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Feasibility assessment of renewable energy resources for tea plantation and industry in India - A review

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ABSTRACT

In tea production, India ranks second largest in the world, after China. Indian tea industry is one of the largest in the world and with over 13,000 gardens and produces 1350 million kg of tea leaves. Tea production and processing require electrical and thermal energy in various processes such as irrigation, withering, rolling, fermentation, drying, sorting/grading, and packaging. To produce one kg of tea requires thermal and electrical energy in the range of 4.45–6.84 kWh and 0.4–0.7 kWh respectively. In tea gardens, diesel generators are commonly used for irrigational needs in off-grid areas. In tea industry, fossil fuels such as coal, low sulphur diesel are mostly used to encounter the thermal energy needs and these energy sources heavily pollute the environment. This is a serious cause of concern for all including national and international agencies. These conventional fuels may be replaced by suitable renewable energy resources to meet the energy demand of tea plantations and industries. The identification of suitable renewable energy technologies to satisfy the energy requirement of both tea plantation and industry for north-eastern states and the southern part of India are reviewed extensively and the technological barriers are delineated.

1. Introduction

India enjoys an ace position in the production of black tea. The growth and production of tea have been reported higher than other plantation crops in the country (Table 1). After water, the most sought and consumed drink is tea [1]. Over the past decades, production and consumption of tea have increased steadily and its production became one of the economic pillars of the countries like China, India, Sri Lanka, and Kenya [2]. An ever increasing energy demand and depletion of non-renewable energy sources will shortly result in the reduction of energy resources by 2030s–40s [3]. The major challenges that are related to the usage of conventional energy sources are the extent of pollution, greenhouse gas emission in the environment, etc. The sector-wise emissions of greenhouse gas in the world during the years 1990–2015 are represented in Table 2. The major contribution of CO_2 emissions is electricity and heat production areas as compared to manufacturing and other sectors [4].

Electricity is required for the plantation as well as tea production. In plantations, electricity is required for several agricultural practices mainly for irrigation and in the case of tea production, it is required to operate the machinery. Thermal energy (heat) is required only in tea industries for moisture removal from the tea leaves during withering and drying. Tables 1 and 3 represent the comparative energy requirements among the key plantation crops and it reveals that tea plantation crops require the highest energy as compared to rubber and coffee. The tea cultivation and industry require 0.679 kWh of electrical energy and 28.39 MJ of thermal energy for producing one kg of tea [5]. In tea plantations and industries, conventional fuels such as coal, diesel are used to meet their energy requirements and these energy sources pollute the environment. These conventional fuels may be replaced by suitable renewable energy resources to encounter the energy demand in tea plantations and industries. The main objectives of this manuscript are to explore the feasibility of renewable energy sources to satisfy the energy requirement of tea plantations and industries, and challenges involved in the implementation of the same.

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Nomenclature

Abbreviations

AC	Alternating Current
C	Cost
CFA	Central Finance Assistance
CTC	Crush, Tear, Curl
DC	Direct Current
DPR	Detailed Project Report
DSI	Detailed Survey & Investigation
FPO	Farmer Producer Organisations
GDP	Gross Domestic Product
HTF	Heat Transfer Fluid
ha	Hectare
LCoE	Levelised Cost of Electricity
LF	Levelising Factor
MPPT	Maximum Power Point Tracking
MT	Metric Tonnes
NPV	Net Present Value
PG	Power Generation
PV	Photovoltaic
REPP	Renewable Energy Power Plants
RPG	Renewable Power Generator
SHP	Small Hydro Power

Superscripts

lt	Life Time
n	No. of years

Subscripts

aux	Auxiliary
Cap	Capital
e	Equivalent Discount Rate
eff	Effective
FCap	Fixed Capital
FOM	Fixed Operational Maintenance
LOM	Levelised Operational and Maintenance
OM	Operational and Maintenance
VOM	Variable Operational Maintenance

Table 1
Production of Rubber, Coffee and Tea in India (in million kg).

