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Is decentralized hybrid system a suitable option for inclusive energy transition of India?

Rapid population growth coupled with urbanization and industrialization are some of the critical challenges of Indian energy sector. Simultaneously India's fossil fuel dominated power sector is a big source of carbon emission. Increasing renewable power is a mission of India. Government has also a mission for maximum rural electrification. India has widely varying geographical topography including high mountains and a long coastal line etc. Extending the Indian national grid to remote poor villages may not be techno-economically feasible. Instead introducing decentralized hybrid renewable power to remote poor villages of India may help inclusive growth. This study explores the feasibility of such options with a few case studies. Including some other energy utilities in addition to power may be an even better support to poor villagers. A few case studies on such efficient polygeneration are also included.

Keywords : Energy crisis, decentralized renewable energy system, hybridization, polygeneration, inclusive growth.

Abbreviations

AT&C losses aggregated technical and commercial losses

CC	Cycle charging
CS	Capacity shortage
CO_2	Carbon di-oxide
COE	Cost of energy (all costs are in $/kWh)
DC	Direct current (amp)
DDUGJY	Deen Dayal Upadhyaya Gram Jyoti Yojana
DG	Diesel generator
GHG	Greenhouse gas
GOI	Government of India
HOMER	Hybrid optimization of multiple electric renewable
IPCC	Intergovernmental panel on climate change
IPDS	Integrated power development scheme
LF	Load following
LA	Lead acid battery
Li-ion	Lithium-ion battery
MOP	Ministry of Power
NPC	Net present cost (all costs are in $)
O & M.	Operational and maintenance cost (all costs are in $/year)
PV	Photovoltaic
PHES	Pumped hydro energy storage
RGGVY	Rajiv Gandhi Grameen Vidyutikaran Yojayan
RVE	Remote Village Electrification
TOPSIS	Technique for order of preference by similarity to ideal solution
T&D	Transmission and distribution
UL	Unmet load
VR	Vanadium redox battery
ZB	Zinc bromide battery

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1.0 Introduction

Since the last few decades global energy demand is exponentially increasing due to high population growth, improved lifestyle and rapid industrialization. Maximum amount of electricity is supplied by fossil fuel based centralized grid systems though it has several limitations [1]. Still globally over 700 million people are suffering from least access to electricity [2]. The availability of fossil fuel is limited and also these plants emit greenhouse gases causing climate change.

According to the Indian census report, in 2011, approximately 400 million people in India had no electric supply [3,4]. In April 2018 the government had a mission of 100% village electrification of the country [5]. However, many recent studies indicate that overall electricity access rate in India is much lower [6]. The poor inhabitants in remote villages are still unable to access a continuous power supply.

Kumar G. [7] reviewed the recent Indian energy sector. He studied different energy policies developed by the ministry. Anandan et al.[2] studied the factors that affect Indian energy sectors. According to the study, the Indian energy market was influenced by energy pricing, demand and supply gap and on several other factors. The Indian government designed the strategies and policies to reduce the energy crisis. Franco et al.[8] studied the increase in energy demand vis-a-vis high carbon emission from Indian power sector.

All these previous studies showed the poor energy scenario of the rural and remote areas of the country. According to these studies it is clear that rural and remote households of India are suffering from limited access to reliable power. In this paper a few case studies on possible sustainable solution of remote Indian villages without grid power have been discussed. Local renewable resources are optimally integrated in decentralized hybrid systems for minimum cost and carbon emission with assured uninterrupted supply of power and other energy utilities.

2.0 Indian power scenario

India is one of the global fastest growing economies. Since the last few decades, the population of India is also increasing rapidly. Figure 1 shows the population growth of the country [9]. The data showed that the population growth in India increased from 450.55 million to 1.38 billion during 1960 to 2020. The approximate growth rate is 206.3% in 60 years. The highest population growth is observed in the year 1974 (approximately 2.36%) and in 2020 the growth rate is minimum (0.99% approx.) [10].

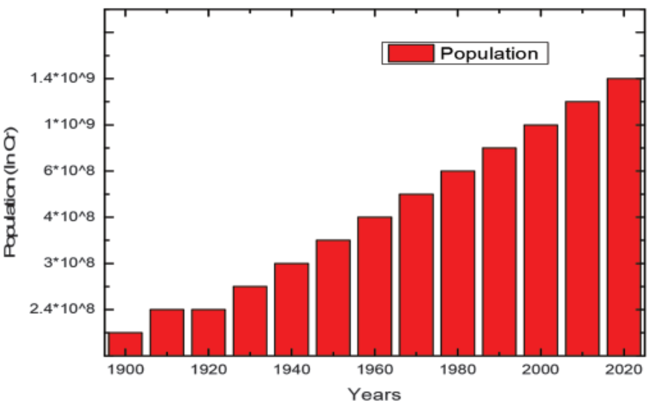


Fig.1: India's population growth (9, 10)

However, urbanization, industrialization and gross domestic product (GDP) are also increasing. As a result, the energy demand is also rapidly increasing in India. The study made by IEA showed that the demand of energy in India increased from 76% in 2010 to 98% in 2019 [3,11]. The energy consumption trend in India over the years is shown in Fig.2. According to this report the per year energy consumption is approximately 1137.00 billion kWh in India in the year 2020 [10]. In 2020, the per capita energy consumption remains approximately 0.6 to which is half of the Asian average. Also, the per capita electricity consumption reached 940 kWh in 2020. In this year, India ranked third among the Asian countries in electricity consumption. After rapid increase in energy consumption from 2010 to 2019 (approximately 4% per year) the energy consumption decreased by 5.6% in 2020 to 885 Mtoe due to Covid-19 crisis [12].

To meet India's energy demand, the Ministry of Power has increased generation capacity over the years. Fig.3 shows the energy generation scenario of India from different fuels. According to the report, coal is the most significant fuel contributing to about 74% of India's electricity in 2018. During Covid-19 crisis the energy generation was reduced. Figure 4 shows the total energy generation during 2000 to 2021. The figure shows that in 2021 total produced energy is 138.1 TWh. The energy generation growth of the country is shown in Fig. 5 [11-13]. Fig.5 shows that the energy generation was significant up to the year 2018. Then due to the downfall in industry and at the time of Covid-19 situation the energy generation growth decreased. During 2019-2020 and 2020-2021 the energy generation growth were approximately 0.95% and -0.52% respectively [13]. The data implies that during this period significant reduction in growth happened due to major industrial downfall.

