catalunya, Barcelona, Spain, sergior@ac.upc.edu
[2] Information Engineering Department, Seconda Università di Napoli, Aversa, Italy, fpalmier@unina.it
[3] University Centre of Computer Science Services, Università di Napoli Federico II, Naples, Italy, ufiore@unina

***Abstract*—Energy consumption and the concomitant Green House Gases (GHG) emissions of network infrastructures are becoming major issues in the Information and Communication Society (ICS). Current optical network infrastructures (routers, switches, line cards, signal regenerators, optical amplifiers, etc.) have reached huge bandwidth capacity but the development has not been compensated adequately as for their energy consumption. Renewable energy sources (e.g. solar, wind, tide, etc.) are emerging as a promising solution both to achieve drastically reduction in GHG emissions and to cope with the growing power requirements of network infrastructures.**

The main contribution of this paper is the formulation and the comparison of several energy-aware static routing and wavelength assignment (RWA) strategies for wavelength division multiplexed (WDM) networks where optical devices can be powered either by renewable or legacy energy sources. The objectives of such formulations are the minimization of either the GHG emissions or the overall network power consumption. The solutions of all these formulations, based on integer linear programming (ILP), have been observed to obtain a complete perspective and estimate a lower bound for the energy consumption and the GHG emissions attainable through any feasible dynamic energy-aware RWA strategy and hence can be considered as a reference for evaluating optimal energy consumption and GHG emissions within the RWA context. Optimal results of the ILP formulations show remarkable savings both on the overall power consumption and on the GHG emissions with just 25% of green energy sources.

I. INTRODUCTION

The energy consumption and the concomitant GHG emissions (mainly CO_2) are becoming more and more a sensible issue for the ICS, governments and standardization bodies [1]. The Kyoto protocol imposes on industrialized States to reduce their GHG emissions by 5% from the 1990 level in the 2008-2012 period. It has been estimated [2] that network infrastructures alone consume 22 GW of electrical power corresponding to more than 1% of the worldwide electrical energy demand, with a growth rate of 12% per year, further stressing the need for energy-efficient network devices and energy-aware protocols and algorithms. In fact, the solely deployment of energy-efficient devices is not enough, as their total cost of ownership (TCO) decreases, the demand for using such devices increases and the gained benefits are overcome by greater energy consumption and concomitant GHG emissions. Such a phenomenon is known as *rebound effect* (or, in other contexts, as Jevons paradox or Kazzoom/Brookes postulate [3]). In order to overcome the rebound effect, it is necessary to adopt the *carbon neutrality* or, when available, the *zero carbon* approach. In carbon neutrality, GHGs emitted by legacy (dirty) energy sources (e.g. fossil-based plants) are compensated – hence, neutrality – by a credit system like the cap and trade or the carbon offset [3]. In the zero carbon approach, renewable (green) energy sources (e.g. sun, wind, tide) are employed and no GHGs are emitted at all. Clearly, green energy sources are always preferable with respect to the dirty ones as they limit (or avoid at all) GHG emissions, although renewable sources are variable in nature and their availability may change in time. Therefore, we advocate an energy system in which network elements (NE) are provided with green energy sources alongside the legacy power system and, at the occurrence, they are able to switch to the fossil-based power supply without any energy interruption. Such NEs are *energy-aware* as they adapt their behavior and performance depending not only on the current load but also on the source of energy that is supplying them.

Several approaches to achieve energy efficiency in network infrastructures have been proposed in the literature [4][5][6][7][8][9][10], but, at the state-of-the-art, none of them takes into consideration green and dirty energy sources for all the NEs together with the energy requirements of the different traffic types (optical/electronic, pass-through, add/drop, amplification, 3R regeneration, etc.). Furthermore, all prior works are focused on the reduction of the network energy consumption by switching off network elements. However, the power drawn by NEs is assumed to be given and thus it is not derived from a realistic energy model. In addition, putting into sleep mode entire NEs is not the sole possible solution and has its drawbacks. In [7] several ILP formulations for optical network planning are illustrated, and results show that switching off network nodes is not practically feasible as it was possible only in few experiments for very low loads. Furthermore, putting into sleep mode one big router is economically unviable and technically immature, at least with the architectures and technologies currently employed. A router is a rather costly piece of equipment and it still takes minutes to "wake up"; when returning from sleep mode, a peak in the power consumption is registered and the lifetime of the router will decrease if frequent power up/down cycles occur. Moreover, routing operating systems are not so stable and additional manual configurations may be needed at each power

