Blackout Resilient Optical Core Network

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***Abstract*—A disaster may not necessarily demolish the telecommunications infrastructure, but instead it might affect the national grid and cause blackouts, consequently disrupting the network operation unless there is an alternative power source(s). In disaster-resilient networks, fiber cut, datacenter destruction, and node isolation have been studied before with different scenarios, but the power outage impact has not been investigated before. In this paper, power outages are considered, and the telecommunication network performance is evaluated during a blackout. A mixed Integer Linear Programming (MILP) model is developed to evaluate the network performance for a single node blackout under two scenarios: minimization of blocking and minimization of renewable and battery energy consumption. Insights analyzed from the MILP model results have demonstrated the trade-off between the two evaluated optimization cost functions and shown that the proposed scheme can extend the network lifetime while minimizing the required amount of backup energy.**

***Index Terms*—Blackout, core network, disaster-resilient, IP/WDM, power outage.**

I. Introduction

POWER outage is one of the main disruption causes for telecommunication network operations. Although telecommunication networks depend on the power grid, the authors in [1] described the relation between the Internet and the power grid as an example of infrastructure interdependence as the Internet depends mainly on the power grid to stay operational while the Supervisory Control And Data Acquisition (SCADA) systems use the Internet to communicate.

Natural disasters, man-made disasters or technology faults can cause blackouts. In [2], the researchers classified large scale blackouts as technology-related disasters. During the Japan Earthquake in 2011, the affected area was left in a blackout, where 1500 telecommunications switching offices were left without mains power supply except few limited batteries. Eventually, the switching systems shut down after a few hours when the batteries charge was depleted [3]. In 2005, Hurricane Katrina caused telecommunication disruption due to power outages for 134 networks for ten days [4]. In Italy in 2003 [5], a substation failure led to communication network shut down. Consequently, this shutdown caused a failure in the SCADA power control system which caused more substations failures and led to a total blackout. This interdependency problem has been studied in a number of papers such as [6]–[8].

Most countries rely on the national grid network, and any disruption in the grid might bring systems in the country as a whole, that rely on electricity, down. The telecommunications Central Offices (COs) are regularly powered by the national grid, while diesel generators and battery cells are used as a backup power supply. Obviously, these are of limited availability. Operators are obliged to ensure Business As Usual (BAU) during disasters, though using backup power sources is essential to avoid Service Level Agreement (SLA) violation due to power outages. The recent energy strategies that promote the use of renewable energy can alleviate grid network shut down, however still the use of renewable energy is limited even in developed countries.

Disaster survivability is a trending topic that has been researched extensively within the multi-correlated and large-scale failures that happen to nodes and links. In [9], a Software Defined Networking (SDN) approach was developed to mitigate the disaster risk by fast rerouting at the network node and a splicing approach at the controller was used to restore the failed paths. In [10], a disaster resilient virtual network mapping was modelled using a probabilistic approach to evaluate network performance post-disaster to ensure minimal impact on network performance after a single physical link failure. The researchers in [11] proposed mapping virtual networks for SDN controllers, so that any physical infrastructure failure does not compromise the communication between the control and data planes.

In [12], the authors presented Disaster-Resilient Optical Datacenter Networks. They developed an integer linear programming (ILP) optimization model to design an optical datacenter network that considers content placement, routing and protection paths to content. Virtual machines placement across geo-distributed datacenters are studied in [13] to avoid content being isolated in a failed datacenter.

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Post-disaster progressive network recovery was investigated in [14], where an ILP was developed to prioritize a recovery plan that considers the restoration of high impact damaged parts. In [15], the availability and the cost of upgrading a damaged core optical network in a post-disaster scenario are considered. The researchers addressed the problem of selecting a set of edges to be upgraded at a minimum cost, while guaranteeing desired values of end-to-end availability through developing geo-diverse routing. In [16], the researchers proposed deploying disaggregated subsystems for rapid post-disaster recovery. Integrating these multi-vendor optical network technologies is possible due to their open interfaces in the control and data planes.

Disasters may have an indirect impact on telecommunication networks, such as huge traffic and power outages. In [17] and [18], we have investigated the network traffic floods that are stimulated by disasters. We have studied the network performance with different volumes of traffic, and then suggested four approaches to minimize traffic blocking and serve more traffic using MILP modeling and heuristic approaches. The researchers, in [19], surveyed the impact of recent power outages and the number of affected users. Any of these events would affect not less than a few millions of users. They have suggested the use of Software Defined Networking (SDN) technology to build a Disaster-Resilient SDN Network that can be adaptive to blackout situations. In [20], the authors studied the disasters that cause power outages, and proposed a framework for disasters risk assessment. Based on the assessment, the logistic resources are planned by providing portable generators and permanent solar cells. Table I summarises the related work in building disaster resilient networks.

Energy-efficiency is another important metric when designing and operating networks under normal conditions and under disaster conditions. It can be considered a mitigation approach for blackouts, as minimizing power consumption can save the limited power sources available. In the energy-efficiency context, we have explored different strategies and approaches to minimize the overall network power consumption [21]–[25]. We considered the use of renewable energy [26], energy efficient physical topology design optimization [27], content placement, caching and replication in the clouds [28]–[30], to reduce power consumption, and energy efficient virtual network embedding [31]. The use of network coding in IP over WDM networks for energy efficiency was evaluated in [32], and green and energy efficient processing of big data was studied in [33], finally [34] studied advance reservation demands scheduling.

Combining these two contexts: energy-efficiency and disaster-resiliency has not been studied before in a power outage scenario. However, building an energy-efficient survivable network was investigated in a number of papers, but the approaches did not consider disaster survivability (multi-correlated failures), large scale disasters or limited power sources.

Authors in [35], carried a comparison study to evaluate the power consumption of protected WDM networks for all-optical and opaque network architectures. The evaluation study carried out for two scenarios of protection; 1:1 and Shared backup Path Protection (SPP). Authors reported that with all-optical SPP scenario, the power consumed was lower.