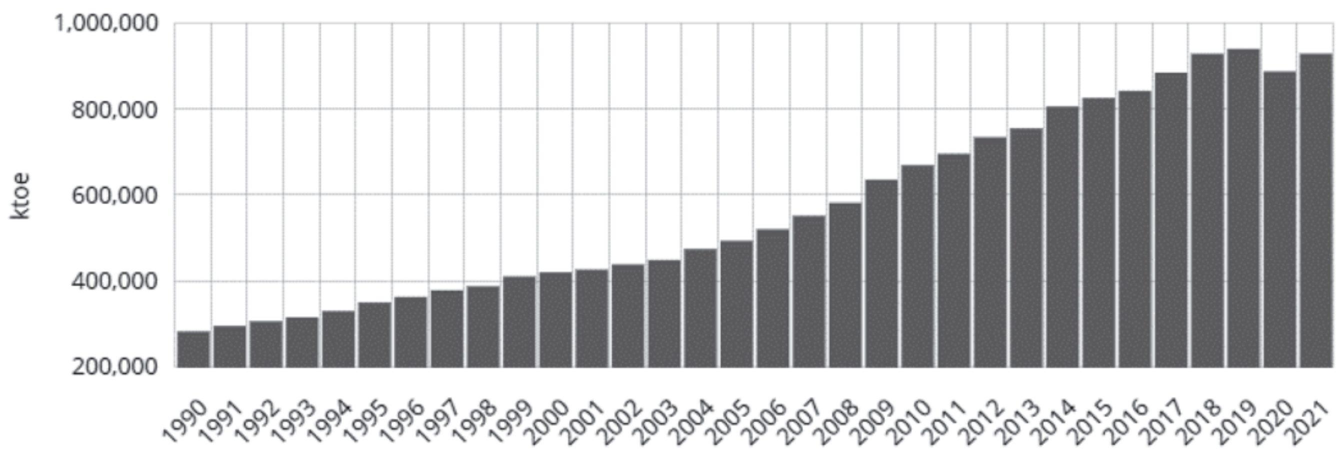


Fig.2: India's energy consumption (10) growth

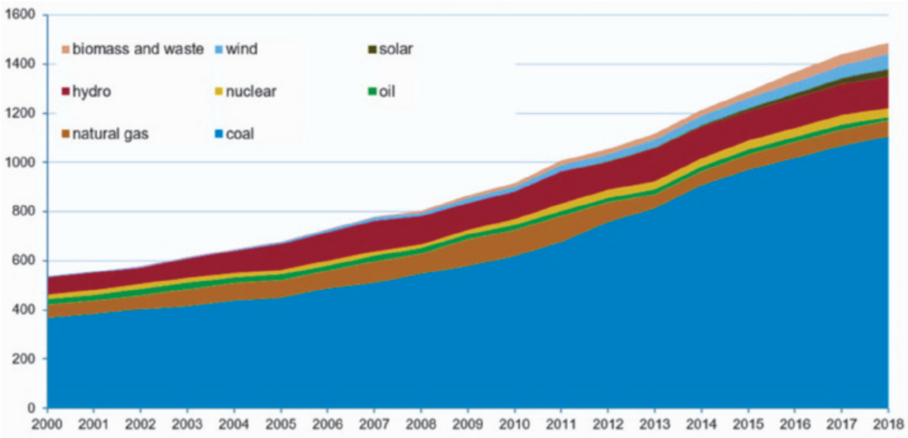


Fig.3: India's energy generation from different sources (3, 11-13)

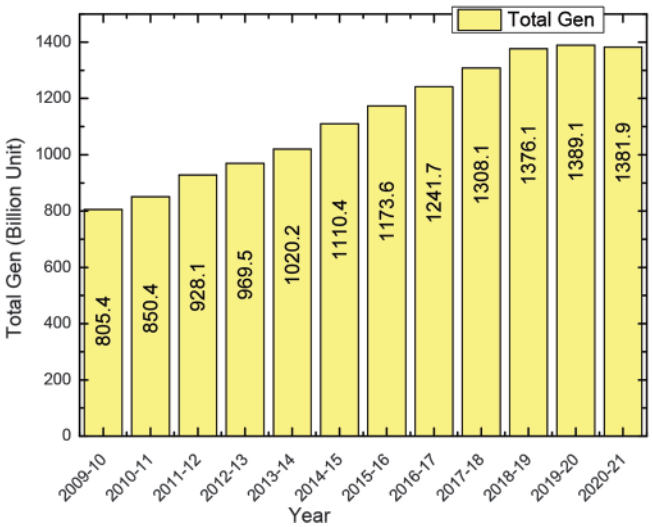


Fig.4: India's energy generation (3, 11-13)

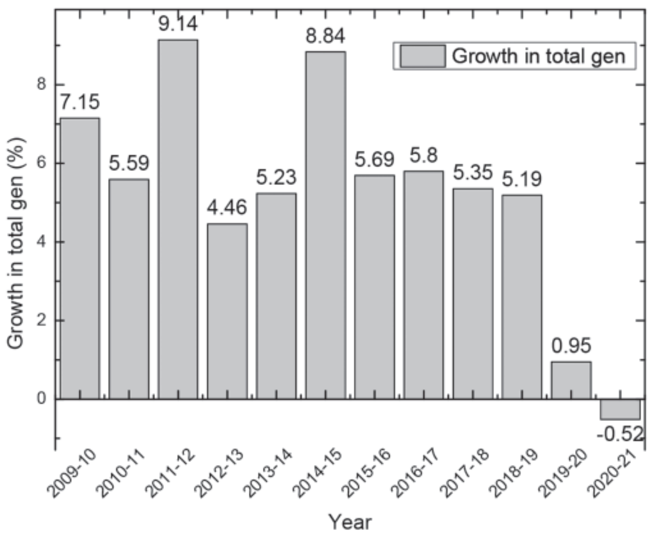


Fig.5: Energy generation growth (3, 11-13)

Fig.6 shows the amount of installed capacity from different energy resources. According to Fig.6 it is noted that 64% of the total energy is catered from the fossil-fuel resources such as coal, oil and natural gas [14]. The renewable resources like solar, wind, hydro etc. provide 36% of the total energy share. In India, there is more than 370 GW of electricity distributed through the central grid system in 2020. According to the report published by the Central Electricity Authority, the contribution of coal in the electric capacity was 55% and the share of renewable resources was 24% in 2020. The Government of India targeted to increase the share of renewable energy from 87 GW in 2020 to 175 GW in 2022 to reduce the emission, particularly from the large fossil fuel-based power plants which supply electricity mostly to the urban areas. In India, only 6.3 GW electricity was supplied from the nuclear power plants in 2020 [14].