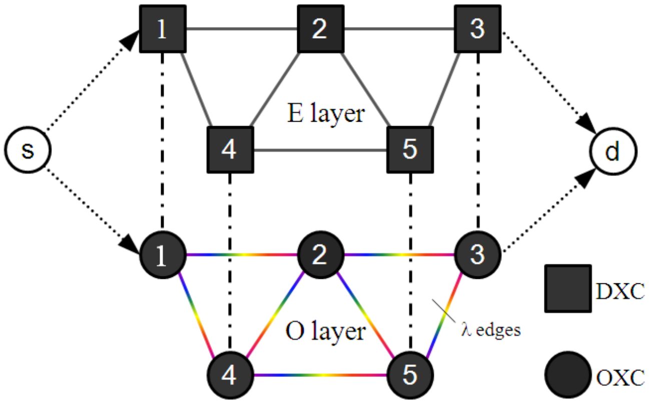

Fig. 1. Schematic representation of the network model with the electronic (E) and optical (O) layers.

up. Finally, powering off routers in a network results in reduced load balancing, as the traffic flows have to be routed only on the subset of active routers.

To the best of our knowledge, this paper represents the first work in which (1) green and dirty energy sources are explicitly considered for all the NE types and (2) sleep mode is assumed to be not available, with energy savings coming exclusively from the optimal routing of the connection requests. Specifically, we tried to combine all the notable features that a comprehensive dual energy-aware network model should have and put them together into a general Routing and Wavelength Assignment (RWA) framework. In doing this, all the energy-related information and concepts associated to devices and links have been abstracted and defined in a formal and concise way within the context of a specific energy-aware network optimization problem. To achieve a more compact and precise representation of such a problem we formally model it as an ILP problem working on the physical network topology comprising routers and links, in which each device is characterized by a known power consumption, varying under different loads, energy source, capacity, and cost. The energy model defining the energy requirements of each NE considers electrical and optical technologies, and differentiates the consumption according to the various flavors of NEs and traffic types. We also assume to have the complete knowledge of the average amount of traffic exchanged by any source/destination node pair. The proposed formulation is applied to a multilayer IP/WDM network with the twofold aim of minimizing the overall GHG emissions and the power consumptions by setup optimal lightpaths through a suitable energy-aware RWA scheme. Solving the above ILP requires knowledge in advance of the entire traffic matrix and hence restricts us to the static, offline, RWA case. In turn, in a dynamic scenario, the optimal solution of the ILP represents a lower bound for the GHG emissions and energy consumptions of energy-aware RWA heuristics.

II. NETWORK & ENERGY MODEL

A. The Network Model

TABLE I
TRAFFIC SUPPORTED BY THE DEVICES

Type of Device (NE)	Type of Traffic
Electronic Router [a]	Electronic
Optical Switch [b] w/ WC	Optical (with or without WC)
Optical Switch [b] w/o WC	Optical (without WC)
Fiber Optic	Optical (without WC)
Optical Amplifier	Optical (without WC)
3R regenerator	Electronic

[a] DXC; [b] OXC.

We consider wavelength-routed networks in which the traffic unit is the lightpath. Network nodes may be electronic routers (digital cross connects, DXC) or optical switches (optical cross connects, OXC) connected by fiber links with up to λ wavelengths on each. The network is represented as a multigraph $G=(V,E)$ with $|V|=n$ nodes and $|E|=m$ edges (with one edge for each wavelength in the optical layer) (see Fig. 1). We assume that the traffic is unsplittable in the optical domain: i.e. a traffic demand is routed over a single lightpath; (in theory, in the electronic domain a demand may be splitted into n flows, but in the optical domain these will appear as n unsplittable optical flows). The *type* of traffic depends on the NE that is being traversed, thus three types of traffic are possible: (1) opaque electronic traffic; (2) transparent optical traffic with wavelength conversion (WC) and (3) transparent optical traffic without WC. The Table I reports the types of network element and the corresponding supported traffic types. Note that each type of traffic accounts for different power consumption when traversing NEs, as explained in following subsections. We assume that all the nodes have the possibility to convert wavelengths, either in the electronic or in the optical domain, depending on their technology. In the electronic domain, the full range of operations is supported: wavelengths routing/switching, wavelengths add/drop, WC, 3R regeneration; in the optical domain the operations supported are the transparent wavelength switching/pass-through and the WC. NEs may be powered either by green or dirty energy sources statically assigned to each at the network topology definition time. We assume that each node is able to distinguish which power source is currently feeding it through an energy-aware GMPLS-like control plane intelligence. This corresponds to a scenario in which network infrastructure planners consider the construction of new portions of the network or the change of power source for existing parts, and they evaluate the reduction in CO_2 emissions against other issues such as the technical aspects and costs of using green or dirty energy sources.

