Technical feasibility study and optimisation analysis on solar biomass-based pumped storage hydropower plant

Somudeep Bhattacharjee and Champa Nandi*

Department of Electrical Engineering,
Tripura University,
Agartala, India
Email: somudeep.ee@tripurauniv.in
Email: cnandi@tripurauniv.in
*Corresponding author

Abstract: The potential of hydroelectric plants in north-eastern region is very much promising for supplying electricity. But the reservoirs of hydroelectric plants are facing water shortage during the lean season, which results in a very low power generation. Gumti Hydroelectric Plant generates power to diminish the power crisis of Tripura but it remains inoperative during the lean season due to the shortage of water. Therefore, this study proposes an advancement to Gumti Hydroelectric Plant in Tripura by designing a hybrid energy system using renewable energy sources to supply a dependable, continuous and economical power supply. This study includes optimisation analysis by utilising real-time data of renewable energy sources, which help us to understand the extent of power generation and its cost of energy. The results of this study indicate that a hybrid system is a viable option as compared to a single hydroelectric plant in maintaining the continuity of power supply.

Keywords: climate change; solar power; hydro power; bio power; pumped storage system; hybrid energy system; optimisation.

Reference to this paper should be made as follows: Bhattacharjee, S. and Nandi, C. (2021) 'Technical feasibility study and optimisation analysis on solar biomass-based pumped storage hydropower plant', *Int. J. Environment and Sustainable Development*, Vol. 20, Nos. 3/4, pp.404–429.

Biographical notes: Somudeep Bhattacharjee received his BE degree in Electrical Engineering from Tripura Institute of Technology, Narsingarh, Tripura, India. He received his MTech degree in Electrical Engineering from Tripura University, Tripura, India. He is currently pursuing his PhD in Electrical Engineering at Tripura University, Tripura, India. His research interests include hybrid power plant, microgrid protection, climate change, chaos communication, renewable energy sources, electric vehicle, solar energy, wind energy, bio energy, hydro energy, energy management system, smart grid, cost analysis of hybrid energy system, feasibility analysis of hybrid energy system and optimisation analysis of hybrid energy system.

Champa Nandi received her BE degree in Electrical Engineering from the Tripura University, India in 2004 and MTech in Electrical Engineering from Tripura University, India in 2008. From 2008 to 2010, she served as a Lecturer at the Department of Electrical Engineering, NIT, Agartala. She received her PhD in the Dept. of Electrical Engineering from NIT Agartala in May 2016 and also from 2010 to till date she is serving Department of Electrical Engineering, Tripura University as an Assistant Professor. Her research interest includes renewable hybrid energy, micro grid protection, controller design, energy management controller and FACTS devices.

This paper is a revised and expanded version of a paper entitled 'Technical feasibility study and optimization analysis on solar-biomass based pumped storage hydropower plant' presented at 2nd International Conference on New and Renewable Energy Resources for Sustainable Future, Jaipur, India, 7–9 November 2019.

1 Introduction

The hydroelectric plant produces power from running water and any adjustment in the normal water loop brought about by the environmental change influence electrical energy production. Climate change affects the hydro energy production by influencing the waterway runoff. Variations in rainfall and temperature are mainly responsible for it (Bhattacharjee and Nayak, 2019). Also, the increment of the outrageous atmospheric occasions and broadened erosion weights the hydro energy generation (Bhattacharjee and Nayak, 2019). Rainfall fluctuates from year to year, and variations in quantity, intensity, recurrence and type influence the whole world (Bhattacharjee and Nayak, 2019). Nearby and territorial variations in the character of rainfall depend a lot on the changeability pattern of the climate movement. A portion of these variations is related to environmental change. Rainfall variations have built up a unique pattern in recent years, causing higher latitudes to become wetter and the subtropics and a major part of tropic to dry up (Bhattacharjee and Nayak, 2019; Trenberth, 2011). In tropical Asia, there are spatial changes in rainfall due to hills and mountain ranges. Roughly 70% of the absolute yearly rainfall over the Indian subcontinent is bound toward the southwest rainstorm season (June–September) (Bhattacharjee and Nayak, 2019). The western part of Himalayas receives more snowfall during winter than the eastern part of Himalayas. The eastern Himalayas and Nepal receive more precipitation during the storm season than the western Himalayas. Surely, the variation pattern in the observed rainfall is a mark of worldwide environmental change (Bhattacharjee and Nayak, 2019; Dore, 2005). Because of deforestation and numerous other natural reasons, there has been a drop in precipitation in various parts of India as well as in various parts of the world and this has resulted in a steep drop in water levels in many hydroelectric plants (Bhattacharjee and Nayak, 2019). The yearly precipitation has diminished by 0.3% of the average/100 years on an all-India premise (Bhattacharjee and Nayak, 2019; Kumar et al., 2010).

Hence, due to insufficient water available in the reservoir during the lean season, electrical energy production is influenced. In this circumstance, continuing the process of producing electrical energy by storing water in the reservoir can create a severe water emergency in the river basins and unfavourably influence the livelihood of the individuals of those river basins. Under these situations, various units of hydroelectric projects are being shut down and therefore production capacity is reduced to a great extent (Bhattacharjee and Nayak, 2019). This problem is faced by Gumti hydroelectric plant of Tripura, India. Tripura is one of the North-Eastern states of India. The North-Eastern locale of India possesses 38% of the total hydropower generation capacity of India (Bhattacharjee and Nayak, 2019; Bhakta et al., 2015). The locale is for the most part hilly (with wide varieties in slope and elevation), with much tough and difficult to reach landscape. The locale is overwhelmingly occupied by the indigenous ancestral populace. The locale has distinct geographical and demographical features compared to the rest of India (Bhattacharjee and Nayak, 2019; Bhattacharjee and Bhakta, 2013). Rich in environmental assets, the locale is recognised as one of the hotspots of biodiversity of the world (Bhattacharjee and Nayak, 2019). The maximum precipitation in the nation is received by the hilly states of India, with average yearly precipitation fluctuating from 1,400 mm to 6,000 mm in Arunachal Pradesh. Cherrapunji (Meghalaya) is probably the wettest spot on the planet, with a normal yearly precipitation of over 11,000 mm (Bhattacharjee and Nayak, 2019). Yet, the examination and situations in various North-Eastern states of India (such as Manipur, Mizoram, Nagaland and Tripura) suggest that the rainstorm precipitation has been in the negative significant pattern. The pattern of negative rainfall faced by North-Eastern states is –0.52 mm/year (Bhattacharjee and Nayak, 2019; Kumar et al., 2010).

The current investigation is envisaged with the Gumti hydroelectric plant ($3 \times 5 = 15$ MW), only hydroelectric station in Tripura. Also, this hydroelectric plant is the first own power production unit in the state, which is situated at Tirthamukh, 120 km from the capital city of Tripura (Agartala) (Bhattacharjee and Nayak, 2019). The dam has been built across the Gumti River. Yet, this hydropower producing station has been confronting issues because of lack of water in the reservoir throughout a previous couple of years. Also, the effort to generate electricity by keeping water in the reservoir may prompt an outrageous water shortage in the river basin (Bhattacharjee and Nayak, 2019). Many villages dependent on the Gumti River will confront serious water scarcity for their living. Also, several irrigation projects and drinking water delivering stations situated in the Gumti basin are to be stopped, which will affect the agricultural sector as a whole. Due to these situations, two units of Gumti hydroelectric project are being switched off. Currently, the plant is not equipped for producing power consistently for the entire year. Through all the dry seasons (usually from October to May), the power station remains practically inactive as there is barely any water accessible for electrical energy production (Bhattacharjee and Nayak, 2019). In the rainy season, after the water gathered in the reservoir, electricity production begins. Even then the average power output is only 5 MW (Bhattacharjee and Nayak, 2019). The emission of greenhouse gases from fossil fuels is also responsible for these changing climatic conditions which result utilisation of renewable energy sources need to be increased (Hiloidhari et al., 2019; Nandi et al., 2018, 2019; Bhattacharjee et al., 2018, 2020a, 2020b; Bhattacharjee and Nandi, 2019, 2020b, 2020c). However, the overall energy generation capacity scenario of Tripura indicates that the gas-based generation capacity contributes 78.70% of the total generation capacity as compared to 21.3% of hydro generation capacity (*24X7 Power for All Tripura*, 2019). To promote renewable energy utilisation in changed climatic condition of Tripura, there is an urgent need to upgrade the Gumti hydroelectric plant so that it can produce power consistently for the entire year. To tackle the problem of the hydropower plant, the concept of the hybrid energy system is introduced in the present study, which is defined as the mix of more than one energy sources for maintaining continuity of power supply (Nandi et al., 2019; Bhattacharjee et al., 2018, 2020a; Bhattacharjee and Nandi, 2020a, 2020c).

The present study includes technical, feasibility and optimisation analysis of grid-connected solar-biomass-hydro-based hybrid system with pumped storage system using the real-time data of solar radiation, clearness index, ambient temperature, hydro stream flow and biomass resource of the selected location in order to supply cost-effective, reliable and continuous power in changed climatic conditions of Tripura. The present study foresees the modernising of small hydro plants in general and Gumti hydropower plants in particular so that it can produce power consistently for the entire year. This paper comprises of the following sections apart from the introduction. Section 2 describes the climatic condition of the selected location in terms of its availability of renewable resources. Section 3 focuses on the description of the hybrid energy system. Section 4 describes the research methodology utilised for analysis. Section 5 describes the results obtained from the analysis. Section 6 discusses the results obtained from the analysis. Section 7 describes the conclusion.