The total electric capacity of the country is dominated by the private agencies. These agencies produce 1,95,637 MW electricity in 2022 which is 49% of the total installed capacity. The state sectors produce 1,04,855 MW of the electricity and it is 26.2% of the total installed capacity. The central share is minimum in installed electricity capacity and the share is

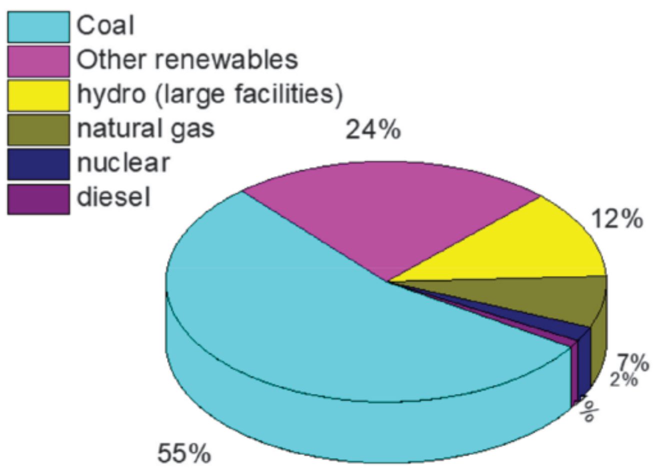


Fig.6: Energy generation amount from different fuels (14)

Table 1: Sector wise installed capacity share (%) (15)

Sector	MW	% of Total
Central Sector	99.005	24.6%
State Sector	1,04,855	26.2%
Private Sector	1,95,637	49.0%
Total	3,99,497	100,0%

approximately 24.6% [15]. The detailed installed capacity from different sectors is shown in Table 1 [15].

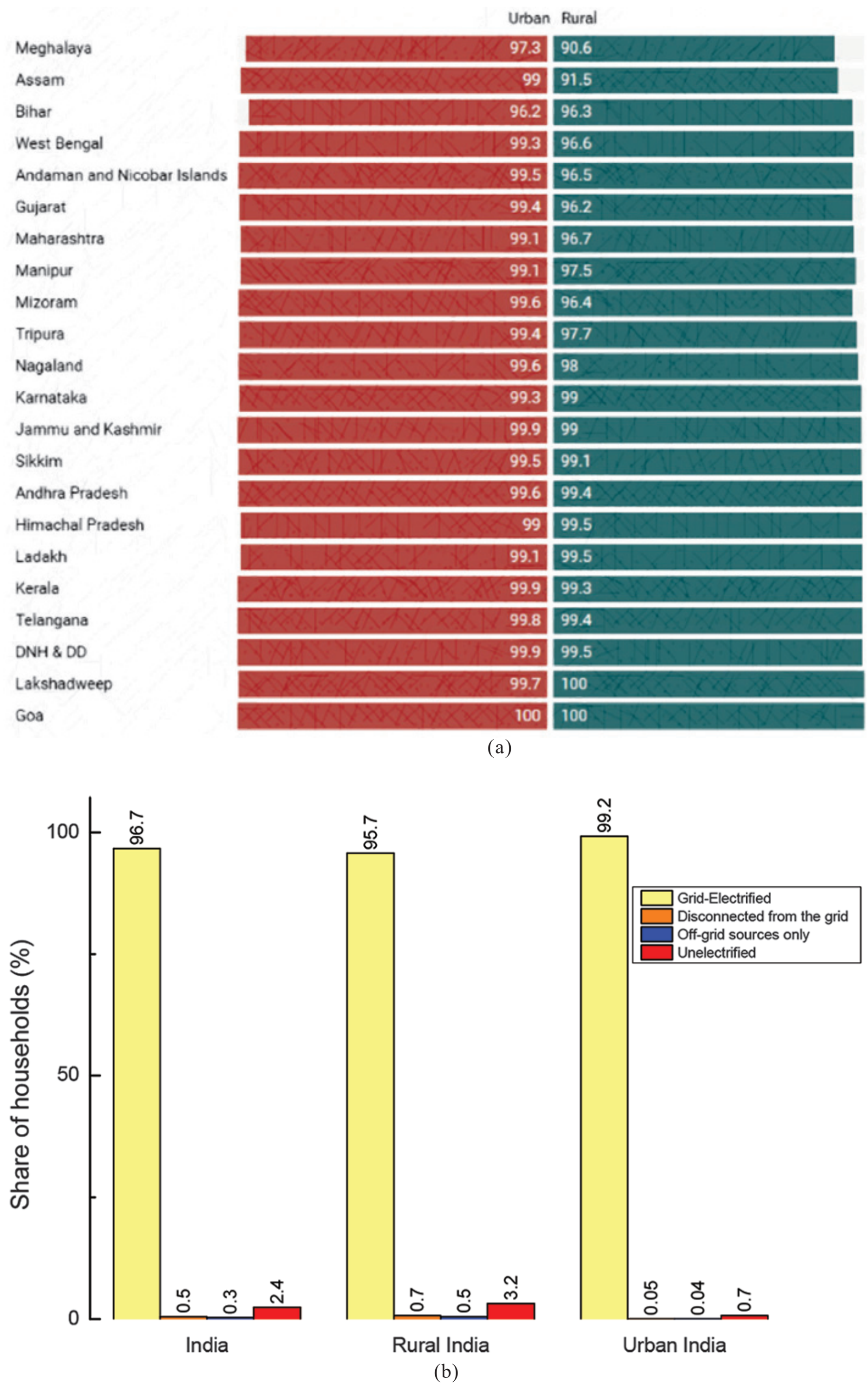
2.1. Rural and urban energy situations of India

Several studies showed the urban and rural areas' household electrification situation of India [16]. Fig.7 reported the electrification condition of the urban and rural areas of the states in India [16,17].

According to Fig.7(a) the rural areas are generally still lagging from the urban areas regarding electrification. The rural areas of the North-eastern states of the country are mostly suffering from this lack of electrification [16,17]. Fig.8 shows the electrification percentage of the Indian states. According to this figure, the regions with limited electricity are located mostly in Uttar Pradesh followed by Chhattisgarh, Rajasthan, Karnataka, Madhya Pradesh and Jharkhand [16].

Additionally, in India the major problem is to access reliable and continuous power. Figure 9 demonstrates the power supply situation of the country [16]. The figure shows that in maximum states the power supply is better for the urban areas than the rural regions. Remote villages are the worst sufferers. In these areas supplying continuous and reliable power with cost effectiveness is difficult due to difficult terrain conditions. The centralized grid systems are not extended to these locations. Hence, the households of these areas remain mostly un-electrified [16,17].

The urban areas of India use mostly fossil fuel-based electricity through the national grid. On the other hand, the rural areas of the country depend more on diesel generator sets for a limited period of the day. This also emits carbon to the atmosphere and adding to local air pollution [17].