B. The Energy Model

In this model we explicitly considered the influence of traffic on power consumption by using realistic data for traffic demands, network topologies, link costs, and energy requirements of single network elements. Specifically, the amount of power consumed by the NEs depends on the type of device and on the type and load of traffic that it is currently supporting (e.g. an OXC may support transparent optical traffic with or without WC). Even though the energy consumption of current node architectures does not scale with traffic (the energy demand of heavily loaded devices is only 3% greater than that of idle ones [12]), energy-aware architectures that adapt their performances to the traffic load lowering the power requirement under low traffic loads are strongly advised and are being designed [1][12]. Consequently, we assume that the power consumption of the NEs, i.e. both network nodes and links, consists of two factors. When turned *on*, a NE consumes a constant amount of power depending on the router size and technology (measured in *J/s=W*) and independent on the traffic load (*fixed* power Θ). The second factor consists of an amount of power proportional to type and quantity of the traffic load (*proportional* power ε). The overall power drained by the WDM network is thus given by the sum of the fixed and proportional powers of the NEs subject to the current traffic load and varies with the routing of the connection requests. This implies that, as the NEs are always turned on, the routing optimization process works "only" on the proportional power. Table II reports the mean values of NEs variable energy consumptions. As we can see, electronic traffic, i.e. traffic that undergoes O/E/O conversion, consumes more power than optical traffic. In the electronic domain the energy necessary for forwarding 1 unit of traffic is 150 times greater than the energy needed in the optical domain w/o WC and 50 times greater if WC is available in the optical domain. Although they are mean values, in our model each NE has its own particular energy consumption factor – resulting from the individual architecture, technology and configuration – that have been obtained by further elaborations of the real measurements in [2] and account for fixed and proportional power consumptions which is a significant portion of the total consumption, according to [4].

III. ENERGY-AWARE ROUTING AND WAVELENGTH ASSIGNMENT

In this section, the problem of energy-aware RWA in WDM networks with dual power sources has been formulated as ILP formulations with different objective functions. In subsection III.A, the problem of minimizing the overall GHG emissions (*MinGas-RWA*) is presented, whilst the problem of minimizing the overall network power consumption (*MinPower-RWA*) is discussed in subsection III.B. To evaluate the power effectiveness and the reduction in GHG emissions of the two previous strategies, minimum cost RWA (*MinCost-RWA*) – i.e. energy-unaware RWA – is presented in subsection III.C.

A. *Energy-aware RWA at minimum GHG emissions (MinGas-RWA)*

The energy-aware RWA in WDM networks with dual power sources (*MinGas-RWA*) is formalized as an ILP problem. The objective is to route the requested lightpaths so that the overall network GHG emissions are minimized. Only NEs powered by dirty energy sources emit GHGs, whilst NEs powered by green energy sources do not emit any GHG at all, according to the energy model discussed in Section II.B. The ILP problem can be mathematically formulated as follows.

TABLE II

MEAN ENERGY SCALING FACTORS OF DIFFERENT ROUTING/SWITCHING TECHNOLOGIES AS FUNCTION OF THE AGGREGATED BANDWIDTH[1]

Router Technology	Energy Consumption Rate (ECR) (W/Gbps)	Energy Scaling Index (ESI) (nJ/bit)	*P* as function of *B* *P(B)*
Electronic DXC	1.5 W/Gbps	1.5 nJ/bit	$P = 1.5 \cdot B$
Optical OXC w/ WC	0.03 W/Gbps	0.03 nJ/bit	$P = 0.03 \cdot B$
Optical OXC w/o WC	0.01 W/Gbps	0.01 nJ/bit	$P = 0.01 \cdot B$

P: Power consumption function; *B*: Aggregated bandwidth;

[1] ECR and ESI are different power consumption metrics that may be reduced to equivalent values, in fact it holds that: W/Gbps = (J/s)/(Gbit/s) = J/Gbit = nJ/bit.