2 Description of the selected location and renewable resources

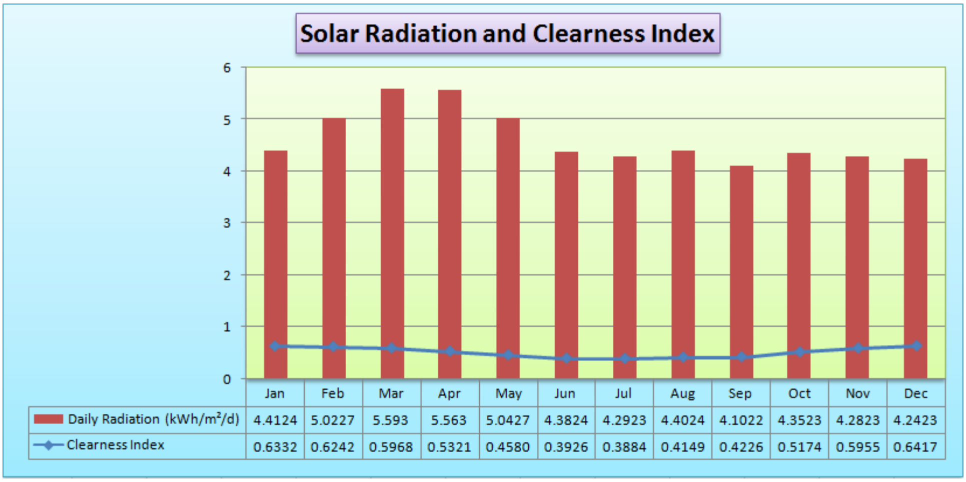
Gumti hydroelectric plant is situated at Paschim Kalajari R.F. part, Tirthamukh, South District of Tripura, Tripura 799104, India (Bhattacharjee and Nayak, 2019; HOMER Energy, 2019; *NASA Prediction of Worldwide Energy Resources*, 2019). For the analysis of the hybrid system, the location of the Gumti hydroelectric plant is selected. The latitude and longitude of the selected location are 23°25.4'N and 91°48.2'E. The selected location of Tripura is shown in Figure 1 (HOMER Energy, 2019; *NASA Prediction of Worldwide Energy Resources*, 2019). The proposed hybrid system is analysed based on the data of solar radiation, clearness index, ambient temperature, water stream flow through the turbine of Gumti hydroelectric plant from its reservoir and biomass resources of the selected location.

Figure 1 The selected location of Tripura for analysing the proposed hybrid system (see online version for colours)

2.1 Solar radiation and clearness index

The monthly average data of solar radiation and clearness index of the selected location is shown in Figure 2, where the range of solar radiation is from 4.1022 kWh/m^2/day to 5.593 kWh/m^2/day and the range of clearness index is from 0.38849 to 0.64176. The average annual solar radiation is 4.638 kWh/m^2/day and the average annual clearness index is 0.503. The data of solar radiation and clearness index of the selected location is taken from the database of NASA Prediction of Worldwide Energy Resources (2019).

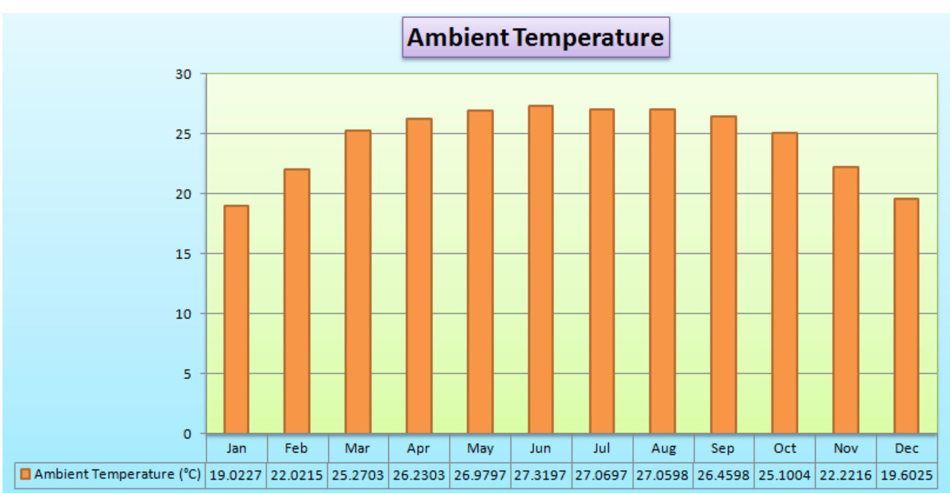
Figure 2 The monthly average data of solar radiation and clearness index (see online version for colours)



2.2 *Ambient temperature*

The monthly average data of the ambient temperature of the selected location is shown in Figure 3, where the range of ambient temperature is from 19°C to 27.3°C. The average annual ambient temperature is 24.5°C. The data of the ambient temperature of the selected location is taken from the database of NASA Prediction of Worldwide Energy Resources (2019).

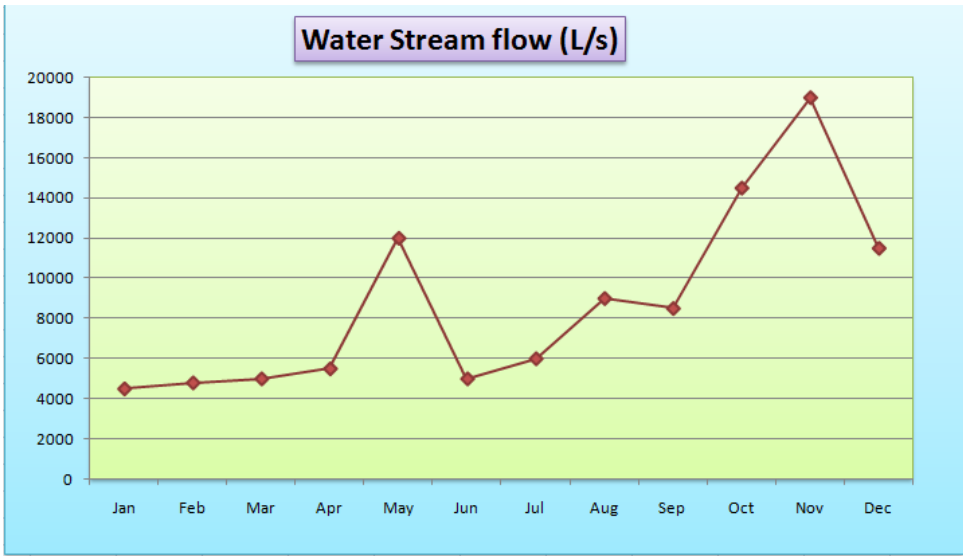
Figure 3 The monthly average data of ambient temperature (see online version for colours)



2.3 Water stream flow

The monthly average data of water stream flow through the turbine of Gumti hydroelectric plant from its reservoir is shown in Figure 4, where the range of water stream flow is from 4,500 L/s to 19,000 L/s. The average annual water streamflow is 8,800 L/s (Bhattacharjee and Nayak, 2019).

Figure 4 The monthly average data of water stream flow (see online version for colours)



2.4 Biomass resources from the forest and wasteland

The south district of Tripura has a good potential for power generation from biomass resources. The surplus biomass generated from forest and wasteland on the area of 257.2 kHa of south district of Tripura is 192.6 kT/year. Also, the surplus biomass generated from agro-residues on the area of 3 kHa of south district of Tripura is 6.9 kT/year. In addition, the total surplus biomass generated from the state Tripura is 704.7 kT/year (*Biomass Resource Potential in Tripura*, 2019). On the basis of this data of biomass resources, it is clear that the selected location of the south district of Tripura is capable to generate electrical energy from biomass resources. Therefore, the biomass resources required for the proposed hybrid system is taken as 100 tonnes/day in all the months of the year. The price of biomass is considered as 28 $/T (Patel and Singal, 2018).

3 Description of hybrid energy system

The block diagram of grid-connected solar-biomass-hydro-based hybrid system with pumped hydro storage system is shown in Figure 5. The main components of the proposed hybrid system are PV array system, biomass gasifier, hydroelectric plant, pumped hydro storage system, converter, electrical grid, and electrical load. This hybrid system is designed and analysed using Hybrid Optimization Model for Multiple Energy Resources (HOMER) software, which is a software application developed to design and analyse economically and technically the options for both on-grid and off-grid hybrid power systems for remote, standalone and distributed generation applications (HOMER Energy, 2019; Kassam, 2019). The lifetime of the proposed hybrid system is 25 years and its annual real interest rate is 6%. The viable configurations used for the analysis of the proposed hybrid system are shown in Table 1.

Figure 5 The block diagram of grid-connected solar-biomass-hydro-based hybrid system with pumped hydro storage system (see online version for colours)

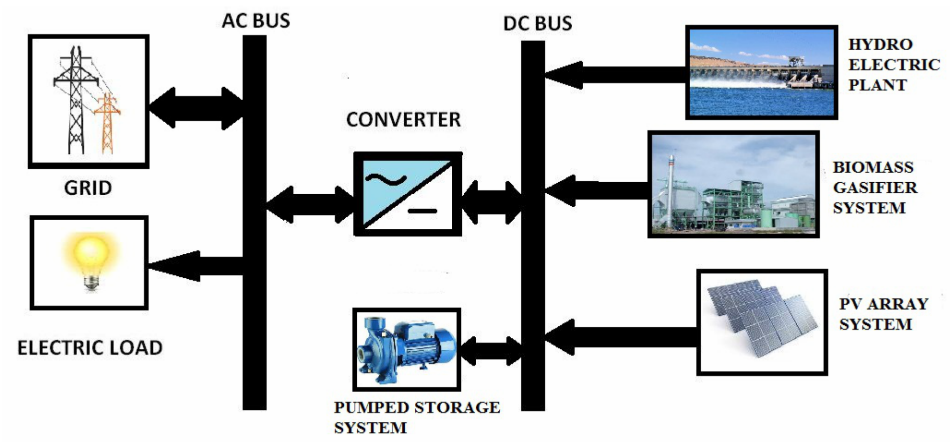


Table 1 The viable configurations used for the analysis of the proposed hybrid system

Configurations	*Size of components of the proposed hybrid system*		
	PV array system (kW)	*Biomass gasifier system (kW)*	*Hydroelectric plant (kW)*
I	10,000	2,000	6,126
II	10,000	3,000	6,126
III	10,000	4,500	6,126
IV	20,000	2,000	6,126
V	20,000	3,000	6,126
VI	20,000	4,500	6,126

3.1 PV array system

The PV array system generates electrical energy by utilising sunlight. The capital cost of PV array system is $1,046,181/MW and the replacement cost of the PV array system is $1,046,181/MW. Its operation and maintenance cost for every 1 MW is $104,618/year. Its lifetime is 25 years and its derating factor is 90%. The ground reflectance of solar radiation is 20%. In this PV array system, the two-axis tracking system is utilised and it also consider effect of temperature with a temperature coefficient of power is –0.5%/°C, the efficiency at standard test condition is 15% and the normal operating cell temperature is 47°C (Bhattacharjee and Nayak, 2019; Nandi et al., 2019; HOMER Energy, 2019).