(a)

(b)

Fig.7: (a) State wise electrification condition, (b) rural and urban area's electrification status (16, 17)

3.0 Limitations of Indian power

The fossil fuel-based centralized grid system mostly supplies the electricity in India. Among the fossil fuels coal has the major share [18]. The fossil fuel-based centralized grid systems have several limitations.

3.1 Inefficiencies of the power plants

The large coal-based power plants are currently suffering from major inefficiencies too. For the large power plants the plant load factor (PLF) is a

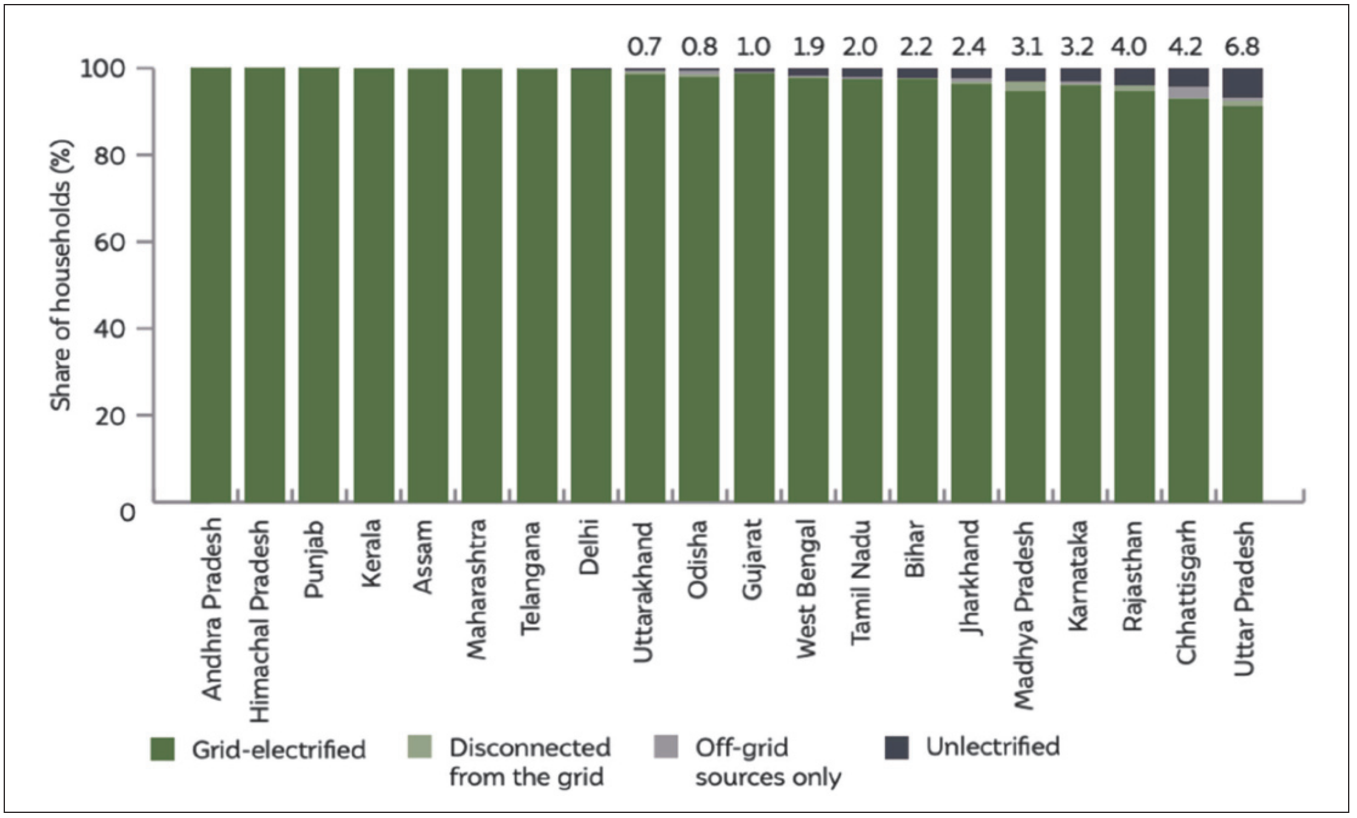


Fig.8: State wise electrified and un-electrified comparison (16)

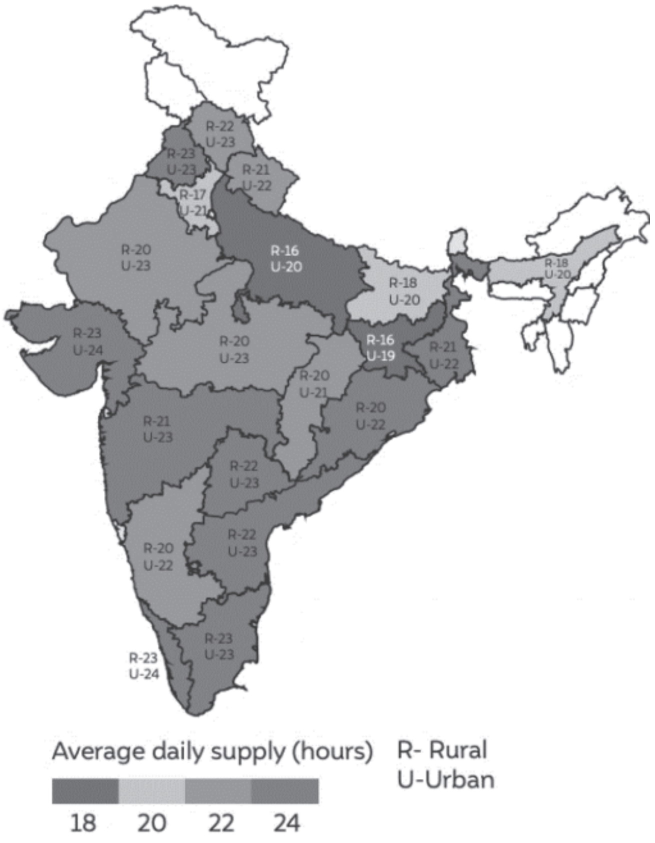


Fig.9: State wise electric supply timing (16, 17)

major concern. Equation 1 defines the plant load factor [19].

$$PLF = \frac{Used\ capacity\ of\ the\ plant}{maximum\ capacity\ of\ the\ plant} \quad ...(1)$$

Higher the PLF better is the efficiency of a coal-based power plant. However, it is not possible to achieve due to the unavailability of the large storage systems. Hence there is a mismatch in electricity generation and consumption. Large gaps between demand and supply may even lead to the failure of the grid. Fig.10 shows the PLF of Indian power plants [20]. The figure shows that the central and state operated power plants are running at lower PLF values and are unable to reach their maximum efficiency. The efficiency of the central coal-based power plants is significantly lower. Owing to this lower PLF value the efficiency and the return on investment of the central power plants are getting affected [19, 20].

