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Fog-Assisted Caching Employing Solar Renewable Energy and Energy Storage Devices for Video on Demand Services

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ABSTRACT This paper examines the reduction in the non-renewable power consumption of transport networks including core, metro and access layers when Video-on-Demand (VoD) content is cached in solar-powered fog data centres with Energy Storage Devices (ESDs). The effects of considering optical bypass routing and Mixed Line Rate (MLR) in the core network, the availability of solar renewable energy in the access network, and optimising the use of ESDs were addressed. A Mixed Integer Linear Programming (MILP) model that considers the above factors was developed to optimise delivering VoD content from cloud data centres in the core network or fog data centres in the access network.

INDEX TERMS Mixed integer linear programming (MILP), IP over WDM networks, cloud data centres, fog data centres, video-on-demand (VoD), renewable energy, energy efficiency, energy storage device (ESD).

I. INTRODUCTION

A Compound Annual Growth Rate (CAGR) of 54% from 2016 to 2021 in video traffic was estimated in [1]. As a result, the power consumption of transport networks (i.e. core, metro, and access networks) that link cloud data centres containing video workloads and end users in the access network is expected to increase massively. Moreover, as these systems are typically powered by brown energy (i.e. non-renewable energy), this would also lead to an increase in CO_2 gas emission and operational costs [2]. To address both issues, several greening approaches were suggested in the last decade such as hardware improvement, routing and workload scheduling optimisation, in addition to considering renewable power sources [3]–[14]. The authors in [2] considered the lightpath bypass approach in IP over WDM core networks to reduce the power consumption and achieved energy savings between 25% to 45%. As part of the efforts in GreenTouch, the work in [15], [16] considered a combination of greening approaches for IP over WDM core networks and introduced a comprehensive Mixed Integer Linear Programming (MILP) model and heuristics. The greening approaches included the consideration of optical bypassing, optimising the core network topologies, employing Mixed Line Rates (MLRs), utilising efficient protection and sleep modes, in addition to considering two improvements for hardware which are the Business-As-Usual (BAU) equipment improvement due to advances in Complementary Metal Oxide Semiconductor (CMOS) technology, and BAU accompanied by further GreenTouch improvements. The first achieved 4.23× energy efficiency improvements compared to 2010 networks while the second achieved 20× improvements.

The energy efficiency in Content Delivery Networks (CDNs) and Information-Centric Networks (ICNs) was extensively surveyed in [17] and [18]. Optimising the placement of workloads and content to reduce the power consumption was also considered in greening core networks as in [19]–[29]. In [19], the authors studied several data centre allocation and popular content placement strategies. Their study found that locating the data centres at central locations in the network and replicating the contents in multiple data centres according to their popularity minimised the power consumption by 28%. In [20], the energy efficiency of Video-on-Demand (VoD) services was examined by numerically

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evaluating five strategic locations for caching in core, metro, and access networks. In [21]–[23], the caching of VoD contents was optimised to reduce its energy consumption for storage and transport while considering the cache sizes and the hourly-varying content popularity and suggested dynamic cache content replacement. To reduce the energy consumption of various cloud services, the work in [24] optimised the distribution of contents and services in cloud data centres and found that the optimised replications reduced the power consumption by 43% compared to centralised placements.

Reducing CO_2 emission, which rises with the increase in brown power consumption, was considered by using renewable resources to power core network nodes and data centre equipment. The authors in [30] suggested using renewable energy sources in IP over WDM core nodes and optimised the routing to maximise the renewable energy usage which resulted in reductions in CO_2 emission between 47% and 52%. The dynamics of solar power availability and workloads was considered in [31] while optimising the use of solar energy for cloud data centres and IP over WDM equipment and reductions by up to 32% in CO_2 emission was obtained. In [32], wind energy was considered for cloud services while considering the cloud locations, content replication and the renewable energy transmission losses.

Different computing systems such as Fog computing, Mobile Edge Computing (MEC), and cloudlet Computing were recently evaluated to reduce the latency associated with delivering various services through cloud computing to end users [33]–[35]. Such implementations are also capable of reducing the energy consumption of core networks [36]. Nano Data Centres (NaDa) were introduced in the early work in [37] where gateways were regarded as a peer-to-peer computing and storage infrastructure and energy consumption reduction by at least 20-30% was obtained. The use of fog data centres for smart city applications was considered in [38] to reduce core networks power consumption and maintain Quality of Service (QoS). The authors in [39] suggested edge caching for Device-to-Device communications to improve the performance and reduce the power consumption of back-haul networks. The trade-offs in terms of performance and power consumption when using different data centre topologies in fog environments were addressed in [40]. The authors in [41] suggested integrating micro data centre (Micro-DC) in Optical Line Terminals (OLTs) to reduce the traffic in core networks. The work in [42] proposed an architecture which integrates fog computing at Central Offices to improve telecommunication services. In [20], the power consumption and delay trade-offs of caching VoD contents from different layers including core routers, metro routers and switches, and at the OLT and ONU were analysed.

To increase the usage of unreliable renewable resources such as solar power, the use of Energy Storage Devices (ESDs) was suggested. In [43], ESDs were utilised to store surplus renewable energy and discharge it during high workload peaks or when the brown energy price is high. The authors in [44] optimised the use of ESDs when the renewable energy is not available or during peak workloads and proposed an opportunistic scheduling algorithm to delay batch workloads until the renewable energy is available. The work in [45] reduced the cost for powering cloud data centres by implementing ESDs and energy trading for different renewable sources by optimising the consumption, storage and trading with power grids while addressing the inefficiencies with charging and discharging the batteries. In [46] we utilised solar-powered fog data centres with ESDs to cache video content and in [47] we also considered metro network-located fog data centres.

The work in this paper extends the work in [46] and utilises a MILP model to optimise the reduction in transport networks non-renewable power consumption when delivering VoD traffic by maximising the use of solar renewable energy in fog data centres with ESDs in the access network. The remainder of this paper is organised as follows: Section II introduces the system model considered and parameters. Section III presents the MILP model for efficient content delivery while Section IV presents the results and discussion. Finally, Section V provides a summary and conclusions.

II. SYSTEM MODEL AND PARAMETERS

A. TRANSPORT NETWORK

In this work, the core network has an IP over WDM architecture with the bypass routing approach. The NSFNET network topology was considered. In NSFNET, 14 nodes are connected via 21 bidirectional links with distances, $D_{(m,n)}$ in km, provided in Figure 1. This network is modelled as a

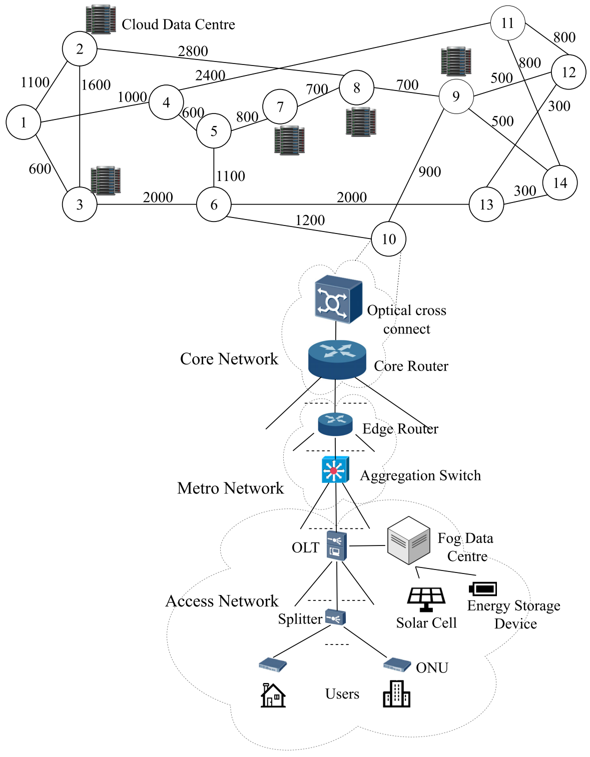

FIGURE 1. System model for fog data centre VoD caching to assist cloud data centres [46].