3.2 Biomass gasifier system

The biomass gasifier system generates electrical energy from biomass resources such as wood, etc. Biomass gasifier system is designed to generate power during the night for eight hours. The capital cost of the biomass gasifier system is $1,138/kW and the replacement cost of the PV array system is $1,120/kW. Its operation and maintenance cost is $0.50/year. Its lifetime (operating hours) is 40,000 hours and the minimum load ratio is 10% (Patel and Singal, 2018). The emission factors used for analysis are 10 g of carbon monoxide obtained from one kg of fuel, 0.181 g of particulate matter obtained from one kg of fuel and 2.7 g of nitrogen oxide obtained from one kg of fuel (Ahmed et al., 2019).

3.3 Hydroelectric plant

The hydroelectric plant generates electrical energy from running water. The capital cost of the hydroelectric plant is $20,176,398 and the replacement cost of the hydroelectric plant is $20,176,398. Its operation and maintenance cost is $2,017,639.8/year. Its lifetime is 30 years, the available head is 93 m, the design flow rate is 8,953 L/s, the minimum flow rate is 50%, maximum flow ratio is 150%, pipe head loss is 0.081% and the efficiency is 75%. Its nominal power capacity is 6.126 MW (Bhattacharjee and Nayak, 2019).

3.4 Pumped hydro storage system

The nominal capacity of the pumped hydro storage system is 245 kWh. The pumped hydro storage system generate potential energy by storing water in the reservoir at a fixed height when there is surplus energy and it transforms the potential energy into electrical energy by releasing water to run turbine generator when energy demand increases. Its capital cost is $22,000 and the replacement cost is $20,000. Its operation and maintenance cost is $2,000/year (HOMER Energy, 2019; The Electricity Storage Association, 2019).

3.5 Electrical grid

The electrical grid is used to provide electrical energy during requirement to the hybrid system for fulfilling the load demand and it is also used to consume excess energy from the hybrid system during surplus energy generation. During 4:00 hours to 20:00 hours (time of day), rate 1 is used for selling and purchasing energy. During 20:00 hours to 4:00 hours (time of day), rate 2 is used for selling and purchasing energy. In rate 1, the price at which excess electrical energy is selling to the grid is $0.180/kWh and the price at which required electrical energy is purchasing from the grid is $0.220/kWh. In rate 2, the price at which excess electrical energy is selling to the grid is $0.150/kWh and the price at which required electrical energy is purchasing from the grid is $0.200/kWh. In general, during day time, load demand for electrical energy is high so prices are considered high and during the night, load demand for electrical energy is low so prices are considered low. The interconnection charge of grid is consider as $0.2 and standby charge is consider as $0.3/year (Nandi et al., 2019; HOMER Energy, 2019; Bhattacharjee and Acharya, 2015).

3.6 Converter

In the proposed hybrid system, the converter indicating inverter which is used to convert DC electrical energy into AC electrical energy and it has an efficiency of 90%. It has a lifetime of 15 years. The capital cost of the converter is $43,341/MW and the replacement cost of the converter is $43,341/MW. Its operation and maintenance cost for every 1 MW is $4,334/year. Its rated capacity is 26,130 kW (Nandi et al., 2019; Bhattacharjee et al., 2015).

3.7 Electrical load

In the current analysis, it is considered that the hybrid system is operated in a grid-connected mode to fulfil the supposed load demand of the area. In the selected location, household load occupies the highest part of the demand. Also, miniature level industry, cottage industrial loads, water pumping load and community loads such as school, colleges, etc., are taken into consideration for formulating the electric load profile of the proposed hybrid system (Bhattacharjee and Nayak, 2019). The average yearly electric load demand is considered as 14.347 MWh/day. Figure 6 indicates the daily average electric load profile. Figure 7 indicates the average electric load profile in months. The peak electric load demand is 1.234 MW. Here the day to day random variability is considered as 15% and the time-step to time-step random variability is considered as 20% (Bhattacharjee and Nayak, 2019).

Figure 6 The daily average electric load profile (see online version for colours)

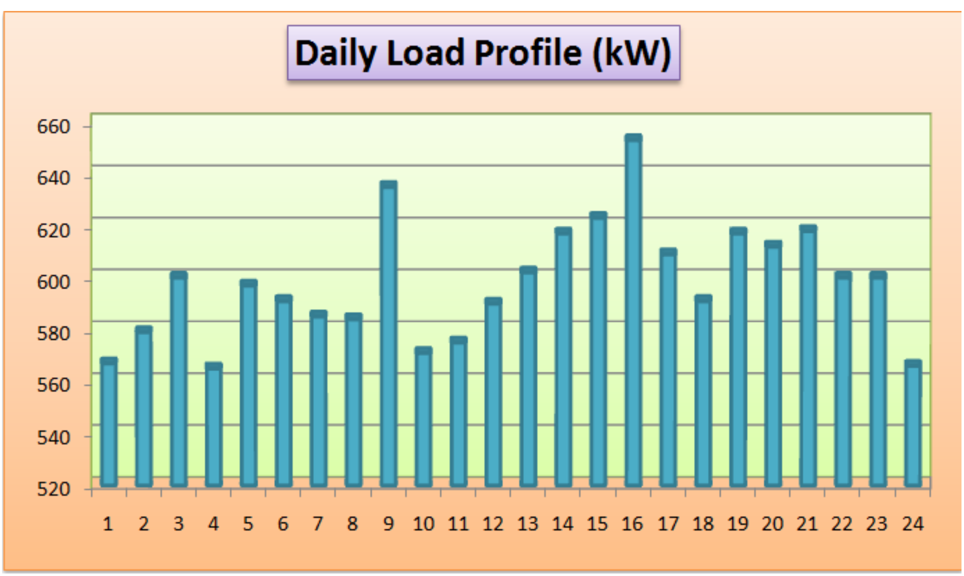
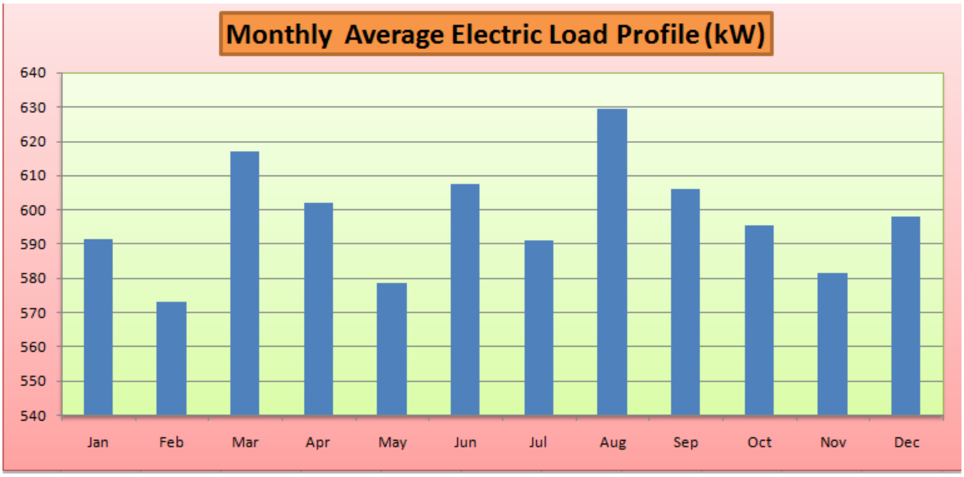


Figure 7 The average electric load profile in months (see online version for colours)



4 Research methodology of hybrid energy system

The outline described by Bhattacharjee and Nayak (2019) in their research paper is utilised as a directive parameter to assess the design and implementation of this grid-connected hybrid energy system. In Bhattacharjee and Nayak (2019), the authors try to utilise the promising hydro potential of North-Eastern region by integrating solar pumped storage system with a hydroelectric plant in one of the North-East states of India. Due to declining precipitation in the North-Eastern region, many hydroelectric plants facing scarcity of water due to which many units of it are shut down and therefore hydropower generation drop down to low level. This problem is faced by Gumti hydroelectric plant of Tripura, India. To solve this problem, the authors integrate a solar pumped storage system with Gumti hydroelectric plant of Tripura, India. The results of this analysis indicate that the solar pumped storage system is a feasible alternative for refurbishing the stable performance of the hydroelectric plant. This study mainly focuses on delivering consistent, incessant and cost-effective power supply (Bhattacharjee and Nayak, 2019). But this study possesses some demerits which are requiring be addressing and solving for preserving the continuity of power supply. The proposed energy system is a standalone system so it fully depends on pumped storage water for supplying electricity during the night. Due to climate change, water scarcity now slowly becoming a big issue and it may further increase in the future. It may be possible that there may be a scarcity of water in the lower reservoir from where water is pumped to the upper reservoir. In this situation, this advancement is not capable to maintain continuity of power supply. Another perspective which is ignored is that solar power generation continuously varies all over the day and it may be possible pumped storage system not able to store good amount of water in the upper reservoir due to some environmental or technical reason then, in that case, one backup source must be there for maintaining continuity of power supply during night.