3.2 Transmission and Distribution (T&D) losses and Associated Technical and Commercial (AT&C) Losses

Another major problem for extending central grid system to the remote and rural areas of the country is T&D and AT&C losses. Equations 2 and 3 define T&D and AT&C losses [19].

$$T\&D = \left\{1 - \frac{Total\ energy\ billed}{Total\ energy\ input\ to\ the\ system}\right\} \times 100 \quad ...(2)$$

AT&C = {1–(*Billing efficiency* × *Collection efficiency*)} × 100 ... (3)

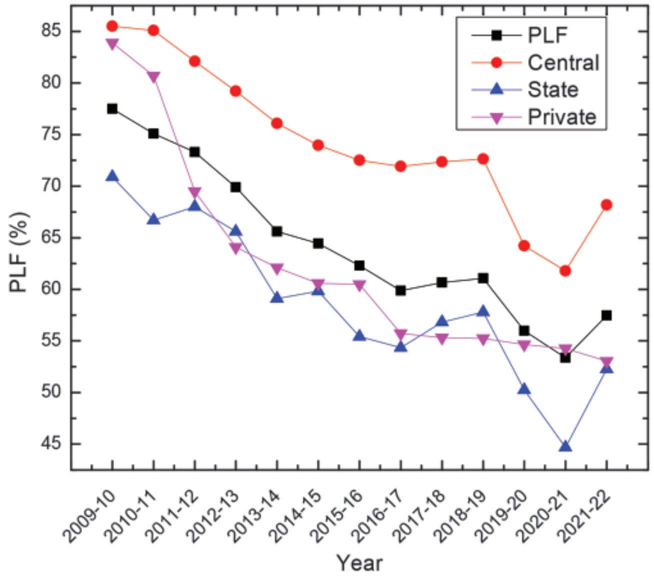


Fig.10: PLF of the plant (19, 20)

Where

$$Billing\ efficieny = \frac{Total\ unit\ billed}{Total\ unit\ inputs} \quad ...(4)$$

$$Collection\ efficieny = \frac{Revenue\ collected}{Amount\ billed} \quad ...(5)$$

Fig.11 shows the losses related to T&D and AT&C of central grid systems of India. It is observed that these losses are significantly reducing in recent times. However, the T&D loss in India is still much higher than global average, i.e., 8% [20]. These problems increase the techno-economic difficulties to supply power to the remote villages of the country.

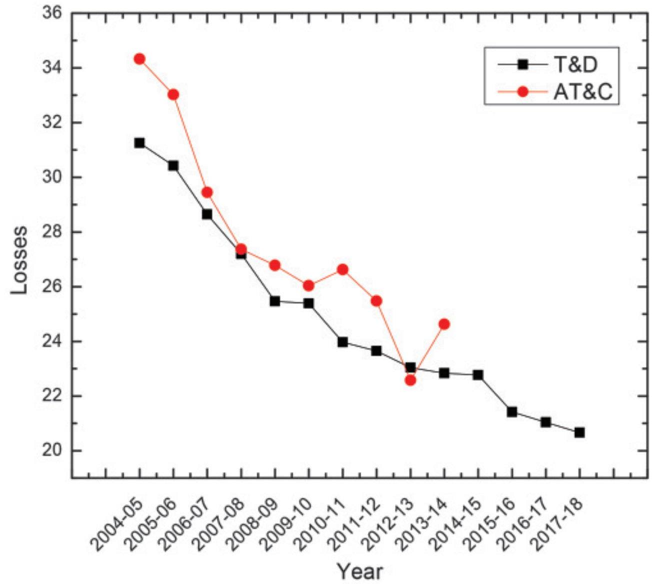


Fig.11: Losses of the plant (20)

3.3 Costing for Coal transportation

Another major problem of coal-based central grid systems is the cost for transportation of coal from mines to the plants. The major coalfields in India are located in the eastern, central, and southern states. However, the large central coal-based power plants are located in the northern and western states of the country. Hence, the transportation of the coal accounts for about 45% of the overall freight movement [21,22]. There are several modes of coal transport. Rail is the major transport mode (approximately 50%) [20–23]. The transportation of coal itself consumes energy and adds to the cost of electricity.

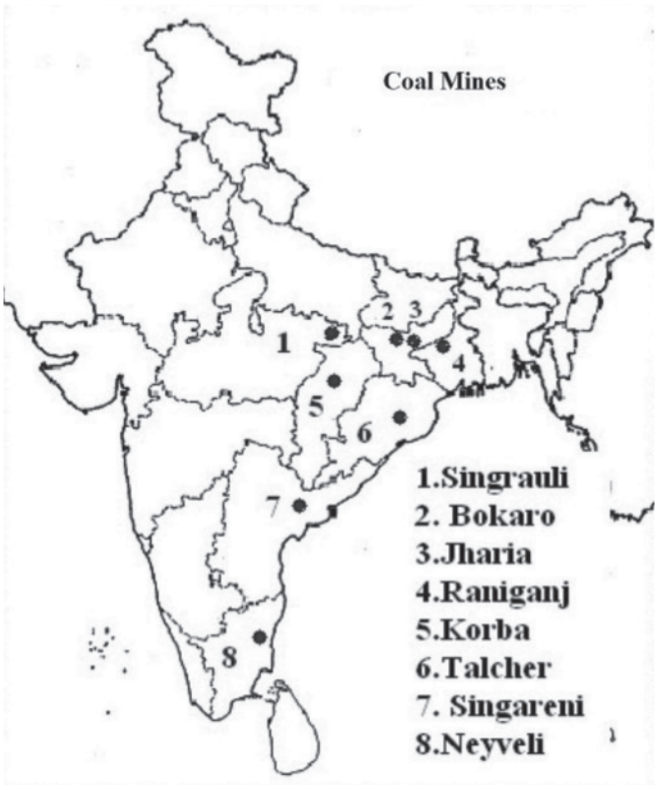


Fig.12: Location of the coal-fields in India (20-23)

