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REVIEW

A review of renewable energy based power supply options for telecom towers

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Abstract

Telecom services play a vital role in the socio-economic development of a country. The number of people using these services is growing rapidly with further enhance growth expected in future. Consequently, the number of telecom towers that are critical for providing such services has also increased correspondingly. Such an increase in the number of telecom towers in a country implies a corresponding increase in the electricity demand of the country. Moreover, in view of growing concerns about climate change, it is necessary that the decarbonization of telecom towers is prioritized so as to minimize their carbon footprint. In view of the above, the primary objective of this paper is to provide a comprehensive analysis of various renewable energy-based systems and the advantages they offer for powering telecom towers, based on a review of the existing literature and field installations. Telecom towers are powered by hybrid energy systems that incorporate renewable energy technologies such as solar photovoltaic panels, wind turbines, fuel cells, and microturbines. Utilizing these systems helps to reduce the consumption of fossil fuels and consequently mitigates the anthropogenic carbon emissions. Moreover, information related to growth of the telecom industry, telecom tower configurations and power supply needs, conventional power supply options, and hybrid system combinations and their benefits. Several field installations of renewable energy-based hybrid systems have also been summarized. This review can help to evaluate appropriate low-carbon technologies and also to develop policy instruments to promote renewable energy-based telecom tower power systems.

Keywords Renewable energy · Solar photovoltaic · Wind · Fuel cells · Battery storage · Hybrid systems · Telecom towers

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Abbreviations

3G	3Rd generation
4G	4Th generation
5G	5Th generation
A	Ampere
AC	Alternating current
Ah	Ampere hour
ATS	Automatic transfer switch
BSC	Base station controller
BSNL	Bharat Sanchar Nigam Limited
BSS	Base station subsystem
BTS	Base transceiver station
CAGR	Compounded annual growth rate
CHP	Combined heat and power
ICT	Information and communication technology
CPU	Central processing unit
CSP	Concentrated solar power
DC	Direct current
DG	Diesel generator set
DWDM	Dense wavelength-division multiplexing
EIR	Equipment identity register
FC	Fuel cell
FDI	Foreign direct investment
GBT	Ground-based towers
GMSC	Gateway mobile service switching centre
GSMA	Mobile communications association
GT	Gas turbine
HLR	Home location register
HOMER	Hybrid optimization of multiple energy resources
IC	Internal combustion
IDU	Indore unit
IMEI	International mobile equipment identity
IMSI	International mobile subscriber identity
IoT	Internet of things
ISDN	Integrated services digital network
kg	Kilogram
kVA	Kilo volt ampere
kW	Kilo watts
LFP	Lithium-ion phosphate
LPG	Liquefied petroleum gas
MCB	Miniature circuit breaker
MSC	Mobile service switching centre
MTNL	Mahanagar Telephone Nigam Limited
MUX	Multiplexer
MW	Mega watts
NPC	Net present cost
NREL	National renewable energy laboratory
NSS	The network switching subsystem
ODU	Outdoor unit

OEMs	Original equipment manufacturers
OTN	Optical transport network
PCC	Point of common coupling
PEM	Proton-exchange membrane
PHP	Pico-hydroplant
PLMN	Public land mobile network
PV	Photovoltaic
RF	Radio frequency
RTT	Rooftop towers
SFC	Specific fuel consumption
SIM	Subscriber identity module
SMPS	Switched mode power supply
TMSI	Temporary mobile subscriber identity
TR	Ton of refrigeration
TRAI	Telecom regulatory authority of India
TRAU	Transcoding rate and adaption unit
TRX	Transceiver
USA	United states of America
V	Voltage
VLR	Visitor location register
VRLA	Valve-regulated lead acid (VRLA)
W	Watts
WCDMA	Wideband code division multiple access
WT	Wind turbine

1 Introduction

In view of growing evidence of the manifestations of climate change around the world, it is critically important that efforts be made to reduce anthropogenic emissions of greenhouse gases. There is an immediate need to hasten the worldwide shift to clean energy and achieve "net-zero" emissions as quickly as possible (). The global fossil fuel-based carbon dioxide emissions are expected to increase by 1% in 2022, reaching a new high of 37.5 billion metric tonnes (UNFCCC, 2022), and the same is expected to reach about 50 billion metric tonnes under business as usual scenario by 2050 (Lu et al., 2022). Many countries of the world are establishing aggressive emission reduction targets and net-zero targets based on mitigation and adoption pathways (Naqvi et al., 2020a, 2020b; Oryani et al., 2022; UNFCCC, 2022; Zhao et al., 2022). Because of its heavy reliance on fossil fuels, the energy industry is often held accountable for a sizable portion of the world's carbon dioxide emissions (Zhang et al., 2022a). One of the main options being considered to reduce reliance on fossil fuels and lessen the impact of carbon pollution is the widespread harnessing of renewable energy sources (Gielen et al., 2019; Naqvi et al., 2021; Pata et al., 2022).

The field of information and communication technology (ICT) has grown at an astounding rate over the last seventy years (Freitag et al., 2021; Shah et al., 2022). Because of the widespread use of ICT today, people are beginning to recognize that this technology may have negative environmental consequences, most notably global warming (Shahzad et al., 2022; Zhang et al., 2022b). Greenhouse gases (GHG) emitted at different stages of the ICT life cycle contribute to an increasing carbon footprint (Nejati & Shah, 2023). The ICT sector reportedly accounted for approximately 1.4 per cent of total carbon emissions and nearly 3.6 per cent of global electricity consumption in 2020 (Ericsson, 2020). The electricity consumption is further likely to grow rapidly with adoption of 5G and 6G technologies (Malmodin & Lundén, 2018). At the same time, the carbon footprint of the ICT sector could be reduced by more than 80% if a transition to renewable energy electricity is made to meet electricity demand.

Telecom towers are an essential component of the ICT sector. They are the physical infrastructure that allows mobile phones, internet devices, and other electronic devices to communicate wirelessly. Telecom towers provide cellular network coverage, allowing people to make and receive calls, connect to the internet, and use other mobile services. They can also contribute to a rapid expansion of the Internet of Things (IoT) and the connected world with faster data transmission. Multiple factors affect the amount of energy needed to run a telecom tower, including the tower's design, the equipment installed, the number of antennas, the power output, and the surrounding environment (KMB, 2015). A telecom tower's monthly energy consumption is typically between several hundred and several thousand-kilowatt hours (kWh) (Carmine Lubritto, 2008a). Traditionally, these electricity requirements are met using grid electricity, and in the event that this is not available, a diesel generator is utilized which is very carbon intensive (Islam, 2020). This opens up enormous possibilities for replacing traditional power supply options with renewable energy-based solutions. In views of this, an attempt has been made in this paper to review different renewable energy-based power supply options to meet electricity demand of telecom towers to identify and asses (a) telecom tower types and their power requirements; (b) traditional telecom tower power supply options; (c) power supply options based on renewable energy; (d) various energy storage options; and (e) possible hybrid system configurations and their merits.

1.1 Mobile telephone communication network

The mobile telecom sector is experiencing rapid growth across the globe due to customer inclination towards new technologies, availability of smart phones, demand for high-speed data connectivity, digitalization, and increasing number of subscribers (GSMA, 2021a; GVR, 2021). According to the real-time intelligence data of Global System for Mobile Communications Association (GSMA), about 10.47 billion mobile connections were being used in 2021 and this number was 2.58 billion more than the world population at that time (GSMA, 2021b). This number of mobile connections includes people with multiple devices, provision of dual subscriber identity module (SIM) cards in the mobile phone, connected equipment and devices. To fulfil the growing demand of mobile subscribers, the required infrastructure in terms of network, technology, connectivity, and supporting hardware needs to be developed and expanded.

Mobile telephone communication network comprises of active as well as passive equipment. The active equipment is broadly categorized three subsections (Dulz et al., 1999; ETSI, 1993; Garg, 2007; GSMA, 2015; Lee, 1989; Lin & Chlamtac, 2000; Pandya, 2000; Tcha, 2003) such as (i) base station subsystem (BSS) includes (mobile phones, base transceiver station (BTS), transcoding rate and adaption unit (TRAU), switch arrays, data storage units and a central processing unit (CPU) and base station controller (BSC)); (ii) mobile service switching centre (MSC) include (home location register (HLR), visitor location register (VLR), equipment identity register (EIR)), and

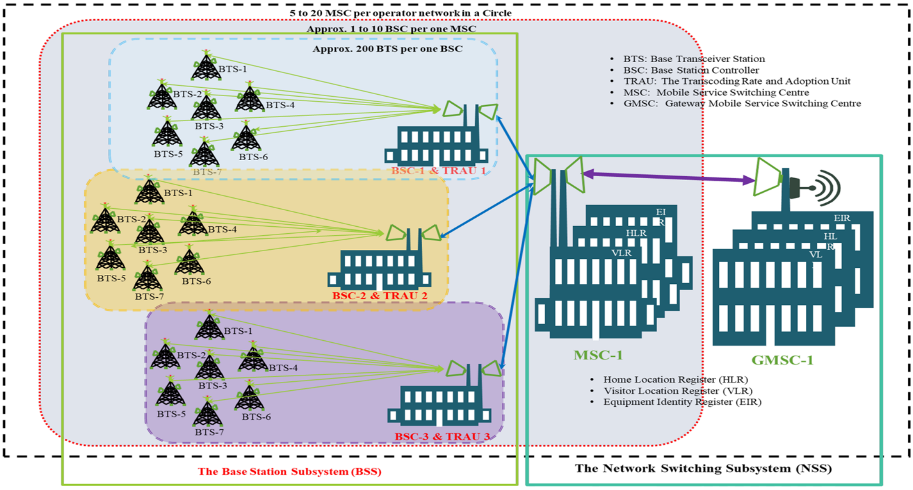

Fig. 1 A schematic of the components and connectivity of typical mobile telecom network

(iii) gateway mobile service switching centre (GMSC) include same components as MSC. Both MSC and GMSC are part of the network switching subsystem (NSS).

The passive equipment on the other hand, include (i) physical structures (telecom towers, antenna mounting structure, antenna, equipment housing shelters), (ii) power supply systems (grid supply, diesel generator (DG) sets, switched mode power supply (SMPS), battery bank, AC and DC power management system), (iii) cooling systems (air-conditioners, fan coil units, exhaust fans, passive cooling materials) and, (iv) security systems (alarm monitoring systems, earthing and lightning protectors, lighting systems and aviation lamp) (BIL, 2010). Various components and their interaction in a typical mobile communication system are shown in Fig. 1 (Dulz et al., 1999; ETSI, 1993; Garg, 2007; GSMA, 2015; Lee, 1989; Lin & Chlamtac, 2000; Pandya, 2000; Tcha, 2003).

A BSS is the centre of intelligence and controls BSC and BTS. BTS is housed in a shelter and it acts as a wireless link between mobile phone and network. BTS comprises of antennas, input and output filters, transmitters, receivers, signal transmission, and reception modules. Each BTS is supported with passive equipment. TRAU transmits the data in a compressed form on the wireless interface. A central processing unit (CPU) in BSC performs hand over decisions, such as connecting mobile phone users and ensuring wireless connection from one telecom tower to other when a user is moving. Moreover, BSS connects all the BTS to mobile service switching centre (MSC) with the help of switching arrays and stores the information on quality and availability of wireless network signals in data storage unit (Garg, 2007).

The MSC is a typical integrated services digital network (ISDN) switching device used in mobile communication networks. It executes the interchange of channels inside a public land mobile network (PLMN) or between several public land mobile network and governs transfer between several MSC areas. GMSC facilitates a connection of a PLMN to another network. The information about the subscribers such as international mobile subscriber identity (IMSI), restriction of services, location, algorithm, and number of MSC is stored in HLR (ETSI, 1993; Tcha, 2003).

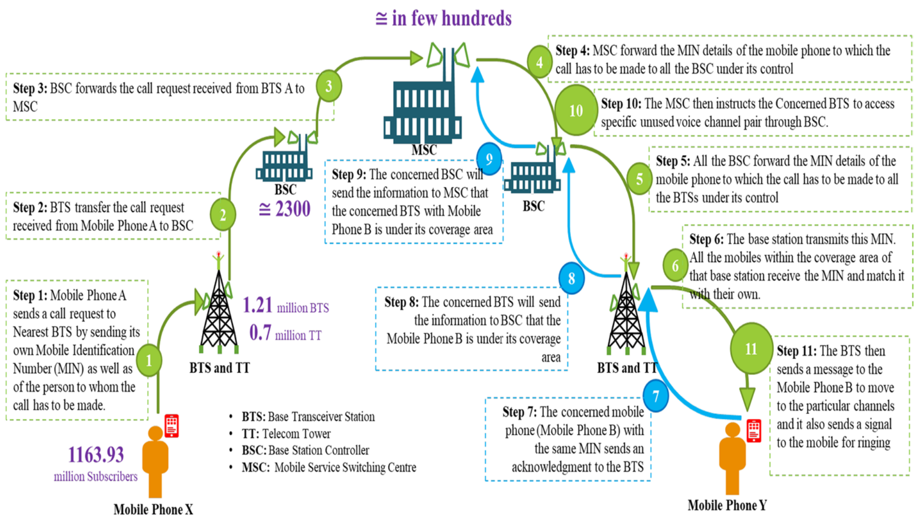

Fig. 2 Steps involved in making a call from a mobile phone X to another mobile phone Y (The numbers shown corresponds to mobile telecom network in India in March 2022)

The information about subscribers located within the service of an MSC is stored in the VLR. In addition, the information on IMSI and temporary mobile subscriber identity (TMSI) is stored in VLR. Information about international mobile equipment identity (IMEI) is stored in EIR. With the help of IMEI numbers, EIR blocks the defective or stolen mobile phones from utilizing services (GSMA, 2015; Lee, 1989; Lin & Chlamtac, 2000; Pandya, 2000).

As mentioned previously, both MSC and GMSC are part of the network switching subsystem (NSS). NSS is the heart of communication system and it controls several BSC. These components of NSS are responsible for carrying out processing and monitoring of telephone calls and information storage functions which are necessary to examine the authentication of a call, to connect a call, to encrypt the data, and to control national and international roaming services (Dulz et al., 1999; Garg, 2007). Various steps and roles of different components involved in making a call from a mobile phone (X) to another mobile phone (Y) are explained in the schematic shown in Fig. 2. It may be noted that there are approximately 11 steps involved in making a call from mobile phone X to mobile phone Y before the mobile phone Y rings. Steps 1–6 and 10–11 are call forward requests, while steps 7–9 are acknowledgements from the mobile phone Y. These eleven steps along with the components MSC NSC TT and BTS are very important for initiating requests/acknowledgements at various stages and also for authenticating both mobile phones X and Y while making a call.