Year/Plantation crops	2015–2016	2016–2017	2017–2018	2018–2019
Rubber [6]	558.9	584.6	612	640
Coffee [7]	348	312	316	319.5
Tea [8]	1208.66	1267.36	1321.76	1338.63

2. History of tea

Tea (*Camellia Sinensis)* is native to China. Since pre-historic times, tea has been cultivated in that country. A legend from China named as Shen-Nung discovered the tea in 2732 BC, when the leaves from fierce tea bush accidently dropped into boiling water in a vessel. Later, an indigenous species of tea plant was discovered throughout the North-eastern region of India and primarily in Assam. These species were propagated throughout South East Asia. Tea was introduced in Java and India around 1835 and cultivation in Sri Lanka began in the 1870s. Further, it has spread from South East Asia to many tropical and sub-tropical regions in the world. Since 1891, Tea is a cash crop in Malawi, South Africa. In 1920s, tea emerged as a profit-oriented plantation in East African countries namely Zimbabwe, Uganda, Kenya and Tanzania. Also, tea is planted in the hilly areas of Mozambique, Zaire, Ethiopia, and Cameroon and on the islands of Mauritius, and St. Helena. It is also planted in Papua, Fuji, South America, Pacific region of Australia, Iran, Georgia, and Turkey in western Asia. Numerous livelihoods depend on tea cultivation and the production of tea plays a key economic role in countries like China, India, Sri Lanka, Kenya, and Bangladesh which accounts for around 80% of world tea production [11]. In India, tea is an important cash crop in north-eastern states. The productivity of the tea gets affected if the average atmospheric temperature goes greater than 26.6 °C. The drought intensity does not affect productivity but the increase in average temperature and global warming leads to a decrease in the yield [12].

Table 3
Energy required for the production of plantation crops.

Types of crops	Energy requirement for production	
	Electrical Energy (kWh/kg)	Heat Energy (MJ/kg)
Rubber [9]	0.596	2.019
Coffee [10]	0.264	27.78
Tea [5]	0.679	28.39

2.1. Tea cultivation and production in India

India ranks second among the tea production countries across the

Table 4
World tea production (in million kg) [14].

Country	2014	2015	2016	2017	2018
China	2095.72	2249.00	2404.95	2496.41	2616.00
India	1207.31	1208.66	1267.36	1321.76	1338.63
Kenya	445.11	399.21	473.01	439.86	493.00
Sri Lanka	338.03	328.96	292.57	307.72	304.01
Vietnam	175.00	170.00	180.00	175.00	163.00
Indonesia	144.37	132.62	137.02	134.00	131.00
Others	803.43	796.43	818.73	823.24	851.01
Total	5208.97	5284.88	5573.64	5697.99	5896.65

Table 2
Sector-wise carbon dioxide emissions (CO_2 equivalent) in the world over the years (MT) [4].

Year/ Sector	Electricity and heat producers	Other energy industries	Industry	Transport	Residential	Commercial and public services	Agriculture	Fishing	Final consumption not elsewhere specified
1990	7625	977	3959	4595	1832	774	398	18	342
1995	8169	1071	3943	5018	1848	727	402	18	192
2000	9364	1186	3882	5757	1827	705	340	19	158
2005	10979	1395	4945	6473	1898	783	397	24	181
2010	12527	1634	6102	6992	1886	815	394	22	199
2015	13405	1653	6361	7702	1850	832	413	20	195

World as illustrated in Table 4. Tea is a cash crop and is usually grown in moderately hot and humid climate. Tea contributes about 1% of GDP and its growth in different parts of the country is depicted in Fig. 1 [13]. Dark green regions in Fig. 1 show high production area and light green regions show low production area. Assam is the single largest tea-growing state in the world producing 57% of India's tea production and providing one of the finest black tea in the World. Tea industries provide sectoral employment in remote and rural areas. The tea cultivation covers 636,557 ha, that consists of both big and small growers across India, as represented in Table 5.

The tea production involves the preparation of seed nursery for growing new tea bushes, cultivation and agricultural practices, pruning and plucking, etc. These processes are energy consuming in the form of manpower. The irrigation for tea bushes is one of the major causes for the utilization of fossil fuels in the tea plantation. Diesel pump set is used for irrigation in off-grid areas. The post-harvest processing for black tea involves withering, rolling, fermentation, drying, sorting/grading, and packing. In India, most of the factories are manufacturing tea by Crush, Tear and Curl (CTC) method. CTC is a method of preparing black tea in which tea leaves are moved through a sequence of cylindrical rollers with saw toothed blades that crush, tear, and curl the tea into small, even-shaped mass. The operating temperature and moisture content of each process maintained in CTC tea manufacturing process are listed in Table 6. The processing steps consume both thermal (heat) and electrical energy. Withering and drying processes consume heat and in almost all stages of processing, electrical energy is required.