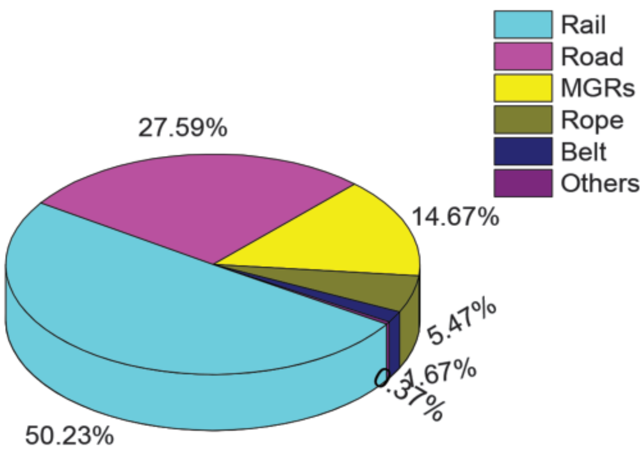


Fig.13: Coal transportation (20-23)

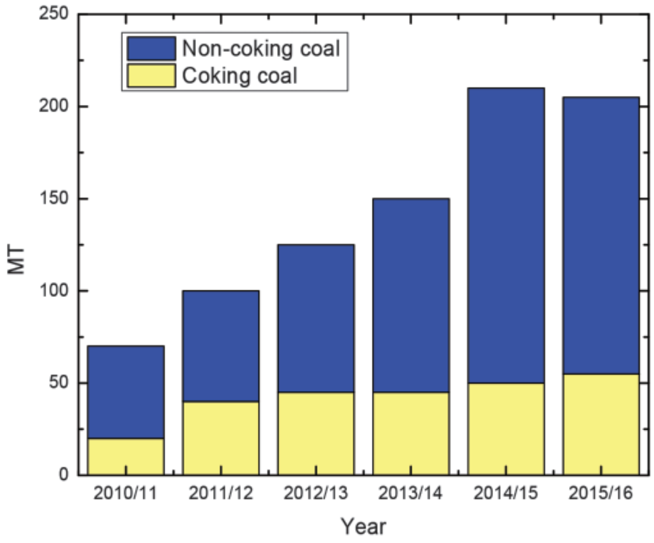


Fig.14: Imported coal (19, 20)

3.4 Demand and supply of coal

Previously, India used to build large coal-based power plants depending on the coal available in India. Afterwards, it was found that the quality of the coal is poor with respect to high ash content. Hence, the private and the central sectors started to import better quality coal from other countries to improve efficiency. Fig.14 shows the yearly percentage of importing coal. Imported coal also adds to carbon emission from the country [19, 20].

3.5. Carbon Di-oxide (CO_2) emission and climate change problem

Fig.15(a) shows the CO_2 emission from India. It is increasing. In year 2021 the emission is approximately 650Mt. Fig.15(b) shows the emission from different fuels [3,12].

4.0 International initiatives and India's commitments for clean energy

To address the climate change several global initiatives have been adopted by the international community. Kyoto protocol (1997), Bali Road map (2007), Cancun agreements (2010), UN climate change conference (2011), Doha Climate gateway (2012), Warsaw outcomes (2013), Paris Agreement (2016), Climate action summit (2019), COP 25 Madrid (2019), COP 26 Glasgow (2021) are a few such international initiatives till date [8, 24–27]. India is also committed to these agreements. Increasing renewable share and shifting from the existing fossil fuel-based systems is a long-term goal of India. However, immediate gross replacement of large infrastructure in coal-based power is also almost impossible for India. So renewable installations, specifically with smaller capacity may be a good option for new additions of power and other energy utilities.

Several Indian policies such as Electricity Act, 2003, rural electrification policy, 2006 are announced to increase the rural electrification. Electricity Act, 2003 included many new features like introduction of renewable energy, rural electrification etc. According to Rural Electrification Policy, 2006, the target was set to supply electricity to all households of the country by 2009 [15]. Additionally, Rajiv Gandhi Grameen Vidyutikaran Yojana (RGGVY) was announced to provide electricity to below poverty line (BPL) families free of cost. The scheme was focused on developing

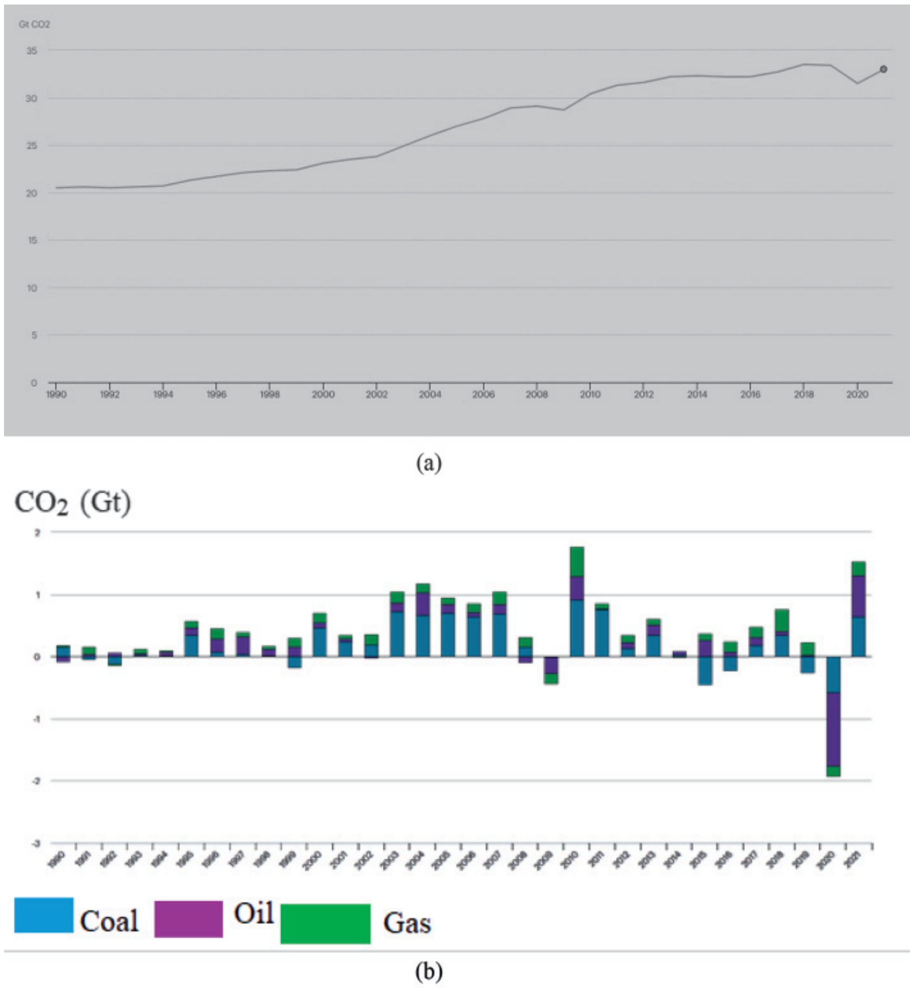


Fig.15(a) CO_2 emission status (b) Emission from different fossil fuels (3, 12)