The wireless network can be divided into two main categories, such as operators (which includes the BSS and NSS as shown in Fig. 1) and subscribers (which includes mobile phones). Over 90% of electricity consumption in a telecom system can be attributed to the category of operators and BTS accounts for a substantial share of the same (Roy, 2008). The electricity consumption of a BTS essentially depends on its rating that ranges from 600 W to 10 kW based on its coverage range and installation type. The total number of BTS essentially decides the overall electricity consumption. For example, about 4 million BTS have already been installed around the world and the same are grown at rapid rate

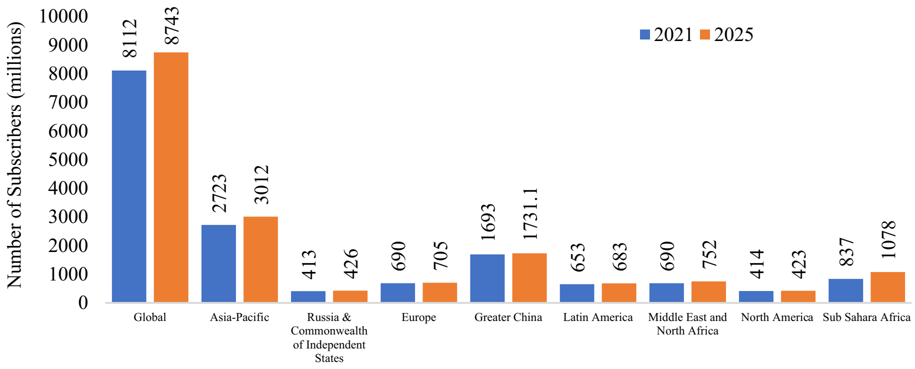

Fig. 3 Number of mobile telephone connections in 2021 and projections for 2025 in different regions of the world (GSMA, 2022)

(Roy, 2008). As an example, in India, as on October 2021, more than 2.3 million BTS cabinets are using in 0.7 million telecom towers (DoT, 2021).

1.2 Global status of mobile telecom systems

As against a total of 10.62 mobile connections, the actual number of unique mobile phones connections were around 5.33 billion in May 2022 (GSMA, 2018, 2020, 2022). The extent of mobile telephone adoption is often expressed in terms of two parameters, (a) penetration rate and (b) tele-density. Penetration rate is defined as "the number of users adopting mobile phone within a specific geographical boundary (country, state, circle or an area). On the other hand, tele-density refers to "number of telephone connections per 100 inhabitant within a specific area".

A geographical region-by-region breakdown of the mobile telephone connections worldwide in the year 2020 presented in Fig. 3 (GSMA, 2018, 2020, 2022) along with the projected numbers for the year 2025. Figure 4 (GSMA, 2018, 2020, 2022) presents the penetration of mobile telephone connections in terms of tele-density.

From Fig. 4, it may be noted that in terms of penetration rate (% of total population), the mobile telephone penetration is significantly higher in Europe, China, North America, and Russia. On the other hand, sub-Saharan Africa, Asia–pacific, Middle East and North Africa, and Latin America have relatively much lower tele-densities. One of the primary reasons for such a variation in tele-density is unavailability of appropriate mobile network in the country /region. For example, in sub-Saharan Africa, an estimated 30% of the population (majorly rural inhabitants) remains outside the reach of all mobile networks mainly due to unavailability of grid-based electricity. For example, more than 600 million people in sub-Saharan Africa (Paul et al., 2017), and another 300 million people in other parts of Asia reportedly did not have access to electricity. Thus, for a mobile network operator, it may be uneconomical to provide reliable and quality services in such unelectrified regions unless an appropriate alternative option is made available for meeting the electricity requirement of telecom towers.

The regions with poor penetration rate represent immense opportunities for future market growth for mobile network providers. With increasing emphasis on grid extension as well adoption of decentralized renewable energy-based power supply options

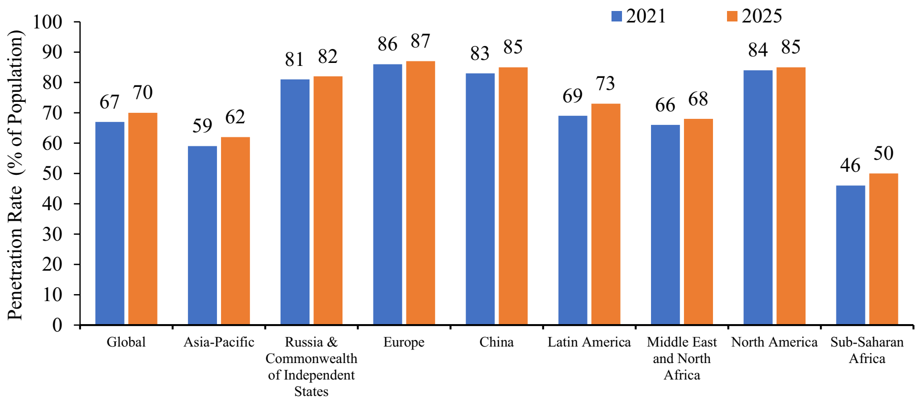

Fig. 4 Region-wise penetration rates of mobile telephone connections as a percentage of the total population (GSMA, 2022)

Table 1 Number of off-grid telecom towers in different regions of the world along with towers in areas with constrained grid access in 2007 and 2014 (GSMA, 2014)

S. No	Region	Number of telecom towers in the year					
		2007			2014		
		Constrained Grid	Off-Grid	Total	Constrained Grid	Off-Grid	Total
1	Middle East/ North Africa	44,643	13,393	58,036	69,200	0	69,200
2	Latin America and Caribbean	98,214	17,857	116,071	265,600	58,400	324,000
3	Sub-Saharan Africa	22,321	66,964	89,286	84,300	145,100	229,400
4	Asia and Pacific	482,143	191,965	674,107	281,900	116,600	398,500
5	Total	647,321	290,179	937,500	701,000	320,100	1,021,100

the same appears to be quite feasible. It is estimated that by the end of 2025, about 710 million new individuals may subscribe to a mobile connection for the first time with half of the comes from the Asia Pacific regions and about a quarter from the sub-Saharan Africa (GSMA, 2019). The number of off-grid telecom towers and also of towers located in areas with constrained grid availability (limited number of hours power supply) in different regions across the globe in 2007 and 2014 (GSMA, 2014) are presented in Table 1.

It was estimated that, by end of 2021, the global telecom industry may deploy approximately an additional 390,000 off- grid telecom towers and 790,000 towers in constrained grid availability locations (GSMA, 2022). This represents an increase of 22% and 13%, respectively, as against the corresponding number of towers in the year 2014 (GSMA, 2014). However, as number of towers growing steadily across the world, it was estimated that, by 2020 the number of off-grid towers were declined about 33% from 2014 numbers and bad-grid towers are nearly half of 2014 value (Tillekeratne et al., 2020).

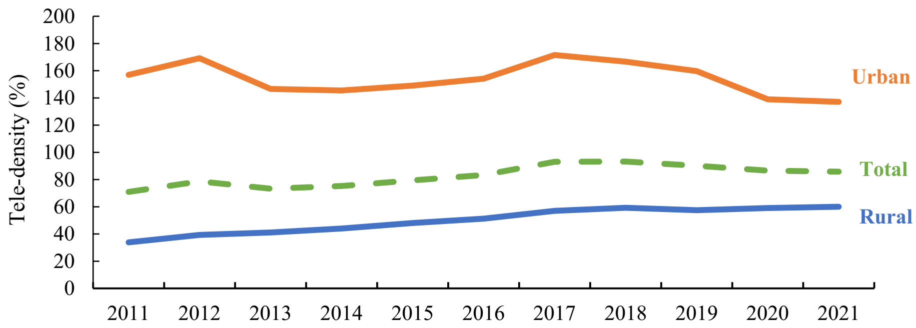

Fig. 5 Time variation of Tele-density in India (DoT, 2018, 2022)

1.3 Status of telecom sector in India

India is the world's second largest telecom market with 1166.93 million subscriber base as on 31.03.2022 (tele-density of 84.88%) out of which 519.82 million connections are in rural areas (DoT, 2015). Reliance Jio and Bharti Airtel are two major players with subscriptions of 444 million and 354 million, respectively, as on March 2022 [8]. Another noteworthy feature of Indian telecom sector is a large difference between the tele-densities of its urban (137%) and rural (60%) areas. Figure 5 presents the time–variation of tele-density in India from 2011 to 2021 (DoT, 2018, 2022).

The primary drivers for rapid growth of Indian telecom sector includes (i) encouraging policy and regulatory environment with regards to mobile number portability, (ii) Government support for 3rd generation (3G), 4th generation (4G) and 5th generation (5G) technologies, (iii) strong consumer demand due to the availability of telecom services at fair prices, and digitalization (internet of things, artificial intelligence, smart automation, industry 4.0 and digital payments). Moreover, relaxation in Foreign Direct Investment (FDI) norms has also helped the telecom industry to become one of the rapidly growing industries in the country. As on August 2021, there have been a total of 6 licensed wireless service providers operating in India, which includes Bharat Sanchar Nigam Limited (BSNL), Bharti Airtel Limited, Mahanagar Telephone Nigam Limited (MTNL), Reliance Communications Limited, Reliance Jio Infocomm Limited, and Vodafone Idea Limited (MoC&I 2021).

The total revenue generated by telecom sector in third quarter of 2020–21 was 6.822 trillion Indian Rupees[1] (MoC&I 2021; TRAI, 2017). The energy consumption share of telecom sector is relatively much lower as compared to that of several other sectors such as industry, transportation, and construction. Consequently, the telecom sector is expected to contribute much smaller amount of greenhouse gas emissions into the atmosphere. The energy consumption of telecom sector may, however, increase somewhat with adoption of new technologies such as 5G, Internet of Things (IoT), industry 4.0 and artificial intelligence-based solutions and services. For example, adopting 5G technology may increase total telecom sector energy consumption by about 150 to 170 per cent form existing levels

[1] (1 US$ = 82.42 Indian Rupees as on December 11, 2022).

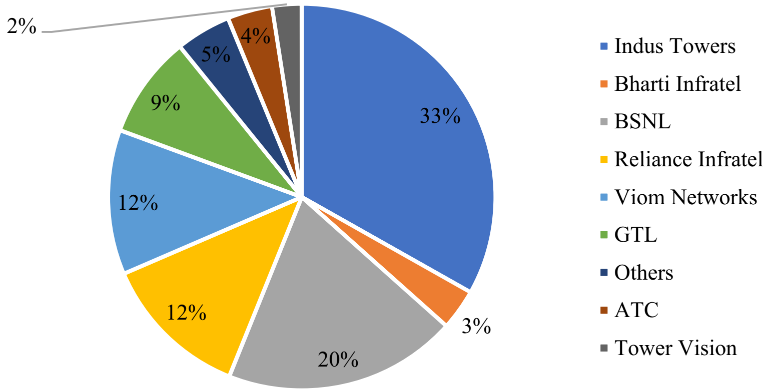

Fig. 6 Distribution of telecom tower ownership by different tower companies in India (TRAI, 2012)

(Lingham, 2019) and these development also leads to an ecological impact (Zhang et al., 2021).

As reported, the number of telecom towers have been increased from 0.4 million in 2014 to about 0.7 million in 2022. Subsequently, the BTS also increased from 0.8 million in 2014 to 2.3 million in 2022 with an increment of 187% in last 8 years (DoT, 2022). The telecom tower number is estimated to increase at a compounded annual growth rate (CAGR) of 3.2% over next 4–5 years (TRAI, 2012). With further increase in tele-density, a further increase in the number of towers is expected. There are several companies that provide dedicated infrastructure services to mobile telecom service providers. Figure 6 presents the share of telecom towers of different tower companies in the county in the year 2021 (CRISIL, 2018; KPMG, 2017; TRAI, 2012).

1.4 Decarbonizing electricity supply system for telecom towers

Availability of reliable and continuous supply of electricity is critically important to ensure reliable uninterrupted telecom services (Max & Berman, 2018). As mentioned earlier, the energy demand of the telecom sector is increasing rapidly in both urban and rural areas leading to significant increase in energy demand and associated carbon emissions (Naqvi et al., 2020a, 2020b). In general, telecom towers are powered with grid electricity. However, due to rapid expansion of mobile telephone services in rural and far-off areas without access to grid or in areas with unreliable supply from grid fossil fuel-based generators (primarily diesel generators (DGs)) are being used to meet the demand (Modi & Singh, 2020). Electricity delivered by DGs is not only carbon-intensive besides it also increases the cost of operation for telecom towers also increases in such a case (Islam, 2018; Kumar et al., 2014). Electricity load of telecom towers varies in the range of 1 kW to 10 kW based on their configurations, number of BTS used, configurations of BTS, tower type, ambient conditions (further details in Sect. 2.3) (Ayang et al., 2016; Deevela et al., 2018).

There has been some interest in harnessing renewable source of energy for providing electricity to meet the power requirement of telecom towers (Carmine Lubritto, 2008b). The primary motivation for the same is the possibility of reducing diesel consumption by reducing/eliminating the operating hours of DGs (and consequently reduced carbon emissions), reduced size of battery backup, and of course, reduced operating cost. There is huge

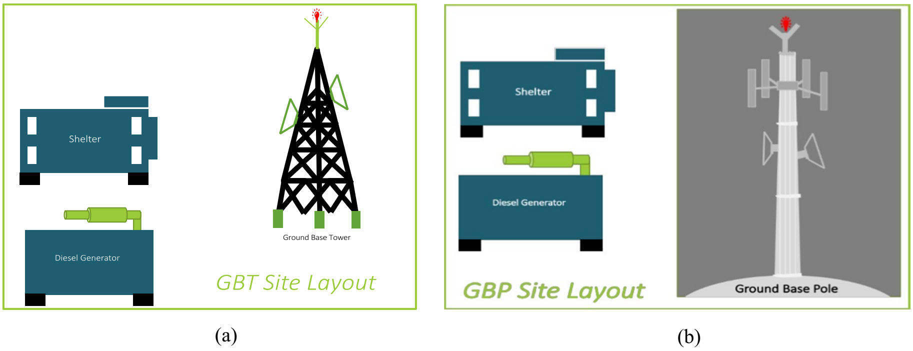

Fig. 7 Schematic diagrams of (a) ground-based tower and (b) ground-based pole used in telecom towers (DoI, 2021)

potential of establishing renewable energy-based power supply systems for telecom towers, particularly in renewable energy-rich developing countries with rapidly expanding telecom sector (Amutha et al., 2018; Babatunde et al., 2019; Gandhok & Manthri, 2021; Jansen et al., 2021; Muthusamy et al., 2021; Odoiyorke & Woenagnon, 2021; Podder et al., 2021; Reilly & Chu, 2008; Zeljković et al., 2021).

The organization of the paper is as follows: Sect. 2 presents the information about telecom towers and their load requirement. Conventional options used for telecom tower power supply is presented in Sect. 3 and renewable energy-based power supply options are discussed in Sect. 4. Various storage options used in telecom tower power supply is presented in Sect. 5. Different hybrid power supply options for telecom towers are presented in various subsections of Sect. 6, followed by concluding remarks in Sect. 7.