Input parameters (data)

- $G(V,E)$: directed graph representing the physical network topology; V set of vertices that represent the network nodes; E the set of edges that represent the network links; $|V| = N$, $|E| = M$;
- a_{ij} : number of wavelengths available on link (i, j);
- ℓ_{ij} : length of link (i,j) (in *km*);
- Λ : maximum length (in *km*) of links without need of amplification (80/100 *km*);
- t^{sd}: number of lightpaths to be established from s to d; i.e. $\{t^{s,d}\}_{s,d\in V}$ is the traffic matrix;
- $\pi^{sd,k}$: k-th pre-computed route from s to d;
- $\rho^{sd,k}$: the geographical length of route $\pi^{sd,k}$ (in *km*);
- Θ_n : fixed power of node n; depends on node size/type;
- $\varepsilon_n^{t_1}$: proportional power for transporting one lightpath as *transparent pass-through* traffic at node n;
- $\varepsilon_n^{t_2}$: proportional power for transporting one lightpath as *opaque pass-through* traffic at node n (e.g. 3R regeneration or opaque wavelength conversion);
- $\varepsilon_n^{t_3}$: proportional power for *add/drop* one lightpath at node n;
- Ψ_{ij} : fixed power for devices in link (i, j), (e.g. optical amplifiers); among 3 and 15 W;
- δ_{ij} : proportional power for transporting one lightpath through link (i, j); it is assumed that each device (e.g. OA) on the same link (i, j) has the same fixed and proportional power consumption;
- $x_n^{sd,k}$ identifies the presence of O/E/O conversion at the node n:

$$x_n^{sd,k} = \begin{cases} 1 & \text{if } n \in \pi^{sd,k} \text{ and } \pi^{sd,k} \text{ undergoes O/E/O} \\ & \qquad \text{conversion at node } n \\ 0 & \text{if } n \notin \pi^{sd,k} \text{ or } \pi^{sd,k} \text{ transparently passes} \\ & \qquad \text{through node } n \end{cases}$$

Note that 3R regeneration and opaque wavelength conversion are implicitly considered in this matrix and this information will be used in the power consumption calculus.

- the following node attributes model the energy source:

$$g_n = \begin{cases} 1 & \text{if node } n \text{ is powered by a green energy source} \\ 0 & \text{if node } n \text{ is powered by a dirty energy source} \end{cases}, \forall n \in V$$

- $$h_{ij} = \begin{cases} 1 & \text{if link } (i,j) \text{ is powered by a green energy source} \\ 0 & \text{if link } (i,j) \text{ is powered by a dirty energy source} \end{cases}, \forall (i,j) \in E$$

Variables

- integer $w^{sd,k}$ indicates the number of lightpaths using route $\pi^{sd,k}$ (on the same route there may be several lightpaths using different wavelengths);
- $PC_{G(V,E)}$ indicates the objective function to be minimized;
- $TC_{G(V,E)}$ indicates the overall power consumption of the NEs in *G(V,E)* evaluated in the chosen traffic model;
- $GC_{G(V,E)}$ indicates the power consumption of the NEs in *G(V,E)* due only to green power sources.

Objective function

$$Minimize\, PC_{G(V,E)} \tag{1}$$

Constraints

$$PC_{G(V,E)} = (TC_{G(V,E)} - GC_{G(V,E)}) + \log TC_{G(V,E)} \tag{2}$$

$$TC_{G(V,E)} = \sum_{n\in V} \begin{pmatrix} \Theta_n + \varepsilon_n^{t_1} \cdot \sum\limits_{sd,k\,:n\in\pi^{sd,k},n\neq s,d} w^{sd,k} \cdot (1 - x_n^{sd,k}) + \\ \varepsilon_n^{t_2} \cdot \sum\limits_{sd,k:n\in\pi^{sd,k},n\neq s,d} w^{sd,k} \cdot x_n^{sd,k} + \varepsilon_n^{t_3} \cdot \sum\limits_{sd,k:n=s,d} w^{sd,k} \end{pmatrix} \tag{3}$$