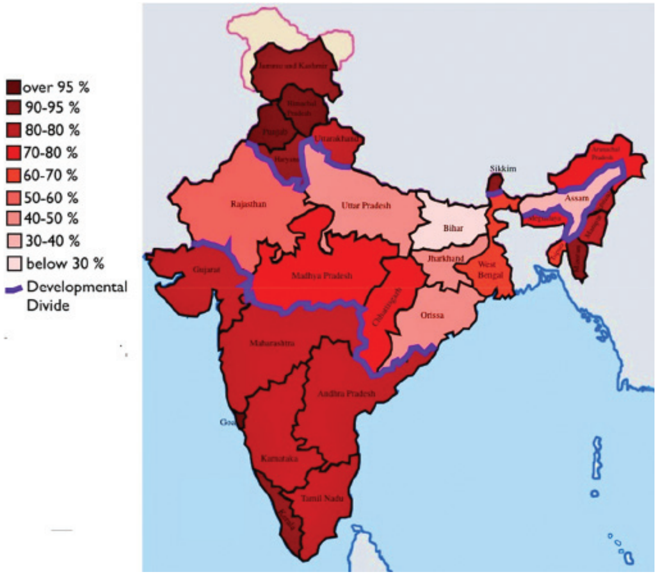


Fig.16: % of household electricity in India (30)

decentralized energy systems based on conventional and non-conventional energy sources [1]. India started Remote Village Electrification (RVE) Program to provide electricity to remote poor villages by developing decentralized off-grid energy technologies where grid power is not available through RGGVY Scheme. The government announced Integrated Power Development Scheme (IPDS) in 2014 [28, 29]. The main objective of this scheme is to strengthen sub-transmission and distribution networks for the urban areas. Also, this scheme is focused on improving the metering of distribution transformers, feeders and consumers in urban locations. The scheme also provides security to reduce the distribution losses. The Ministry of Power (MOP) announced Deendayal Upadhyaya Gram Jyoti Yojana (DDUGJY) scheme in 2014 to strengthen electrification in rural areas by improving the sub-transmission and distribution network [15]. This scheme also focused on improving the electrification for agricultural sectors. Through all these schemes the Indian Government is now trying to provide reliable and continuous electricity to rural areas. Fig.16 shows the recent electrification status of the states of India [30].

According to this figure, there exists several states with limited access to electricity with a distinct developmental divide. Even in states with reasonable power supply remote and rural areas are badly affected due to non-access of national grid. Considering these researchers are focused on finding appropriate solutions. The researchers have proposed decentralized energy systems based on local renewable resources as a possible option to overcome the energy crisis in remote areas of India.

5.0 A few reported case studies on sustainable energy solutions for remote Indian villages

In their earlier studies, researchers considered mostly a single renewable resource for developing the decentralized renewable energy systems. Studies reported by Gonzalez et al.[31], Leary et al. [32], and Njoh et al., [33] showed that single renewable energy resources such as solar or wind is able to meet the required energy demand of the study areas. However, it is evident though these resources somehow meet the demand but it is not reliable for uninterrupted supply. These renewable resources are intermittent, dilute and hence both the capacity and reliability of power supply is limited.

To overcome this issue integrating multiple renewable energy resources with storage was recommended later. This process of integration of multiple renewable resources is known as "hybridization" [1]. The storage module is used to supply the electricity at the time of peak load. The diesel generator (DG) may also integrate with this hybrid renewable system, if required to increase the reliability of power supply at a lower cost. If renewable energy generators and storage modules fail to meet the energy demand then only DG is used. Though DG sets emit carbon and other pollutants to the atmosphere, restricted usage may reduce the emission.

Das et al. [1] explored an optimum solution with locally available renewable resources for a reliable power supply at a minimum cost and carbon emission for a small remote village of Arunachal Pradesh. In this study, local energy resources such as PV, wind, mini hydro are considered along with the storage and DG set to develop the hybrid combination. Then different combinations were analysed based on their techno-economic performance factors like cost of energy (COE), net present cost (NPC), operation and maintenance cost (O&M), unmet load (UL). The optimization was done in Hybrid Optimization of Multiple Electric Renewable (HOMER) and according to this optimization four different combinations were found to meet the local energy demand. Table 2 shows the combinations along with values of their techno-economic

TABLE 2: HYBRID MODELS ANALYSIS DATA

Combinations	COE in $/kWh	NPC in$	O&M in $/year	RF in %	Emission in Kg/year
Wind-PV- Battery-Gen	0.872	27456.21	1091.25	51.22	1056
Hydro-Wind-Battery- Gen	0.630	23808	806.31	88.1	481
Hydro-PV-Battery- Gen	0.712	25698.01	948.32	74.14	625
PV- Hydro-Wind-Battery- Gen	0.682	24158.56	831.24	89.51	318

Table 3: Optimum solution

Scenario	Distance from positive and negative ideal solution		Relative distance		Rank
	S+	S-	S (+) +S (-)	P(i)	
Wind-PV- Battery-Gen	0.085	0	0.085	0	4
Hydro-Wind-Battery- Gen	0.002	0.084	0.086	0.973	1
Hydro-PV-Battery- Gen	0.035	0.05	0.086	0.588	3
PV- Hydro-Wind-Battery- Gen	0.009	0.079	0.089	0.895	2

Table 4: Optimum analysis result

Combinations	Individual capacity(kW) of the components					
	PV in kW	Wind in kW	Hydro in kW	Gen in kW	Battery	Converter in kW
Wind-PV- Battery-Gen	0.00108	2	-	10	12	1.84
Hydro-Wind-Battery- Gen	-	1	12.30	10	7	1.96
Hydro-PV-Battery- Gen	0.774	-	12.30	10	4	2.56
PV- Hydro-Wind-Battery- Gen	0.011	1	12.30	10	6	2.01

performance factors. Then in this study, to obtain the techno-economically and environmentally optimal solution, a multi-criteria decision making (MCDM) approach was used. Among several MCDM techniques, Technique for Order of Preference by Similarity to the Ideal Solution' (TOPSIS) algorithm was used. The result of this MCDM is shown in Table 3.

According to Table 3, wind-hydro-generator-battery system was found to be the final optimum solution for the study area to meet the required load demand at a minimum cost (COE- \$0.63/kWh, NPC- \$23808) and corresponding minimum CO_2 emission (481 kg/year). The optimum technical details of the combinations considered in this study is shown in Table 4.