2 Telecom towers

Mobile network operators use a wide range of telecom towers, each with its own unique design, capacity, and type of equipment. Also, the technology employed in such towers is highly customizable. (Daniel & Daniel, 2012; KMB, 2015). Some relevant information is presented in the following paragraph.

2.1 Type and configuration of telecom towers

Telecom towers are broadly categorized as indore and outdooe towers. As name suggest, indore towers are instaled inside a building to catter the telecom needs of the users. Where as, outdoor towers are installed on rood of a building or in a open ground which catter larger geographical area. Outdore towers use many different type of anteena structures such as (i) ground-based tower, (ii) ground based pole, (iii) guyed masts, (iv) mini pole, (v) rooftop, (vi) rooftop, (vii) solar street pole, (viii) slim tower, (ix) fake trees, (x) decorative or camouflage sites. Amoung various options, ground-based towers/poles installed on the ground and rooftop towers/poles installed on roofs of the buildings are popular (DoI, 2021; TRAI, 2011a). Schematics of the ground-based tower, as well as that of ground-based pole, are presented in Fig. 7 (DoI, 2021).

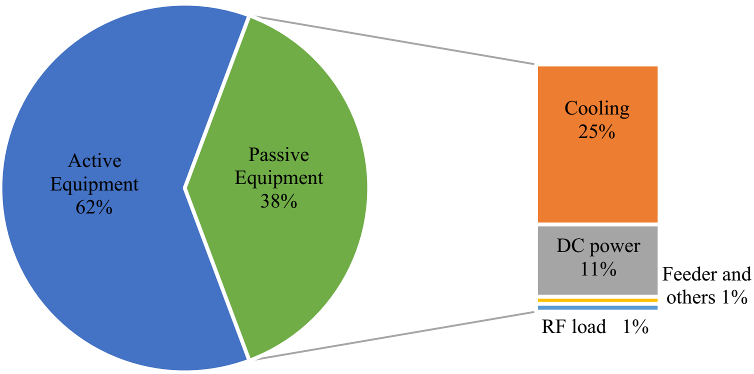

Fig. 8 Share of electricity consumption for each equipment at telecom tower (Carmine Lubritto, 2008b; Roy, 2008)

2.2 Electricity requirement

In a typical telecom tower, about 60 per cent of the electricity is used by active equipment (mainly BTS) and the remaining electricity is used by passive equipment such as DC power systems (i.e. 11%) and cooling equipment (i.e. 25%) and others including radio frequency (RF) load and feeder load (line loses) each about 1 per cent (Roy, 2008). For example, telecom towers consume about 10 kW to produce 120 W of transmitted radio signals and process the incoming signals from the subscriber's cell phones (Matthews et al., 2010; Roy, 2008). The average share of electricity consumption for each equipment of the telecom tower is shown in Fig. 8 (Carmine Lubritto, 2008b; Matthews et al., 2010; Roy, 2008).

It is worth mentioning that the configuration of active equipment in a telecom tower depends on the call traffic and number of tenancies (BIL, 2010). Table 2 presents details of typical configurations of various active equipment used in telecom towers (BIL, 2010).

A telecom tower receiving electricity from the grid also often requires batteries, SMPS, inverter, and an automatic transfer switch. Moreover, to ensure uninterrupted power supply to telecom towers, a DG is also included. The BTS of the telecom tower runs on 48 V DC and is connected to a DC bus. Each electronic equipment is powered by the DC bus through controllers. Electricity from the grid/DG is supplied to BTS through DC busbar using SMPS. All cooling and auxiliary loads are connected to the AC busbar (Cordiner et al., 2017; Karthigeyan et al., 2017). A schematic depicting the interconnectivity of electrical equipment at a typical telecom tower site is presented in Fig. 9 (Cordiner et al., 2017; Karthigeyan et al., 2017; Ramamurthi & Jhunjhunwala, 2012).

In case a power outage occurs, initially, for a short duration, electricity is supplied to the critical loads through batteries. Thereafter, an automatic transfer switch shifts the loads from energy storage system (battery) to the DG. Thus, a grid-based conventional power supply system for telecom towers usually depends on a DG and batteries to provide uninterrupted power during grid power outages (Amutha & Rajini, 2015; Gandhok & Manthri, 2021; Olabode et al., 2021). In telecom towers, both alternating current (AC) and direct current (DC) loads are being used and same are discussed in detailed in following paragraphs.

Table 2 Configurations of BTS of different original equipment manufacturers used in a telecom tower (BIL, 2010)

S. No	Original equipment manufacturer	Model	BTS configuration	Maximum power consumption (W)	Maximum current required (A)
1	Nokia	Ultra (indoor/outdoor)	2+2+2*	1670	35
2			4+4+4*	3160	66
3		Metro BTS	2+2*	400	8
4		Flexi (indoor/outdoor)	2+2+2*	1160	24
5			4+4+4*	2200	46
6		Flexi WCDMA	3 s-RRH20W	750	16
7		MW-flexi hopper (IDU & ODU)	1+0	60	1
8	Huawei	BTS 3900	2+2+2*	1060	22
9			4+4+4*	2000	42
10		BTS 3900A	2+2+2*	1150	24
11			4+4+4*	2070	43
12		MW-RTN 900 series (IDU & ODU)	1	40	1
13		Optical transport Network sub-rack (OTN)	8800	5400	113
14			6800	1500	31
15			3800	350	7
16		DWDM MUX	1600	2000	42
17	Ericsson	RBS 2206 (indoor)	2+2+2*	1750	36
18			4+4+4*	3200	67
19		RBS 6101 (outdoor)	3 s-RRH20W	730	15
20		RBS 6202 (outdoor)	3 s-RRH20W	700	15
21		RBS 6601	3 s-RRH20W	680	14
22		MW-Mini link (IDU & ODU)	1	37	1

*2+2+2 implies that there are two transceivers in each of the three sectors (i.e. A cell tower normally covers an area that is roughly circular in shape and can be divided up into sectors (120^O apart) (Daniel & Daniel, 2012; KMB, 2015) of BTS. Out of two transceivers in each sector, one is for stand by for emergencies. Same is true for 4+4+4 and 6+6+6.

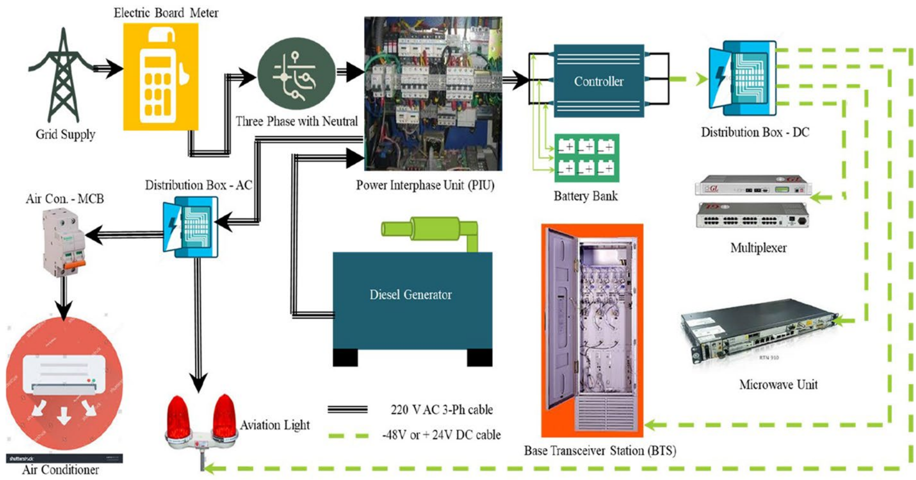

Fig. 9 Typical interconnectivity of electrical equipment in a telecom tower (BIL, 2010)

2.2.1 AC and DC loads

Electrical loads in telecom towers can be broadly categorized into two different types viz. AC loads and DC loads. AC loads are further classified into critical and non-critical types (Fraisse & Buchsbaum, 2005). AC non-critical loads are powered through a utility grid and do not require any backup power. One example of these loads is air-conditioning systems. The DC loads such as switching equipment, BTS, multiplexer etc. are powered through a DC busbar and use of rectifiers (Abiad et al., 2018; Fraisse & Buchsbaum, 2005; Prasad, 2008). Load break-up of AC and DC equipment in a typical indoor and outdoor telecom tower with BTS configuration of 4+4+4 is shown in Fig. 10 (Prasad, 2008).

The electricity requirements of telecom towers with different BTS configurations along with the capacities of various electricity supply options is presented in Table 3 (Prasad, 2008).

Ramamurthy and Jhunjhunwala (Ramamurthi & Jhunjhunwala, 2012) have developed a simulation tool using MATLAB to assess alternative strategies for a reduction in (a) the operating cost, (b) energy consumption and (c) carbon emissions from telecom towers. These strategies include adoption of improved cooling method for BTS (Haghighi 2016), harnessing of renewable energy such as solar photovoltaics (PV) and wind, and use of improved batteries with a lifetime of 10,000 cycles or more.

A typical BTS shelter can house a single BTS and a maximum of 3 BTS units. Based on the range of the telecom tower, number of voice calls and data transfer at any given point of time, the BTS can be classified into 2+2+2, 4+4+4, 6+6+6 TRX (transceiver) configurations as shown in Table 2. The configuration (2+2+2) implies that there are two transceivers in each of the three sectors (A cell tower normally covers an area that is roughly circular in shape and can be divided into three sectors each being120^{O} apart) of BTS. Out of the two transceivers in each sector, essentially a standby is there for emergencies. Figure 11 shows typical hourly load profile of different BTS configurations (Ramamurthi & Jhunjhunwala, 2012).

The shelters that houses BTS often need to be cooled particularly in indoor type systems. Such a cooling requires substantial amount of energy. The battery bank with

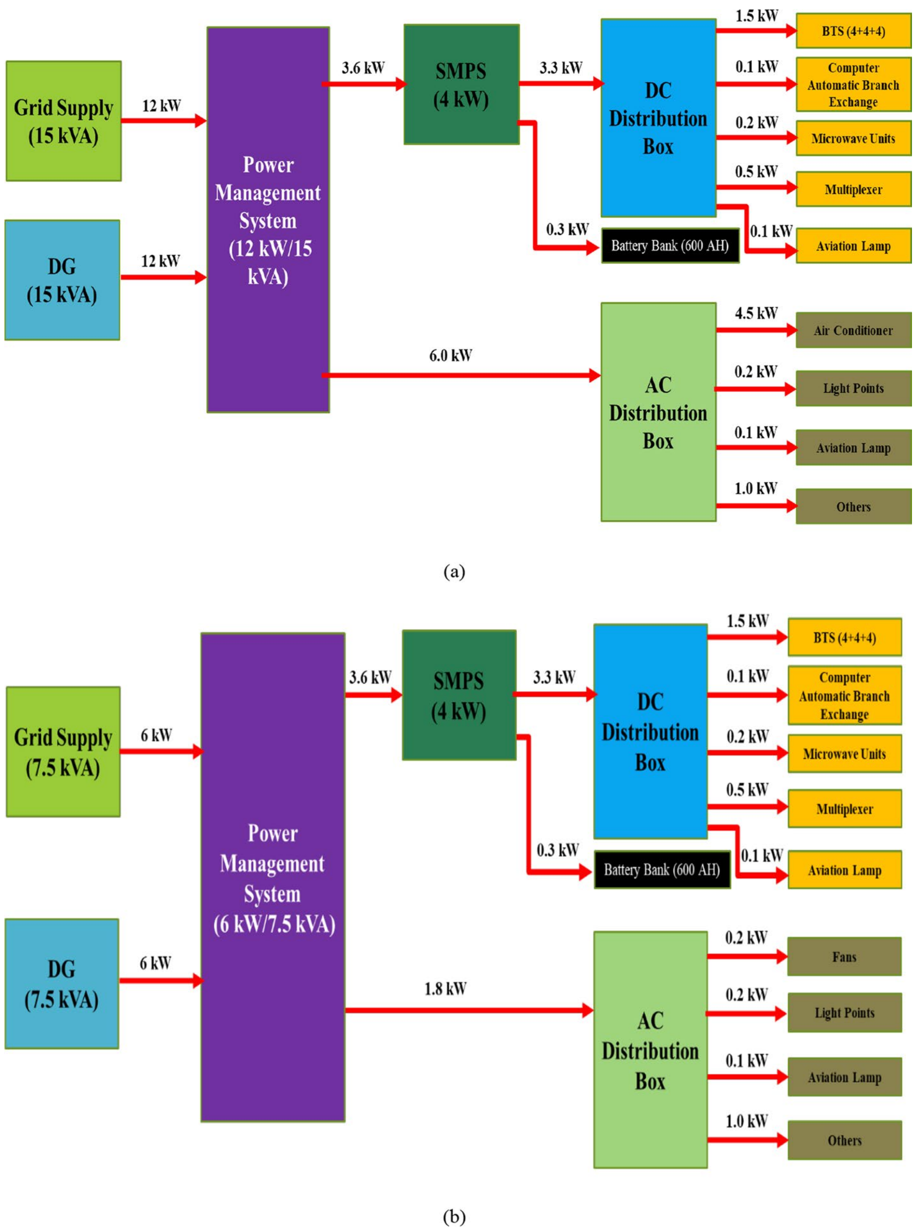

Fig. 10 Typical break-up of the load due to AC and DC equipment in **a** indoor telecom tower and **b** outdoor telecom tower with BTS configuration of 4 + 4 + 4 (Prasad, 2008)

the system is also to be maintained at optimal temperature (Lubritto et al., 2011; Petraglia et al., 2015; Tu et al., 2011). A common practice is to place the entire battery bank and BTS equipment in the shelters and cool the same to extend the life of batteries. For example, a single tenancy indoor BTS shelter requires two 0.9-ton capacity air-conditioning systems and battery chillers to keep the battery temperature within the

Table 3 Various possible BTS configurations with minimum required power rating of passive (grid supply, DG, SMPS, battery bank) equipment (Prasad, 2008)

S. No	Configuration		Power management system	DG Set	Battery bank	SMPS	Grid supply
	Number of indoor BTS	Number of outdoor BTS	Rating (kVA)	Rating (kVA)	Capacity (Ah)	Capacity (A)	Capacity (kW)
1	1	0	12.5	15	300	150	12
2	2	0	12.5	15	600	250	12
3	3	0	12.5 + 7.5	25	600	250	20
4	0	1	7.5	7.5/10	300	150	10
5	0	2	12.5	10	300	250	10
6	0	3	12.5	15	300	250	15
7	1	1	12.5	15	600	250	12
8	2	1	12.5 + 7.5	15	600	250	18
9	1	2	12.5 + 7.5	15	600	250	18
10	2	2	12.5 + 7.5	25	900	350	18
11	1	3	12.5 + 7.5	25	900	350	18
12	3	1	12.5 + 7.5	25	900	350	18
13	4	0	12.5 + 7.5	25	900	350	20
14	0	4	12.5 + 7.5	15	900	350	18

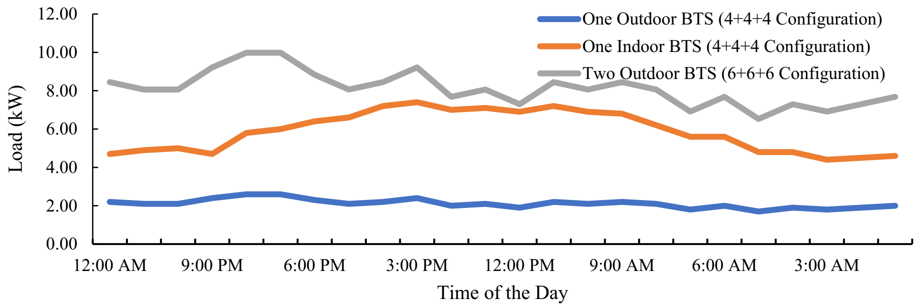

Fig. 11 Hourly load profile of different BTS configurations (Ramamurthi & Jhunjhunwala, 2012)

prescribed limits and they consume approximately 2.2 to 4.5 kW per hour (Xiaoqin et al., 2014). Cooling load details for different BTS configurations are presented in Table 4 (Xiaoqin et al., 2014).