In [36], authors proposed an iterative routing scheme by assigning different weights to the communication links to allow switching-off the dedicated backup path resources. Authors suggested active, sleep and off as the operational modes for the devices, so that for saving more energy they attempted to put the backup protection path resources on sleep

TABLE I
RELATED WORK IN BUILDING DISASTER-RESILIENT NETWORKS

Article reference	Investigated context	Optimization approach	Disaster impact	System Features
[9]	SDN	Heuristic	Fiber cut/Node failure	Fast rerouting
[10]	Virtual Network Mapping	ILP	Fiber cut	single physical link failure
[11]	SDN with Virtual Network Mapping	ILP	Node isolation	Data and Control planes separation.
[12]	Disaster-Resilient Data center Network	ILP	Node isolation	content placement, routing and protection paths to content.
[13]	Server Placement	ILP	Data center isolation	Virtual machines placement across geo-distributed datacenters.
[14]	Progressive Network Recovery	ILP	Fiber cut	prioritize a recovery plan that considers the restoration of high impact damaged parts.
[15]	Geo-diverse Routing	ILP/Heuristic	Fiber cut	the cost of upgrading a damaged core optical network.
[16]	SDN		Post-disaster recovery	deploying disaggregated subsystems for rapid post-disaster recovery.
[17] & [18]	Traffic Routing	ILP/ Heuristic	Post-disaster Traffic Floods	Minimize blocking by rerouting, excess capacity, traffic filtering and differentiated services.

mode while keeping the other unused resources on a switch-off mode. The outcome of the algorithm is a static routing along with the wavelength assignment resulting in a minimum power consumption [REsults].

In [37], the authors proposed a method to save energy and minimize CAPEX and OPEX for WDM network with shared backup path protection. In [38], the authors attempted to solve the complexity problem they struggled through in [37] as their model appeared to be NP- Complete. Authors presented their proposed solution through a heuristic algorithm for energy-efficient shared backup path protection by using auxiliary graph. The developed heuristic designed for routing through the primary and secondary paths to support the share ability while saving consumed energy. Authors reported energy savings reaching 46% were achieved.

In [39], Authors proposed an energy-aware network planning with dedicated path protection. They developed a model for planning a network based on static routing and wavelength assignment at minimum power by using sleep mode with dedicated protection. Authors reported energy savings reaching 25% were achieved with the proposed model. In [40], the authors employed sleep mode for energy efficiency with dynamic provisioning for dedicated path protected network. Authors claimed that with the sleep mode technique, 35% saving in the total energy consumption could be accomplished. In [41], a heuristic is proposed for routing both the working and protection light paths with an objective to maximize the power saving. The algorithm first attempted to separate the working paths from backup paths, after that put the backup resources (links and nodes) in sleep mode.

In [42], the authors evaluated the hourly traffic variation impact for energy-efficient protected core network. The evaluated protection scheme was 1+1 with Mixed Line Rate (MLR), by which the backup resources stay active all the time and only the transceivers line rates are adjusted based on traffic demands. Authors have compared and evaluated power consumption using single line rate, mixed line rate and E-OFDM. Results indicated that the higher energy savings (27%) can be achieved with E-OFDM solution. In [43], the researchers evaluated the power consumption for different types of protection schemes. They suggested the use of differentiated Quality of Protection (DQoP) depending on the type of client to enhance the energy efficiency of fixed-grid WDM networks and flexible-grid elastic OFDM-based network. They have shown energy saving of 21% when compared with 1+1 protection scheme. In [44], the authors evaluated the energy efficiency by using sleep mode devices in the four protection schemes (DPP, SPP, SLP and DLP). They developed a mathematical linear model to design power-aware protected networks. Reported power savings were up to 60% when using the sleep mode in protection.

In [45], the authors evaluated the power consumption in Link Sleep Mode (LSM) and Opto-Electronic device Sleep Mode (OESM) and compared the results with dedicated path protection. In this work, authors also proposed a hybrid approach to combine LSM and OESM which is called HSM. The HSM attempted to put both link equipment and OE in sleep mode for protection paths when they are in idle state. The results showed that the HSM outperformed the LSM and OESM in power reduction.

In this work, we consider scenarios in which network nodes are powered by the national grid, a renewable power source and backup batteries. The survival time of a blackout node is extended by reducing the amount of traffic that is routed through the limited power nodes. Furthermore, during renewable energy production hours, the available renewable energy is exploited first before using the battery energy. Section 2 presents the proposed scenarios for building blackout resilient networks. Section 3 presents the developed MILP formulation for modeling the scenarios. Section 4 evaluates the scenarios and discusses the network performance under these scenarios. Section 5 concludes the paper.

II. Blackout Resilient Scenarios

We study two scenarios to show the impact of blackouts when building a Blackout-Resilient Network. The first scenario follows the traditional practices that network operators follow in normal and disaster times, while the second scenario is intended for adding resilience to the network to adapt to the blackout situation.

In this work, we consider an IP over WDM core network architecture. Generally, the core network topology is a mesh topology. Therefore, there is more than one path from source to destination.

In the core network, a node failure does not only impact the originated/destined traffic of the failed node but also the transit traffic through the node is disrupted unless there is a protection path for the transit traffic to be rerouted over. Switching the traffic to the protection paths is activated only if the node shuts down. Otherwise, if the node is still working, even with limited power, the transit traffic is not rerouted over the protection paths, till the backup energy is depleted.

A. Blocking Minimization Scenario

One of the main Key Performance Indicators (KPIs) for network performance is the blocking probability. Therefore, network operators are obliged to minimize the expected blocking that might happen due to traffic anomalies/growth, within the design and operation phases. During the network design, minimizing the expected blocking is typically solved by capacity overprovisioning. The overprovisioning is done by doubling/tripling (or increasing by a larger factor) the network infrastructure resources. These overprovisioned resources are generally put to sleep or standby, and are activated whenever they are needed. In the operation phase, whenever a fault happens in a node or a link, traffic bypassing the faulty node/link should be rerouted on a protection path to avoid traffic disruption. Rerouting the traffic can be done by activating and reconfiguring the overprovisioned resources to serve the rerouted traffic. The other indicator that network operators look for is the power consumption. Minimizing the power consumption reduces the operational costs, and this is an objective for network operators. Minimizing the consumed power and/or minimizing the blocking probability can be achieved through several approaches during both the design and the operation phases. One of the intuitive routing approaches that can be employed is the minimum hop routing algorithm [21], [22]. This approach minimizes the operational resources, consequently minimizing the consumed power.

In the blocking minimization scenario, we follow the usual operator practices in network operation by minimizing both blocking and the consumed power, while giving priority to blocking over power consumption.