$$+ \sum_{(i,j)\in E} \left(\left\lfloor \frac{\ell_{ij}}{\Lambda} \right\rfloor \cdot \left(\Psi_{ij} + \delta_{ij} \cdot \sum_{sd,k:(i,j)\in\pi^{sd,k}} w^{sd,k} \right) \right)$$

$$GC_{G(V,E)} = g_n \cdot \sum_{n\in V} \begin{pmatrix} \Theta_n + \varepsilon_n^{t_1} \cdot \sum\limits_{sd,k\,:n\in\pi^{sd,k},n\neq s,d} w^{sd,k} \cdot (1 - x_n^{sd,k}) + \\ \varepsilon_n^{t_2} \cdot \sum\limits_{sd,k:n\in\pi^{sd,k},n\neq s,d} w^{sd,k} \cdot x_n^{sd,k} + \varepsilon_n^{t_3} \cdot \sum\limits_{sd,k:n=s,d} w^{sd,k} \end{pmatrix} \tag{4}$$

$$+ h_{ij} \cdot \sum_{(i,j)\in E} \left(\left\lfloor \frac{\ell_{ij}}{\Lambda} \right\rfloor \cdot \left(\Psi_{ij} + \delta_{ij} \cdot \sum_{sd,k:(i,j)\in\pi^{sd,k}} w^{sd,k} \right) \right)$$

$$\sum_k w^{sd,k} = t^{sd} \quad \forall s,d \in V \tag{5}$$

$$\sum_{sd,k:(i,j)\in\pi^{sd,k}} w^{sd,k} \le a_{ij} \quad \forall (i,j) \in E \tag{6}$$

$$w^{sd,k} \in \aleph, \quad \forall s,d \in V, \forall k \tag{7}$$

The objective (1) is the minimization of the network power consumption due to the network elements powered by dirty energy sources (as we want to minimize GHG emissions) and – among the solutions at minimum power consumption – the minimization of the total power consumption of the network, as reported in Eq. (2). Eq. (3) sets the overall power consumption of the network elements in *G(V,E)* evaluated in the energy model, whilst Eq. (4) indicates the power consumption of the network elements in *G(V,E)* due only to green power sources. Constraint (5) selects the routes for the lightpaths among the *k* pre-computed ones and assures that the whole traffic demand matrix is satisfied. Constraint (6) ensures that the maximum number of lightpaths passing on a link does not exceed the number of available wavelengths on that link. Constraint (7) imposes the integrality of the ILP problem by forcing integer values for the variables $w^{sd,k}$. Note that the fixed power consumptions terms in (3) and (4) are reported only for completeness sake but they are not involved in the optimization process (as sleep mode is not considered, fixed power consumptions are always present and the optimization is realized only on the variable energy consumptions).

B. Energy-aware RWA at minimum power consumption (MinPower-RWA)

The objective of the *MinPower-RWA* problem is to minimize the overall power consumption regardless of the energy sources types and, thus, of the GHG emissions. The set of the input parameters is the same as the *MinGas-RWA* problem except for the g_n and h_{ij} vectors which are no longer necessary; also, an additional constant ξ is considered, where $\xi:\ 0 < \xi \cdot \left(\sum_{n\in V} \Theta_n + \sum_{(i,j)\in E} \Psi_{ij} \right) < 1$. The mathematical formulation of *MinPower-RWA* is the following:

Objective function

$$Minimize\ \ TC_{G(V,E)} + \xi \cdot \sum_{sd,k} w^{sd,k} \cdot \rho^{sd,k} \tag{8}$$

Constraints

constraints (3) (5) (6) (7).

The objective function (8) is the minimization of the overall network power consumption due to fixed and proportional power consumed by all the devices installed in the network, and – among the solutions at minimum power consumption – the minimization of the installation cost (with the assumption that the installation cost is proportional to the number of wavelengths required and to the length of the chosen lightpaths).

C. Minimum Cost RWA (MinCost-RWA)

The objective of the *MinCost-RWA* problem is the minimization of the installation cost regardless of the NEs energy consumptions and GHG emissions. It will try to aggregate as much lightpaths as possible while minimizing their physical lengths.

Objective function

$$Minimize\ \ \sum_{sd,k} w^{sd,k} \cdot \rho^{sd,k} \tag{9}$$

Constraints

constraints (5) (6) (7).