unidirectional graph $G = (N, L)$, where N is the set of the 14 core nodes, and L is the set of physical links between the nodes. Each core node is equipped with adequate Internet Protocol (IP) router and transponder ports in addition to an optical switch. For the links, a number of Erbium-Doped Fiber Amplifiers (EDFAs) and regenerators are considered according to the link budget requirements at different line rates. The Cloud Data Centres (CDCs) are assumed to be in nodes 2, 3, 7, 8, and 9 [16]. Each core node is connected to a metro network that contains edge routers and Ethernet switches to provide connection with access networks within that node. All the aggregation IP ports in core and metro routers are assumed to operate at 40 Gbps. For metro Ethernet, C9500-32QC switches [48] are utilised. The access network is mainly a Passive Optical Network (PON) composed of a number of OLTs, each connects the metro network with a Fog Data Centre (FDC) to assist the five CDCs in delivering VoD services to users, in addition to splitters, ONUs, and end users. The future-proof OLT in [49] was considered. The four 40 GE ports are utilised for metro network connections. The twelve 10 GE ports of Ethernet uplink and the switching and control cards and additional 2 Ethernet interface service cards providing a total of 4 10 GE ports are utilised for the connections with the FDC. This configuration provides a capacity of up to 160 Gbps between the OLT and the metro network and up to 160 Gbps between the OLT and the FDC.

B. CLOUD AND FOG DATA CENTRES

For the CDCs and FDCs, the content server in [32] with a maximum streaming capacity of 1.8 Gbps was considered. This allows the FDC to maximally provide 160 Gbps via about 88 servers. The networking equipment power consumption in the data centres is assumed to be 30% of the servers' power consumption [50]. Each FDC can be powered by brown sources, directly by solar cells with areas between 50 m^2 and 250 m^2, or by stored solar energy in an ESD with a capacity of 100 kWh [51]. The Power Usage Effectiveness (PUE) values for FDCs was considered to be between 1.25 and 1.1 and a PUE of 1.1 was considered for CDCs. Table 1 summarizes the networking equipment and data centre parameters considered. In this work, bi-hourly consumer video traffic estimated according to the Cisco Visual Network Index (VNI) forecast for 2020 as part of the work in [16] was considered for the demands from the five CDCs to users in the 14 NSFNET nodes. Figure 2 shows the total volumes at different times of the day in Tbps.

TABLE 1. Parameters of the cloud transport network and fog and cloud data centres.

Set of wavelength rates ($\mathbb{WR}$)	40,100,400,1000 Gbps		
Span between two neighbouring EDFAs (DA)	80 km		
Number of wavelengths in a fibre (W) [54]	32		
The duration between consecutive hours in $\mathbb{T}$ (S)	2 hours		
Reach of regenerator (R_r) and power consumption of a regenerator (PG_r) at a wavelength rate r; [16] $r \in \mathbb{WR}$	r (Gbps)	R_r (km)	PG_r (W)
	40	2500	71.4
	100	1200	221.8
	400	400	857.4
	1000	350	2065.2
Power consumption of a router port (PR_r) at wavelength rate r; $r \in \mathbb{WR}$ [16]	r (Gbps)		PR_r (W)
	40		178.2
	100		309.3
	400		367.8
	1000		425.1
Power consumption of a transponder (PT_r) at wavelength rate r; $r \in \mathbb{WR}$ [16]	r (Gbps)		PT_r (W)
	40		35.7
	100		110.9
	400		428
	1000		1032.6
Power consumption of an optical switch (PO_m) at core node m; $m \in \mathbb{N}$ [54]	85 W		
Power consumption of an EDFA (PE) [16]	15.3 W		
Power consumption of a metro Ethernet switch port at a rate of 40 Gbps (PS) [48]	50 W		
Power consumption of a content server per Gbps (P_{CS}) [24]	211.1 W/Gbps		
Capacity of a content server (C_S) [24]	1.8 Gbps		
PUE of cloud data centres (PUE_C)	1.1		
PUE of fog data centres (PUE_F)	1.1-1.3		
PUE of core, metro, and access networking equipment (PUE_N) [16]	1.5		
Ratio to account for networking equipment power consumption in fog data centres (Z_{FDC}) [50]	1-1.3		
Ratio to account for networking equipment power consumption in cloud data centres (Z_{CDC}) [50]	1.3		
Power consumption of an OLT (P_{OLT}) [49]	904 W		
Total capacity of links between OLT and metro network (C_{OLT})	160 Gbps		
Total capacity of links between OLT and fog data centre (C_{FDC})	160 Gbps		
Size of a solar cell per OLT (SSC)	50, 100, 150, 200, 250 m^2		
A very large number (M)	10000000000		
Battery maximum capacity (E_{MAX}) [51]	100 kWh		
Charging efficiency during S (α) [45]	72.25%		
Discharging efficiency during S (β) [45]	90.25%		

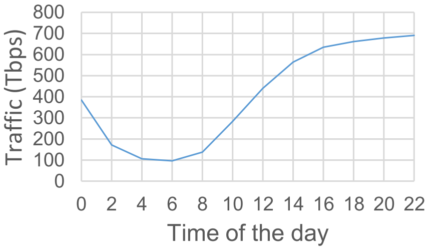

FIGURE 2. Total 2020 consumer video traffic at different times of the day.

C. RENEWABLE ENERGY SOURCES

In this work, we considered solar renewable energy due to its suitability in terms of installation in fog environments in cities as opposed to wind turbines which are noisy and aesthetically not suitable due to size and visual pollution. Solar cells are assumed to be installed in central offices which can provide required cells area. The solar irradiance values in the 14 cities connected by NSFNET were obtained from [52] which are based on SOLPOS calculator-based predictions and were averaged over two hour windows. Considering several factors that affect solar cells efficiency and based on [53], an efficiency of 26.3% was considered. Accordingly, Table 2 summarizes the solar power availability in W/m^2.

III. MILP MODEL FOR EFFICIENT CONTENT DELIVERY

In this Section, we list the parameters, the variables, objective, and constraints of the MILP model. Small letters in superscripts and subscripts indicate indices while double-lined letters indicate sets.