B. Weighted Energy Sources Optimization (WESO) Scenario

Typically, the Central Office (CO) buildings, that contain the core node, are powered by more than one power source such as grid power, renewable power, and batteries. The power sources have different operational and capital expenditures (OPEX and CAPEX). For example, the grid power has different operational pricing schemes from city to city, or during the day. On the other hand, the renewable power sources have low OPEX, except in terms of preventive maintenance, and while such renewable sources typically have higher CAPEX. In contrast, the batteries have limited energy, which means they cannot handle the network operation for long time periods without being charged by another power source. From the operation perspective and according to the above we can conclude that, renewable is preferable to handle network operation as long as it is available, while the grid comes next due to its higher operational costs. Finally, backup batteries come last, and can be used to power the network for a few hours, if both grid and renewable fail.

The above approach can be used by operators to route the traffic in normal times, while in a blackout scenario prioritization should be changed. The change should ensure that the use of grid power is prioritized over the battery and renewable power to preserve the battery energy and the renewable energy to power the blackout node(s). Therefore, this approach attempts to ensure that during a blackout, the available energy is used only to serve the originated and destined traffic of the blackout node, while the transit traffic should be routed away from the blackout node to other nodes where grid power is available. Also, the use of renewable energy in the blackout node is given priority over the power drawn from the battery as long as renewable energy is available; to preserve the battery energy to the times when there is no renewable production (i.e., no sunlight or wind).

III. MILP FOR BLACKOUT RESILIENT SCENARIOS

A MILP model was developed to optimize the routing in core networks under a single node blackout scenario where limited alternative energy sources are available to the blackout node. These energy sources can be renewable sources, batteries or diesel generators used to supplement the national grid power. The objective of the model is to reduce the total power consumption where the batteries power is prioritized in the minimization.

The model considers a bypass IP over WDM architecture which is shown in Figure 1. The available energy sources are assumed to be used to power the network equipment only, i.e. the power consumption of CO cooling system, servers are not

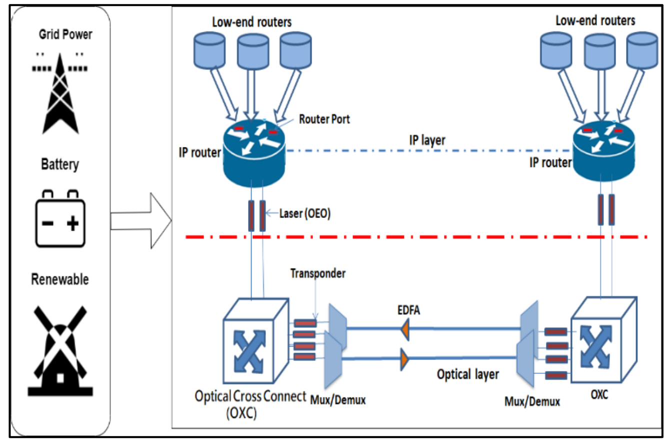


Fig. 1. IP over WDM network architecture.

considered. In addition, as the focus in this paper is on the core network, the access network and aggregation routers are not considered.

The IP over WDM architecture consists of [46]:

IP Routers: The IP routers represent the only electronic part of the core node. They act as an interface for traffic aggregation from the metro networks to the core optical networks. The IP router is connected to the optical switch (OXC) via short reach optical interconnects.

Transponders: The optical transponders are used for electronic to optical or optical to electronic signal conversion. These transponders connect the IP router with the Optical Cross Connect.

Optical Cross Connect (OXC): OXC is the most important part in the WDM layer. It acts as the interface between the edge router and the optical network. The OXCs work as a cross-connect which means connecting input (i) with output (j) by using preconfigured cross-connect tables. When establishing a lightpath through the core network, all the OXCs which are ingress, egress and intermediate should be configured according to the cross-connect table to allow the lightpath to pass physically through them. In general, an OXC has the ability to wavelength convert an incoming optical signal to facilitate routing or remove OXC blocking.

Erbium-Doped Fiber Amplifier (EDFA): EDFA is an optical amplifier that represents the key component for enabling the WDM system to efficiently transmit signals for long distances reaches to 80 km. The gain of the EDFA reaches to 30dB, but the amplification does not consider the reshaping or bit rate.

Regenerators: After some distance, the cumulative loss of signal strength causes the signal to become too weak to be detected. And to restore signal strength, regenerators should be used. A regenerator converts the optical signal to an electrical signal, cleans it up, and converts it back into an optical signal for onward transmission.

Under the bypass IP over WDM network architecture, the power consumption is composed of:

1- Power consumption of router ports at time t:

$$\sum_{i \in N} \sum_{\substack{j \in N \\ i \neq j}} P_r C_{ij}$$

2- Power consumption of transponders:

$$\sum_{m\in N}\sum_{n\in N_m} \boldsymbol{P_t W_{mn}}$$

3- Power consumption of EDFAs:

$$\sum_{m\in N}\sum_{n\in N_m} \boldsymbol{P_e F_{mn} A_{mn}}$$

4- Power consumption of regenerators:

$$\sum_{m\in N}\sum_{n\in N_m} \boldsymbol{P_g RG_{mn} W_{mn}}$$

5- Power consumption of optical switches:

$$\sum_{m\in N} \boldsymbol{P_o}$$

Before introducing the model, the parameters and variables used in the model are defined in Table II.