The energy requirement for cooling of telecom load is quite substantial and is often attributed by inefficient cooling equipment and use of conventional controls. In summary, the energy requirement for cooling in telecom towers is quite substantial (Wang et al., 2016). In the literature, several innovative techniques for cooling such as free cooling, heat pipe, waste heat recovery from other equipment and ventilation cooling have been reported (Zhang et al., 2008, 2014).

Table 4 Cooling load details for different BTS configurations (as presented by one-off leading telecom tower company) (Xiaoqin et al., 2014)

S.No	BTS configuration		Air-conditioning (AC) systems			Number of exhaust fans (50 W)	Number of battery chillers
	Number of indoor BTS	Number of outdoor BTS	Quantity	Cooling capacity (TR) of each AC	Number of fan coil unit		
1	1	0	2	0.9	1	-	1
2	2	0	3	0.9	1	-	1
3	3	0	3	0.9	1	-	1
4	0	1	-	-	-	2	1
5	0	2	-	-	-	2	1
6	0	3	-	-	-	2	-
7	1	1	2	0.9	1	-	-
8	2	1	3	0.9	1	-	1
9	1	2	2	0.9	1	-	1
10	2	2	3	0.9	1	-	2
11	1	3	2	0.9	1	-	2
12	3	1	3	0.9	1	-	2
13	4	0	4	0.9	1	-	2
14	0	4	-	-	-	2	2

2.2.2 Additional load due to conversion losses in battery

BTS with a (2+2+2) configuration is generally equipped with a 48 V, 300 Ah battery bank. Science typical charging and discharging losses of a battery including power conversion losses are in the range of 10—15%. the overall energy efficiency of a battery can be expected in the range of 70 to 90% (Krishnan et al., 2012; Zurfi et al., 2017). Such losses are also considered as loads and are accounted for during the design of power supply system for telecom towers. Moreover, the charging and discharging efficiencies of the battery storage system may change with the type of power source. Qureshi et al. (Qureshi et al., 2017) have observed a 6% overall efficiency improvement while using DC source input power over AC source input power for the same application.

3 Conventional options to meet electricity requirements of telecom towers

Between Lille and Paris in France, the first visual telegraphy (semaphore) system was constructed in the year 1790. Subsequently, in the year 1844, a commercial communications system began operating and the same quickly spread in the country. In 1850, for the first time, telegraph systems were operational within the country, with an American-led consortium laying the first cable connecting Britain and the USA, which ultimately failed after a few months. Later, with further efforts by a few companies,, success was achieved in 1866 (Normans, 2015). With technology development, by the early twentieth century, there were over three million phones in the US. For the next half-century, the network behind the telephone grew progressively larger and much more efficient (Mitel, 2020; Technofunc, 2010).

Early seventies of twentieth century, the success of the evaluation of wireless communication systems has changed the face of cellular mobile phone utilization and thus leads to rapid expansion of infrastructure including telecom towers (Gaibi et al., 2021). Conventionally, the electricity required for telecom towers either supplied from grid or with the help of a diesel generator set. A brief description of these two conventional options is presented in the following paragraphs.

3.1 Grid power supply

As on date, electricity from the grid is usually cheaper and preferred source for powering telecom towers. However, powering telecom towers uninterruptedly with grid electricity is a significant challenge in locations with unavailability of reliable grid-based electricity supply. For example, in case of India, the results of an analysis of availability of electricity in terms of duration of its unavailability, at 133 locations, including some of the state capitals, district headquarters, municipalities, and villages across the country (Prayas, 2015) are presented in Table 5.

From the analysis, it was noted that, at pan India level, rural telecom towers are powered only for about 13.5 h per day through the grid as compared to 20 h per day in metro cities (NITI AAYOG, 2015). About 70% of all telecom towers have less than 12 h per day of electricity supply from grid (GSMA & IFC, 2011). Moreover, even with the official electrification rate approaching 100%, at least 10% of telecom towers did not have access to the electric network in the year 2017 (TRAI, 2017). Moreover, this number is increasing due to

Table 5 Total annual hours of unavailability of electricity at 133 locations in India [69]

S.No	Location name	Period of power cut (Hours)
1	Marol, Mumbai	1
2	Congress Road, Belgaum	4
3	Meerut Road, Ghaziabad	10
4	Arera Colony, Bhopal	14
5	Shaniwarpeth, Pune	20
6	Yelahanka, Bengaluru	21
7	Palghar Town	25
8	Sahakarnagar, Pune	28
9	Dhakuria, Kolkata	30
10	Mandideep, Bhopal	30
11	Aundh, Pune	38
12	Radgaon MIDC, Ratnagiri	38
13	Samta Colony, Raipur	39
14	Capital Electrical Subdivision, Guwahati	42
15	Dandia Bazar, Vadodara	45
16	Congress Nagar, Nagpur	47
17	Banjara hills, Hyderabad	48
18	Malcha Marg, Delhi	50
19	Gogal Madgaon, Goa	55
20	Prithvi Avenue, Chennai	59
21	Ameerpeth, Hyderabad	60
22	Khadki, Akola	60
23	Sadar, Nagpur	62
24	Sector 37, Chandigarh	75
25	Rajaji Nagar, Bengaluru	80
26	Tarnaka, Hyderabad	80
27	Sikandra, Agra	80
28	PEG (Kothrud), Pune	82
29	Amar Nagar, Nagpur	85
30	Bajirao Road, Pune	88
31	Saheed Nagar, Bhubaneswar	93
32	Hindawadi, Belgaum	94
33	Sector 70, Mohali	98
34	Sadashiv Nagar, Belgaum	100
35	Mukundapur, Kolkata	103
36	Baner, Pune	107
37	Vijay Nagar, Hyderabad	115
38	Patrakar Colony, Dhule	120
39	Kapoorthala, Lucknow	128
40	Alambagh, Lucknow	129
41	Kalpataru Nagar, Nashik	130
42	Nippani	130
43	Renuka Nagar, Akola	130
44	Jankipuram, Lucknow	132

Table 5 (continued)

S.No	Location name	Period of power cut (Hours)
45	Kakatiya Nagar, Hyderabad	138
46	Subhash road, Ratnagiri	140
47	Besa, Nagpur	141
48	Kothi Bazar, Hoshangabad	150
49	PWD Guest house road, Gairsain	150
50	Khed, Ratnagiri	154
51	Kedar Nagar, Agra	156
52	Aliganj, Lucknow	159
53	Srirampura, Bengaluru	170
54	Raj Nagar, Ghaziabad	171
55	Halbhavi Camp, Belgaum	177
56	Indirapuram, Ghaizabad	178
57	Ashoka Garden, Bhopal	179
58	Talegaon	180
59	Sumerpur, Chamoli	180
60	Badgujar Colony, Dhule	186
61	Mahabubnagar, Raichur	189
62	Shyam Nagar, Bhopal	190
63	Devpur, Dhule	191
64	Jangaon, Warangal	199
65	Sector 9, Chandigarh	200
66	Jaydev Vihar,Bhuvaneshwar	204
67	Inder Vihar, Dehradun	216
68	Madhal, Ratnagiri	224
69	Malakhedi, Hoshangabad	230
70	Arjun Nagar, Ghaziabad	231
71	Tarun Nagar, Guwahati	240
72	Cuncolim, Goa	246
73	Malakhedi road, Hoshangabad	280
74	Kasbe Sukene, Nashik	284
75	Brahmavar	287
76	Sri Ram Rang Pura, Bellary	290
77	UPSIDC Site C, Agra	290
78	Alandur, Chennai	293
79	Guhagar (C)	294
80	Bethora, Goa	295
81	Garladinne	297
82	Sainikpuri, Hyderabad	300
83	Sector 3, Kurukshetra	310
84	Yellur, Belgaum	320
85	Datalpara, Guwahati	327
86	Awas Vikas colony, Barabanki	348
87	Masvanpur, Kanpur	351
88	Carambolim, Goa	363

Table 5 (continued)

S.No	Location name	Period of power cut (Hours)
89	Mohol	379
90	Gimhavne, Ratnagiri	383
91	Kondhanpur	430
92	Avadi, Chennai	446
93	Khindaura, Sitapur	460
94	Jan Path, Bhubaneswar	463
95	Guhagar (R)	479
96	Bhadupur Sidhauli	499
97	Malwada, Palghar	500
98	Jhundapur, Ghaziabad	500
99	Rajendra Gunj, Raichur	503
100	Bangi Kunta, Raichur	538
101	Rishibhumi, Risia	540
102	Kanoongopura, Bahraich	557
103	Paud	624
104	Bodireddypally, Prakasam	659
105	Chandori, Nashik	679
106	Jamui Town	706
107	Takia Jarwal, Kasba	800
108	MG Road, Ghaziabad	800
109	Gondur, Dhule	805
110	Pabal	950
111	Bhopoli, Palghar	1105
112	Raja Bazar, Nanpara	1150
113	Fatehpur, Barabanki	1269
114	Kasraila, Barabanki	1466
115	Jamboti, Belagum	1483
116	Chouksey Nagar, Bhopal	1596
117	Baijnathpur, Saharsa	1666
118	Ganeshpur, Barabanki	1750
119	Shingave, Nashik	2010
120	Paigwa, Barabanki	2300
121	Mihinpurwa, Bahraich	2394
122	Allipur, Fatehpur	2537
123	Brandawan, Barabanki	2744
124	Kanjaya, Bahraich	2806
125	Chunaitee Gara, Saharanpur	2889
126	Chowk Bazar Jarwal, Kasba	2898
127	Biswan, Sitapur	2968
128	Bahadurpur, Bahraich	3088
129	Firozpur, Suratganj	3186
130	Bardaha, Bahraich	3288
131	Ibrahimpur, Barabanki	3799
132	Kotanka, Andhra Pradesh	4300

Table 5 (continued)

S.No	Location name	Period of power cut (Hours)
133	Bhatbigha, Hazaribagh	4370

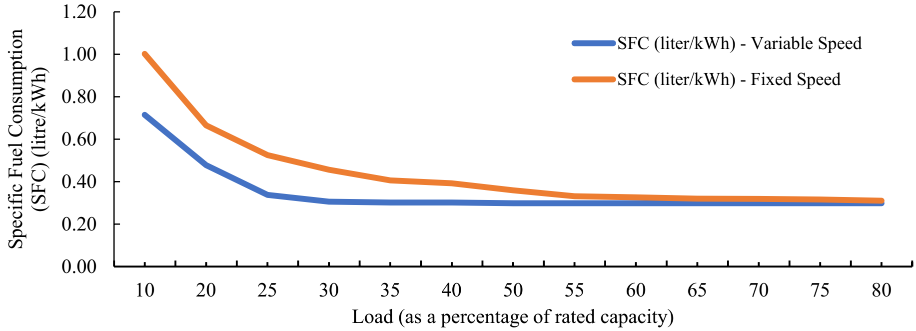

Fig. 12 Specific fuel consumption of **a** 15 kW fixed speed DG and **b**12 kW variable speed DG at different loading percentages (Jhunjhunwala et al., 2012)

continuous deployment of new telecom towers in remote rural areas. As a result, the electricity requirement of around 80 to 90% of rural telecom towers is fulfilled with DG sets (GSMA & IFC, 2014a).

3.2 Diesel generator (DG) set

Almost, all telecom towers are equipped with a DG set as a backup power supply option during outages of grid power supply. Telecom tower companies have been using DG sets of capacity varying from 7.5kVA to 25kVA capacity based on the peak load demand. Electricity delivered by DG is costlier as compared to the electricity from the grid (for example in the range of Indian Rupees 18 to 28 per kWh for India). Moreover, most often, these DGs are operating at part loads leading to inefficiency in operation and thus resulting in higher specific fuel consumption. A typical value of the useful life of the DG is around 15,000 h of operation. Usually, all telecom tower companies have annual maintenance contracts with original equipment manufacturers (OEMs) and some OEMs are selling their product with lifetime free maintenance options as well (Cummins, 2021).

In a fixed speed DG, an alternating current generator produces 230 V AC, which is then converted to 48 V DC to charge the battery and power the BTS equipment. In another design, a variable speed DC generator is used and that produces DC power to fed directly to battery and BTS equipment. However, the DC power is to be converted to AC to feed air-conditioning loads (Jhunjhunwala et al., 2012). The effect of partial loading on the specific fuel consumption (SFC) of a 15 kW fixed speed DG and also of 12 kW variable speed DG is shown in Fig. 12 (Jhunjhunwala et al., 2012).

It may be noted from Fig. 13 that, at lower loads, specific fuel consumption of variable speed DG is lower compared to fixed speed DG. This may be attributed to the fact that the speed of the generator can be controlled at lower loads in a variable speed DG and not in

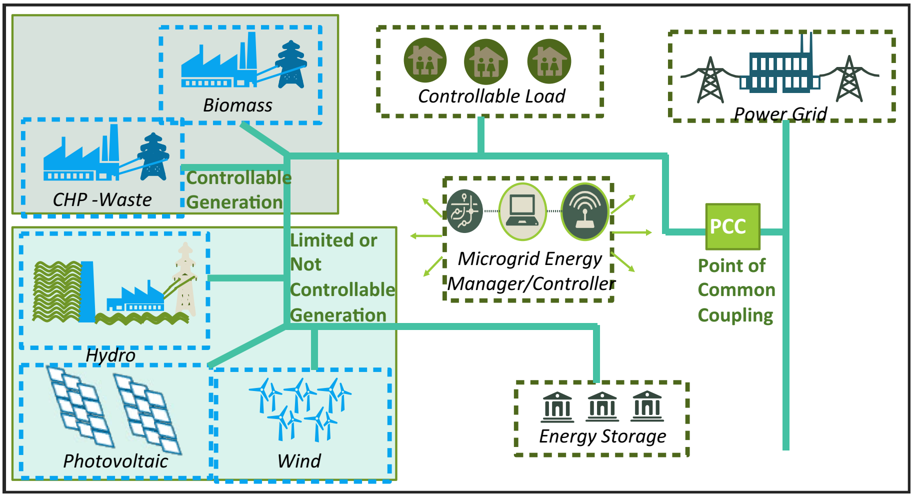

Fig. 13 A schematic of a hybrid system for power supply

case of fixed speed DG. Moreover, with the variable speed DG producing DC output, the losses incurred in AC to DC conversion can be avoided. Variable speed DGs producing DC output can be installed in outdoor telecom towers with minimal cooling load and low conversion losses.