Das et al. [18] also analysed the different energy combinations under different dispatch strategies along with five different storage modules. The study found a techno-economically feasible combination with appropriate storage modules and dispatch strategy. To increase the technical efficiency by simultaneously minimizing the COE of the distributed energy combination this analysis compared different available storage modules such as lead-acid (LA), lithium-ion (Li-ion), vanadium redox (VR), zinc bromide (ZB) and pumped hydro energy storage (PHES) and dispatch strategies like cycle charging (CC) and load following (LF). The schematic diagram of the energy combination is shown in Fig.17.

The optimization is performed in HOMER simulation based on different input parameters. Primarily, the feasible energy combination was selected based on techno-economic performance analysis. Then the optimum combination was separately determined under the dispatch strategies to find the techno-economically feasible dispatch strategy. Finally, different storage modules are compared. According to that study, PV-hydro-DG-ZB system is found to be the optimal solution under load following dispatch strategy. The analysis result shows that the selected combination meets the load demand of the study at a minimum cost and carbon emission (COE- \$0.197/kWh, NPC- \$362384, CO_2 emission – 8854 kg/year).

These studies showed that the distributed hybrid renewable energy systems are possible solutions to supply reliable and continuous electricity at remote poor villages by simultaneously minimizing the energy cost and emissions. However, few other studies showed that integrating more energy utilities than only power increases the overall performance of the integrated energy systems. Efficient system integration based on local demand and resources is the key for success of such polygeneration energy systems.

The analysis performed by Das et al. [5], Ray et al. [34], Ray et al., [35], Jana et al. [29], Jana et al. [36] significantly justified the importance of polygeneration systems in terms of economy and efficiency. The case studies performed by Jana et al. [36, 37] also significantly showed that the environmental impact of the renewable-based decentralized off-grid energy system is significantly lower as compared to the DG based energy system or coal-based centralized grid system. The study performed the LCA analysis and justified the environmental sustainability of a polygeneration system too.

Therefore, all the analyses validate that the decentralized hybrid renewable power and polygeneration systems are techno-economically and environmentally feasible solutions to reduce the energy crisis of the remote poor villages of India where grid power is not available.

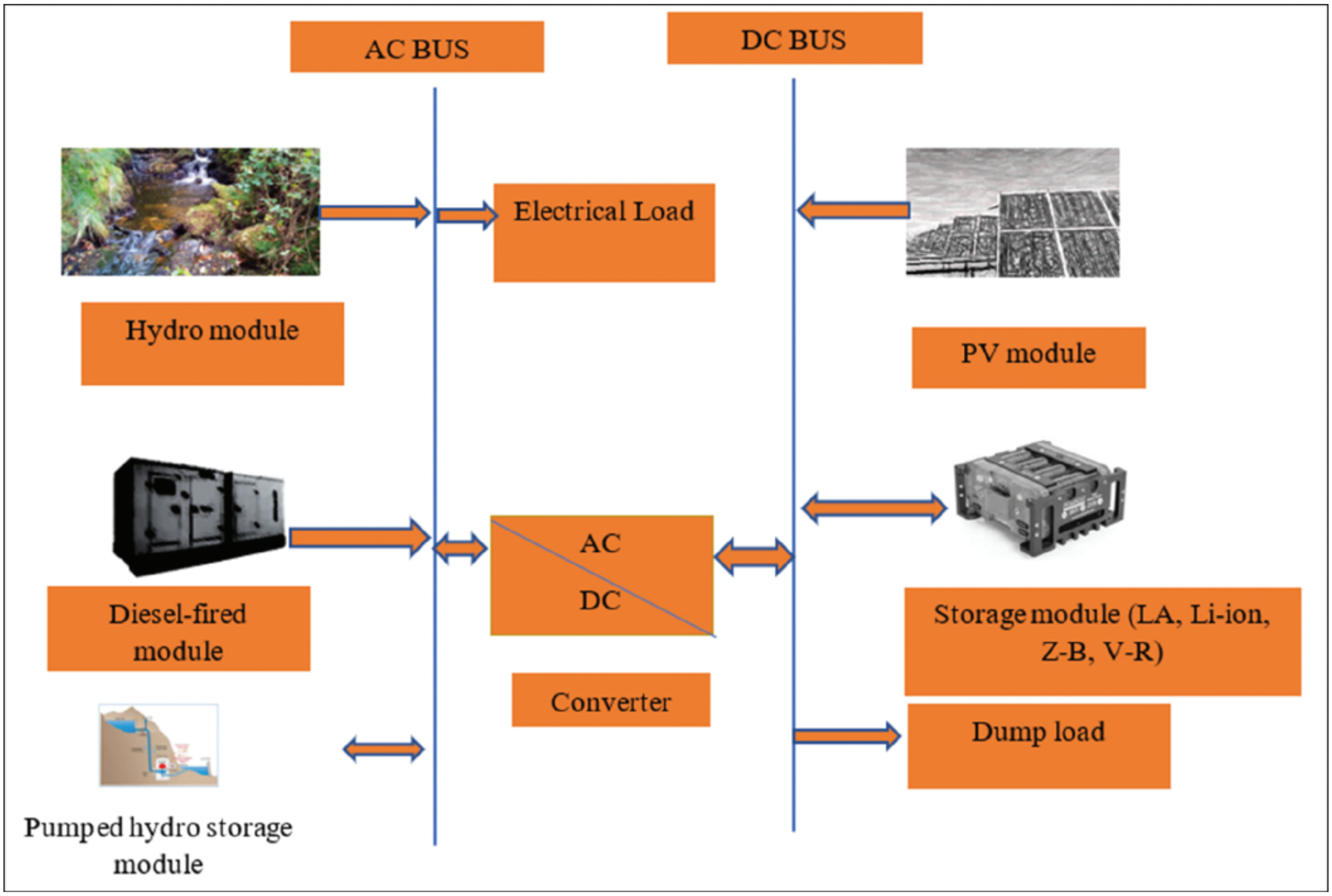


Fig.17: Proposed scheme

6.0 Conclusions

The need and possible sustainable solution for remote and poor Indian villages are explored. Optimum hybrid renewable power and polygeneration systems have been identified through several case studies on remote Indian villages as possible future potential sustainable solutions. Optimized solutions are determined through techno-economic and environmental optimization. However, these options are feasible for remote areas where there is no grid power and the load demand is also low or moderate. For large scale electric supply, the country still depends on central grid systems. This may be a suitable option for poor remote villages of India for an inclusive growth of the country along with large scale main stream power still from coal.

Acknowledgements

Mr. Sayan Das gratefully acknowledges Jadavpur University, Kolkata, India for giving the West Bengal State Government SRF fellowship for this research work.

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