The research study of the research paper (Bhattacharjee and Nayak, 2019) is further refurbished in this paper by utilising the concept of a hybrid energy system. The main novelty of this research work is that it solves the problem of irregularity in power supply of the hydroelectric power station all over the year, by proposing a modified model of the hybrid energy system, where it establish a grid-connected solar-biomass-hydro-based hybrid system with pumped storage system. The proposed system is designed and analysed by using the real-time data of solar radiation, clearness index, ambient temperature, hydro stream flow and biomass resource of the selected location to supply cost-effective, reliable and continuous power in changing climatic conditions of Tripura. During day time, solar power and hydropower together fulfil load demand, store a fixed amount of energy using a pumped-storage system and sell excess energy to the grid for earning money profit. Here photovoltaic (PV) array system not only helps to store water in the upper reservoir by utilising a pumped storage system but also help to work as a second major energy source. During the night, biomass gasifier system, hydroelectric plant and stored energy of the pumped storage system together fulfil the load demand and sell excess energy to the grid. The storage energy of the pumped storage system can be utilised to fulfil load demand during day time if needed. During an emergency, backup grid connection also there. The excess energy generated from this hybrid system helps to reduce the contribution of nearby thermal power plants. Due to the presence of backup grid connection and biomass gasifier system, risk of not maintaining continuity of power supply now reduces to a very low value. The present study foresees the modernising of small hydro plants in general and Gumti hydro power plants in particular so that it can produce power consistently for the entire year. This hybrid system is designed and analysed using HOMER software (Hybrid Optimization Model for Multiple Energy Resources), which is a software application developed to design and analyse economically and technically the options for both on-grid and off-grid hybrid power systems for remote, standalone and distributed generation applications (HOMER Energy, 2019; Kassam, 2019). This software utilises the following cost optimisation parameters:

4.1 Net present cost

It includes initial capital cost, maintenance cost, installation expenses, replacement expenses, revenues, cost of grid purchased power and operating expenses for the hybrid system all through its life and it is measured by the succeeding formula (Bhattacharjee and Nayak, 2019; Nandi et al., 2019; Bhattacharjee et al., 2020a):

$$\text{Net present cost (NPC)} = \text{Total annualised cost (TAC)}/\text{CRF}(i, R_{prj}) \quad (1)$$

Here, net present cost (NPC) in \$, total annualised cost (TAC) in \$, CRF specifies the capital recovery factor, i specifies the rate of interest in terms of % and Rprj specifies the project lifespan in terms of a year (Nandi et al., 2019; Bhattacharjee et al., 2020a).

4.2 Total annualised cost

It includes expenses of all equipment utilised in the hybrid energy system that consists of capital charge, maintenance charge, operation charge, replacement charge, and fuel charge measured yearly (Nandi et al., 2019; Bhattacharjee et al., 2020a).

4.3 Capital recovery factor

It measures the series of cash flow yearly in ratio to the present value and it is measured by the succeeding formula (Nandi et al., 2019; Bhattacharjee et al., 2020a):

$$\text{Capital recovery factor (CRF)} = \left(i \times (1+i)^n\right) / (1+i)^{n-1} \tag{2}$$

Here, i specify the rate for real interest yearly and n specify the years (Nandi et al., 2019; Bhattacharjee et al., 2020a).

4.4 Annual real interest rate

The annual real interest rate specifies the nominal interest rate as a function and it is measured by the succeeding formula (Nandi et al., 2019; Bhattacharjee et al., 2020a):

$$\text{Annual real interest rate (i)} = \left(i_1 - F\right) / (1+F) \tag{3}$$

Here, i_1 specifies the nominal interest rate and F specify the annual inflation rate.

4.5 Cost of energy

It specifies the average cost of one unit of energy in $/kWh of the useful electrical energy generated by the hybrid system and it is measured by the succeeding formula (Nandi et al., 2019; Bhattacharjee et al., 2020a):

$$COE = TAC / \left(L_{prim,AC} + L_{prim,DC}\right) \tag{4}$$

Here, $L_{prim,AC}$ specifies primary AC load, TAC specifies total annualised cost and $L_{prim,DC}$ specifies primary DC load (Nandi et al., 2019; Bhattacharjee et al., 2020a).

5 Results of hybrid energy system

5.1 Selection of most viable configuration

The optimisation results of all the viable configurations of the proposed hybrid system obtained from the software is shown in Table 2, which shows a comparative analysis of different configurations in terms of net present cost (NPC) in $, levellised cost of energy (COE) in $/kWh, renewable fraction, biomass in tonnes, operating hours of biomass gasifier system (BGENO), operating cost in $/year and initial capital cost ($).

From Table 2, it is clear that the most economical configuration of the proposed hybrid system is IV configuration as its COE and NPC are lowest, and the most costly configuration of the proposed hybrid system is III configuration as its COE and NPC are highest. The most optimal configuration IV has 20 MW rated capacity PV array system, 2 MW rated capacity biomass gasifier system and 6.126 MW rated capacity hydroelectric plant. Its net present cost is -37,215,540$, the renewable fraction is 1, the initial capital cost is $44,530,520 and levellised cost of energy is –$0.034/kWh. This configuration utilises 5,840 tonnes of biomass in each year and also biomass gasifier system operates 2,920 hours in each year.

Table 2 The optimisation results of all viable configurations of the proposed hybrid system

	Viable configurations of the proposed hybrid system					
	I	*II*	*III*	*IV*	*V*	*VI*
NPC ($)	–20,717,546	–4,451,389	19,923,872	–37,215,540	–20,949,384	3,425,889
COE ($/kWh)	–0.024	–0.005	0.021	–0.034	–0.019	0.003
Renewable Fraction	1	1	1	1	1	1
Biomass (T/year)	5,840	8,760	13,136	5,840	8,760	13,136
BGENO (hour/year)	2,920	2,920	2,919	2,920	2,920	2,919
Operating cost ($/year)	–4,285,749	–3,102,323	–1,329,059	–6,394,726	–5,211,300	–3,438,035
Initial capital cost ($)	34,068,708	35,206,708	36,913,708	44,530,520	45,668,520	47,375,520

5.2 Performance results of most viable configuration

This section describes the performance results of the most viable configuration, i.e., IV configuration. Table 3 shows the annualised expenses of the proposed hybrid system. Table 4 shows the net present expenses of the proposed hybrid system. Table 5 shows the grid purchases and grid sales of the proposed hybrid system on a monthly basis. Table 6 indicates the electrical generation summary of the proposed hybrid energy system. Table 7 indicates the electrical consumption summary of the proposed hybrid energy system. Table 8 indicates the emission summary of the proposed hybrid system. Figure 8 indicates the monthly average electric power production in kW. Figure 9 indicates the solar power production in kW on the basis of months of a year and hours of a day together. Figure 10 indicates the hydropower production in kW on the basis of months of a year and hours of a day together. Figure 11 indicates the biopower production in kW on the basis of months of a year and hours of a day together. Figure 12 indicates the state of charge of the pumped storage system in % on the basis of months of a year and hours of a day together. Figure 13 indicating the yearly cash flow throughout the lifetime of the proposed hybrid system. Figure 14 indicates the converter output on the basis of months of a year and hours of a day together. Figure 15 indicates the plot of hydropower (kW) with respect to the month of a year. Figure 16 indicates the plot of solar power (kW) with respect to the month of a year. Figure 17 indicates the plot of biopower (kW) with respect to the month of a year. Figure 18 indicates the plot of AC primary load (kW) with respect to the month of a year. Figure 19 indicates the plot of total renewable power output (kW) with respect to the month of a year. Figure 20 indicates the plot of total electrical load served (kW) with respect to the month of a year. Figure 21 indicates the plot of grid power sales (kW) with respect to the month of a year. Figure 22 indicates the plot of renewable penetration (%) with respect to the month of a year. Figure 23 indicates the plot of state of charge (%) of the pumped storage system with respect to the month of a year. Figure 24 indicates the plot of inverter input power (kW) with respect to the month of a year. Figure 25 indicates the plot of inverter output power (kW) with respect to the month of a year.

Table 3 The annualised expenses of the proposed hybrid system

Component	*Capital ($/yr)*	*Replacement ($/yr)*	*Operation and maintenance ($/yr)*	*Fuel cost ($/yr)*	*Salvage ($/yr)*	*Total ($/yr)*
PV array system	1,636,786	0	2,092,361	0	0	3,729,147
Hydroelectric plant	1,578,333	0	2,017,641	0	–61,292	3,534,682
Biomass gasifier system	178,044	78,877	2,920,001	163,520	–7,145	3,333,297
Grid	0	0	–13,752,949	0	0	–13,752,949
Pumped storage system	1,721	8,929	2,000	0	–3	12,647
Converter	88,592	36,966	113,247	0	–6,881	231,925
Hybrid energy system	3,483,476	124,772	–6,607,699	163,520	–75,320	–2,911,252

Table 4 The net present expenses of the proposed hybrid system

Component	*Capital ($)*	*Replacement ($)*	*Operation and maintenance ($)*	*Fuel cost ($)*	*Salvage ($)*	*Total ($)*
PV array system	20,923,620	0	26,747,396	0	0	47,671,012
Hydroelectric plant	20,176,398	0	25,792,220	0	–783,513	45,185,100
Biomass gasifier system	2,276,000	1,008,307	37,327,416	2,090,336	–91,336	42,610,724
Grid	0	0	–175,808,848	0	0	–175,808,848
Pumped storage system	22,000	114,142	25,567	0	–41	161,667
Converter	1,132,500	472,553	1,447,683	0	–87,957	2,964,780
Hybrid energy system	44,530,516	1,595,002	–84,468,568	2,090,336	–962,847	-37,215,576

Table 5 Grid purchases and grid sales of the proposed hybrid system on a monthly basis

Month	*Energy purchased (kWh)*	*Energy sold (kWh)*	*Net purchases (kWh)*	*Peak demand (kW)*	*Energy charge ($)*	*Demand charge ($)*
Jan	0	5,560,958	–5,560,958	0	–971,612	0
Feb	0	5,227,254	–5,227,254	0	–912,951	0
Mar	0	5,818,107	–5,818,107	0	–1,015,751	0
Apr	0	5,558,236	–5,558,236	0	–967,658	0
May	0	8,352,629	–8,352,629	0	–1,439,668	0
Jun	0	4,467,563	–4,467,563	0	–773,622	0