Most of the telecom tower companies are replacing their old DGs with variable speed DG due to the fuel efficiency advantage by controlling the speed. Variable speed operation of the internal combustion engine facilitates fuel savings with a change of load, but it requires a power conditioning unit such as an electronic converter (Iwanski et al., 2018). DGs with variable speed engines guarantee fuel savings in the range of 20 to 40% as compared to standard DGs at lower loads (Obukhovet al., 2017). These variable speed DGs have longer useful life (about 20% more than standard DGs) and have less maintenance cost (Waris & Nayar, 2008). Telecom Industry in India is said to be the second largest consumer of diesel after the Indian Railways (TRAI, 2017). Estimates made by Telecom Regulatory Authority of India (TRAI) in 2011 by assuming eight hours of DG set operation for meeting electricity requirement of a 3 to 4 kW capacity telecom tower accounted for 8760 L of diesel consumption every year (TRAI, 2012). Cumulatively, diesel consumption in telecom towers is more than 3.5 billion litres annually and it accounts for a significant share in operating cost of telecom towers and a big burden for telecom companies.

4 Renewable energy-based options to meet electricity requirements of telecom towers

The electricity demand of telecom sector is continuously growing and at the same time, dependence on alternative options to supply electricity (majorly DG) is also increasing due to non-availability of reliable electricity supply from grid in all the places (Avikal et al., 2020, 2021; Kaur et al., 2020; Scamman et al., 2015a).

In view of increasing energy requirements of telecom towers and the importance of decarbonizing the power supply to them, harnessing renewable sources of energy makes considerable sense (Kazem et al., 2017; Muruganantham et al., 2017; Tang et al., 2021; Zhao et al., 2022). In addition to regulations pertaining to the frequency of electromagnetic radiation emissions, there are several environmental regulations aimed at (a) stipulating carbon emission reduction targets; (b) limiting the use of DGs in urban areas; (c) renewable energy purchase obligations; (d) zero diesel usage in certain environmentally sensitive areas; (e) declaring carbon foot print by telecom tower operators; (f) star labelling of equipment used in telecom towers etc. Such regulations also encourage the adoption of low-carbon power supply options (GSMA, 2021c; International Telecommunication and Union, 2016; C Lubritto et al., 2011; TRAI, 2011b). Recent technological developments in solar, wind, biomass energy-based options and also storage technologies are encouraging the penetration of renewable energy-based powering solutions in the telecom sector (GNESD, 2014; López-gonzález et al., 2017; TRAI, 2011b). A study carried out by the GSMA, in 2014, mentioned that approximately 43,000 telecom towers had already adopted renewable energy-based measures in East Asia, sub-Saharan Africa, South Asia, Latin America, the Pacific, and the Caribbean (GSMA & IFC, 2014b). In case of India, one of the leading telecom tower companies is claimed in August 2017 that 50 per cent of their total tower portfolio (i.e. 62,000) has become zero diesel usage with the adoption of various measures including renewable energy and energy efficiency technologies (ITL, 2011). Moreover, in a recent report published by International Renewable Energy Agency (IRENA) mentioned that many leading telecom tower companies are adopting renewable energy-based technologies for powering telecom towers and pledged usage of 100% renewables by 2030 (IRENA, 2018). It is also mentioned in the report that currently, only 7% of energy consumed by telecom companies are coming from renewables. It indicated a huge potential for telecom companies to adopt renewable energy (Tillekeratne et al., 2020).

Renewable energy-based options have been preferred choices for electricity supply to telecom towers due to their availability in vast geographical areas around the world at low to negligible operating costs (Badawe et al., 2012; Sams, 2011). Additionally, the modular nature of wind and solar technologies provided much-needed flexibility in designing systems to supply electricity to telecom towers (Alsharif et al., 2017; Aris & Shabani, 2015; L. Olatomiwa et al., 2015; Salih et al., 2014).

As previously stated, presently, telecommunication services plan an important and an integral role in the private and the business life of most of the population in a country (David, 2019). For example, during recent Novel Coronavirus 2019 (COVID-19) pandemic, telecommunication services have been played a crucial role as most f the services made available to people were essentially facilitated by telecommunications services (Mbunge et al., 2022). During difficult times of the pandemic, telecom services provided much-need avenues for remote working, thus allowing many businesses, industries, academia etc. to continue operations despite the disruption caused by COVID-19 (Papadopoulos et al., 2020). In addition to facilitating communication and collaboration among family, friends, and co-workers, they offer access to health services, education, and entertainment (Venkatesh, 2020). They have been used to disseminate vital health information, such as preventative measures and where to seek assistance.

In many areas of the world, it may be challenging to ensure upkeep of telecommunication services only by relying on conventional power supply based on grid electricity and DG sets (Wang, 2023). Renewable energy-based power supply systems offer a much-needed alternative that can be effective even in pandemic situations such as that of COVID-19 (Ayub et al., 2022). For example, renewable energy sources are more resilient to power grid disruptions in the event of a pandemic. In addition, harnessing of renewable energy sources of energy helps mitigate emissions from combustion of fossil fuels (Tsao et al., 2021). Lastly, renewable energy sources can deliver energy at lower cost, which is extremely beneficial particularly in a pandemic situation with many individuals and business struggling financially (Xu & Sharma, 2022).

4.1 Solar photovoltaics (PV) systems

Solar PV can offer attractive options for powering telecom towers due to abundance of solar energy in many parts of the world, modularity of PV systems, ease of planning, simple installation and less maintenance (Aris & Shabani, 2015; Hemmati & Saboori, 2016; Priyono et al., 2018; Zhu et al., 2015).

A large number of the PV installations used for powering telecom towers are in the peak capacity range of 4kWp to 8kWp (Kumar & Patil, 2016). It is also mentioned that for a specific location with a 4 kW peak telecom load, an 8.1kWp solar PV system can eliminate DG usage, provided, the grid is available for about 8 h per day. Battery life is also improved with the help of a solar PV system due to reduced cycles (Siah et al., 2014).

Electricity generation through grid-connected PV system is cheaper than stand-alone systems in Nigeria (Dawadi et al., 2020; Ike et al., 2014). A study conducted in South Africa (Aderemi et al., 2017) found that the use of electricity from solar PV for a telecom tower can reduce up to 49% of the operational cost as compared to conventional DGs. Vishal and Vandana (2016) have discussed control techniques to extract maximum power from PV and boost the voltage to an optimum level so that it can be connected to battery storage for powering telecom towers. Sheeja et al. (Sheeja and Singh 2020; Sheeja & Kalpana, 2018, 2021) have proposed various control techniques to optimize the performance of solar PV based system for powering telecom tower loads.

4.2 Wind energy-based systems

Small capacity (1—10 kW) wind turbines can offer another feasible option for powering telecom towers at appropriate locations with adequate wind resources availability (Sarmah et al., 2016). A 10 kW vertical axis wind turbine is proposed by Eriksson et al. (2012) to electrify telecom towers. La et al. () have proposed wind energy-based hybrid systems for telecom tower applications. The authors have proposed to use small scale wind (1.5–7.5 kW) turbines by installing on the top of the telecom tower pylon or on a separate mast.

4.3 Systems based on biofuels

Biomass energy-based systems can also provide electricity to meet the requirements of telecom towers (Shah et al., 2020). Use of biodiesel in conventional diesel based electricity generators is a potential option (GSMA, 2012). Electricity can also be produced at decentralize level with biomass gasifier based systems that use the produce producer gas delivered by the gasifier in a 100% gas engine (Mahmudul et al., 2022). Biomass energy-based systems have added advantage of offering better dispatch ability as compared to solar and wind energy systems as many of the biomass feed stocks can be stored (Lin et al., 2008). In view of continued requirement of biomass feedstocks, such systems may find applications in rural areas with adequate supply of biomass feed stocks (Makhija & Dubey, 2018, 2019). Each biomass energy-based electricity supply systems has to be designed specific to each of the case being studied (Kumar et al., 2015). Moreover, most studies found that biomass use has negative impact on carbon emissions (Shah et al., 2021).

4.4 Pico-hydro systems

At some of the locations, there may be a possibility of harnessing locally available hydro power resources for powering telecom towers. Pico-hydro system with a typical capacity of less than 5 kW (ZekâiŞen, 2018) that can designed to harness the kinetic energy of moving water in streams and rivers (Lau & Tan, 2021). Such systems are being considered for rural electrification applications at suitable sites (Chauhan & Saini, 2015; Hajimiragha & Zadeh, 2013; Lahimer et al., 2012; Williams & Simpson, 2009). In the case of powering telecom towers, the availability of appropriate sites may limit the adoption and deployment of this technology (GSMA, 2012). Abdulmula et al. (2022) have proposed a micropower system with photovoltaic system, 2 kW pico-hydropower, and battery for powering telecom towers.

4.5 Fuel cell-based systems powered with renewable source of energy

Fuel cells act as alternate electricity supply systems for powering telecom tower sites operating with poor grid power supply (Akinyele et al., 2020). Fuel cell-based hybrid systems are still in emerging stage due to limited proven commercial applications in the telecom towers. Hybrid solutions, such as a combination of renewable energy with regenerative fuel cells, are one of the potential solutions to power the telecom towers. Globally, telecom tower companies have started using regenerative fuel cells for power supply (Akinyele et al., 2020; Jansen et al. 2018). Fuel cells also function as a backup and disaster recovery system during emergency periods (Cordiner et al., 2017; Fosberg, 2010; Scamman et al., 2015b; Yilanci et al., 2009).

The electricity generated from renewable energy sources can be used to generate hydrogen through electrolysis of water and the same can be stored and converted into electricity with the help of regenerative fuel cells (Branco et al., 2018; ESA, 2017; Nikolaidis & Poullikkas, 2018). Studies carried out by Bak et al. (2002), Li (2017), Agbossou et al. (2004) and Al-Badi et al. (Luo et al., 2015) have emphasized the importance of this method as applicable to hybrid systems.

When compared to conventional electrochemical storage systems, hydrogen-based storage is more environmentally friendly with no direct carbon emissions (Osman et al., 2021; Saeedmanesh et al., 2018). The flexibility of storing the hydrogen in all the three phases is an additional advantage to design a compact and portable energy storage system. These systems can be deployed for various applications (e.g. hybrid vehicles, rural electrification, commercial, household, telecom, etc.) (Bocklisch, 2015; Chen & Mei, 2015; Hemmati & Saboori, 2016; Scamman et al., 2015a; Tezer & Yaman, 2017; Zimmermann et al., 2016).

Despite the recent technology developments over the entire value chain of renewable energy-based regenerative fuel cells, the round-trip efficiency is still on the lower side with a high capital cost. However, regenerative fuel cells provide advantages such as higher specific energy, excellent cycle capability, environmental friendliness, zero carbon emissions, compactness, multiple capacities, and ready to use energy storage solution that have made them to be considered as a long-term energy storage solution (Chen et al., 2009; Kaldellis et al., 2009; Luo et al., 2015; Nikolaidis & Poullikkas, 2018). As reported in the literature, solar PV powered hydrogen-based fuel cell system was first employed for telecom applications in the year 2000 in Madrid, Spain (Yilanci et al., 2009). Cordiner et al. (2017) have reported testing of a fuel cell and solar PV system to generate and store power required to run the telecom tower systems. The test results have shown the effectiveness of hybrid renewable energy solutions as an energy efficient power supply option that helps reduce fossil fuel usage in an off-grid telecom tower.

In a case study from a telecom network operator in UK (Fosberg, 2010), replaced Liquefied Petroleum Gas (LPG) based power generator with 5 kW integrated fuel cell system. This system comprises of 2.5 kW PV panel and a 2.5 kW wind turbine connected with 1000 Ah battery bank to store electricity generated by the fuel cell. It has been reported that with the help of 1 kW fuel cell and 1.6 kW of electrolyzer; it had been possible to reduce the size of batteries in the range of 54–77% and also to improve the minimum state of charge from 37 to 55% for 1 kW of telecom load (Scamman et al., 2015b).

Along with regenerative fuel cells, Proton-Exchange Membrane (PEM) fuel cells are commercially well developed and also appropriate for use with telecom towers due to their peak efficiency in a wide range of ambient conditions (−40 °C to + 50 °C). PEM fuel cells are quiet, durable, compact, reliable and require minimal maintenance. Such systems can be designed in sizes ranging from 250 W to 250 kW (Fosberg, 2010). Adopting clean and highly reliable solutions for a variety of applications across the world reiterates the necessity of adopting robust technologies such as fuel cell systems and fuelling solutions (Cecilia & Paulmier, 2007; Saathoff, 2014).

5 Energy storage options for telecom tower power supply system

Considering the importance of uninterrupted power supply, energy storage is an integral part of systems designed to supply electricity to telecom towers. The addition of a component for energy storage is anticipated to increase the reliability of the power supply. Storing energy also helps to meet the sudden capacity shortage in case of renewable energy-based systems (e.g. during an overcast day, intermittent cloud passage, at low wind speeds, unexpected and irregular loads) (Belmili et al., 2014). An energy storage system stores excess energy during surplus generation and reverts it during lean periods. It may also be possible to reduce the optimal size of the DG set by using a storage component of appropriate size. (IEC, 2015; Koutitas & Demestichas, 2010). In fact, with the inclusion of an appropriate energy storage option (Brunarie et al., 2009), it may be possible to design an optimal system for electricity supply (Farahmand et al., 2017; Rohit & Rangnekar, 2017; Shahirinia et al., 2005). Energy storage systems are being used at different stages in the electricity generation, distribution systems as well as off-grid applications. (Branco et al., 2018; Ferguson & Bristol, 2017; Guney & Tepe, 2017; Rohit & Rangnekar, 2017; Zhang et al., 2018; Zhou et al., 2010).