IV. NUMERICAL RESULTS

A. Simulation scenario

In the following we present and analyze the results obtained through ILP optimizations exploiting minimum power consumption and minimum GHG emissions on the well known

Geant2 Pan-European core optical network with 16 nodes and 23 fiber links each with 16 wavelengths [13]. Simulations were performed under different power distribution systems, with green energy sources powering 25, 50 and 75% of the NEs and randomly generated traffic matrices. Connection requests are fully satisfied, i.e., the blocking probability is kept strictly *null*. In order to evaluate the amount of emitted CO_2 of the legacy energy plants, we consider the carbon footprints illustrated in Table III. To solve the ILP problems, the CPLEX software tool was used on an Intel® Xeon® 2.5 GHz dual processor Linux server. The available memory (physical RAM + swap area) amounted to 16 GBytes. To reduce the notable requirements in terms of computational and memory resources, we first bound the problem dimension by restricting the paths' alternatives to a static set of *k* pre-computed routes, obtained by using a traditional *k*-shortest paths first (K-SPF) algorithm and hence satisfying the traditional network management objectives without considering any energy-related information. Secondly, we limited the depth of the branch-and-bound/cut algorithms after calculating a pre-definite number of integer solutions. While such simplification techniques are certainly useful to contain the computational burden, the solution they produce is only an approximation of the actual optimal (in terms of power consumption) virtual network topology built on the available physical infrastructure. However in these cases the ILP approach maintains its added value, as far as the approximated solutions can be close to the exact one. Some of the selected paths would probably not be the best ones, but the resulting power savings could be substantial without significant losses on the other optimization objectives.

TABLE III
ENERGY PLANTS CARBON FOOTPRINTS

Type of Energy Plant	Emitted CO_2 per kWh (in grams)*
Natural Gas	880
Fuel	890
Coal	980
Nuclear	6

* Emissions during the use phase only; neither the construction costs nor other environmental effects such as fuel preparation and waste dismissal are accounted for. *Source: ACV-DRD study [2].*

B. Results and discussion

The power consumption resulting from the three ILP RWA strategies with 50% of the NEs powered by green energy sources is reported in Fig. 2. As expected, the *MinCost-RWA* is the most power consuming strategy, whilst the *MinPower-RWA* is the best strategy as for the power consumption, but the best one as GHG emissions is the *MinGas-RWA*. Anyway, the difference in energy consumption between the two latter strategies is lower than 15% in the worst case. This result was somehow expected, as the minimum power RWA strategy saves as much energy as possible regardless of the sources of energy, whereas the minimum GHG emissions may route the lightpaths on longer – thus, more energy consuming – paths but preferring those NEs that are powered by green energy sources. The *MinGas-RWA* energy consumption curve is further decomposed into two parts: the energy consumption resulting from dirty (*MinGas-RWA dirty*) and green (*MinGas-RWA green*) energy sources. At low loads, *MinGas-RWA* attempts to use only green-powered nodes, at the expense of possibly choosing longer paths. The effect of these suboptimal choices is visible at higher loads, when the overall power consumption rises more steeply that that of *MinPower-RWA*. This becomes relevant at network loads as high as 75%, whereas in the 30% - 70% operating range the savings achieved by *MinGas-RWA* with respect to *MinCost-RWA* remain consistently substantial. As for the energy consumption, compared with *MinCost-RWA*, *MinGas-RWA* saved up to 23% of energy while *MinPower-RWA* reached savings up to 32% of the overall energy consumption.

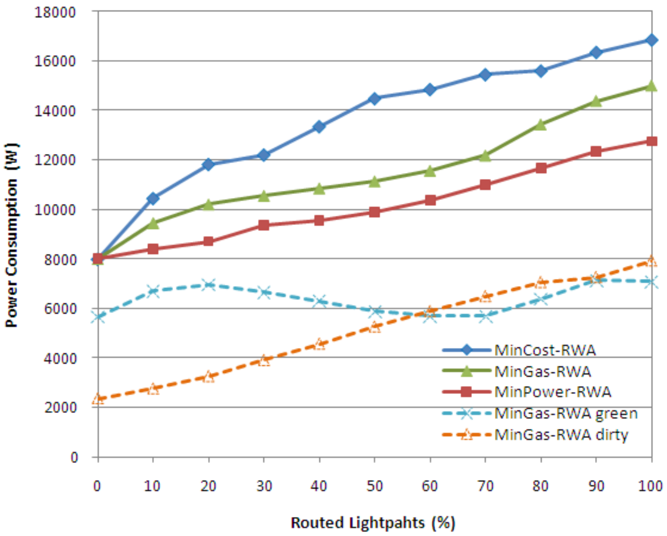

Fig. 2. Power consumption *vs* network load, 50% green power sources.