SETS AND PARAMETERS

$\mathbb{N}$	Set of IP over WDM nodes
$\mathbb{N}_m$	Set of neighbours of node m; $m \in \mathbb{N}$
$\mathbb{T}$	Set of hours in the day
$\mathbb{WR}$	Set of wavelength rates
$\mathbb{CDC}$	Set of cloud data centres (CDCs) ($\mathbb{CDC} \subset \mathbb{N}$)
$\mathbb{S}$	Set of servers in a fog data centre
S	The duration between consecutive hours in $\mathbb{T}$
W	Number of wavelength in a fibre
B_r	Line rate at wavelength rate r; $r \in \mathbb{WR}$ (In Gbps)
B_M	Line rate of an aggregation port (In Gbps)
D_{mn}	Length of the physical link (m, n); $m \in \mathbb{N}, n \in \mathbb{N}_m$ (In km)
DA	Span between neighbouring EDFAs (In km)
A_{mn}	$= \left\lfloor \frac{D_{mn}}{DA} - 1 \right\rfloor + 2$, number of EDFAs in the physical link (m, n); $m \in \mathbb{N}, n \in \mathbb{N}_m$
R_r	Reach of regenerators at wavelength rate r; $r \in \mathbb{WR}$ (In km)
G_{mnr}	$= \left\lfloor \frac{D_{mn}}{R_r} - 1 \right\rfloor$, number of regenerators in the physical link (m, n) at wavelength rate r; $m \in \mathbb{N}, n \in \mathbb{N}_m, r \in \mathbb{WR}$
PR_r	Power consumption of a router port at wavelength rate r; $r \in \mathbb{WR}$
PR_M	Power consumption of an aggregation router port
PT_r	Power consumption of a transponder at wavelength rate r; $r \in \mathbb{WR}$
PO_m	Power consumption of an optical switch at core node m; $m \in \mathbb{N}$
PE	Power consumption of an EDFA
PS	Power consumption of a metro Ethernet switch port
P_{CS}	Power consumption of a content server per Gbps
C_S	Capacity of a content server
PUE_C	PUE of cloud data centres
PUE_F	PUE of fog data centres
PUE_N	PUE of core, metro, and access networking equipment
Z_{CDC}	Ratio to account for networking equipment power consumption in cloud data centres
Z_{FDC}	Ratio to account for networking equipment power consumption in fog data centres
P_{OLT}	Power consumption of an OLT
C_{OLT}	Capacity between an OLT and metro network
C_{FDC}	Capacity between an OLT and fog data centre
PG_r	Power consumption of a regenerator at wavelength rate r; $r \in \mathbb{WR}$
PS	Power consumption of a metro Ethernet switch port
VoD_{cdt}	Demands from CDC c to node d at time t; $c \in \mathbb{CDC}, d \in \mathbb{N}, t \in \mathbb{T}$ (In Gbps)
SP_{dt}	Available solar power per m^2 in node d at time t; $d \in \mathbb{N}, t \in \mathbb{T}$ (In Watts)
SSC	Size of a solar cell
M	A very large number
E_{MAX}	Battery maximum capacity
α	Charging percentage per hour
β	Discharging percentage per hour

VARIABLES

λ_{ijt}^{cd}	Traffic between node pair (c, d) passing through virtual link (i, j) at time t; $c \in \mathbb{CDC}, d \in \mathbb{N}, i, j \in \mathbb{N}, t \in \mathbb{T}, c \neq d$
C_{ijrt}	Number of wavelengths at rate r on the virtual link (i, j) at time t; $i, j \in \mathbb{N}, r \in \mathbb{WR}, t \in \mathbb{T}, i \neq j$
ω_{ijrt}^{mn}	Number of wavelengths at rate r of the virtual link (i, j) in the physical link (m, n) at time t; $i, j, m, n \in \mathbb{N}, r \in \mathbb{WR}, t \in \mathbb{T}, i \neq j$
F_{mnt}	Number of fibres used on the link (m, n) at time t; $m \in \mathbb{N}, n \in \mathbb{N}_m, t \in \mathbb{T}$
W_{mnrt}	Total number of wavelengths at rate r in the physical link (m, n) at time t; $m \in \mathbb{N}, n \in \mathbb{N}_m, r \in \mathbb{WR}, t \in \mathbb{T}$
CCQ_{ct}	Number of aggregation ports required to connect core node c with the CDC in c at time t; $c \in \mathbb{CDC}, t \in \mathbb{T}$
CMQ_{dt}	Number of aggregation ports required to connect core node d with the metro network in d at time t; $d \in \mathbb{N}, t \in \mathbb{T}$
MCQ_{ct}	Number of aggregation ports required to connect the metro network in c with the cloud data centre c at time t; $c \in \mathbb{CDC}, t \in \mathbb{T}$
MAQ_{dt}	Number of aggregation ports required to connect the metro network in d with the access network in d at time t; $d \in \mathbb{N}, t \in \mathbb{T}$
$VoDC_{cdt}$	Demands by users in node d that are served by CDC c at time t; $c \in \mathbb{CDC}, d \in \mathbb{N}, t \in \mathbb{T}$ (In Gbps)
$VoDF_{cdt}$	Demands by users in node d from cloud data centre c that is instead served by the FDC in d at time t; $c \in \mathbb{CDC}, d \in \mathbb{N}, t \in \mathbb{T}$ (In Gbps)
OLT_{dt}	Number of OLTs required in node d to accommodate VoD demands at time t; $d \in \mathbb{N}, t \in \mathbb{T}$
$VoDFS_{dst}$	Demands served in FDC d by server s powered by solar at time t; $d \in \mathbb{N}, s \in \mathbb{S}, t \in \mathbb{T}$ (In Gbps)
$VoDFB_{dst}$	Demands served in FDC d by server s powered by brown sources at time t; $d \in \mathbb{N}, s \in \mathbb{S}, t \in \mathbb{T}$ (In Gbps)
$VoDFE_{dst}$	Demands served in FDC d by server s powered by stored solar power at time t; $d \in \mathbb{N}, s \in \mathbb{S}, t \in \mathbb{T}$ (In Gbps)
E_{dt}	Energy stored in the battery at FDC d at time t; $i \in \mathbb{N}, t \in \mathbb{T}$
RS_{dt}	Energy to be charged in the battery from the surplus renewable energy at FDC d at time t; $d \in \mathbb{N}, t \in \mathbb{T}$
ED_{dt}	Energy to be discharged from battery to the FDC d at time t; $d \in \mathbb{N}, t \in \mathbb{T}$

TABLE 2. Solar power availability per m^2 in Watts recorded in February 2018 from different cities in the NSFNET network.

$\mathbb{N}$ \ $\mathbb{T}$	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**
	Seattle, WA	***Palo Alto, CA***	***San Diego, CA***	***Salt Lake, UT***	***Boulder, CO***	***Houston, TX***	***Lincoln, NE***	***Champaign, IL***	***Pittsburgh, PA***	***Atlanta, GA***	***Ann Arbor, MI***	***Ithaca, NY***	***College Park, MD***	***Princeton, NJ***
00:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
02:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
04:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
06:00	12.13	22.8	45.1	9.66	24.9	21.5	9.94	30.5	13.31	9.60	5.93	18.90	22.3	26.110
08:00	105.46	141.00	176.00	112.00	139.00	151.00	113.00	146.00	120.60	122.74	100.00	126.00	137.00	140.48
10:00	178.53	227.00	255.00	203.00	218.00	252.00	203.00	220.00	208.29	227.45	192.00	204.00	220.00	217.69
12:00	191.34	241.00	257.00	228.00	227.00	277.00	228.00	225.00	229.22	261.87	221.00	217.00	233.00	225.59
14:00	140.41	181.00	181.00	181.00	165.00	219.00	180.00	158.00	177.71	216.68	179.00	159.00	173.00	162.06
16:00	41.70	62.60	50.60	75.30	49.80	95.00	74.30	42.20	68.06	104.17	78.90	49.50	57.10	46.88
18:00	0.00	0.00	0.00	0.40	0.00	1.16	0.33	0.00	0.03	3.65	0.98	0.00	0.00	0.00
20:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
22:00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The power consumption in IP over WDM networks at t; $t \in \mathbb{T}$, $P_{t(IPoverWDM)}$, is composed of the power consumption due to:

1) IP Router ports under optical bypass:

$$P_{t(IP)} = \sum_{i\in\mathbb{N}} PR_M(CCQ_{it} + CMQ_{it}) + \sum_{j\in\mathbb{N}:i\neq j}\sum_{r\in\mathbb{WR}} PR_r\, C_{ijrt}. \tag{1}$$

2) Transponders:

$$P_{t(T)} = \sum_{m\in\mathbb{N}}\sum_{n\in\mathbb{N}_m}\sum_{r\in\mathbb{WR}} PT_r\, W_{mnrt}. \tag{2}$$

3) Optical switches:

$$P_{t(O)} = \sum_{m\in\mathbb{N}} PO. \tag{3}$$

4) EDFAs:

$$P_{t(E)} = PE\sum_{m\in\mathbb{N}}\sum_{n\in\mathbb{N}_m} A_{mn}\, F_{mnt}. \tag{4}$$

5) Regenerators:

$$P_{t(R)} = \sum_{m\in\mathbb{N}}\sum_{n\in\mathbb{N}_m} PG_r\, G_{mnr}\, W_{mnrt}. \tag{5}$$

Then,

$$P_{t(IPoverWDM)} = PUE_N\left(P_{t(IP)}+P_{t(T)}+P_{t(O)}+P_{t(E)}+P_{t(R)}\right). \tag{6}$$

The power consumption of metro and access networks, FDCs and CDCs at time t is composed of the power consumption due to:

1) Metro router and Ethernet switch ports:

$$P_{t(Metro)} = PUE_N\left(\sum_{i\in\mathbb{N}} PS(CMQ_{it}+MCQ_{it}+MAQ_{it})\right). \tag{7}$$

2) OLTs in Access Network:

$$P_{t(Access)} = PUE_N\sum_{d\in\mathbb{N}} P_{OLT}\, OLT_{dt}. \tag{8}$$

3) FDCs and CDCs:

$$P_{t(FDC)} = P_{CS}PUE_F Z_{FDC}\sum_{c\in\mathbb{CDC}}\sum_{d\in\mathbb{N}} VoDF_{cdt}. \tag{9}$$

$$P_{t(CDC)} = P_{CS}PUE_C Z_{CDC}\sum_{c\in\mathbb{CDC}}\sum_{d\in\mathbb{N}} VoDC_{cdt}. \tag{10}$$

Objective: Minimise the total brown energy consumption, (PC_b), subject to the following constraints:

1) Flow conservation in IP layer: The allocation of virtual links to the demands follows the flow conservation law:

$$\sum_{j\in\mathbb{N},i\neq j}\lambda_{ijt}^{cd} - \sum_{j\in\mathbb{N},i\neq j}\lambda_{jit}^{cd} = \begin{cases} VoDC_{cdt} & i=c \\ -VoDC_{cdt} & i=d \\ 0 & otherwise, \end{cases}$$
$$\forall c\in\mathbb{CDC},\quad d\in\mathbb{N},\ i\in\mathbb{N},\ t\in\mathbb{T},\ c\neq d. \tag{11}$$

2) Flow conservation in optical layer: Allocation of wavelengths to virtual demands follows flow conservation law:

$$\sum_{n\in\mathbb{N}_m}\omega_{ijrt}^{mn} - \sum_{n\in\mathbb{N}_m}\omega_{jirt}^{mn} = \begin{cases} C_{ijrt} & m=i \\ -C_{ijrt} & m=j \\ 0 & otherwise, \end{cases}$$
$$\forall i,\quad j,m\in\mathbb{N},\ r\in\mathbb{WR},\ t\in\mathbb{T},\ i\neq j. \tag{12}$$

3) Virtual IP link capacity constraint: To ensure that traffic flows through a virtual link do not exceed its capacity.

$$\sum_{c\in\mathbb{CDC}}\sum_{d\in\mathbb{N},c\neq d}\lambda_{jit}^{cd} \leq \sum_{r\in\mathbb{WR}} C_{ijrt}\, B_r,$$
$$\forall i,\quad j\in\mathbb{N},\ t\in\mathbb{T},\ i\neq j. \tag{13}$$

4) Capacity constraints: Constraint 14 ensures that wavelengths in the physical link do not exceed the maximum capacity of the fibres. Constraint 15 calculates W_{mnrt}.

$$\sum_{i\in\mathbb{N}}\sum_{j\in\mathbb{N},i\neq j}\sum_{r\in\mathbb{WR}}\omega_{ijrt}^{mn} \leq W\, F_{mnt},\quad \forall m\in\mathbb{N},\ n\in\mathbb{N}_m,$$
$$t\in\mathbb{T}. \tag{14}$$

$$\sum_{i\in\mathbb{N}}\sum_{j\in\mathbb{N},i\neq j}\omega_{ijrt}^{mn} = W_{mnrt},\quad \forall m\in\mathbb{N},\ n\in\mathbb{N}_m,$$
$$r\in\mathbb{WR},\ t\in\mathbb{T},\ m\neq n. \tag{15}$$

5) Aggregation ports constraints: Constraints 16, and 17 determine the aggregation ports required in the core

node. Constraint 16 determines the number of aggregation ports required to connect core node c; $c \in \mathbb{CDC}$ with the cloud data centre c located nearby, while Constraint 17 specifies the number of aggregation ports that are required to connect core node d with the networking equipment of the metro network at d; $d \in \mathbb{N}$. This is required to deliver VoD demands from CDCs in other nodes. Constraints 18, and 19 calculate the remaining aggregation ports in the metro network. Constraint 18 calculates the number of aggregation ports required to connect the cloud data centre c with the metro node in c; $c \in \mathbb{CDC}$. Constraint 19 calculates the number of aggregation ports required to connect metro networking equipment at node d with the access network located in node d; $d \in \mathbb{N}$. This is required to deliver the total VoD demands to users in node d.

$$B_M\, CCQ_{ct} = \sum_{d\in\mathbb{N},\, c\neq d} VoDC_{cdt}, \quad \forall c \in \mathbb{CDC},\ t\in\mathbb{T}. \tag{16}$$

$$B_M\, CMQ_{dt} = \sum_{c\in\mathbb{CDC},\, c\neq d} VoDC_{cdt}, \quad \forall d \in \mathbb{N},\ t \in \mathbb{T}. \tag{17}$$

$$B_M\, MCQ_{ct} = \sum_{d\in\mathbb{N},\, c=d} VoDC_{cdt}, \quad \forall c \in \mathbb{CDC},\ t \in \mathbb{T}. \tag{18}$$

$$B_M\, MAQ_{dt} = \sum_{c\in\mathbb{CDC}} VoDC_{cdt}, \quad \forall d\in\mathbb{N},\ t\in\mathbb{T}. \tag{19}$$

6) Number of OLTs in the access network: Constraint 20 determines the number of OLTs required.

$$OLT_{dt} = \sum_{c\in\mathbb{CDC}} VoD_{cdt}/C_{OLT}, \forall d \in \mathbb{N}, t \in \mathbb{T}. \tag{20}$$

7) Demands distribution: Constraint 21 ensures that the sum of the demands served by CDCs and the demands served by FDCs is equal to the total demands.

$$\begin{aligned} &VoDC_{cdt} + VoDF_{cdt}\, OLT_{dt} \\ &\quad = VoD_{cdt}, \quad \forall c \in \mathbb{CDC},\ d \in \mathbb{N},\ t \in \mathbb{T}. \end{aligned} \tag{21}$$

8) OLT capacity: Constraint 22 ensures that FDC demands do not exceed the capacity of its links to the OLT.