The model is defined as follows:

Objective function:

$$\text{Minimize} \sum_{i\in N}(\alpha BR_i + \beta RE_i + \gamma BT_i) + \delta \sum_{s\in N}\sum_{d\in N: s\neq d} bl_{sd} \quad (1)$$

The objective function minimizes the power consumed from the different power sources at each node, while keeping the blocking to a minimum. Each power source is weighted by a coefficient. Tuning these coefficients adjusts the operator's energy strategy. The traffic flow conservation can be formulated as:

$$\sum_{j\in N i\neq j}\lambda_{ij}^{sd} - \sum_{j\in N i\neq j}\lambda_{ji}^{sd} = \begin{cases}\lambda^{sd}(1-bl_{sd}) & m=s\\ -\lambda^{sd}(1-bl_{sd}) & m=d\\ 0 & otherwise\end{cases}$$
$$\forall s,d,i\in N: s\neq d, \quad (2)$$

Constraint (2) is the flow conservation constraint in the IP layer. It ensures that the total outgoing traffic is equal to the total incoming traffic except for the source and destination nodes.

$$\sum_{s\in N}\sum_{d\in N s\neq d}\lambda_{ij}^{sd} \le C_{ij}X \quad \forall j,i\in N: i\neq j, \quad (3)$$

Constraint (3) is the virtual link capacity constraint. It ensures that the summation of all traffic flows through a lightpath does not exceed the lightpath capacity.

$$\sum_{n\in N_m} W_{mn}^{ij} - \sum_{n\in N_m} W_{mn}^{ij} = \begin{cases} C_{ij} & m=i\\ -C_{ij} & m=j\\ 0 & otherwise\end{cases}$$
$$\forall i,j,m\in N: i\neq j, \quad (4)$$

Constraint (4) is the flow conservation constraint in the optical layer. It assumes that the total outgoing wavelengths in a virtual link should be equal to the total incoming wavelengths except the source and the destination nodes of the virtual link.

$$\sum_{i\in N}\sum_{j\in N} W_{mn}^{ij} = W_{mn} \quad \forall m\in N,\ n\in N_m, \quad (5)$$

$$W_{mn} \le W.F_{mn} \quad \forall m\in N,\ n\in N_m, \quad (6)$$

TABLE II
LIST OF THE SETS, PARAMETERS AND VARIABLES USED IN THE MILP MODEL

Symbol	Description
N	Set of nodes
N_i	Set of neighboring nodes of node i
s and d	Denote source and destination nodes of a traffic request
i and j	Denote end nodes of a virtual link in the IP layer
m and n	Denote end nodes of a physical link in the optical layer
T	Time slot duration
P_r	Power consumption of a router port
P_t	Power consumption of a transponder
P_o	Power consumption of an optical switch
P_e	Power consumption of an EDFA
P_g	Power consumption of a regenerator
BPC_s	Baseline Power Consumption at node s
X	Capacity of a wavelength
W	The number of wavelengths per fiber
F_{mn}	Number of fibers in link (m,n)
RG_{mn}	The number of regenerators in link (m,n)
λ^{sd}	Traffic request from node s to destination node d
B_i	The available battery energy at node i
R_i	The maximum output power of the renewable source
$\alpha,\beta,\gamma,\delta$	Weighing coefficients
A_{mn}	Is the number of amplifiers between nodes m and n, on a link L_{mn}, $A_{mn} = \left(\frac{L_{mn}}{s}-1\right)+2$, where s is the distance between two neighboring EDFAs and L_{mn} is the distance between nodes m and n.
λ_{ij}^{sd}	The traffic flow of request (s,d) that traverses the virtual link (i,j)
C_{ij}	The number of wavelength channels in the virtual link (i,j)
W_{mn}^{ij}	The number of wavelength channels in the virtual link (i,j) that traverse link (m,n)
bl_{sd}	Binary blocking variable. If $bl_{sd}=1$ then the request from node s to node d is blocked, otherwise it is not blocked.
RE_s	The amount of renewable power consumed at node s
BT_s	The amount of power withdrawn from a battery during time slot t at node s
BR_s	The amount of grid (brown) power consumed at node s

Constraint (5) finds the total wavelengths per link (m,n), while constraint (6) ensures that the total wavelengths per link do not exceed the fiber link capacity.

$$RE_i \le R_i \quad \forall i\in N \quad (7)$$

$$BT_iT \le B_i \quad \forall i\in N \quad (8)$$

Constraints (7) and (8) ensure that the power consumed per node does not exceed the available generated energy for

TABLE III
NETWORK PARAMETERS

Parameter	Value
Distance between two neighboring EDFAs (S) [21]	80 (km)
Number of wavelengths in a fiber (W) [28]	32
Capacity of a wavelength (B) [22]	40 (Gb/s)
Power consumption of a router port (P_r) [21]	825 (W)
Power consumption of a transponder (P_t) [21]	167 (W)
Power consumption of a regenerator (P_g) [21]	334 (W)
Power consumption of an EDFA (P_e) [22]	55 (W)
Power consumption of an optical switch (P_o) [29]	85 (W)

renewable and battery sources. Constraint (7) ensures that at each time point the amount of power consumed from renewable sources does not exceed their produced power. In constraint (8) the formulation ensures that the power withdrawn from a battery for the duration of the time slot does not exceed the battery residual energy.

$$\sum_{i\in N}\sum_{\substack{j\in N\\ :i=s\vee j=s,\\ i\neq j}}\frac{1}{2}P_rC_{ij}+\sum_{m\in N}\sum_{\substack{n\in N_m\\ :m=s\vee n=s}}\frac{1}{2}P_tW_{mn}$$
$$+\sum_{m\in N}\sum_{\substack{n\in N_m\\ :m=s\vee n=s}}\frac{1}{2}P_gRG_{mn}W_{mn}$$
$$+\sum_{m\in N}\sum_{\substack{n\in N_m\\ :m=s\vee n=s}}\frac{1}{2}P_eF_{mn}A_{mn}+P_o$$
$$=BT_s+BR_s+RE_s\quad\forall s\in N \tag{9}$$

Constraint (9) makes sure that the power consumed in the node (which consists of power consumed in the router ports, transponders, regenerators, EDFAs and optical switch) should equal the total power withdrawn from all energy sources (batteries, brown and renewable).

IV. Network Performance Evaluation

The model is evaluated using the Italian Network topology shown in Figure 2 which consists of 21 nodes and 36 bidirectional links and one DC located in Milan (node 19). Table III shows all the input parameters used, in terms of number of wavelengths, capacity of a wavelength, distance between two neighboring EDFAs, and the energy consumption of different components in the network. The average traffic between a node pair varies throughout the day following the profile in Figure 3 with the busiest hour at 22:00. The traffic is generated using a gravity model based on the population of the city where the node is located [21].