5.1 Batteries

A battery is an electrochemical energy storage device that converts stored chemical energy into electrical energy by oxidation and reduction reactions of electrolytes with metals. Currently, batteries are predominantly used to store energy as a backup source for powering telecom towers. The battery size depends on various system specifications such as voltage, current, charging and discharging rates, state of charge, operating temperature, depth of discharge, cost, size, weight, and any other requirement of end-use applications (Casacca and Lynch 1992; Farahmand et al., 2017; Ma et al., 2014; Shahirinia et al., 2005). The useful life of the battery is smaller as compared to that of telecom tower and thus significant replacement costs are to be incurred at regular intervals. Inefficient charging and discharging techniques and variations in the operating temperature may reduce the capacity and useful life of the battery (Leng et al., 2015). In general, lead acid batteries are predominately used in telecom tower applications. In future, deployment of more durable and efficient batteries such as sodium-metal halide, Li-ion, vanadium-redox flow may help in the reduction of operating cost as well as operating hours of DG (Rijssenbeek et al., 2011). These advanced batteries can also be used in hybrid systems to facilitate optimal utilization of renewable energy sources (Kear et al., 2012; Merei et al., 2013; Vetter et al., 2005). The success of sustainable hybrid power supply solutions for telecom towers hinges heavily on the selection of the most appropriate battery technology. (Swingler & Torrealba, 2019). Lithium-ion batteries, which have a higher energy and power density as well as a longer lifespan than other commercially available battery types, may be considered among the available options. There are several advantages of lithium-ion phosphate (LFP) battery over current valve regulated lead acid (VRLA) battery for telecom applications (Karthigeyan et al., 2017) and the same includes (i) LFP batteries having low operating expenses and double the life than VRLA battery, (ii) LFP batteries are environmentally friendly while VRLA batteries have lead, (iii) LFP battery surpasses the higher rate of charging as compared to VRLA battery and this is most needed for telecom applications, (iv) LFP batteries are efficient, compact, lightweight over VRLA batteries. A comparison among different types of battery technologies is given in the Table 6 (Karthigeyan et al., 2017).

Merei et al. (Merei et al., 2013) have studied the economics of employing three distinct battery technologies for a PV–wind- and DG-based hybrid system. Vanadium-redox-flow battery technology has been found to be the cheapest (\$0.73/kWh) against the lead-acid (\$0.77/kWh) and Li-ion batteries technology (\$0.81/kWh). It has also been reported that the energy delivery cost of the hybrid renewable energy-based system (e.g. PV-wind-battery system) is found to be higher (about \$1.52/kWh) than those that are not using batteries (Lawan et al., 2020).

6 Hybrid Systems to Meet Electricity Requirements of Telecom Towers

In general, a combination of two or more energy resource options to supply electricity can be defined as a hybrid power supply system (Wang et al., 2015) (e.g. PV with DG; PV, wind and battery storage system). Such hybrid systems are designed to achieve reliable, economic and environment friendly power supply solutions (Anoune et al., 2018; Jiang, 2013; Rauf et al., 2019; Sharma & Goel, 2016). It may be desirable to develop and deploy hybrid power supply solutions including renewable source of energy to provide reliable power supply at lower costs (Chaurey & Kandpal, 2010; Chowdhury et al., 2021; Kusakana & Vermaak, 2013; Ombra et al., 2012; Serincan, 2016). An energy storage system is often necessary component of such hybrid systems to take care of the power outages likely to caused due to the intermittent nature of renewable energy sources such as solar and wind.

A hybrid system may usually connected to electricity grid. However, these hybrid systems can also be employed in stand-alone mode (Mannah et al., 2018). As mentioned earlier, energy storage devices provide energy balance and energy when no other power supply option is available. Power electronic units are deployed to convert DC to AC and vice versa. A schematic block diagram of a hybrid system is shown in Fig. 13.

Table 6 Comparison among different types of battery technologies (Karthigeyan et al., 2017)

S.No	Attribute	Battery Type				
		Lead acid	Nickel cadmium	Sodium sulphur	Lithium ion	Sodium nickel chloride
1	Achieved upper limit power	Multiple tens of MW	Tens of MW	MW scale	Tens of kW	Tens/low hundreds of kW
2	Specific energy (Wh/kg)	35–50	75	150–240	150–200	125
3	Specific power (W/kg)	75–300	150–300	90–230	200–315	130–160
4	Cycle life	500–1500	2500	2500	1000–10,000	2500 +
5	Charge/discharge Energy efficiency	~80	~70	up to 90	~95	~90
6	Self-discharge (per month)	2–5%	5–20%	–	1% per month	–

Fig. 14 Geographical distribution of hybrid systems installations across the world

Fig. 15 Distributed energy sources and storage options being employed in various hybrid systems

Several hybrid systems are reported operating successfully in the world (Zebra et al., 2021). Some of these have been established primarily for research purposes and some for powering institutional/campus, commercial/industrial, community, military systems including those in the remote areas. As part of this study, 152 hybrid systems with geographical distribution as depicted in Fig. 14 have been studied and those details with telecom towers have been briefly presented in following subsections.

The preliminary information available about 152 hybrid systems was analysed and it was noted that (Fig. 15), such systems often use different energy sources besides including a storage.

Results of an initial attempt to categories the 152 hybrid systems based on the technologies used is presented in Table 7.

Some of the configurations presented in Table 8 can be used for meeting electricity demand of telecom towers. It can be inferred that a combination of one or more

Table 7 Configurations of installed hybrid systems based on distributed energy sources

S.No	Configuration	No of physical installations	S.No	Configuration	No of physical installations
1	PV	35	22	PHP + DG	1
2	PV + DG	19	24	PV + WT + GT + DG	1
3	PV + WT + DG	18	25	PV + WT + GT + CHP + CSP + DG	1
4	PV + GT + DG	15	26	PV + CHP + CSP + Boiler	1
5	WT + DG	11	27	PV + CHP	1
6	PV + WT	9	28	WT + CHP	1
7	PV + WT + FC + DG	6	29	Biogas DG	1
8	WT	6	30	PV + WT + HP + FC	1
9	PV + FC	3	31	PV + WT + DG + FC	1
10	PV + WT + FC	3	32	PV + CHP + Heat Pump	1
11	PV + WT + GT	2	33	PV + WT + CSP	1
12	WT + MPH + DG	2	35	WT + FC + DG	1
13	PV + WT + PHP + DG	2	36	PV + WT + GT + FC	1
14	WT + PHP	1	37	PV + WT + FC + CHP	1
15	MHP + DG	1	38	PV + GT	1
16	PV + PHP	1	39	PV + GT + FC	1
17	PV + Wave	1	40	DG + CHP	1
18	WT + GT + DG	1	41	GT + DG	1
19	Grid + Battery	1	42	PV + WT + GT + FC + CSP	1
20	PV + WT + PHP + FC + DG	1	43	GT + Boiler	1
21	GT	1	44	CHP	1

PV photovoltaic, *WT* wind turbine, *DG* diesel generator set, *GT* gas turbine, *FC* fuel cell, *PHP* pico-hydro-plant, *CHP* combined heat and power, *CSP* concentrated solar power (battery storage is to be included in each configuration)

solar photovoltaic (PV), wind turbine (WT), diesel generator set (DG), gas turbine (GT) and fuel cell (FC)-based systems can be used for designing/establishing the electricity supply system for telecom towers due to resource availability, technology appropriateness, modularity and maturity of the technology. In several cases, the use of individual renewable energy technologies may result in considerable over-sizing, which makes the implementation of single renewable energy source-based power supply very costly. Employing system optimization techniques to reduce the system cost with maximum power reliability may provide more efficient alternative cost effective options (Anoune et al., 2018; Branco et al., 2018; Chauhan & Saini, 2015; Koufopoulos & Vokas, 2012; Tomar & Tiwari, 2017; Ullah et al., 2014). Moreover, policy measures and incentives from government will also help to boost the adoption of hybrid renewable systems for powering telecom towers especially in rural areas, where grid electricity prices are lower (Dinata & Saputro, 2020; Wijesinghe, 2019).

As a first approximation, it is inferred that out of various energy technologies included in 152 hybrid systems configuration as summarized in Table 8, only Photovoltaic (PV), Wind Turbine (WT), Diesel Generator Set (DG), Gas Turbine (GT) and Fuel Cells (FC) have higher potential to provide electricity for telecom towers (Abdulmula et al., 2019). This may primarily be attributed to the factors related to availability of resources, appropriate technologies and their merits as well as modularity.

Table 8 Summary of field installations of renewable energy-based hybrid systems for powering telecom towers in urban and rural areas

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
1	A1 Telekom Austria Group	Austria, Bulgaria, Croatia, Belarus, Slovenia and the Republic of Serbia	100	Solar PV + wind and hydrogen in few cases	A hybrid power supply system with a combination of solar PV, wind and battery storage has been used. In some cases, base stations are also powered with hydrogen		A1 Telekom (2021)
2	American Tower Co	India	10	DG + Solar PV	Installed solar PV with battery backup system	Employing battery storage helped to reduce the operational expenditure as well as CO_2 emissions significantly	TBC (2014)
3	America Movil	–	–	Solar PV + wind	Powered few off-grid telecom sites with solar PV and wind-based systems	As reported, these hybrid installations help to reduce the 90% of diesel consumption from those telecom towers	AM (2020)
4	AT&T	USA	> 500	Solar PV, wind and fuel cell	Installed solar PV, wind- and fuel cell-based power supply systems for various telecom towers across California, New Jersey, Austin, Texas, etc		AT&T (2021)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
5	Axiata	Across various telecom tower operators	1708	Solar PV	Telecom towers are powered with a solar PV system	Across operations, how a telecom company uses various renewable energy technologies to power telecom towers. This will be a good example to showcase the feasibility of different renewable technologies for powering telecom towers	Axiata (2019)
6			12	Wind	Telecom towers are powered with wind turbine systems		
7			277	Solar PV + DG + wind + grid	A hybrid system powers telecom tower		
8			1	Hydrogen based fuel cell	Telecom tower powered with Hydrogen based fuel cell		
9			2	Methanol fuel cell	Telecom tower powered with Methanol based fuel cell		

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
10	BAI Communications (BAI)	Muswellbrook, New South Wales	300	Grid + solar PV	BAI and Photon Energy, with funding from the German Energy Agency (DENA) replaced the grid power supply with 215kWh solar PV with a battery storage system for continuous power supply	Designed integrated solar and battery system for remote telecom towers	Hassell (2019)
11	Bell Canada	Canada	4	Solar PV + wind + DG	Solar PV, Wind and DG based hybrid systems were installed at Nungesser Lake, Wabikon, Badesdawa, Zoar. It is mentioned that about 75% of the power requirement is fulfilled by renewable	An example of using renewable energy-based hybrid systems in harsh and far-off areas to power telecom towers	BC (2019)
12	Bharti Infratel	India	2000	Grid + DG + solar PV	Bharti Infratel uses solar PV panels through a modular approach. The PV system capacity varies from 0.85kW_p (one outdoor BTS) up to 3.3kW_p (3 outdoor BTS)	Bharti infratel chooses only solar panels because of their modularity and lower capital cost	GSMA and IFC (2014b)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
13	Bharati Airtel	India	> 3267	Solar PV + DG	Solar PV and DG based hybrid systems were installed at 3267 sites in 2018. Solar PV capacity varies from 3 to 7 kW. This helps to reduce the DG operation from 20 to 6 h	An example for using solar energy in a country like India (abundant solar energy) to power telecom towers and reduce the DG operation	BAL (2018)
14	Catalyst Energy Technologies	Philippines	Many	DG	Increased the battery size	This installation helps run DG at full load for less time	Schneider (2014)
15	China Mobile	China		Solar PV and Wind	An integrated power supply system which integrates solar photovoltaic power, wind power and energy storage system to minimize the consumption of traditional fossil fuels while ensuring the stable supply of power at base stations		CM (2021)
16	Claro's telecom towers	Nicaragua—Claro		DG + solar PV	Claro's telecom tower installed a hybrid off-grid PV system with battery backup to power a base transceiver station		TBC (2014)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
17	Ecoult	New South Wales, Australia	1	Grid + DG	Ecoult developed a control method to significantly reduce diesel consumption, technician visits, and frequent servicing	Increased the battery storage capacity, avoided low loading operation of DG set and improved fuel efficiency	Ecoult (2016)
18	Edotco	Hatiya, Bangladesh	1	DG + solar PV + wind	Installed green hybrid system consists of $12kW_p$ solar PV and 4 kW wind systems. This system helps to reduce diesel consumption and carbon emissions up to 80%	A hybrid solution combination of wind and solar PV is ideal for the location and used the tower to install the PV modules in a stacked manner	Amina Khatun (2020)
19	Edotco	Bangladesh	1	Solar PV + wind	Installed solar and wind-based systems to power 500 telecom towers, and at the group level, these initiates help to reduce significant carbon emissions	Group level initiate helps to reduce the carbon emissions. Moreover, wind turbines are effectively used for power generation. This is a good example for other telecom tower operators to adopt the similar initiatives	Edotco (2021)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
20	Gilat Satellite Networks Ltd	Peru	35	Solar PV	CIME designed a battery and solar photovoltaic based off-grid hybrid system to power 35 rural telecom towers owned by Gilat	PV based solution is ideal due to ease of installation, and deep-cycle valve-regulated lead-acid battery improves the reliability of the system	TBC (2014)
21	MTN Group	South Africa	> 1330	Solar PV, wind and hydro	MTN's ambition is to incorporate a renewable-only approach as it rolls out new sites with one or a combination of solar, wind or hydro. In 2020, 300 additional rural sites powered by solar were rolled out, bringing it to a total of 1331		MTN (2020)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
22	NTTDOCOMO	Japan	200	Solar PV and fuel cells	As of March 2019, NTTDOCOMO had converted about 200 BTS in to green and all are in operation. Electricity generated by solar panels is used to supply the equipment, and lithium-ion batteries store surplus generated electricity in preparation for a possible power disruption		NTT DOCOMO (2020)
23	Nuran	Nigeria	1	Solar PV + DG	Smart off-grid solar PV based hybrid system to power telecom tower	This hybrid system was installed in 2018 and smart weather forecast and management system is an additional feature to optimize the system performance and achieve low CAPEX/OPEX and maximum uptime	CBT (2018)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
24	Nuran Wireless	Democratic Republic of Congo (DRC)	1000	Solar PV power nano-grid	Smart solar PV nana grid-based off-grid power plants to provide telecom towers reliable power. This solution helps operators to save significant upfront costs, lower operating prices and increase uptime	The need for telecom services is increasing rapidly in DRC. Solar PV powered Nano-Grid pack based power solutions helps to increase the uptime of telecom towers	CBT (2021a)
25	Orange UK	Natural park, Elan Valley, Wales	1	DG + solar PV + wind + fuel cell	Installed a hybrid system consisting of a Solar Photovoltaic array, fuel cell and wind turbine with a capacity of 2.5kW$_P$, 5 kW and 2.5 kW, respectively. This system is supported with a 1000Ah battery to store the energy generated by the system	The fuel cell operates on a mixture of water hydro plus and methanol mixture. This fuel has the advantage of having higher energy density and lowers siting risk than hydrogen alone fuel	Fosberg (2021)
26	PT Indogreen Technology	Indonesia	1	DG + solar PV	Installed solar PV panel, inverter and MMPT controller and Automatic Generator Start (AGS)	This installation helps to reduce diesel consumption up to 75% during day time	Schneider (2014)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
27	Safaricom	Kenya	255	Solar PV and wind	Developed a robust solar designs which occupy minimum space and also used lithium-ion batteries with built-in remote monitoring. There has been positive performance with the acceleration of functional and high capacity solar solutions in the network. In FY21, deployed about 34 solar sites with a capacity of 12kva each. Consequently, fuel supplied to these sites has reduced by about 80%		Safaricom (2021)
28	Telefonica	Atalaya, Amazon Region, Peru	–	Solar PV powered nano-Grid	Off-grid power supply system to provide electricity for a very critical network for a remote telecom tower located at Atalaya in Amazon Jungle	A good example, how solar PV system helps to power small and far–off telecom towers	T&M (2021)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
29	Telefonica	Chile & Latin America	70	Solar PV + wind	Hybrid power supply system with a combination of solar PV, wind and battery storage. 68 number 5 kW and 2 number 3 kW wind turbines were used in 70 telecom tower installations	A wind and solar PV based hybrid system is very suitable for intermittent on-grid telecom tower	RE (2021a)
30	Telefonica	Argentina	14	Solar PV + wind	Hybrid power supply systems with solar PV, wind, and battery storage systems are used		RE (2021b)
31	Telenor	Pakistan	943	Solar PV	Telenor is replaced more than 3000 DG set based telecom towers with solar PV and storage based solution		Telenor (2020)
32		Bangladesh	1200				
33		Malaysia	10				
34		Myanmar	839				
35		Thailand	14				