$$\sum_{c\in\mathbb{CDC}} VoDF_{cdt} \leq C_{FDC}, \forall d \in \mathbb{N}, t \in \mathbb{T}. \tag{22}$$

9) Servers in FDCs: Constraint 23 ensures that demands per server do not exceed its capacity. Constraint 24 equates all servers demands to the total FDC demands.

$$\begin{aligned} &VoDFS_{dst} + VoDFB_{dst} + VoDFE_{dst} \\ &\quad \leq C_S, \quad \forall d \in \mathbb{N},\ s \in \mathbb{S},\ t \in \mathbb{T}. \end{aligned} \tag{23}$$

$$\begin{aligned} &\sum_{s\in\mathbb{S}} (VoDFS_{dst} + VoDFB_{dst} + VoDFE_{dst}) \\ &\quad = \sum_{c\in\mathbb{CDC}} VoDF_{cdt}, \quad \forall d \in \mathbb{N},\ t \in \mathbb{T}. \end{aligned} \tag{24}$$

10) Solar power: Constraint 25 ensures that nodes do not exceed the available solar power.

$$\begin{aligned} \sum_{s\in\mathbb{S}} VoDFS_{dst}\, P_{CS}\, PUE_F\, Z_{FDC} &\leq SP_{dt}\, SSC, \forall d \in \mathbb{N}, \\ &\qquad s\in\mathbb{S},\ t\in\mathbb{T}. \end{aligned} \tag{25}$$

11) Discharge limit: Constraint 26 ensures that the energy discharge does not exceed the amount stored in the ESD. ED_{dt} at $t = 0, \forall d \in \mathbb{N}$ is assumed to be zero.

$$ED_{dt} \leq E_{dt}, \quad \forall d \in \mathbb{N},\ t \in \mathbb{T}. \tag{26}$$

12) Charge limit: Constraint 27 ensures that the stored energy is within the remaining capacity of the ESD.

$$RS_{dt} \leq E_{MAX} - E_{dt}, \quad \forall d \in \mathbb{N},\ t \in \mathbb{T}. \tag{27}$$

13) Energy storage constraints: Constraint 28 relates the energy stored in ESDs at t; $t \in \mathbb{T}$ with the energy stored at $t - S$; $t \in \mathbb{T}$. Constraint 29 ensures that the energy stored in the ESD is within the maximum capacity [45].

$$\begin{aligned} E_{dt} &= \begin{cases} [E_{d(t-S)} - ED_{d(t-S)} + \alpha RS_{d(t-S)}] & t \neq 0 \\ 0 & t = 0, \end{cases} \\ &\quad \forall d \in \mathbb{N}, \quad t \in \mathbb{T}. \end{aligned} \tag{28}$$

$$E_{dt} \leq E_{MAX}, \forall d \in \mathbb{N}, t \in \mathbb{T}. \tag{29}$$

14) Energy discharge: Constraint 30 ensures that the stored energy used does not exceed the available battery energy.

$$\begin{aligned} S \sum_{s\in\mathbb{S}} VoDFE_{dst}\, P_{CS}\, PUE_F\, Z_{FDC} &\leq \beta\, ED_{dt}, \quad \forall d\in\mathbb{N}, \\ &\qquad t \in \mathbb{T} \end{aligned} \tag{30}$$

15) Surplus renewable energy: Constraint 31 specifies the surplus renewable energy to be stored into the battery.

$$\begin{aligned} &S \times SSC \times SP_{dt} \\ &\quad = RS_{dt} + S \sum_{s\in\mathbb{S}} VoDFS_{dst}\, P_{CS} \cdot PUE_F\, Z_{FDC}, \\ &\quad \forall d \in \mathbb{N}, \quad t \in \mathbb{T} \end{aligned} \tag{31}$$

IV. RESULTS AND DISCUSSIONS

A. POWER CONSUMPTION WITH BROWN-POWERED CDCs AND FDCs

We start by evaluating the brown power consumption (PC_B) at time t required to optimally deliver VoD demands in terms of power consumption efficiency from brown-powered cloud and fog data centres for different values of PUE_F. In this case:

$$\begin{aligned} PC_{Bt} = \Big(& P_{t(IPoverWDM)} + P_{t(Metro)} \\ & + P_{t(Access)} + P_{t(CDC)} + P_{t(FDC)} \Big), \end{aligned} \tag{32}$$

and only Constraints 11 to 24 are considered while setting the variables $VoDFS_{dst}$, and $VoDFE_{dst}$ equal to zero; $\forall d \in \mathbb{N}, s \in \mathbb{S}, t \in \mathbb{T}$. For all the cases in this evaluation, PUE_C is

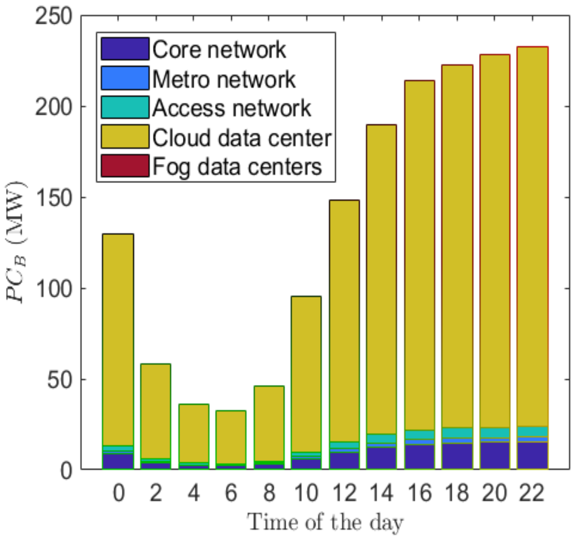

FIGURE 3. Brown power consumption (PC_{Bt}) for a PUE_F of 1.25.

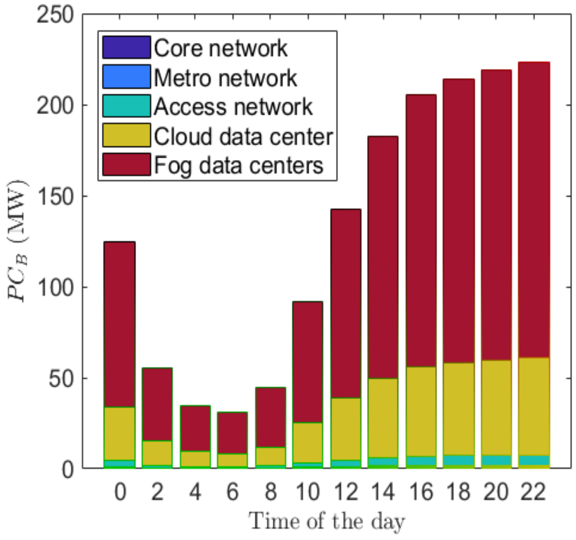

FIGURE 5. Brown power consumption (PC_{Bt}) for a PUE_F of 1.15.

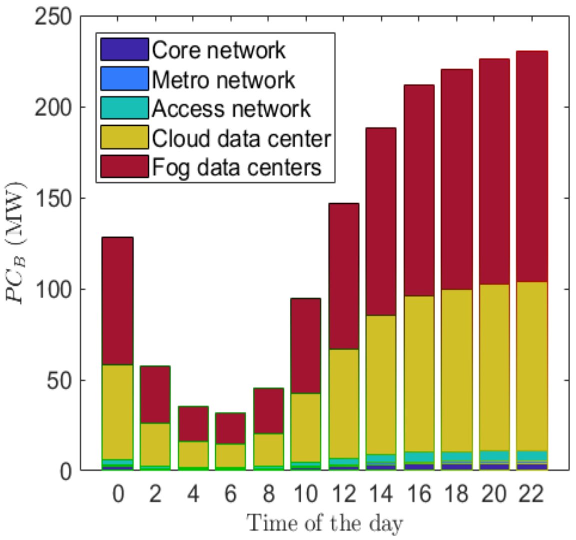

FIGURE 4. Brown power consumption (PC_{Bt}) for a PUE_F of 1.2.