Solar energy is used as the renewable energy source. Each CO is equipped with 100 m^2 of solar panels, so the peak solar energy produced in a day is approximately 70 kW as shown in Figure 4, [26], [47]. The sunrise and sunset and the

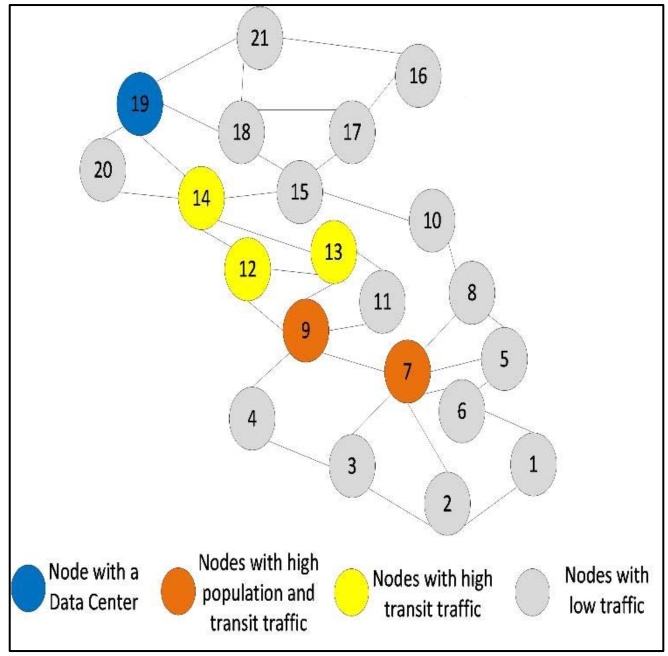


Fig. 2. Italian network.

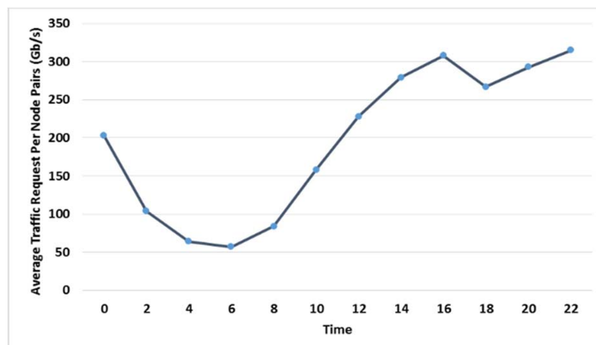


Fig. 3. Average traffic request.

perceived irradiance of April are considered where the sunlight is available for 12 hours approximately [48].

In the following results, we evaluate two optimization approaches with different coefficients weights to show the trade-off between blocking and energy preservation.

A. Blocking Minimization Versus Weighted Energy Sources (WESO) Scenarios

In blocking minimization scenario, the power consumption coefficients α, β and γ were set to 1 while δ was given a very high number (1,000,000 here), as the main objective is to minimize the total network blocking probability while minimizing the consumed power in total.

In Weighted Energy Sources Optimization (WESO) scenario, the weights are set in a way that ensures that the use of grid power is prioritized over the battery and renewable power to preserve the battery energy and the renewable energy of the blackout node. Table IV shows the three different combinations of weighing coefficients used in the evaluation. The chosen values for α, β, γ reflects the fact that, grid power source should always have the highest priority. For the

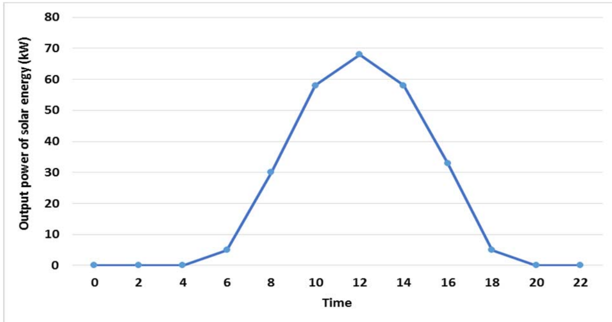


Fig. 4. Solar cells output power at each node.

TABLE IV
WEIGHING COEFFICIENTS

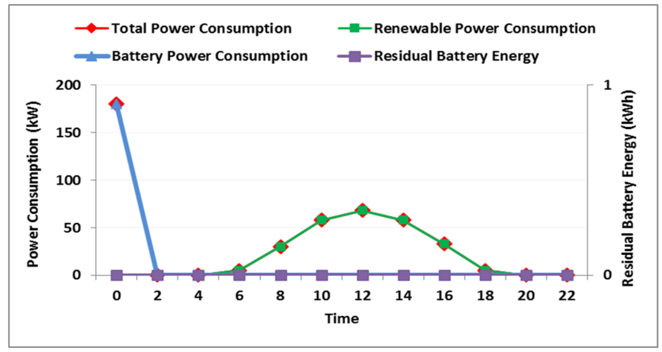
	α	β	γ
WESO 1	1	10	100
WESO 2	6	8	20
WESO 3	5	15	25

evaluated work (WESO 1) α, β, and γ were set to 1,10, and 100 respectively for the purpose of prioritizing grid power over the renewable and the renewable over battery source. These values are chosen to give preference to the power source chosen in the blackout. Since the objective function given in equation 1 is to minimize total power, the power consumption variables of the three sources ($\alpha RE_i + \beta BR_i + \gamma BT_i$) that are multiplied with the smallest (α, β, and γ) will be favored. In this case, the variable multiplied with α will be minimized since it is the smallest, followed by the variables multiplied by β and γ. While in WESO 2, the grid and renewable have a comparable weight, which means node can utilize these energies without a preference to favor one over another and avoid utilizing the batteries as possible.

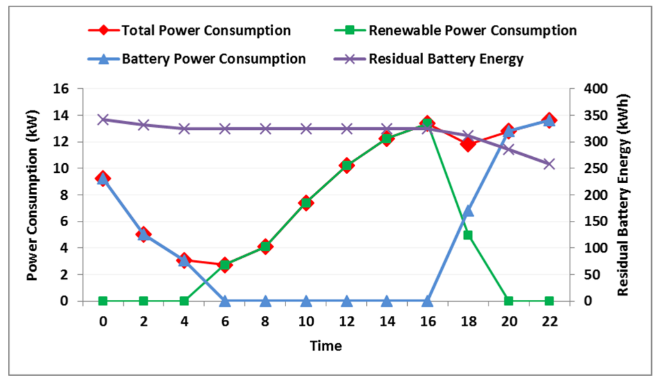
The four proposed scenarios (blocking minimization and three weighted energy optimization) are evaluated for a day long blackout at node 14. The node is assumed to have 360 kWh batteries, (a small saloon, 12 V, car battery is typically rated at 40 ampere hours, which translates to 0.48 kWh. The Tesla electric vehicle battery is 60 kWh to 85 kWh according to the car model [49]).