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
36	Telia	Sweden	–	Renewable energy mainly wind and hydro	Telia is procuring 100% renewable energy for its complete operations	An example of using 100% renewable energy. This is mainly by procuring grid electricity from renewable energy-based power plants	Telia (2020)
37	Telstra	Australia	–	Solar PV, wind and fuel cell	Telstra powered various towers through Solar PV, Wind and Fuel cell-based systems		Telstra (2021)
38	Trinidad's telecom carrier	Islands of Trinidad and Tobago	50	Fuel Cell	The fuel cell system provides continuous power back of 5 kW power output for 50 h. This is due to the large fuel tank with a capacity of 220 L	During power outages, the system will start supplying power immediately without any interruption to telecom service	Fosberg (2021)
39	Vanu	Rwanda	–	Solar PV power nano-Grid	Off-grid solar PV based nana grid system is installed to provide reliable power to rural telecom towers	Vanu telecom base station employed solar PV supported nan grid to power telecom towers. This is a good example of hybrid solutions	CBT (2021b)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
40	Vodafone	Spain	43	Solar PV + wind	Hybrid power supply system with a combination of solar PV, wind and battery storage. 5 kW and 3 kW wind turbines and 1.85 kW solar PV panels have been used in each installation		RE (2021c)
41	Verizon	USA	4	Solar PV and wind	Verizon installed about 28 MW renewable energy on-site capacity installed at various telecom towers		Verizon (2020)
42	Winercon	Valencia	13	Solar PV + wind	A hybrid power supply system with a combination of solar PV, wind and battery storage has been used	These hybrid systems are installed in a week grid-connected telecom towers where more outages and power cuts are encountered	RE (2021d)
43		Sangatta, East Kalimantan, Indonesia	1	DG + solar PV	Solar PV module with MPPT and 2000 Ah battery bank		Frontier and Island (2012)

Table 8 (continued)

S.No	Implemented by	Location/Country	No. towers	Sources of electricity	Brief about measure	Observations	References
44	–	Indonesia	50	DG + solar PV	Installed solar power generation system and it substitutes part of power supply by DG. (70% of electricity from Solar PV and 30% is from DG)		

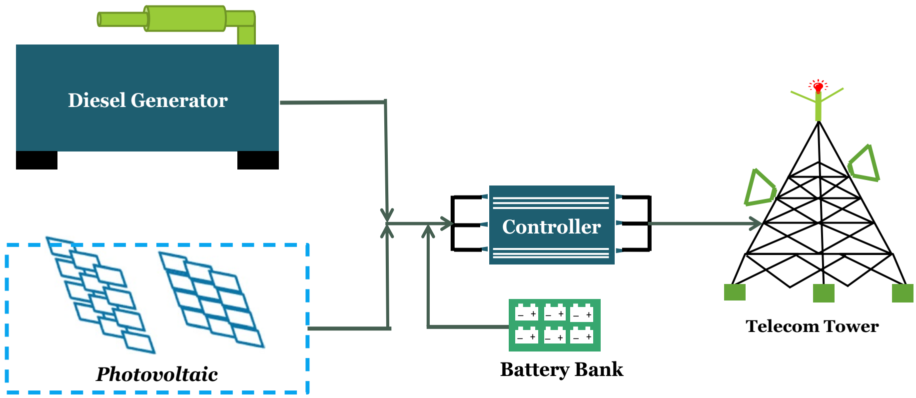

Fig. 16 A schematic of a power supply configuration based on PV, DG and battery storage system

6.1 Potential configurations of hybrid systems for powering telecom towers

The selection and design of hybrid power systems for telecom towers would depend on location-specific characteristics such as available resources, load, ambient conditions, etc. (Nema et al., 2010). Hybrid system solution commonly considered for powering telecom towers are PV-WT-battery, PV-DG-battery, WT-DG-battery, PV-WT-DG-battery, and PV-FC-battery systems (Aris & Shabani, 2015; Siddiqui et al., 2022). Brief information on these hybrid solutions discussed in the following paragraphs.

6.2 PV, DG and battery-based system

Among the various options for supplying electricity to telecom towers, solar photovoltaic (PV) systems, distributed generation (DG), and battery-based hybrid systems are the most common. Most of the time, these setups have battery energy storage systems to handle vital loads when other power options are unavailable. (Siva Subrahmanyam & Anil Kumar, 2021). Such systems are reliable as the DG can deliver electricity on demand (Chandran et al., 2016; Murugesan & Marimuthu, 2019; Oviroh & Jen, 2018; Pelland et al., 2012; Sekhar et al., 2015; Tsuanyo et al., 2015; Usman et al., 2017). A schematic of a hybrid PV-diesel-battery system that can be used for supplying electricity to telecom towers is presented in Fig. 16.

PV and DG-based hybrid power system with storage mainly consists of 4 parts. (i) DG power generation system (which includes an Internal Combustion (IC) engine, electrical generator, automatic transfer switch (ATS), rectifies and converters), (ii) PV power generation system (which includes PV array, MPPT and converters), (iii) single-phase power supply inverter and, (iv) battery storage and battery management system.

The possibility of using PV- and DG-based hybrid systems for meeting electricity demand for various decentralized applications such as rural electrification, telecom towers, hospital, hotels etc. have been reported in the literature. Marquest et al. (2011) compiled experience of first thousand optimized solar BTS stations implemented by Orange group (a telecom company). They mentioned that optimized solar PV systems helps to reduce the DG operation and reduce energy consumption from grid. Kumar et al. (2016)

have discussed the application of a hybrid system having PV, DG and storage for powering telecom tower load. Authors have reported that these systems are financially feasible with a high return on investment under specific optimized conditions of locations (rural/urban areas), loads, solar resource availability and number of hours of grid power outage. Similarly, a PV based system to retrofit an existing 3 kW telecom tower power system have been studied (Chandran et al., 2016). In this study author proposes the use of ultra-capacitors to minimize the use of batteries and to provide power for brief durations of solar resource unavailability owing to passing clouds or when the DG is interrupted. It was observed that the use of ultra-capacitor generally helps to stabilize the inverter output and improve its power quality. The integration of PV module with a cascaded high gain boost converter which can perform MPPT and boost the voltage up to a usable level hybridized with battery to support the telecom towers (Vishal 2016). The authors have discussed system and panel capacity sizing to ensure optimum charging of batteries during the day time. The performance of the system is validated using MATLAB/Simulink environment.

Olatomiwa et al. (2014) have discussed system size optimization of PV array, wind and diesel based hybrid power supply solution to power remotely-located telecom towers in Nigeria. The Hybrid Optimization of Multiple Energy Resources software (HOMER) developed by NREL, USA (Givler & Lilienthal, 2005; Vendoti et al., 2021) is used to carry out techno-economic analysis of the proposed system. HOMER is found to be the most common among the software tools being employed for optimization of hybrid systems. Results show that the proposed hybrid system is technically feasible and cost effective to supply the electricity for BTS site. The most economical solution reported by the author consists of PV, DG and battery with capacities of 8kWp, 5.5 kW and 1800Ah at 48 V, respectively. The total Net Present Cost (NPC) reaches $71,739 with renewable energy fraction of 78% and a diesel consumption of 1050 L (Olatomiwa et al., 2014).

Ullah et al. (2014) have explored the power supply options for supplying electricity to telecom tower using a solar-wind-diesel based hybrid system. The telecom tower is located in Chittagong in Bangladesh. The results of a HOMER based study have pointed towards a preliminary feasibility of using such a hybrid systems for powering telecom towers in Bangladesh. Kabir et al. (2015) is also proposed a microcontroller based power management for proposed hybrid systems in Bangladesh.

Deevela et al. () have proposed a improved control method for stand-alone solar PV, DG and battery based system and validated the performance under various field conditions for reliable power supply. Goud and Goud (2017) have analysed a hybrid system based on PV and DG with battery storage to power remote telecom tower in grid connected as well as stand-alone mode and validated it with the help of HOMER. Chowdhury and Aziz (Bhatti et al., 2016; Chowdhury et al., 2009) and Quashem and 3.5kWAzizul (Walid & Mohammad, 2014) have analysed a solar PV- and DG-based hybrid system for powering telecom towers in Bangladesh. They concluded that the renewable energy-based hybrid systems are economical over only diesel based systems and in future, the scenario will improve further based on the diesel price escalation.

Rizqiawan et al. (2019) have analysed economic aspects of renewable energy-based hybrid systems for powering telecom towers. They are of the opinion that that hybrid renewable energy system of on-grid BTS has higher cost of energy compare to utility charge, but the risk of using costly diesel generator can be eliminated. On contrary, LCOE of hybrid renewable energy system of off-grid BTS is much lower than LCOE of diesel generator operation. In the case of off-grid BTS, the hybrid renewable energy system is potential solution from the economic point of view.

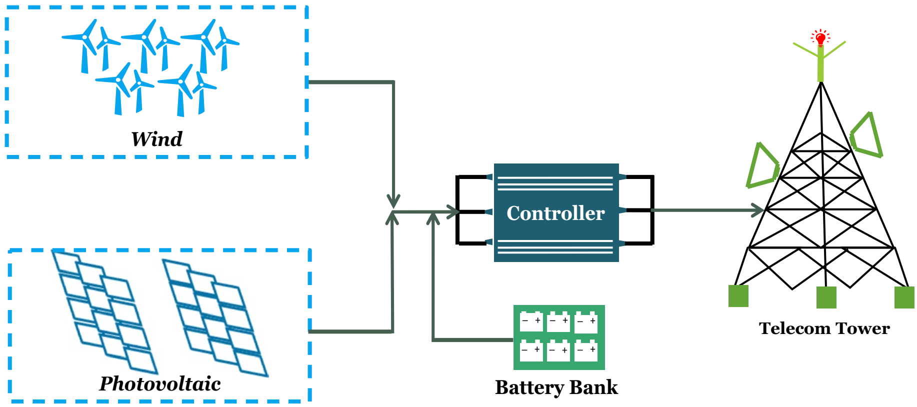

Fig. 17 A schematic of a power supply configuration based on PV, wind, and battery storage systems

6.3 PV-, Wind- and battery-based system

A hybrid system consisting of Photovoltaic modules and wind energy-based generators may be used to produce electricity for meeting power requirements of telecom towers (Acharya & Animesh, 2013; Yeshalem & Khan, 2017). A schematic of a PV-wind-battery-based hybrid system for electricity supply to telecom tower is shown in Fig. 17.

PV and wind-based hybrid power system mainly consists of 3 parts (Yu & Qian, 2009): (i) wind power generation system (which includes a wind turbine, generator, rectifiers and converters), (ii) PV power generation system, and (iii) single-phase power supply inverter.

Salih et al. (2014) have discussed capacity optimization and design of PV and wind-based hybrid power supply system by minimizing capital and operating cost without compromising the electricity demand of telecom towers. With the help of HOMER, three different system configurations have been assessed in terms of system efficiency and performance. The obtained results have indicated that a hybrid system is highly reliable to provide continuous electricity to telecom towers.

Tiwari et al. (2017) have designed and developed a control algorithm for renewable energy (wind and PV) based hybrid energy system for feeding 3-phase 4-wire loads and reported to have achieved maximum power with the help of MPPT on both the wind and PV systems. While the experimental results of the study validated that power quality is found within the prescribed limits, due to the high cost of storage (battery), the electricity cost has been somewhat higher. With emerging battery storage options, such a hybrid system can be potentially appropriate for remote telecom as well as community power supply systems that are currently dependent on DG.

Anoune et al. (2018) have presented a detailed review on various methods and techniques being adopted for sizing hybrid power systems including most commonly used topology based on wind and photovoltaic systems. It has been reported that heuristic approaches and artificial intelligence algorithms may be better as compared to traditional methods due to their ability to search local and global optima, functional computational correctness and processing speed.

Goel et al. (2015) have presented results pertaining to optimal design of a hybrid system based on solar and wind energy to power remote telecom towers (a coastal island in Kendrapara district of Odisha, India). The authors have been reported the results of net present cost and cost of electricity are low for PV and wind-based hybrid system at three different load conditions. (i.e. $ 0.506/kWh at a load of 83 kWh/day; $ 0.552/kWh at a load of 55 kWh/day; $ 0.839/kWh at a load of 22.7 kWh/day). A similar study was carried out by Maoulida et al. (2021) specific to Comoros and they suggested that all the renewable energy combinations are better LCOE over DG and battery based solution.

Kaur et al. (2020) have studied the application of renewable energy-based DC microgrid for powering telecom towers in remote areas. They have implemented a non-dominated sorting genetic algorithm to solve the optimal sizing problem. Different scenarios are presented by estimating different levels of power supply availability, excess electricity, and cost of electricity. The estimates of unit cost of electricity reported by the authors are $0.218/kWh at 100% power supply with zero failures, $0.179/kWh (at 3.8% loss of power supply probability (LPSP)) and $0.089/kWh (at 20% LPSP).

Paudel et al. (2011) proposed a hybrid system based on solar PV and wind system for powering telecom towers. Their proposed system improves the system reliability from 63.4% to 99.9% and reduce LCOE from $1.22 to $0.88.