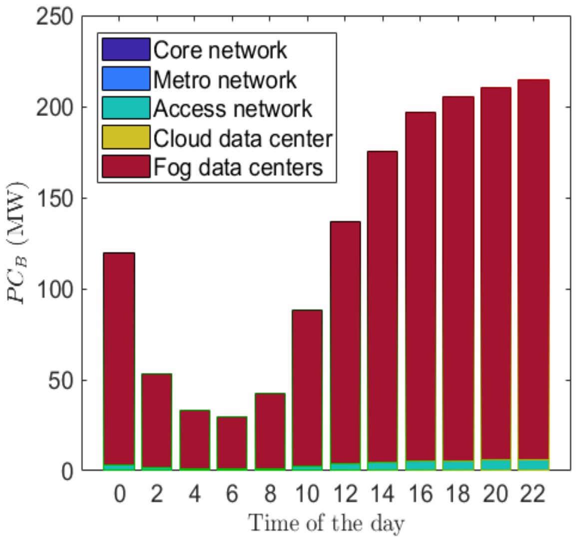

FIGURE 6. Brown power consumption (PC_{Bt}) for a PUE_F of 1.1.

set to 1.1, and Z_{CDC} and Z_{FDC} are set to 1.3. Figures 3, 4, 5, and 6 show the PC_{Bt} at the time of the day when considering PUE_F values of 1.25, 1.2, 1.15, and 1.1, respectively. The results in Figure 3 show that for PUE_F of 1.25, delivering fully from CDCs is the most efficient approach. The results in Figures 4 and 5 show that as PUE_F improves (i.e. to lower values), it becomes more efficient to deliver partially from FDCs. Finally, the results in Figure 6 show that when PUE_F is equivalent to PUE_C, it becomes more efficient to fully stream from FDCs as $P_{(FDC)}$ and $P_{(CDC)}$ required to deliver the same amount of traffic will be equivalent, and the power consumption of the transport network will be the factor that determines the differences in PC_{Bt}.

Figures 7 - 10 show the total amount of traffic served from the cloud data centres (i.e. $\sum_{c\in\mathbb{CDC},t\in\mathbb{T}} VoDC_{cdt}$) and from the fog data centres (i.e. $\sum_{c\in\mathbb{CDC},t\in\mathbb{T}} VoDF_{cdt}$) at different nodes d in the NSFNET network. Figure 7 shows that when PUE_F is as high as 1.25, the fog data centres are not selected to serve the traffic at any node. In this case, the total brown networking power consumption (PC_N) which can be expressed as:

$$PC_N = \sum_{t\in\mathbb{T}} \left(P_{t(IPoverWDM)} + P_{t(Metro)} + P_{t(Access)}\right), \quad (33)$$

was found to be about 167.545 MW. Figure 8 shows that at PUE_F of 1.2, about half of the traffic is served from the fog data centres. The savings in the total brown networking power consumption was found to be 53% compared to the case where the optimal delivery is from the cloud data centres only. Figure 9 shows that when PUE_F is further reduced to 1.15, the majority of the traffic is served from the fog data centre (i.e. about 75% of the VoD traffic). Also, it shows

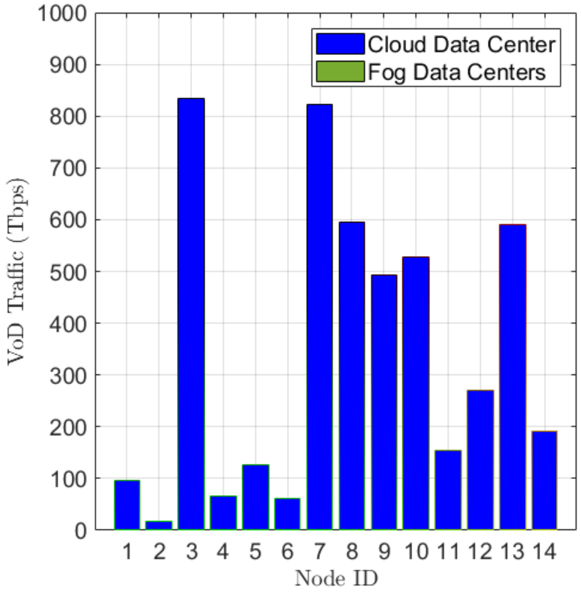

FIGURE 7. Volumes of cloud-served and fog-served VoD traffic for PUE_F of 1.25 (Traffic is fully served from cloud data centres).

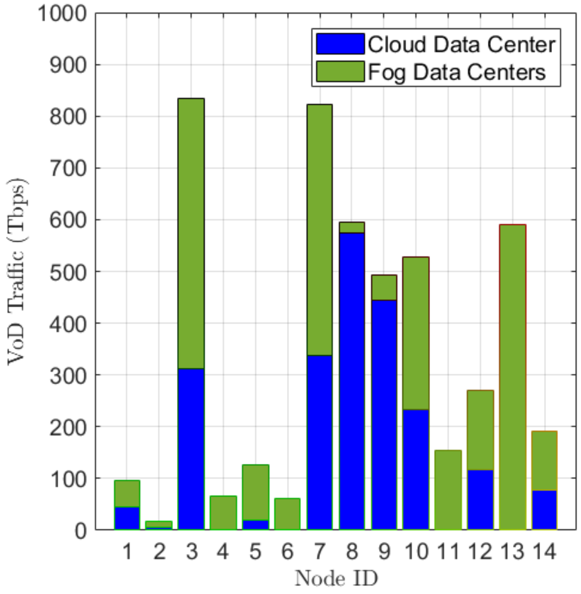

FIGURE 8. Volumes of cloud-served and fog-served VoD traffic for PUE_F of 1.2.

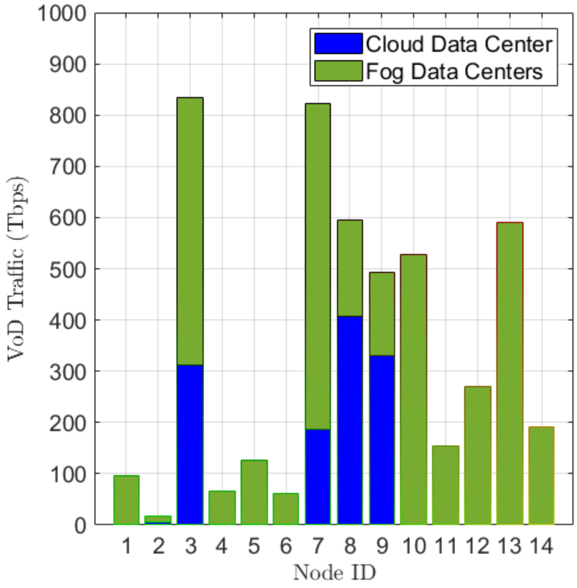

FIGURE 9. Volumes of cloud-served and fog-served VoD traffic for PUE_F of 1.15.