1) Blocking Minimization Scenario: In Figure 5(a) the blocking minimization approach results are shown. In this scenario, the node used the battery energy during the midnight hours till 2:00 am, because the traffic is relatively high. Then from 02:00 to 06:00, the node turned off as no energy source is available yet. At 06:00 the sun rises and the node operation is resumed until sunset at 18:00 where the node shuts down again until the end of the day. During the renewable power availability, the node fully utilized the renewable energy generated to serve the node traffic and the transit traffic.

2) WESO 1 Scenario: The WESO 1 scenario results are shown in Figure 5(b). The node used minimal energy from the battery energy, because the node handled its own traffic only (originated and destined traffic) while the transit traffic is rerouted. This can be seen as the maximum consumed power



(a)



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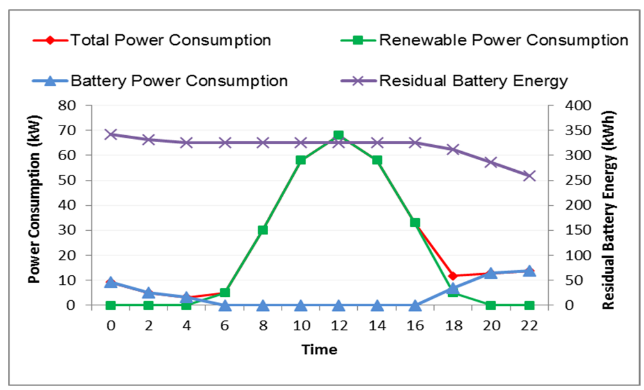
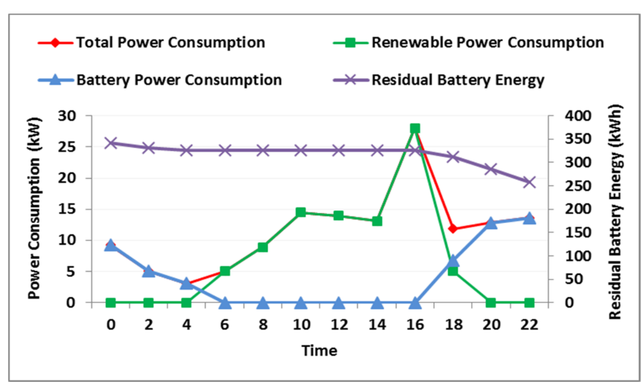


(c)



(d)

Fig. 5. Node 14 power consumption and battery residual energy under a) blocking minimization b) WESO1 c) WESO2 d) WESO3.

in the node is 14 kW. During the sunlight hours, the node used renewable energy, while after sunset, the batteries were used.

3) WESO 2 Scenario: The WESO 2 scenario results are shown in Figure 5(c). The results show that the switching between the batteries and renewable energy is the same as the WESO 1 scenario. During the sunlight hours, however, the node fully used the available renewable energy to route both the destined/originated traffic and transit traffic as the weight given to renewable energy did not stop routing the transit traffic.

4) WESO 3 Scenario: The WESO 3 scenario results are shown in Figure 5(d). This scenario behaves similar to WESO 1 and 2 in switching between the batteries and renewable. The only difference is that in WESO 3, the difference in weights between renewable and battery is larger. Therefore, less transit traffic is routed through the blackout node resulting in lower blackout node power consumption. This can be verified by checking the total consumed power in the node. In WESO 1, the node consumed 14 kW maximum, while in WESO 2 it consumed 70 kW and in WESO 3 it consumed 28 kW. In conclusion, the three scenarios avoided using the battery energy in two cases. The first when the renewable is sufficient for routing the node traffic. The other situation where the battery power was not used is the situation where the node would have had to route transit traffic under normal conditions when the renewable energy is unavailable. The differences are during the availability of renewable energy.

Comparing the four scenarios in terms of battery residual energy, it is observed that WESO 1, WESO 2 and WESO 3 have a similar residual battery energy at the end of the day. This can be justified by two reasons; (1) batteries are avoided when renewable energy is available. (2) batteries energies are only consumed at the node when traffic is originated from it or sinking to it. While for the rerouted transit traffic, power consumption is found lower. When the model is to run for minimization of blocking, the blackout node tempts to drain the batteries within the first two hours of the day and consequently results in power outage at the node.

The WESO 1 scenario is studied throughout this section, because it avoided the blackout node during the 24-hour blackout. This avoidance comes at the cost of higher power consumption in the network, but to preserve the limited available energy in the node for its own traffic.

B. Results Evaluation and Discussion

To maximize the impact of the blackout, the nodes with the most transit traffic are considered to suffer a blackout. To evaluate the most critical nodes, the MILP model is used assuming that there is no blackout in any node. Figure 6 shows the amount of traffic (transit, originating and destined) carried by each node. From the illustrated results in Figure 6, it is observed that nodes (7,9,12,13,14 and 19) transfer the highest volume of traffic. Hence, we focused on these nodes as they suffer a blackout one node at a time. The two evaluated scenarios are for each node to identify the blocking incurred and how much battery power is required. For the blocking comparison, the same battery is considered for the two scenarios. A high-capacity battery is considered with sufficient capacity to run the node till the end of the day.

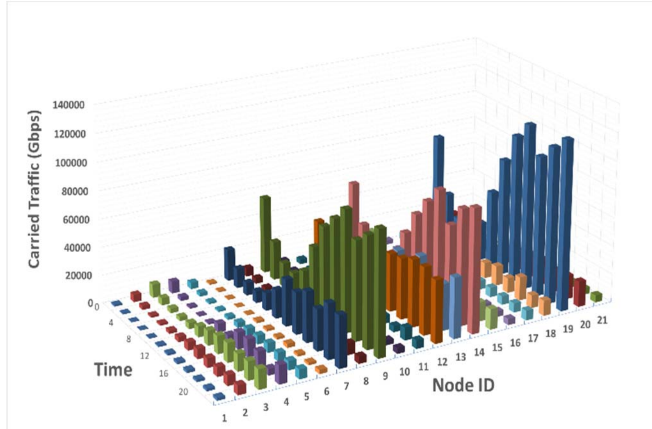


Fig. 6. Node carried traffic through the day.