Table 5 Grid purchases and grid sales of the proposed hybrid system on a monthly basis (continued)

Month	*Energy purchased (kWh)*	*Energy sold (kWh)*	*Net purchases (kWh)*	*Peak demand (kW)*	*Energy charge ($)*	*Demand charge ($)*
Jul	0	5,043,400	–5,043,400	0	–871,521	0
Aug	0	6,534,341	–6,534,341	0	–1,126,407	0
Sep	0	6,053,277	–6,053,277	0	–1,043,445	0
Oct	0	8,902,702	–8,902,702	0	–1,532,147	0
Nov	0	9,120,060	–9,120,060	0	–1,573,416	0
Dec	0	8,812,034	–8,812,034	0	–1,524,744	0
Annual	0	79,450,560	–79,450,560	0	–13,752,944	0

Table 6 Electrical generation summary of the proposed hybrid system

Component	*Generation (kWh/yr)*	*Percent (%)*
PV array system	38,969,192	41
Biomass gasifier system	5,840,000	6
Hydroelectric plant	49,314,540	52
Grid purchases	0	0
Total	94,123,728	100

Table 7 Electrical consumption summary of the proposed hybrid system

Component	*Consumption (kWh/yr)*	*Percent (%)*
AC primary load	5,236,657	6
Grid sales	79,450,560	94
Total	84,687,216	100

Table 8 Emission summary of the proposed hybrid system

Pollutant	*Emissions (kg/year)*
Carbon dioxide	979
Carbon monoxide	58.4
Unburned hydrocarbons	0
Particulate matter	1.06
Sulphur dioxide	0
Nitrogen oxides	15.8

Figure 8 The monthly average electric power production in kW (see online version for colours)

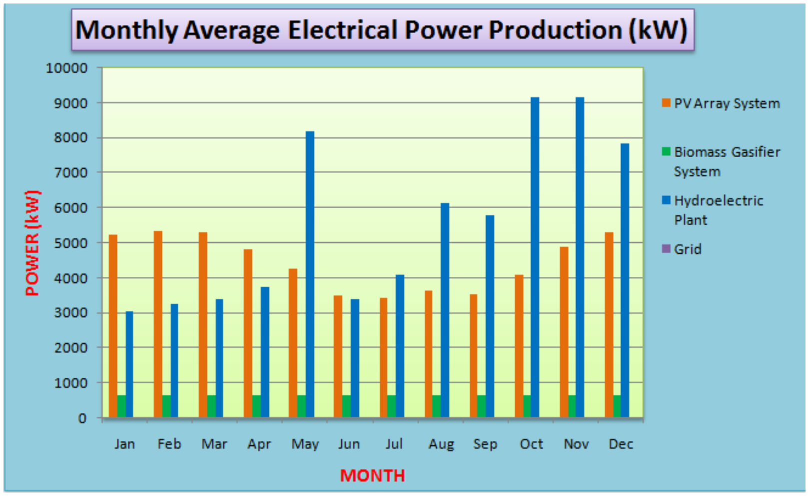


Figure 9 The monthly solar power production in kW (see online version for colours)

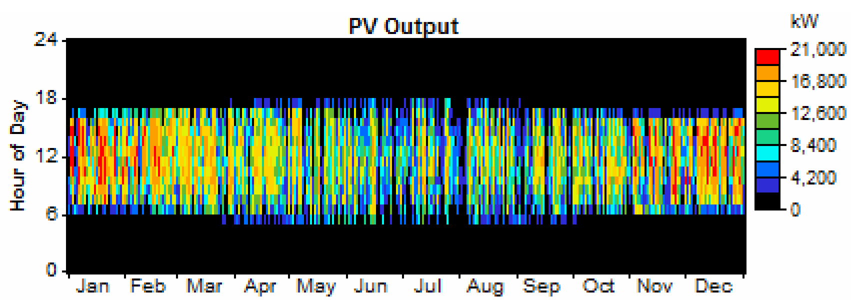


Figure 10 The monthly hydropower production in kW (see online version for colours)

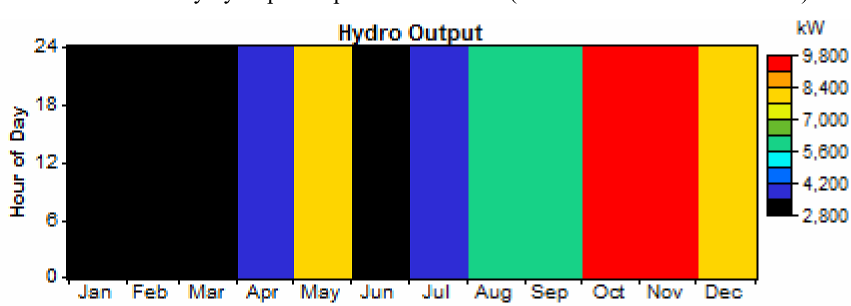


Figure 11 The monthly biopower production in kW (see online version for colours)

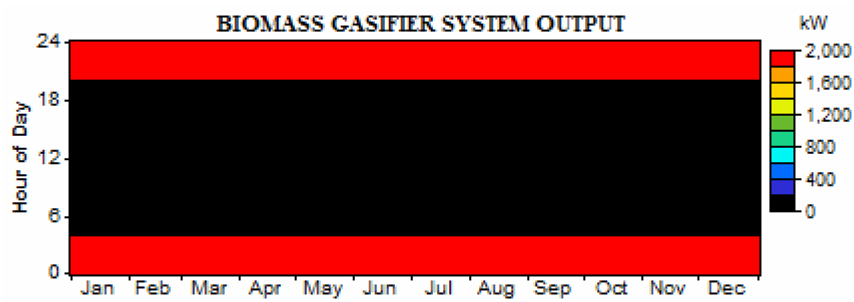


Figure 12 The monthly state of charge (%) of the pumped storage system (see online version for colours)

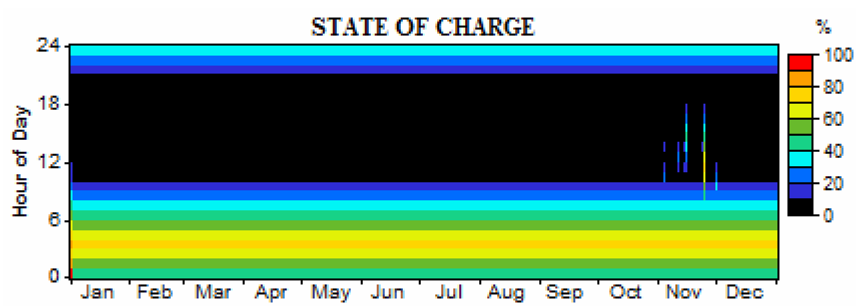


Figure 13 The details of yearly cash flow throughout the lifetime of the proposed hybrid system (see online version for colours)

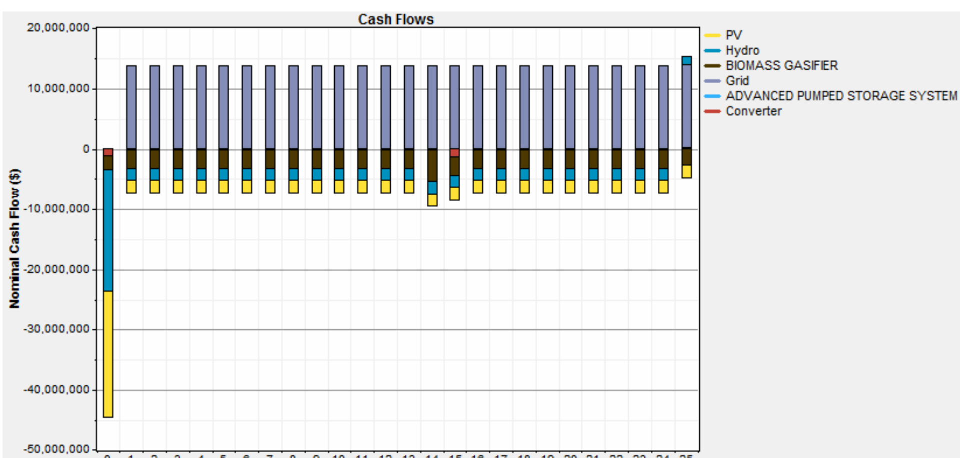


Figure 14 The monthly converter (working as an inverter) output in kW (see online version for colours)

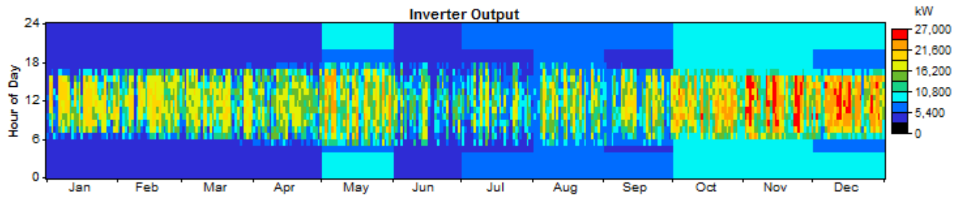


Figure 15 The plot of hydropower (kW) with respect to the month of a year (see online version for colours)

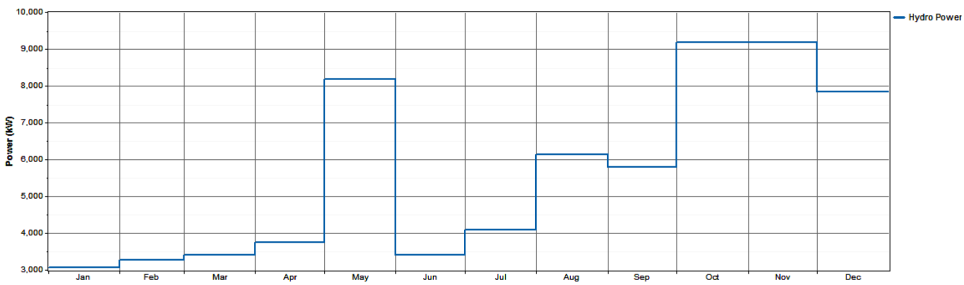


Figure 16 The plot of solar power (kW) with respect to the month of a year (see online version for colours)