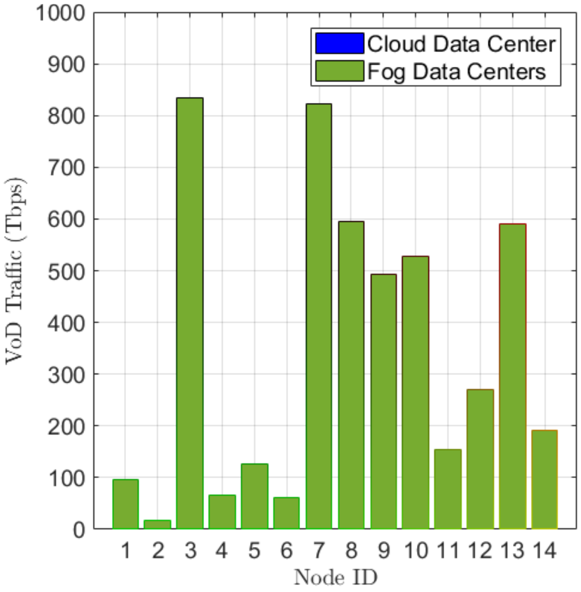

FIGURE 10. Volumes of cloud-served and fog-served VoD traffic for PUE_F of 1.1 (Traffic is fully served from fog data centres).

that the cloud data centres are selected to serve the nodes that contain them (i.e. at nodes 2, 3, 7, 8, and 9) as serving at these locations will have less brown networking power consumption compared to serving at the remaining nodes in the NSFNET network. In this case, the savings in the total brown networking power consumption was found to be 67% compared to the case of serving fully from the cloud data centres. Finally, Figure 10 shows that the traffic is fully delivered from the fog data centres. The savings in the total brown networking power consumption in this case was found to be 75% compared to the same base case of delivering the traffic fully from the cloud data centres.

B. POWER CONSUMPTION WITH FULLY RENEWABLE-POWERED CDCs AND SOLAR-POWERED FDCs

We now consider fully renewable-powered CDCs and solar-powered FDCs with PUE_F equal to 1.1 and solar cells of different capacities. In this case:

$$\begin{aligned} PC_{Bt} = {} & P_{t(IPoverWDM)} + P_{t(Metro)} + P_{t(Access)} \\ & + P_{CS}\, PUE_F\, Z_{FDC} \sum_{s \in \mathbb{S}, d \in \mathbb{N}} VoDFB_{dst}\, OLT_{dt}, \end{aligned} \tag{34}$$

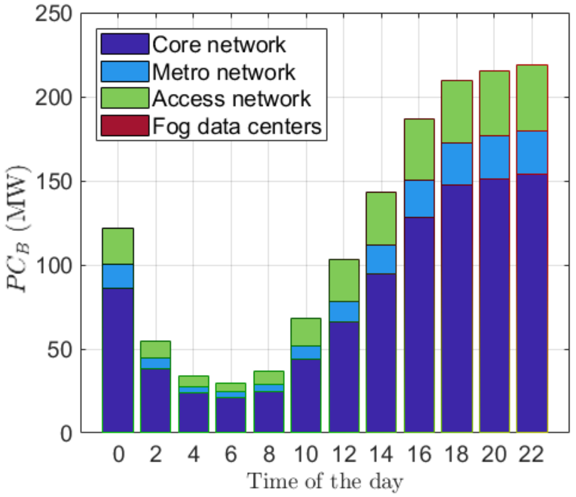

FIGURE 11. Brown power consumption (PC_{Bt}) for a *SSC* of 50 m^2.

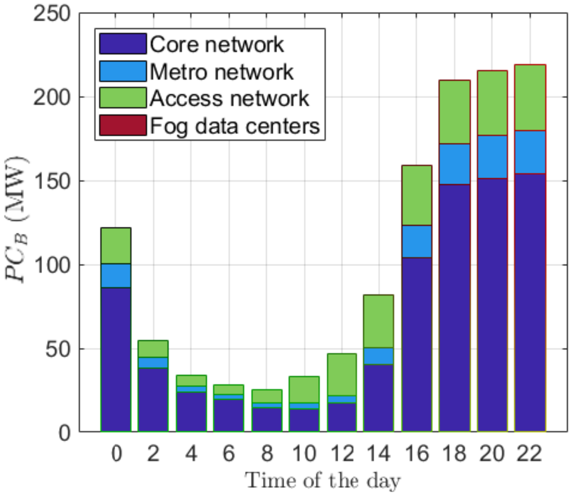

FIGURE 12. Brown power consumption (PC_{Bt}) for a *SSC* of 150 m^2.

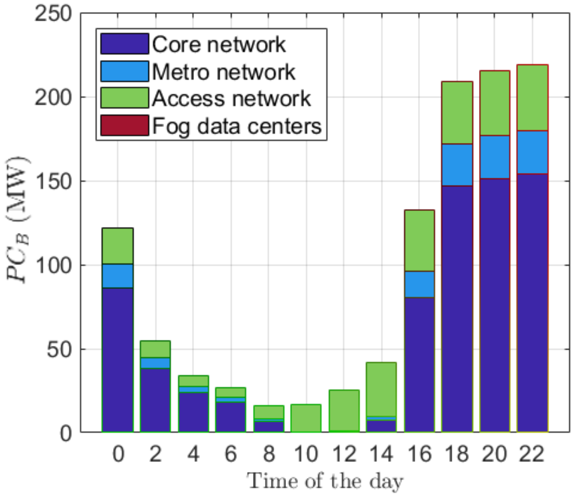

FIGURE 13. Brown power consumption (PC_{Bt}) for a *SSC* of 250 m^2.

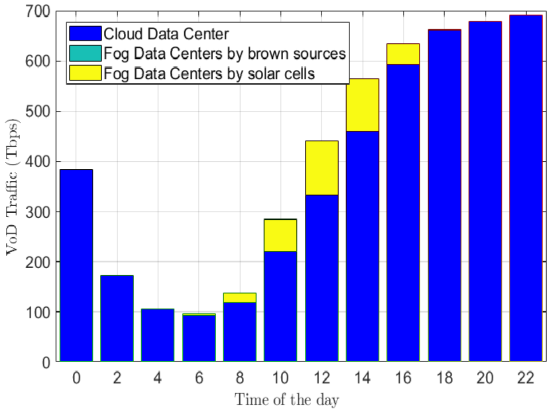

FIGURE 14. Volumes of cloud-served and fog-served VoD traffic for a *SSC* of 50 m^2.

and only constraints 11 to 25 are considered while setting $VoDFE_{dst} = 0, \forall d \in \mathbb{N}, s \in \mathbb{S}$. Figures 11 - 13 show the total brown power consumption (i.e. PC_{Bt}) at the time of the day when considering different sizes for the solar cells (i.e. *SSC*). The results when *SSC* is equal to 50 m^2 (i.e. in Figure 11) indicate a total reduction in the brown power consumption by 15% compared to the case of fully delivering from the cloud data centres. When *SSC* is equal to 150 m^2 (i.e. the results in Figure 12), the total saving in the brown power consumption was found to be 26%. For *SSC* of 250 m^2 (i.e. the results in Figure 13), the reduction in the brown power consumption was found to be 33%. It can be noticed from Figures 12, and 13 that the brown power consumption is no longer proportional to the total traffic in Figure 2. The reduction in the brown power consumption is achieved only between 6:00 and 18:00 during the availability hours of solar power as presented in Table 2. For *SSC* of 250 m^2, the high availability of the solar power between 10:00 and 12:00 enabled almost complete delivery from fog data centres resulting in negligible brown power consumption in the metro and core networks. Figures 14 - 16 show the total amount of traffic served from the cloud data centres and from the fog data centres while being powered by brown sources (i.e. $\sum_{s \in \mathbb{S}, d \in \mathbb{N}} VoDFB_{dst}\ OLT_{dt}$) or solar cells with different capacities (i.e. $\sum_{s \in \mathbb{S}, d \in \mathbb{N}} VoDFS_{dst}\ OLT_{dt}$). It was observed that utilising brown power for the fog data centres is not optimal for the objective of reducing the total brown power consumption when using the above mentioned parameters, in addition to the parameters in Table 1.