3. Tea industries in India: current trends and future perspectives

Globally tea is growing in over 35 countries and India holds second position in the tea production [16]. It is apparent from Tables 7 and 8, the export of tea from India progressively increasing every year. In India, 85% of households are consuming tea and 27% of tea consumed across the world is produced by Indian tea industries. In India, people consume 75% of the tea produced in India. Recent facts on the tea industry show that export was increased by 5.7% in 2017 [17]. Assam ranked first which contributes more than 50% of tea production in India. The tea industry employs more than 6.85 lakh people in Assam and it contributes as the major economic status to the state [18]. The growth rate of industries in Assam decreases due to rising in the production cost and a

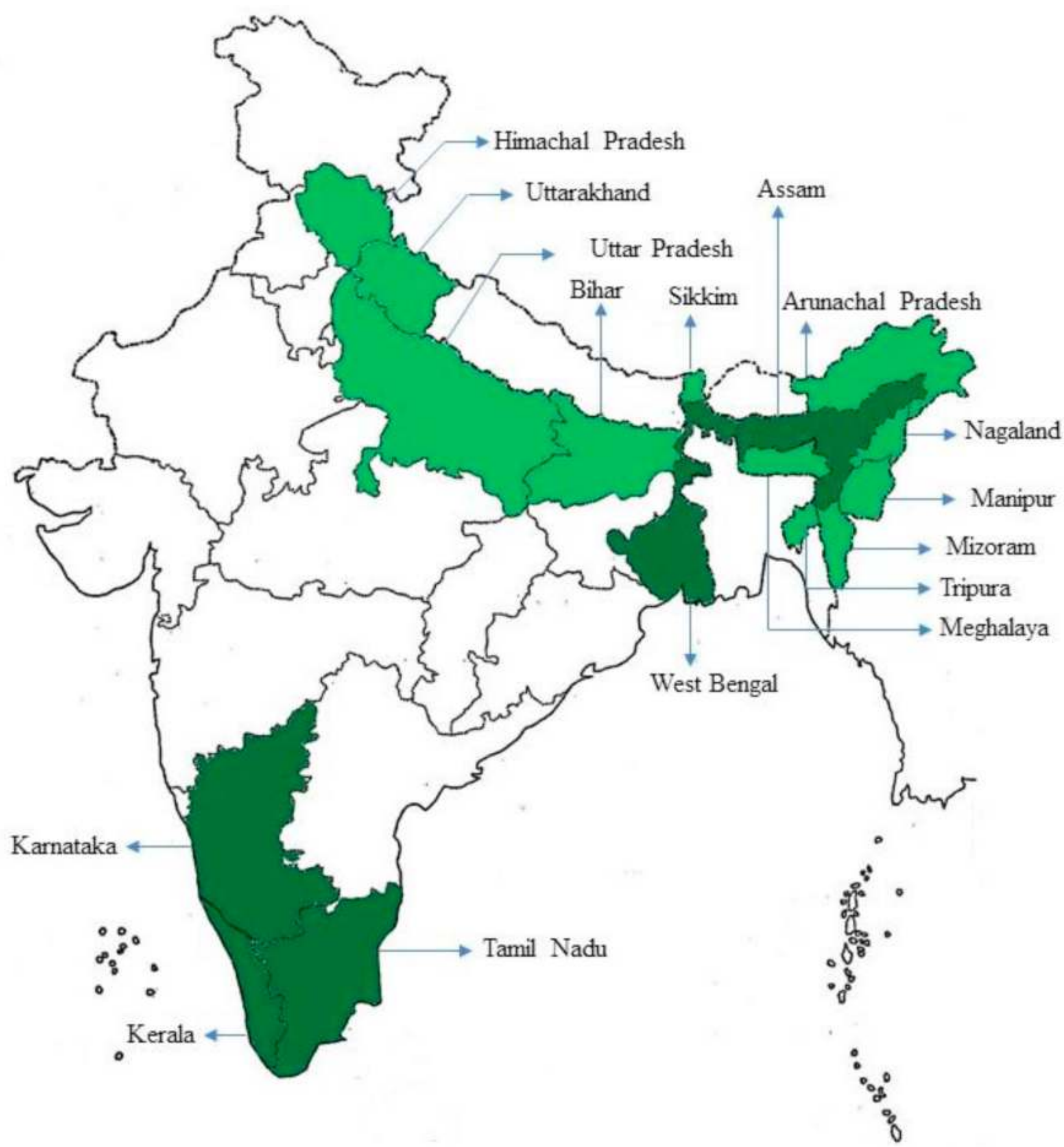

Fig. 1. Tea Growing States in India. (* Dark green regions show high production area and light green regions show low production area).

Table 5
State-wise tea growers in India [9].

State	Big Growers		Small Growers		Total	
	No. of Growers	Area (in ha)	No. of Growers	Area (in ha)	No. of Growers	Area (in ha)
Assam	765	232399.35	101085	105291	101850	337690.35
West Bengal	451	114410.47	37365	33711.27	37816	148121.74
Others North India	111	11785.09	17513	38031.86	17624	49816.95
North India	**1327**	**358594.91**	**155963**	**177034.13**	**157290**	**535629.04**
Tamil Nadu	133	29600.56	45765	33284.57	45898	62885.13
Kerala	93	30303.42	8497	5567.74	8590	35871.16
Karnataka	16	2171.74	0	0	16	2171.74
South India	**242**	**62075.72**	**54262**	**38852.31**	**54504**	**100928.03**
Across India	**1569**	**420670.63**	**210225**	**215886.44**	**211794**	**636557.07**

Table 6
Process parameters maintained in the CTC tea making process [15].

Process Order	Pre-Process	Process	Post process