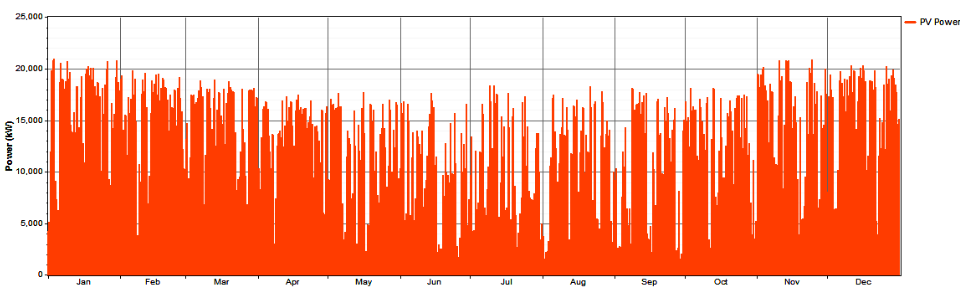


Figure 17 The plot of bio-power (kW) with respect to the month of a year (see online version for colours)

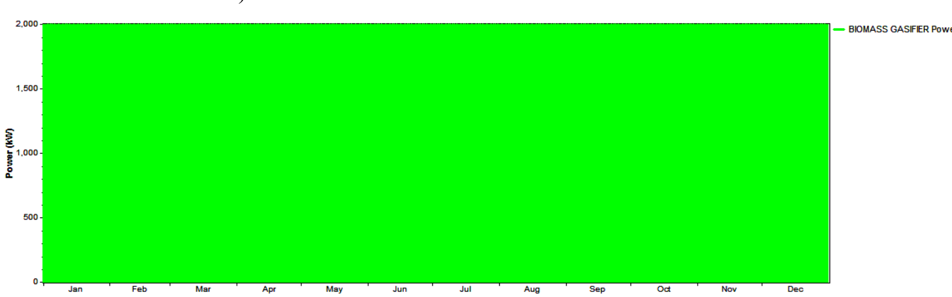


Figure 18 The plot of AC primary load (kW) with respect to the month of a year (see online version for colours)

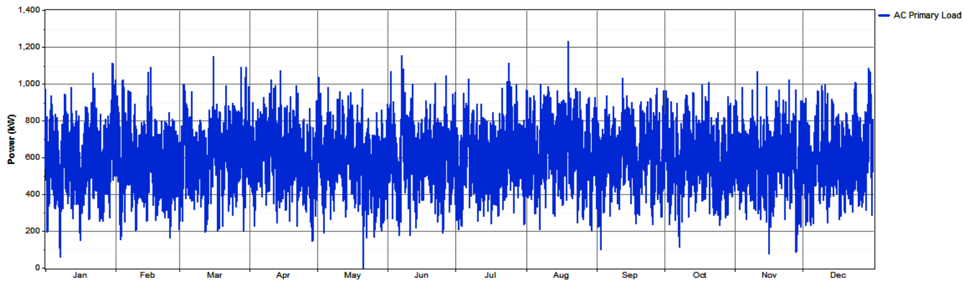


Figure 19 The plot of total renewable power output (kW) with respect to the month of a year (see online version for colours)

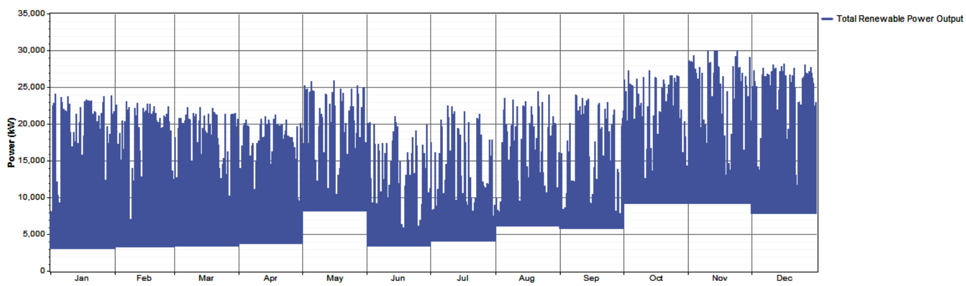


Figure 20 The plot of total electrical load served (kW) with respect to the month of a year (see online version for colours)

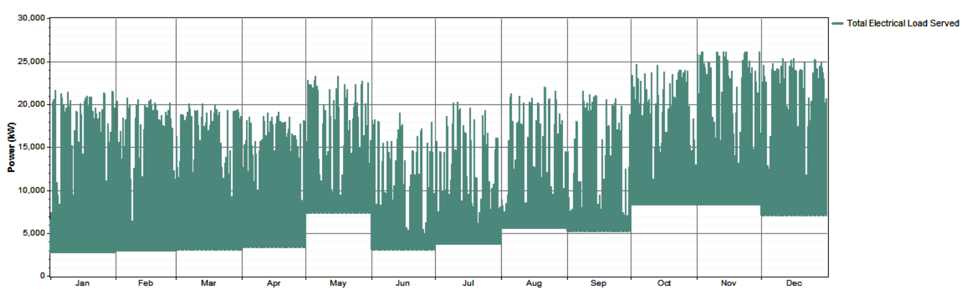


Figure 21 The plot of grid power sales (kW) with respect to the month of a year (see online version for colours)

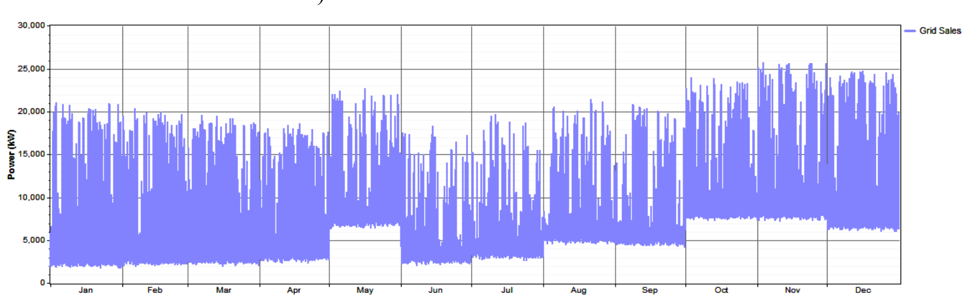


Figure 22 The plot of renewable penetration (%) with respect to the month of a year (see online version for colours)

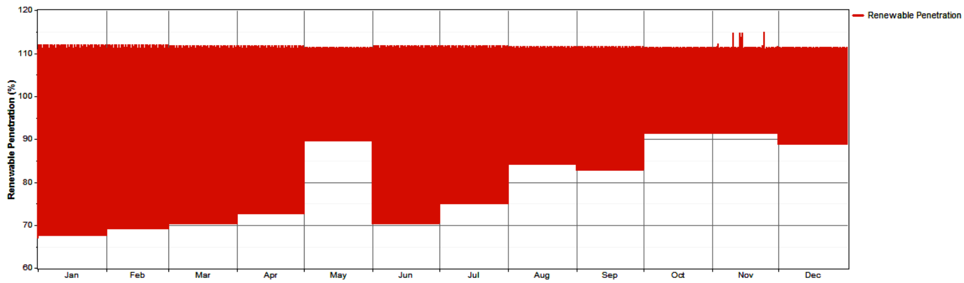


Figure 23 The plot of state of charge (%) of the pumped storage system with respect to the month of a year (see online version for colours)

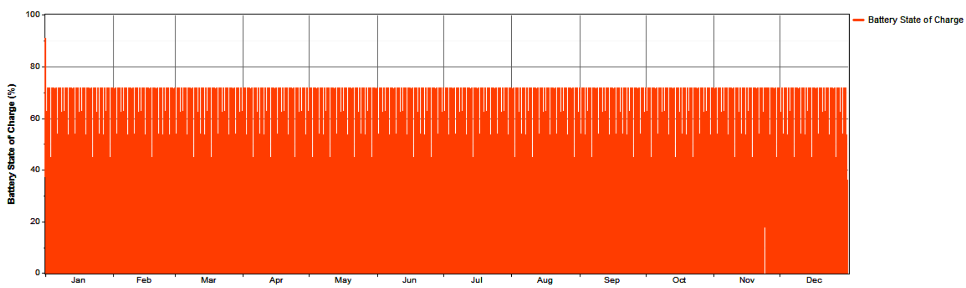


Figure 24 The plot of inverter input power (kW) with respect to the month of a year (see online version for colours)

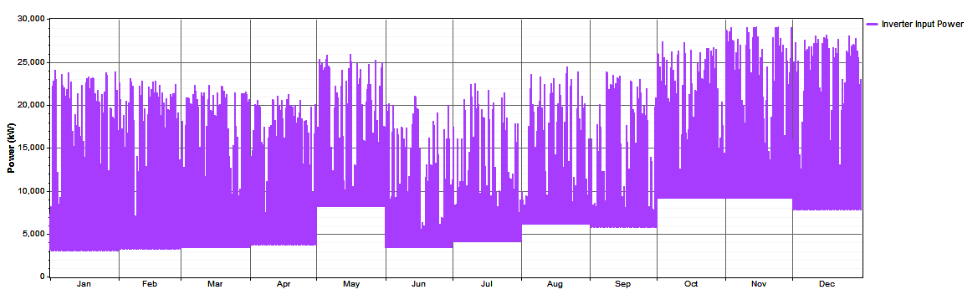
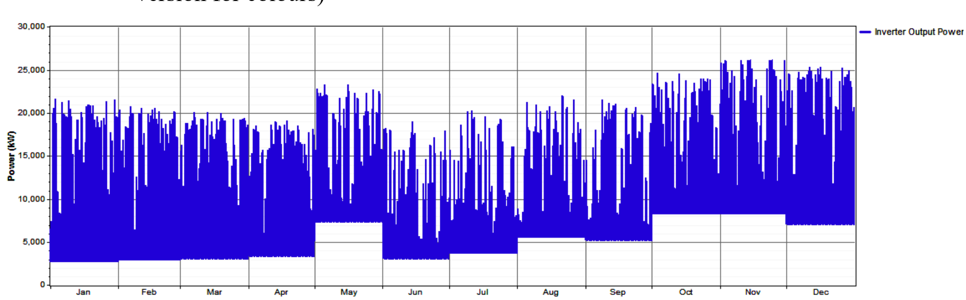