C. POWER CONSUMPTION WITH FULLY RENEWABLE-POWERED CDCs AND SOLAR-POWERED FDCs WITH ESDs

In the case of renewable-powered cloud data centres and fog data centres with solar cells and energy storage devices (ESDs), we consider Constraints 11 to 31. The delivery of VoD demands is optimised so that it is from the cloud data centres or from the fog data centres with PUE_F of 1.1 and

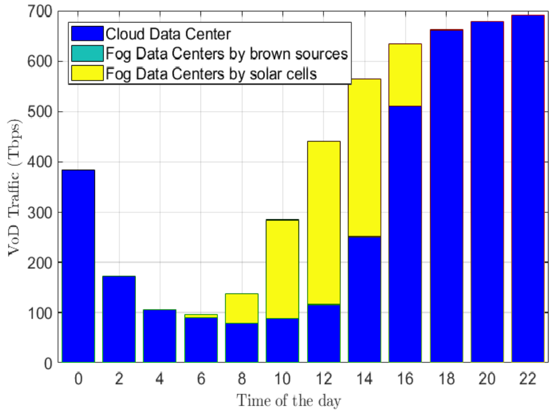

FIGURE 15. Volumes of cloud-served and fog-served VoD traffic for a *SSC* of 150 m^2.

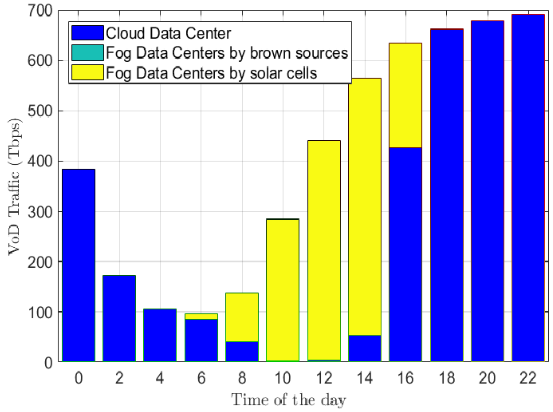

FIGURE 16. Volumes of cloud-served and fog-served VoD traffic for a *SSC* of 250 m^2.

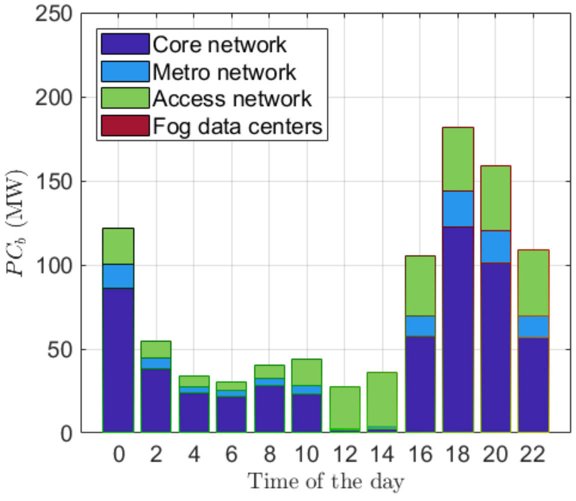

FIGURE 17. Brown power consumption (PC_{Bt}) for a *SSC* of 250 m^2 and E_{MAX} of 100 kWh.

SSC of 250 m^2 while considering the usage of an ESD with a capacity of 100 kWh. Figure 17 shows the total brown power consumption (i.e. PC_{Bt}) at the time of the day. In this case, the reduction in the total brown power consumption, compared to the case of fully streaming from cloud data centres, is 43%. The additional reduction in the brown power consumption is due to optimising the direct use of solar power in the fog data centres and charging the ESD for use when the solar power is not available. Figure 18 shows the total amount of traffic served from the cloud data centres and from the fog data centres while being powered by brown sources (i.e. $\sum_{s\in\mathbb{S},d\in\mathbb{N}} VoDFB_{dst}\, OLT_{dt}$), directly by the solar cells (i.e. $\sum_{s\in\mathbb{S},d\in\mathbb{N}} VoDFS_{dst}\, OLT_{dt}$), or with ESD (i.e. $\sum_{s\in\mathbb{S},d\in\mathbb{N}} VoDFE_{dst}\, OLT_{dt}$). It shows that the optimal use of ESDs is between 14:00 and 22:00.

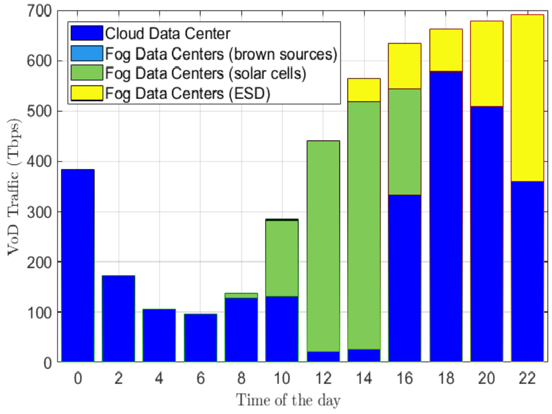

FIGURE 18. Volumes of cloud-served and fog-served VoD traffic for a *SSC* of 250 m^2 and E_{MAX} of 100 kWh.

V. CONCLUSIONS

This paper presented a comprehensive optimisation model for delivering VoD services from cloud data centres or distributed fog data centres in the access network with solar cells and ESDs. The architecture introduced and the optimisation model resulted in reducing the total brown power consumption which includes the brown power used by the brown-powered data centres in addition to the brown power used by the PON access networks, Ethernet metro networks, and IP over WDM core network. For the IP over WDM network, 2020 equipment power consumption was assumed, optical bypassing and MLR were considered to examine the reduction in the brown power consumption while considering efficient future networks. Different scenarios were considered for powering the cloud and fog data centres. For the first scenario (i.e. brown powered cloud and fog data centres), the results show that as the PUE_F reduces, it becomes more energy efficient to deliver from fog data centres. When PUE_F is equivalent to PUE_C, it is more efficient to deliver fully from fog data centres. In this case, the reduction in the brown power consumption is 75% compared to the case of delivering fully from the cloud data centres. As many cloud providers are utilising renewable power for their data centres, we also examined the optimisation when the cloud data centres are fully powered by renewable sources and the fog data centres are solar-powered. The results indicated that savings by up to 33% can be achieved when considering 250 m^2 solar cells (which is considered to be of a suitable size for central offices in the access network) for the fog data centres. Additional saving of about 10% can be achieved when also considering ESDs with capacity of 100 kWh to store surplus solar energy.

The results presented in this paper reflect the need for joint optmisation of the routing in transport networks and the usage of cloud and fog data centres when the objective is to reduce the non-renewable power consumption. A first main finding is that building fog data centres with worse power usage efficiency compared to existing cloud data centres is not optimal, thus when investing in these distributed data centres, it is essential to improve their PUE values. When considering renewable solar power, more savings (carbon footprint reduction) can be achieved with larger solar cells and energy storage devices.

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