Besides the saving in power consumption, *MinGas-RWA* achieves to save also considerable quantity of CO_2. For a medium loaded network (50% of routed lightpaths), where one half of the NEs are powered by green power plants and the other half is powered by fuel-based power plants, *MinGas-RWA* strategy saves an average of 40,800 kg of CO_2 per year.

In the Fig. 3, we compared the estimated CO_2 emissions (for one year period) with the three strategies at different network loads, where one half of the NEs are powered by green energy sources and the other half by fuel-based power plants. As can be seen, at low loads the *MinGas-RWA* strategy achieves prominent CO_2 savings (only about 33% of CO_2 were emitted with respect to *MinCost-RWA* and about 50% relative to *MinPower-RWA*), whilst, as the network load increases, the difference between the *MinGas-RWA* and the *MinPower-RWA* strategies decreases, because at higher loads it becomes more and more difficult to satisfy the demand without resorting to dirty-powered nodes. In other words, at high loads, minimizing the overall power consumption implicitly leads to the minimization of the concomitant CO_2 emissions, while at midrange loads the CO_2 savings induced by *MinGas-RWA* are significant. We also explored the power consumptions and CO_2 emissions when the network is powered with different percentages of green energy sources. Results in the Fig. 4 show that, when a high percentage of the NEs (i.e. 75%) are

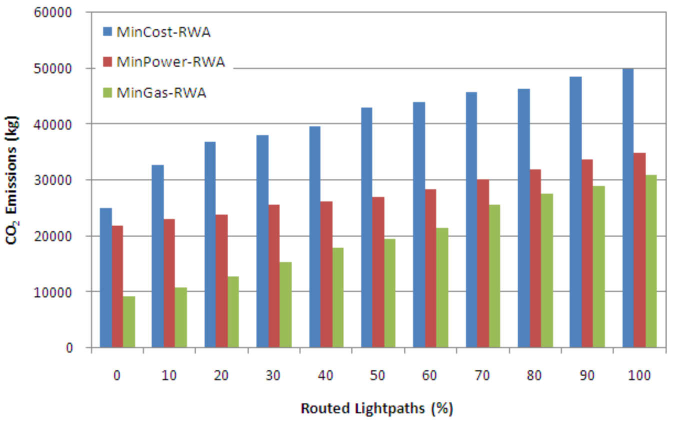

Fig. 3. Emitted CO_2 (during 1 year) *vs* network load; 50% fuel-based power sources; 50% green power sources.

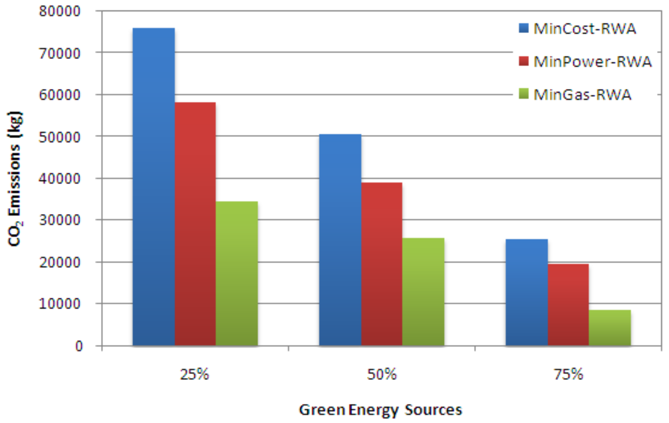

Fig. 4. Average emitted CO_2 at different green power sources percentages (remaining power sources are fuel-based).

powered by green energy sources, good results in terms of CO_2 emissions are obtained also by RWA strategies that do not take into account the type of energy sources, whilst, when green energy sources are scarce (i.e. 25%), a RWA strategy that explicitly optimizes the CO_2 emissions leveraging the green NEs is strongly advised. In the latter case, *MinGas-RWA* would emit only half the CO_2 with respect to *MinCost-RWA*, and one third of the CO_2 with respect to *MinPower-RWA*. These results show that, using the *MinGas-RWA* strategy with as few as 25% of green energy sources, it is possible to considerably reduce the overall network CO_2 emissions. Besides, even without any change in the power sources, with the *MinPower-RWA* strategy it is possible to save up to 25% of the overall network power consumption.