Figure 25 The plot of inverter output power (kW) with respect to the month of a year (see online version for colours)



5.3 Twenty-four hours case study analysis of most viable configuration

This section contains a 24-hour case study analysis to understand all the different circumstances that the proposed hybrid energy system could face. This case study analysis is performed using the real-time data of solar radiation, clearness index, ambient temperature, hydro stream flow and biomass resource of the selected location. This analysis is based on the optimisation results of one day of January month (1 January) obtained from the analysis of the proposed hybrid system. Figure 26 indicates the hourly plot of solar power, hydropower, biopower and AC primary load in kW of one day of January month (1 January). Figure 27 indicates the hourly plot of charge power and discharge power of the pumped storage system (PSS) in kW of one day of January month (1 January). Figure 28 indicates the hourly plot of energy content (kWh) and state of charge (%) of the pumped storage system (PSS) of one day of January month (1 January). Figure 29 indicates the hourly plot of grid power purchases and grid power sales of the proposed hybrid system of one day of January month (1 January). Figure 30 indicates the hourly plot of grid power price and grid sell back rate in $/kWh of the proposed hybrid system of one day of January month (1 January).

Figure 26 The hourly plot of solar power, hydropower, biopower and AC primary load in kW of one day of January month (1 January) (see online version for colours)

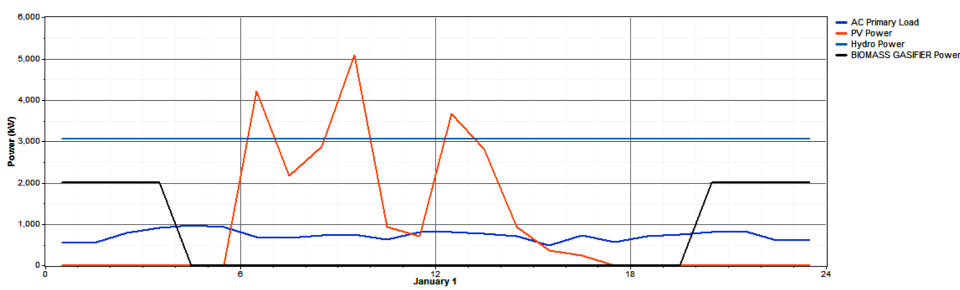
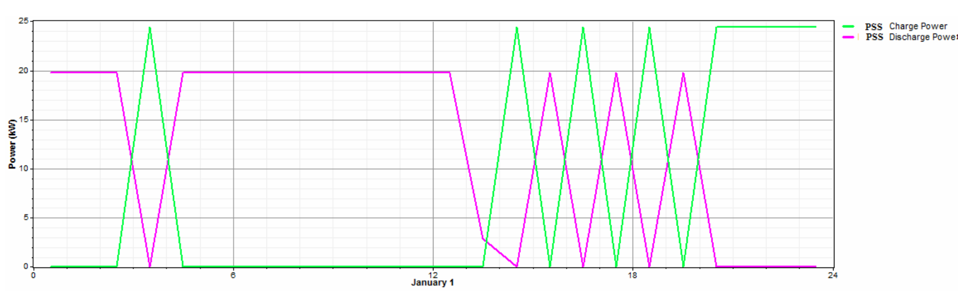


Figure 27 The hourly plot of charge power and discharge power of the pumped storage system (PSS) in kW of one day of January month (1 January) (see online version for colours)



With the help of Figures 26, 27, 28, 29 and 30, it is simple to understand all the different circumstances that the proposed hybrid system mainly faces. During the time of 0:00 to 7:00 hours (12:00 AM to 7:00 AM), solar power is not there but hydropower, biopower and stored power of PSS are there so they together fulfilled the load demand and excess energy is sent to the grid. In this time duration, biopower contributed up to 5: 00 AM then hydropower with the stored power of PSS together fulfilled the load demand and excess energy is sent to the grid. During this time, the charging of PSS also occurs for one hour. Since biopower is not present in the time duration of 5:00 to 21:00 hours (5:00 AM to 9:00 PM) so it does not contribute anything during this time duration. During the time of 7:00 to 18:00 hours (7:00 AM to 6:00 PM), solar power, hydropower and stored power of PSS are there so they together fulfilled the load demand and excess energy is sent to the grid. During this time, the charging of PSS also occurs for three hours. During the time of 18:00 to 0:00 hours (6:00 PM to 12:00 AM), solar power is not there but hydropower and biopower are there so they together fulfilled the load demand and excess energy is sent to the grid. During this time, the charging of PSS also occurs. During the time duration of twenty-four hours, grid power purchase is zero. Here the stored power of PSS is not only designed to discharge power during the night but also the stored power of PSS can be used during day time for fulfilling the load demand. Also, this stored power can be sold to grid during high energy prices for earning extra profit. Since the grid sell-back rate is high during the hours of day time so the stored power of PSS mainly utilised during this time. So based on energy requirement and profit, the stored power of PSS is utilised.

Figure 28 The hourly plot of energy content (kWh) and state of charge (%) of the pumped storage system (PSS) of one day of January month (1 January) (see online version for colours)

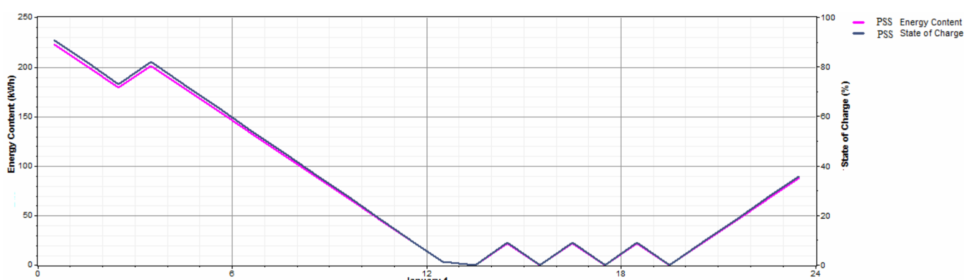


Figure 29 The hourly plot of grid power purchases and grid power sales of the proposed hybrid system of one day of January month (1 January) (see online version for colours)

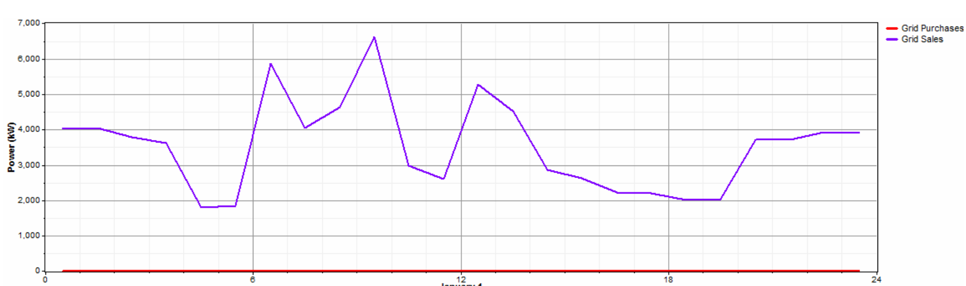
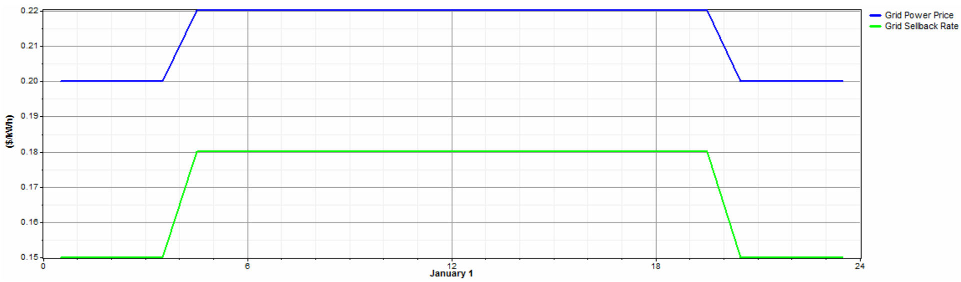


Figure 30 The hourly plot of grid power price and grid sell back rate in \$/kWh of the proposed hybrid system of one day of January month (1 January) (see online version for colours)