1.	• Green Leaf • Moisture content >70%	**Withering:** • Time taken: 12–18 h • Spreading over the trough 30 kg/m^2	• Withered leaf • Moisture content: 58%–62%
2.	• Withered leaf • Moisture content: 58%–62%	**CTC:** • Time taken: 15 min–20 min • Leaves are cut into pieces and polyphenols/enzymes are coated over the leaf	• Wet dhool • Moisture content: 60%
3.	• Wet dhool • Moisture content: 60%	**Fermentation:** • Time taken: 60–90 min • Oxidative reaction facilitated by bacterial action and enzymes	• Wet dhool • Moisture content: 56%–58%
4.	• Wet dhool • Moisture content: 56%–58%	**Drying:** • Time taken: 10–15 min • Bacteria are killed and fermentation is stopped	• Dry dhool • Moisture content: 2%–3%
5.	• Dry dhool • Moisture content: 2%–3%	**Sorting/Grading:** • Time taken: 12–15 min • Separation of fibres and flake tea	• Dry dhool • Moisture content: 2%–3%
6.	• Dry dhool • Moisture content: 2%–3%	**Packing:** • Time taken: 30–60 s • Done to prevent moisture absorption, contamination and for easy transportation	• Dry dhool • Moisture content: 2%–3%

Table 7
Trend of the tea industry in India [20].

Year	Area (in ha)	Production (in million kg)	Export (in Crore)	Employment (Avg. No. of Labours)
1950–51	315656	278.212	80.42	948598
1960–61	330738 (4.77)	321.077 (15.40)	119.98 (49.19)	845166 (−10.90)
1970–71	354133 (7.07)	418.517 (30.34)	149.80 (24.84)	759646 (−10.11)
1980–81	381086 (7.61)	569.172 (35.99)	432.54 (188.74)	846659 (11.45)
1990–91	416269 (9.23)	720.338 (26.55)	1113.35 (157.39)	986781 (16.54)
2000–01	504366 (21.16)	846.922 (17.57)	1898.61 (70.53)	1210055 (22.62)
2010–11	579353 (14.86)	966.400 (14.10)	3058.30 (61.08)	1259950 (4.12)
2017–18	566660 (−2.19)	1321.760 (36.77)	4987.59 (63.08)	1310348 (4.12)

*Values inside the bracket indicates that % of increase or decrease in comparison with previous year.

Table 8
Tea export in India [14].