V. CONCLUSIONS & FUTURE WORKS

In this paper, energy-aware ILP formulations exploiting dual energy sources have been presented along with an energy model in which no sleep mode is available but the optimization relies only on the traffic-variable power consumption of the NEs. Two ILP formulations have been presented: minimum power (*MinPower-RWA*) and minimum GHG emissions (*MinGas-RWA*) strategies with the objectives to minimize respectively the absorbed energy and the emitted GHG. Results show that the *MinPower-RWA* strategy may save a considerable amount of energy by routing the lightpaths on minimum consuming NEs and that the GHG emitted may be notably reduced by the *MinGas-RWA* strategy that prefers NEs powered by green energy sources.

The effectiveness of the ILP formulations may be further evaluated according to the network topology and heterogeneity. Renewable energy sources may vary their availability with time (e.g. solar panels only generates electricity during the day). While in the current work we handled the availability of green and dirty sources in a static way, in future works statistically variable green energy sources may be considered within a totally dynamic scenario in which the availability of the different types of renewable energy sources can be associated with the variations of the day time and traffic load (e.g. night/day cycle).

ACKNOWLEDGMENTS

This work was supported in part by the COST Action IC0804 on Energy Efficiency in Large Scale Distributed Systems, the Spanish Ministry of Science and Innovation under the DOMINO project (TEC2010-18522), the Catalan Government under the contract SGR 1140 and the DIUE/ESF under the grant FI-201000740.

REFERENCES

[1] Energy Star, *Small network equipment*, [Online]. Available: http://www.energystar.gov/index.cfm?c=new_specs.small_network_equip.

[2] BONE project, WP 21 Topical Project Green Optical Networks: Report on year 1 and updated plan for activities, NoE, FP7-ICT-2007- 216863, Dec. 2009.

[3] B. St Arnaud, *ICT and Global Warming: Opportunities for Innovation and Economic Growth*, [Online]. Available: http://docs.google.com/Doc?id=dgbgjrct_2767dxpbdvcf.

[4] L. Chiaraviglio, M. Mellia, F. Neri, "Reducing power consumption in backbone networks", in *Proc. IEEE ICC 2009*, Dresden, Germany, June 2009.

[5] Y. Wu, L. Chiaraviglio, F. Neri, "Power-aware routing and wavelength assignment in optical networks", in *Proc. ECOC 2009*, Vienna, Austria, Sep. 2009.

[6] L. Chiaraviglio, M. Mellia, F. Neri, "Energy-aware backbone networks: a case study", in *Proc. GreenComm'09*, Dresden, Germany, June 2009.

[7] A. Muhammad et al., "Energy-efficient WDM network planning with dedicated protection resources in sleep mode", in *Proc. IEEE Globecom* 2010, Miami, FL, USA, Nov. 2010.

[8] F. Idzikowski, S. Orlowski, C. Raack, H. Woesner, A. Wolisz, "Saving energy in IP-over-WDM networks by switching off line cards in low-demand scenarios", in *Proc. ONDM 2010*, Kyoto, Japan, Feb. 2010.

[9] I. Cerutti, A. Fumagalli, M. Tacca, A. Lardies, R. Jagannathan, "The multi-hop multi-rate wavelength division multiplexing ring", *IEEE/OSA J. Lightw. Technol.*, vol. 18, no. 12, pp. 1649-1656, Dec. 2000.

[10] X. Dong, T. El-Gorashi, J. M. H. Elmirghani, "Renewable Energy in IP Over WDM Networks", in *Proc.* ICTON, Munich, Germany, Jun. 2010.

[11] J. Chabarek et al., "Power awareness in network design and routing", in *Proc. IEEE Infocom 2008*, Phoenix, AZ, USA, Apr. 2008.

[12] S. Aleksic, "Analysis of power consumption in future high-capacity network nodes", *OSA/IEEE J. Opt. Commun. Netw.*, vol. 1, no. 3, pp. 245-258, Aug. 2009.

[13] S. De Maesschalck et al., "Pan-European Optical Transport Networks: An Availability-based Comparison", *Phot. Netw. Commun.*, vol.5, no.3, pp. 203-225, May 2003.