Akuon (2012) has discussed installation procedures, shading effect on power output from a solar PV, wind and battery based hybrid system installed at Angolan, at the shores of South Atlantic Ocean. Author suggested that, where possible, solar panels are best installed at the north-most part of the site if the site is located in the southern hemisphere to avoid shading by other site components and also, he stressed that MPPT has to employed to extract maximum power from renewable energy systems.

6.4 PV, Wind, DG and battery-based system

In this hybrid system, both solar PV and wind energy systems are used to generate electricity and the DG is used as standby power supply during the lean period of PV and wind energy systems (Aris & Shabani, 2015; Baneshi & Hadianfard, 2016; Diamantoulakis et al., 2013; Farahmand et al., 2017; Goel & Ali, 2014; Gökçek & Kale, 2018; Kaur et al., 2018; Merei et al., 2013; Olatomiwa et al., 2015; Paul et al., 2017; Shezan et al., 2016). Figure 18 shows a schematic of a hybrid diesel-wind-PV system for electricity supply to telecom tower.

PV- wind- and DG-based hybrid system with storage usually consists of 5 parts. (i) PV power generation system (ii) wind power generation system, (iii) DG power generation system, (iv) single-phase power supply inverter, and (v) battery storage and battery management system.

Nema et al. (2010) have discussed possible alternative solutions for grid power supply with stand-alone PV and wind-based hybrid solutions with a DG as a backup to power the telecom towers. The study has revealed that, with the help of hybrid power supply option, conventional DG is eliminated approximately 70–80% of the time and the same resulted in reduction of carbon emissions by 18.6 tonnes per year for one telecom tower.

Mercado et al. (2016), have presented a case study on optimal sizing of PV, DG, battery and wind-based hybrid system for powering a remote telecom tower. Techno-economic analysis results show that the COE is $0.448/kWh for the above hybrid system with 8 kW PV panel, 1 kW wind turbine, 5.5 kW DG and 600 Ah battery.

Khan et al. (2017) have studied various combinations of renewable energy-based hybrid solutions for powering telecom towers in various locations in the state of Punjab in India. With the help of HOMER, they analysed possible hybrid system configurations. HOMER results have shown that, for a BTS load of 1.3 kW peak, PV-wind-diesel-battery based

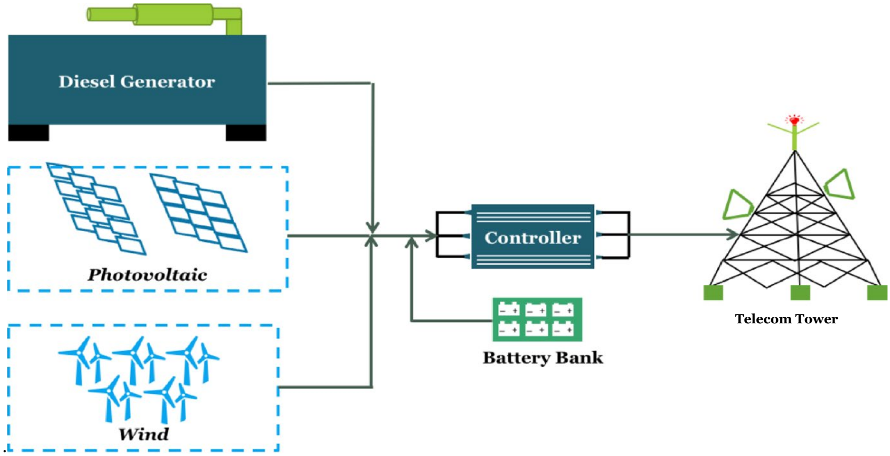

Fig. 18 A schematic of a power supply configuration based on DG, wind, PV and battery storage systems

hybrid system has lowest cost of electricity at 0.162 $/kWh, 0.210 $/kWh, 0.198$/kWh, 0.199 $/kWh for Amritsar, Ludhiana, Patiala, and Chandigarh cities, respectively. Amutha and Rajini (Amutha & Rajini, 2015; Amutha et al., 2013) have conducted a study to analyse techno-economic feasibility of different hybrid options using HOMER. They have suggested that solar PV and wind-based hybrid systems are found to be technically feasible with lower emissions and cost effective. Mathur et al. have also proposed a grid-connected hybrid energy system for powering telecom towers in Thar desert in India (Mathur et al., 2019). Dahono et al. (2009) proposed a hybrid system comprises of 4.8kWp solar PV and 2.5 kW wind turbine along with 750 AH battery and a DG set to power telecom tower with an average load of 36 kWh per day. They have suggested that system performed stable and more economical over conventional options.

6.5 Wind-, DG-, and battery-based system

Some studies on hybrid systems based on wind and DG are also available in the literature. However, the feasibility of these systems is restricted to specific niche locations with abundant availability of wind resource throughout the year (e.g. coastal regions). Figure 19 shows a schematic of a hybrid wind-diesel-battery system for electricity supply to telecom towers.

Wind- and DG-based hybrid power system with storage mainly consists of 4 parts. (i) Wind power generation system, (ii) DG power generation, (iii) single-phase power supply inverter, and (iv) battery storage and battery management system.

6.6 PV, Fuel Cell and battery-based system

A hybrid system consists of fuel cell and a photovoltaic array can be operated in a sustainable manner by producing hydrogen by electrolysis of water using electricity generated by PV array (Reddy & Csio, 2015; Shiroudi et al., 2013). Such a hybrid system is expected to be more suitable for remote off-grid telecom towers (Pachauri, 2014). The advantages

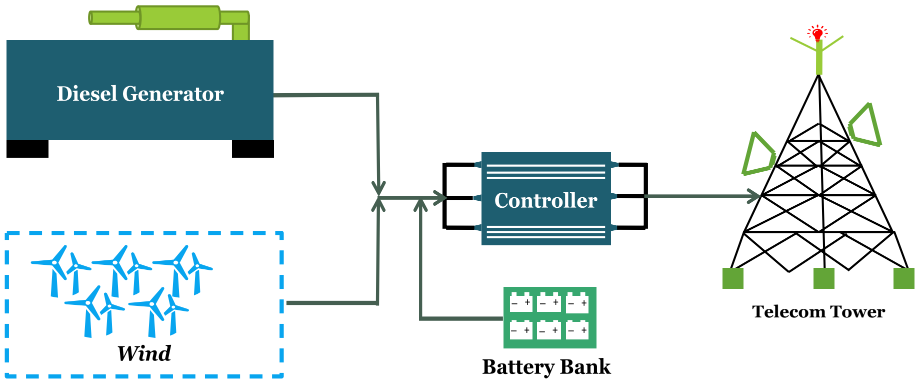

Fig. 19 A schematic of a power supply configuration based on Wind, DG and battery storage systems

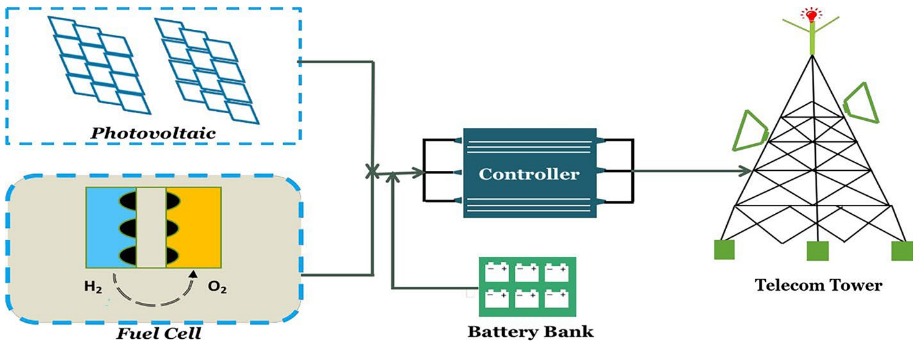

Fig. 20 A schematic of a power supply configuration based on PV array, fuel cell and batter storage systems

of such hybrid system include modularity, fuel (hydrogen, ethanol, methanol) flexibility and high efficiency of both the PV and fuel cell (Balshe, 2015; Cordiner et al., 2017; Dalton et al., 2009; Nelson et al., 2006; Scamman et al., 2015b; Yilanci et al., 2009). Fuel cell-based renewable energy hybrid systems helps to improve the resilience of the cellular network during natural/climate disasters (Niknejad et al., 2021). Figure 20 presents a schematic of a PV–fuel cell-based hybrid system for electricity supply to telecom towers.

PV- and fuel cell-based hybrid power system including battery storage mainly consists of 3 parts. (i) PV power generation system, (ii) Fuel cell power generation system, and (iii) single-phase power supply inverter.

Due to quick start-up and low operating temperature, PEM fuel cell is a preferred choice for powering telecom towers. PEM fuel cell responds very quickly for load variations and supplies smoother power output (Ballard, 2016; Kurtz et al., 2015; USDOE, 2014, 2016).

To power remote telecom towers continuously, Scamman et al. (2015b) have proposed an off-grid hybrid system with a combination of solar photovoltaic array, wind turbine, electrochemical storage and a fuel cell. It was reported that a, 1.6 kW electrolyzer and 1 kW fuel cell is enough to power 1 kW BTS load continuously.

Bain et al. (2013) proposed an electrolyser, PEM hydrogen cell powered with solar panel and wind turbine. This configuration helps to avoid legacy lead acid batteries and able to power the off-grid telecom tower with zero emissions. Odoiyorke and Woenagnon

(2021) studied the possibility of deploying a solar PV–fuel cell hybrid system to power a remote telecom base station in Ghana. The HOMER analysis results show that PV/fuel cell hybrid system is about 0.222 US$/kWh. This LCOE outshines the current average grid tariff (0.25 US$/kWh) paid by grid-connected telecom base stations. Moreover, the LCOE is 67% cheaper than the diesel power system at the same site for a DC peak load of 8.20 kW and AC peal load of 2.5 kW.

Martinho et al. (2022) have proposed a methanol based fuel cell and battery based hybrid system for powering telecom tower along with solar PV system. They have considered a 5 kW reformed methanol fuel cell stack and a 6.5kWh Li-ion battery for powering a telecom tower load varies from 7 kW to 4.5 kW at different degree of grid power outages in the analysis. Authors are of the opinion that for the long power outages scenario, it was found that the hybrid system responded better to longer power outages with lower load demands compared to shorter outages with higher load demands. Therefore, both the load profile and the duration of the power outage are critical parameters for the stability of hybrid backup systems and should be considered early on in the system design process.

Ma et al. (2019) have studied the feasibility and economics of using fuel cell backup power systems in telecommunication cell towers to provide grid services (e.g. ancillary services, demand response (DR)) as well as power for cell towers during emergency conditions. It was inferred from the literature that providing grid services can bring additional benefit to installations of fuel cell systems for cell towers. Few field implementations are summarized in Table 8.

7 Policy aspects

The telecommunication technology is rapidly evolving with consequent changes in the energy requirement for its operation (de Bijl & Peitz, 2004). As a consequence, the power requirement and modalities of supplying power to telecom towers would also change with corresponding implications for greenhouse gas emissions from telecom sector (Mathieu, 2020). Thus, it is critically important to holistically assess and evaluate the regulations and policies, at regular periodic intervals pertaining to various aspects of telecom sector including that for meeting energy requirement of telecom towers. The governments at central (federal), state and local level have, thus, a key role in promoting appropriate low-carbon options for meeting the energy requirement of telecom sector (Raj, 2015).

In order to decarbonize the operation of telecom tower, it may be necessary to design and execute policy interventions that promote harnessing of renewable sources of energy for the purpose (Qadir et al., 2021). For example, appropriate incentivization measures (such as viability gap funding, interest subsidy, accelerated depreciation, and other tax benefits) can be offered to adopt renewable energy-based electricity generation options for powering telecom towers (Tryndina et al., 2022). Similarly, modalities of optimally using hybrid systems for powering telecom towers should also be identified.

8 Conclusions

Since the past two decades, conventional power supply options including the grid, batteries, and diesel generators have dominated the telecom towers' electricity supply. Telecom towers have also been powered by alternative electricity supply options such as photovoltaic panels, wind turbines, and fuel cells. However, in order to increase the reliability of power supply to telecom towers, hybridization of conventional and renewable energy systems have also been considered. Hence, the present study aims to presents a review on the adoption of renewable energy-based hybrid systems to power telecom towers. Different aspects of telecom systems, future growth, major energy consuming areas, different types of telecom towers, electricity load requirements, conventional power supply options and their demerits, renewable energy options, hybrid system combinations have been reviewed. Moreover, information on the adoption of renewable energy-based hybrid systems to fulfil demand telecom tower by major telecom operators across the globe is also compiled and presented. The following conclusions can be drawn from the study.

- Telecom services (communication and data) are growing rapidly in rural and urban areas of most countries. These services are expanding to remote areas and adding millions of users each year. Mobile phones, digital services, and apps are affordable and feature rich. Digitization, Internet of Things, and industry 4.0 will likely increase the need for mobile telecom towers as more businesses move online.
- Demand for telecom services may increase the environmental impact. 4G and 5G technologies also increase energy demand in this sector. Telecom operators could indeed focus on reducing electricity demand, operating cost, and carbon emissions.
- Currently, grid electricity, and electricity from DG sets are the most common forms of conventional power supply for telecom towers. Due to poor or non-existent grid infrastructure, DG sets in remote areas tend to operate for longer hours than in more populated areas. Efforts to reduce diesel use included optimizing the loading of DG sets, installing larger batteries for storage, regulating speeds, and producing power in direct current. Still, getting away from a DG set is not an option.
- Among various renewable energy technologies, solar PV array-based systems have greater potential. However, because renewable energy sources are intermittent, complete reliance on these technologies to provide reliable power to telecom towers may not be possible.
- VRLA batteries have primarily been used for energy storage in telecom towers. However, as technology advances and battery prices fall, LFP batteries are being used to achieve higher efficiency, longer life, and lower operating costs.
- A variety of hybrid power supply systems installed by various telecom operators are examined. Solar PV alone, solar PV and wind, wind alone, and fuel cell-based systems are popular among the various combinations studied. All of these hybrid systems are typically powered by battery storage. Based on availability, these systems are also linked to the grid. In most cases, hybrid systems are used to eliminate or reduce the use of DG sets for powering telecom towers.
- Policy recommendations, such as government support through incentives, subsidies, tax credits, programmes for access to finance from the private sector, and establishing the proper regulatory framework, can be explored in order to expedite the adoption of hybrid systems powered by renewable energy for telecom towers. Future research could also investigate the impact of the aforementioned policy instruments on the adoption of renewable energy-based systems to power telecom towers.

Many telecom service providers adopted these renewable energy-based hybrid systems as a pilot or for a small number of towers. These installations proven that hybrid systems are technically feasible, economically viable, and also helps to reduce the operating cost. More importantly, hybrid systems eliminate/minimize the diesel usage and thus reduce carbon emissions. Finally, the large-scale adoption of these hybrid systems for all the telecom towers across service providers helps to reduce the carbon intensity of the telecom sector.

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