Year	Quantity (in million kg)
2014	207.44
2015	228.66
2016	222.45
2017	251.91
2018	256.06

fall in selling price [19]. The increase in energy demand due to mechanization of several processes results in a persistent rise in the cost of the tea production [20]. The compound growth rate of tea industry may be given as:

$$Compound\ Growth\ Rate = \left[\frac{End\ Value}{Initial\ Value}\right]^{\frac{1}{n}} - 1 \quad (1)$$

The compound growth rate for tea production (million kgs) and export of tea (crore) in India was found to increase by 2.5% and 4.3% respectively for every year from Table 5. This clearly shows that there is a continual increase in tea production in India.

In India, conventional fuel sources such as coal and diesel are used conventionally to generate heat for the tea industry processes. The increase in the cost of fossil fuels and the emission of greenhouse gases are the major drawbacks. This also leads to an increase in the cost of tea production. The future view of the tea industry in India is may be deploying renewable energy systems to mitigate the usage of fossil fuel resources and to minimize the cost of production.

4. Energy requirement in tea plantation and industry

An energy audit was conducted in one of the tea industry in Kerala to identify the types of energy and its requirement for the tea production process. Energy is a key input to the tea manufacturing industries. Thermal energy is required to remove the moisture content from green leaf especially in withering and drying processes and electrical energy is required in almost all the stages of operation. Withering and drying are the energy intensive processes in tea production and consume most of the energy in the form of heat. Since tea manufacturing is an energy intensive process, the required thermal and electrical energy is in the ratio 85:15 [21]. The percentage of energy consumption in different processes of withering, processing, fermentation, drying, sifting and packing are shown in Fig. 2. More than 80% of thermal energy is required for withering and drying [22]. Firewood and other biomass are also used for producing thermal energy in Southern India. Most of the factories use state grid supply to full-fill the need for electricity and

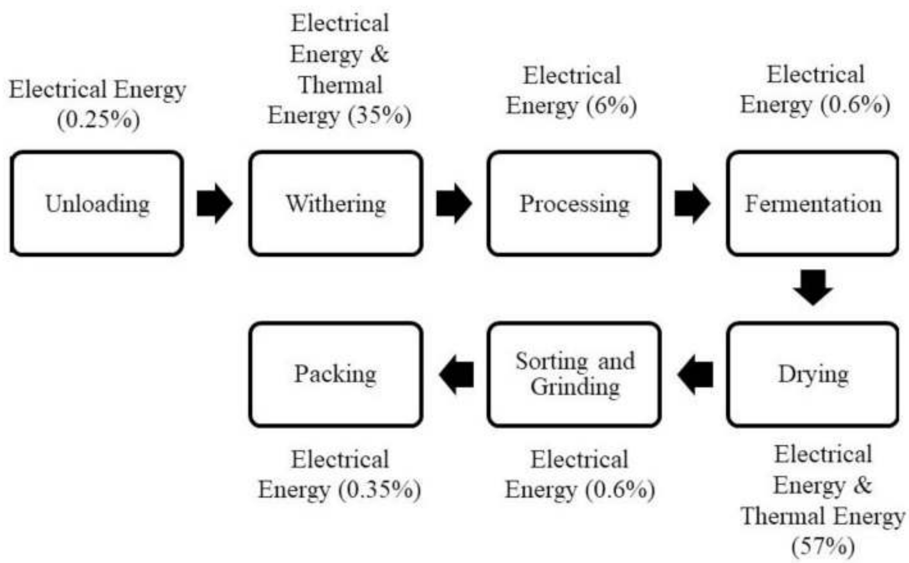

Fig. 2. Process of energy flow in the tea industry.

diesel generator is used during blackout and power cut. For every kg of tea production 3.5–6 kWh of thermal energy and 0.21–0.5 kWh of electrical energy are required. The total energy required for the production of tea in different processes such as withering, rolling, fermentation, drying, sorting/grading and packing is 0.46 kWh, 0.20 kWh, 0.07 kWh, 0.09 kWh and 0.12 kWh respectively [21]. Another energy audit was performed in tea industry in North Bengal. The amount of electrical and thermal energy consumption for 2014 and 2015 is shown in Table 9. It shows that an extensive amount of coal is used for generating process heat in the tea industry. Coal is used in the tea industry to produce thermal energy for the processes of withering and drying [5].