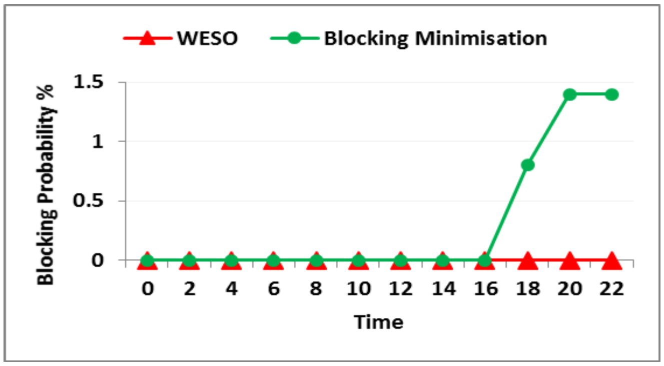
Generally, the nodes can be classified into high traffic nodes and low traffic nodes. The high traffic comes from either a high population in the city, from a DC or from transit traffic passing by the node. According to this classification, nodes 7 and 9 which are in Rome and Napoli have a huge population, while node 19 in Milan has a huge population and there is a DC collocated as well. Nodes 12, 13 and 14 lie in the path leading to the DC. The suggested approaches mainly deal with traffic distribution in the network.

First, nodes 12, 13 and 14 are evaluated for both scenarios considering each node to be equipped with a battery of 360 kWh. This is the battery capacity needed to run the node for 24 hours, for the traffic the node generates and sinks.

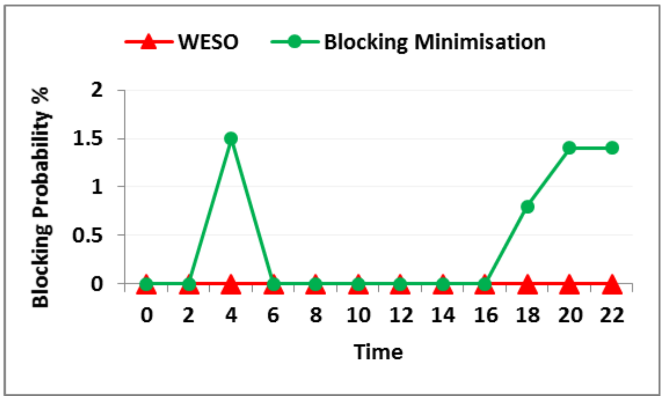
Figure 7 shows the blocking probability % of these nodes. Clearly, the WESO scenario outperforms the blocking minimization approach as it managed to run the node for the entire day; while under the blocking minimization scenario blocking occurred due to the blackout nodes not being able to send/forward traffic after running out of battery when sunlight is unavailable.

Transit traffic is traffic forwarded to a node or multiple nodes which exist in a selected path, and that/these node(s) are neither source nor destination. For optimization purposes paths are chosen by the MILP model are the shortest paths with minimum number of hops between every pair of source and destination. During a blackout, a transit node (if it was the blacked-out node) shall be eliminated from the routing paths, therefore traffic flow through other nodes shall be affected to service all other demands between source and destinations nodes not involved in the blackout. In our evaluated scenario, with the blocking minimization scenario, batteries were used to service the blacked-out node for the first hours of the day after which the available renewable energy was enough to serve all the demands, then blocking starts when no renewable energy is available.

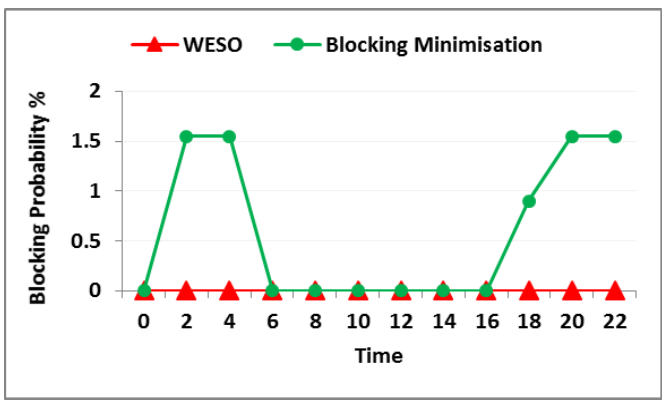
Nodes 13 and 14 start blocking from early hours because all the battery energy is used to carry the transit traffic in the four early hours of the day. The nodes' blocking probability % throughout the day as illustrated in Figure 7 show that node 14 is the worst, then node 13 follows and the least blocking is happening in node 12. This variation is a result of the rerouting which affected the size of transit traffic routed



(a)



(b)



(c)

Fig. 7. The blocking probability % for a) node 12 b) node 13 c) node 14.

through the nodes after the blackout. The increase of the traffic flow through the nodes requires more processing, hence power consumption is further increased. Giving the fact that batteries are capacitated sources of energy, in the modeled network with the extra flow of transit traffic, batteries were fully consumed before sunrise. Our results illustrate that node 14 drained the battery energy at 02:00 hour, while node 13 exploited the battery energy from 00:00 to 04:00, node 12 used the battery energy until sunrise. Outcome from the MILP results proves what explained earlier that the amount of energy consumed depends to a large extent, in many cases on the node transit traffic.

To determine the battery energy at any node to keep the network running under minimum power consumption, an energy minimization scenario was evaluated using the MILP model without blackout (baseline scenario). Power consumption of any node under normal operation without blackout occurrence consists of the power consumed by the node (router, transponders, regenerators, EDFAs and optical switch) which is calculated by Equation (10):

$$BPC_s = \sum_{i \in N} \sum_{\substack{j \in N \\ : i=s \vee j=s, \\ i \neq j}} \frac{1}{2} P_r C_{ij} + \sum_{m \in N} \sum_{\substack{n \in N_m \\ : m=s \vee n=s}} \frac{1}{2} P_t W_{mn} + \sum_{m \in N} \sum_{\substack{n \in N_m \\ : m=s \vee n=s}} \frac{1}{2} P_g RG_{mn} W_{mn} + \sum_{m \in N} \sum_{\substack{n \in N_m \\ : m=s \vee n=s}} \frac{1}{2} P_e F_{mn} A_{mn} + P_o \quad \forall s \in N \tag{10}$$

The obtained result from the model demonstrated a 2000 kWh baseline value for the battery energy is needed to keep node 14 running in service for 24. Nevertheless, actual results for the WESO scenario as illustrated in Figure 5 (b, c and d) has shown that 100 kWh battery energy is sufficient to keep the node on and running. Hence, the blocking minimization approach requires 20 times more battery energy than WESO scenario, which means more space is needed to store the battery system and more power is required to keep the batteries charged. Nonetheless, it might be infeasible to find the space needed to store this larger system.