6 Discussion

The main aim of this paper is to modernise small hydro plants in general and Gumti hydropower plants in particular so that it can produce power consistently for the entire year using the concept of a hybrid energy system. In this paper, a grid-connected solar-biomass-hydro-based hybrid system with pumped storage system is designed and analysed using the real-time data of solar radiation, clearness index, ambient temperature, hydro stream flow and biomass resource of the selected location to supply cost-effective, reliable and continuous power in changing climatic conditions of Tripura. This paper primarily spotlights on the economic, feasibility and optimisation analysis of the proposed hybrid system. This study estimates the price of one unit of energy, amount of total energy production, greenhouse gases emission, net present cost and the annualised cost of each component of the proposed hybrid energy system. Figures 1, 2, 3 and 4 indicate the climatic conditions of the selected location of the Gumti hydroelectric project. These figures also indicate that the selected location is highly capable to generate solar and hydropower in a large amount. Also, the huge availability of surplus biomass resources in the south district of Tripura demonstrates the good possibility of biopower generation. Therefore, it is clear that the selected location is suitable to place a hybrid energy system using solar, hydro and bio resources. Table 2 indicates the most viable and economic configuration of the proposed hybrid energy system for the selected location which has a net present cost of –\$37,215,540 and its levellised cost of energy is –\$0.034/kWh. Tables 3 and 4 indicate the performance-based economic results of the most viable configuration of the proposed hybrid system, which indicate the expenses of each component on an annual and lifetime basis. Also, the levellised cost of energy of the PV array system is \$0.0957/kWh and the levellised cost of energy of the hydroelectric plant is \$0.0717/kWh. Also, the marginal generation cost of biomass gasifier system is \$0.0280/kWh. Table 5 indicates the grid sales and grid energy purchases on a monthly basis. This table helps to understand monthly energy purchases, monthly energy sales, and monthly earnings from selling energy to the grid. From Table 5 and Figure 21, it is clear that the proposed hybrid system is profitable throughout the year and its earnings are high. In addition, there are no energy purchases from the grid so no need to give any money to grid for purchasing energy. Tables 6 and 7 show the generation and consumption summary of the proposed hybrid system. Table 6 indicates that the contribution of hydro energy is maximum, i.e., 52% as compared to 41% of solar energy and 6% of bio-energy. Table 7 indicates that the contribution of energy selling to the grid is 94% and the contribution of energy sending to fulfil load demand is 6%, which is good for the profitable business for the hybrid energy system. However, the most viable configuration of the proposed hybrid system also generates 8,316 kWh/year of excess energy. Table 8 shows the emission summary of the proposed hybrid system which indicates that the contribution of carbon dioxide is highest as compared to other pollutants. From Figures 12 and 23, it is clear that the pumped storage system plays a crucial role in fulfilling the electric load demand during the hours of both day and night time. In addition, the pumped storage system has autonomy of 0.406 hours as well as 20,012 kWh/year of energy is lost during energy stored in the form of water. Figure 13 indicates details of yearly cash flow of each component of the proposed hybrid system throughout the lifetime of the proposed hybrid system, which helps to understand the earnings and spending throughout the lifetime of the proposed hybrid system. From Figure 8, it is clear the monthly average electric power production of hydro is not good in January, February, March, April, June, and July but the total monthly average power production of these months is good due to the presence of solar power and bio-power. From Figure 8, it is clear that the contribution of bio-power is lowest as it is designed to generate power for 8 hours only at night. These scenarios of solar power, hydropower and bio-power are again verified from Figures 9, 10, 11, 15, 16 and 17. This paper furthermore contains a twenty-four case study analysis to understand all the different circumstances that the proposed hybrid energy system could face using Figures 26, 27, 28 and 29. From these results, it is clear that the proposed hybrid system successfully supply cost-effective, reliable and continuous power in changed climatic conditions of Tripura. The results of the proposed hybrid system also indicate that the proposed hybrid system successfully utilising solar and bio-power with hydropower for maintaining continuity of power supply. This shows its capability of solving the problem of low power generation of the hydroelectric plant due to the less availability of water in the reservoir during the lean season. The excess energy generated from this hybrid system helps to reduce the contribution of nearby thermal power plants. Due to the presence of backup grid connection, pumped hydro storage system and biomass gasifier system, risk of not maintaining continuity of power supply now reduces to a very low value.

7 Conclusions

The overall conclusion of this analysis is that the problem of not producing good amount of power consistently for the entire year of Gumti hydroelectric plant can be solved using a grid-connected solar-biomass-hydro-based hybrid system with pumped storage system in such a way that it can supply cost-effective, reliable and continuous power in changed climatic conditions of Tripura. This study includes optimisation analysis by utilising real-time data of renewable energy sources, which help us to understand the extent of power generation and its cost of energy. Results of this study indicate that a hybrid system is a viable option as compared to a single hydroelectric plant and it is capable to maintain the continuity of power supply. The results also indicate that the proposed hybrid energy system successfully fulfil the load demand and sell the surplus energy to grid efficiently. Moreover, it proficiently manages the storage energy of pumped storage system, which increases the overall effectiveness of the proposed hybrid energy system.

The proposed hybrid system does not purchase energy from the grid during the lifetime. However, the proposed hybrid system produces some emissions of greenhouse gases due to the utilisation of biomass power plant. But, these emissions of greenhouse gases are not very high. Therefore, the proposed hybrid system is not only profitable but also environment-friendly to some extent. Consequently, the proposed hybrid system has the capability of solving the problem of low power generation of the hydroelectric plant due to the less availability of water in the reservoir during the lean season. Due to the presence of backup grid connection, pumped hydro storage system and biomass gasifier system, the risk of not maintaining continuity of power supply now reduces to a very low value. The present work can be further extended by utilising the same procedure to other small hydroelectric plants, where the power generation of hydroelectric plant is not consistent throughout the year due to decreasing precipitation trend.

References

24X7 Power for All Tripura (2019) [online] https://powermin.nic.in/sites/default/files/uploads/joint_initiative_of_govt_of_india_and_tripura.pdf (accessed 20 July 2019).

Ahmed, O.Y., Ries, M.J. and Northrop, W.F. (2019) 'Emissions factors from distributed, small-scale biomass gasification power generation: comparison to open burning and large-scale biomass power generation', *Atmospheric Environment*, Vol. 200, pp.221–227, https://doi.org/10.1016/j.atmosenv.2018.12.024.

Bhakta, S., Mukherjee, V. and Shaw, B. (2015) 'Techno-economic analysis of standalone photovoltaic/wind hybrid system for application in isolated hamlets of North-East India', *Journal of Renewable and Sustainable Energy*, Vol. 7, No. 2, pp.023126-1–023126-15.

Bhattacharjee, S. and Acharya, S. (2015) 'PV-wind hybrid power option for a low wind topography', *Energy Conversion and Management*, Vol. 89, pp.942–954, https://doi.org/10.1016/j.enconman.2014.10.065.

Bhattacharjee, S. and Bhakta, S. (2013) 'Analysis of system performance indices of PV generator in a cloudburst precinct', *Sustainable Energy Technologies and Assessments*, Vol. 4, pp.62–71, https://doi.org/10.1016/j.seta.2013.10.003.

Bhattacharjee, S. and Nandi, C. (2019) 'Implementation of Industrial internet of things in the renewable energy sector', *The Internet of Things in the Industrial Sector*, pp.223–259, Springer.

Bhattacharjee, S. and Nandi, C. (2020a) 'Design of a smart energy management controller for hybrid energy system to promote clean energy', *Advances in Greener Energy Technologies, Green Energy and Technology, Springer*, Singapore, pp.527–563.

Bhattacharjee, S. and Nandi, C. (2020b) 'Design of an industrial internet of things-enabled energy management system of grid-connected solar-wind hybrid system-based battery swapping charging station for electric vehicle', *Application of Internet of Things, Lecture Notes in Network and Systems*, pp.1–14, Springer, Singapore.

Bhattacharjee, S. and Nandi, C. (2020c) 'Technical, economic, feasibility and comparative analysis of three different configurations of energy system to control intermittency of renewable energy', *Proceedings of 2nd International Conference on Information systems & Management science (ISMS), SSRN Electronic Journal*, pp.117–124.

Bhattacharjee, S. and Nayak, P.K. (2019) 'PV-pumped energy storage option for convalescing performance of hydroelectric station under declining precipitation trend', *Renewable Energy*, Vol. 135, pp.288–302.

Bhattacharjee, S., Chakraborty, S. and Nandi, C. (2020a) 'An optimization case study of hybrid energy system in four different regions of India', *Advances in Greener Energy Technologies, Green Energy and Technology*, pp.399–437, Springer, Singapore.

Bhattacharjee, S., Das, U., Chowdhury, M. and Nandi, C. (2020b) 'Role of hybrid energy system in reducing effects of climate change', *Dynamics of Energy, Environment and Economy, Lecture Notes in Energy*, pp.115–138, Springer, Switzerland.

Bhattacharjee, S., Nandi, C. and Reang, S. (2018) 'Intelligent energy management controller for hybrid system', *Proceedings of 3rd International Conference for Convergence in Technology (I2CT)*, pp.1–7, IEEE.

Biomass Resource Potential in Tripura (2019) [online] https://biomasspower.gov.in/tripura.php (accessed 15 July 2019).

Dore, M.H. (2005) 'Climate change and changes in global precipitation patterns: what do we know?', *Environment international*, Vol. 31, No. 8, pp.1167–1181.

Hiloidhari, M., Baruah, D.C., Kumari, M., Kumari, S. and Thakur, I.S. (2019) 'Prospect and potential of biomass power to mitigate climate change: a case study in India', *Journal of Cleaner Production*, Vol. 220, pp.931–944, https://doi.org/10.1016/j.jclepro.2019.02.194.

HOMER Energy (2019) [online] https://www.homerenergy.com/ (accessed 20 July 2019).

Kassam, A. (2019) *HOMER Software Training Guide for Renewable Energy Base Station Design*, Green Power for Mobile [online] https://www.gsma.com/mobilefordevelopment/wp-content/uploads/2012/06/HOMER-Software-Training-Guide-June-2011.pdf (accessed 29 September 2019).

Kumar, V., Jain, S.K. and Singh, Y. (2010) 'Analysis of long-term rainfall trends in India', *Hydrological Sciences Journal*, Vol. 55, No. 4, pp.484–96.

Nandi, C., Bhattacharjee, S. and Chakraborty, S. (2019) 'Climate change and energy dynamics with solutions: a case study in Egypt', *Climate Change and Energy Dynamics in the Middle East, Understanding Complex Systems*, pp.225–257, Springer, Switzerland.

Nandi, C., Bhattacharjee, S. and Reang, S. (2018) 'An optimization case study of hybrid energy system based charging station for electric vehicle on Mettur, Tamil Nadu', *International Journal of Advanced Scientific Research and Management*, Vol. 3, No. 11, pp.225–231.

NASA Prediction of Worldwide Energy Resources (2019) [online] https://power.larc.nasa.gov/ (accessed 15 July 2018).

Patel, A.M. and Singal, S.K. (2018) 'Economic analysis of integrated renewable energy system for electrification of remote rural area having scattered population', *International Journal of Renewable Energy Research*, Vol. 8, No. 1, pp.523–539.

The Electricity Storage Association (2019) [online] https://energystorage.org (accessed 19 September 2019).

Trenberth, K.E. (2011) 'Changes in precipitation with climate change', *Climate Research*, Vol. 47, No. 1, pp.123–138.