To describe how the network perform during these scenarios, Figure 8 shows the total number of hops in the three scenarios: WESO scenario, blocking minimization scenario and WESO with no blackout scenario. In WESO with no blackout scenario, the evaluated network is under normal operation without blackout, where the routing in such a scenario is based on minimum-hop. The optimization model in this scenario selected paths with the lowest number of hops to minimize the overall energy consumption. The WESO scenario rerouted the traffic paths away from the blackout node and this can be seen in the Figure as the number of hops stays constant above that of the no blackout scenario. While with the blocking minimization approach, the traffic is routed based on the minimum-hop during the first two hours of the day till the battery power was exhausted. When the node shut down at 02:00 - 04:00, the number of hops decreased due to the rise of the number of blocked requests. A way out to minimize the blocking at 06:00, the blackout node was avoided, so the number of hops increased till 20:00 where the renewable power became insufficient to serve the remaining traffic. After sunset, the node runs out of power, so it shuts down, and as a result the number of hops decreases.

Due to their high originating and destined traffic, nodes 7 and 9 are therefore equipped with batteries of 720 kWh and 1500 kWh, respectively. Figure 9 shows the blocking probability % for nodes 7 and 9 when a blackout takes place for 24 hours. The WESO scenario has succeeded in keeping the node running for the 24 hours, while the node goes completely out of service during the last four hours of the

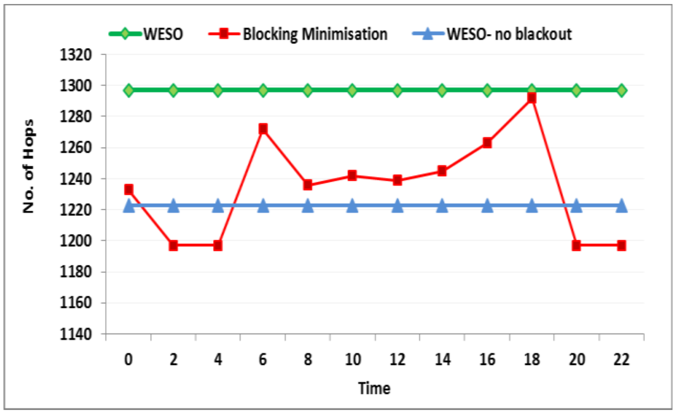
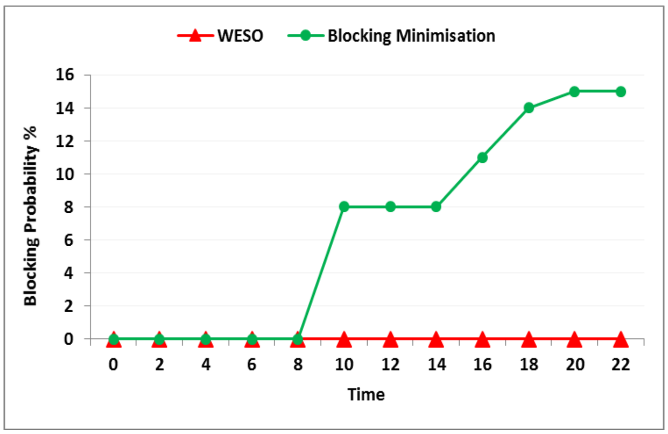
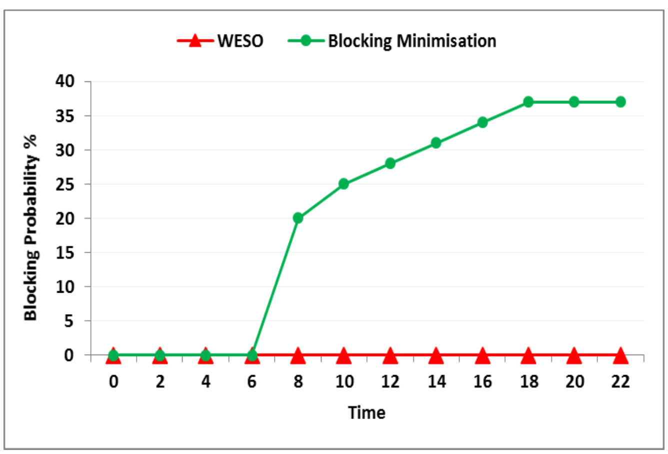


Fig. 8. Number of hops.



(a)



(b)

Fig. 9. The blocking probability % for a) node 7 b) node 9.

day in the blocking minimization approach. Under 24 hours blackout at nodes 7 and 9, the blocking minimization approach started blocking earlier than the scenarios with blackouts at nodes 12,13 and 14 because the available renewable energy during the sunlight hours is not enough to serve all the traffic.

Nodes 7 and 9 originates huge traffic requests in addition to their role in carrying the transit traffic between the datacenter (in the north) and the south edge nodes. Hence, the WESO scenario could perform more efficiently by rerouting the transit traffic away from nodes 7 and 9. It is observed that, at node 19 where the data center exists at the far edge of the network, the WESO scenario cannot solve the problem as the node's originating and destined traffic considerably large.

V. Conclusion

Blackouts are a serious source of disruption in the network during disasters unless there is a backup power source. In this paper, building a blackout resilient network has been investigated in the optical core network. Two scenarios have been considered; one with the objective of minimizing blocking and the other has the aim of optimizing the usage of power sources where the blackout nodes are considered to have access to solar energy and batteries. A weighted energy optimization scenario was introduced. This attempts to maximize the blackout survival time while minimizing the blocking. A MILP model was developed to optimize the IP over WDM network performance under the two scenarios. An example network was used to evaluate the model with realistic traffic requests. The results show that the WESO scenario succeeded in extending the network life time with the smallest battery resource compared with the blocking minimization approach. Using an online routing technology (or programmable networks) is always a solution such as the SDN. Network topology and node location affects surviving time.

Acknowledgment

All data are provided in the results section of this article.

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