5. Utilization of renewable energy sources for tea plantation and tea industry

The usage of conventional fuels results in emission of the greenhouse gases in the environment that leads to global warming. The cost of conventional fuels is also increasing day by day. To mitigate the usage of conventional fuels, industrial sectors are forced to look for renewable energy resources. Renewable energy resources such as solar, wind, hydro, and biomass may be utilized to meet the energy demand of tea plantations and industries. Suitable renewable technologies may be identified based on the availability of the resources, ability to fulfill the necessity and economics. The energy requirements in tea plantations and industries vary throughout the year in both North-Eastern region and Southern India. The energy requirement for irrigation depends on the rainfall and weather conditions of the given location. In North-Eastern region and Southern India, the monsoon period starts from June to October and the winter season starts from November to February. Hence, the irrigational requirements for both the locations are from March to June. In North-Eastern region, the energy requirement for tea industry is from March to November, since from December to February is an off-season. In Southern India, the energy is required throughout the year, since it is a perennial crop. In Sri Lanka, the outcome of the assessment appears that wind energy has great potential to meet the electrical energy demand in tea industries and also integrates the additional electricity generated to the grid. The tea industries in Sri Lanka is one of the potentially energy consuming sectors from their national electricity grid. Therefore, it is a congested and deficient to commercial sectors. The feasibility study was performed to find out the optimal renewable energy technology to satisfy the energy demand in tea sector and even has the opportunity for selling the excess electricity to the grid. Solar and biomass are one of the prominent renewable energy sources in Sri Lanka as compared to hydro power. Since its investment cost is very high and not reliant throughout the year for providing persistent energy [23]. In Indonesia, the heat pipe based heat exchanger concepts were developed and tested for withering and drying process. The heat pipe heat exchanger comprises 42 pipes with 181 fins attached to it. The length and outer diameter of the heat pipe are 700 mm and 10 mm. The pipe is made up of copper and fin is made up of aluminium with a thickness of 0.105 mm and the area of 26220 m^2. Water was considered as HTF to utilize the heat from geothermal source. The temperatures can be varied from 40 to 80 °C with a mass flow rate of 18L/min. Mostly this type of heat is used for withering of tea leaves in tea industry. The effectiveness of the system ranging from 66% to 79.59% and the thermal energy produced for 1 kg of tea leaves ranges from 0.15 to 0.45 kW. The withering of green tea leaves from 80% moisture to 54% moisture takes around l2 hours [24]. Mcleod Russel is one of the leading tea producing companies in the world and its tea estates spreads across the world is 25211 ha. In 2019, the company produces 6150 million kg of tea with 3% increment in production as compared with previous years. They used to spend huge amount of their income on energy. Obviously, they are looking for an alternative which reduces the production cost. In India, 870 g of CO_2 gets emitted into atmosphere per unit generation of electricity. Mcleod Russel invested in solar energy especially in Solar PV to generate electricity for domestic needs. A 100 kW solar PV plant was erected at Attareekhat tea estate in India. It consists of 400 solar PV panels with each capacity of 250 W/module, Neo Watt Sunbird 3000 inverter system and 240 lead acid batteries with a output of 480 V. With this small initiative, the company is looking for huge investment in the future to meet the electrical energy demand [25]. Recently, the solar power plant of 3 MW capacity was built at Madurai District, Tamil Nadu to supply the generated electricity

Table 9
Electricity and coal consumption in tea industry [5].

Parameters	2014	2015	Average Value
Total tea production (in kg)	2682726	2532494	–
Total Electricity consumption (kWh/kg of made tea)	0.679	0.636	0.657
Total coal consumption (kg of coal/kg of made tea)	0.872	0.830	0.851

to The Peria Karamalai Tea & Produce Company Limited. The surplus electricity available from the power plant is connected to the grid. The power plant is spread across 26 acres consisting of 9332 solar PV modules. The annual power production from this power plant is 4.5 million units. This company also erected the wind farms in early 2000. The capacity of the wind farm is 2.3 MW (400 kW–1; 250 kW–3; 225 kW–5) and occupied a land area of 32 acres. The power generation in the last 20 years is estimated as 95 GWhr [26]. The Xishuangbanna tea garden, China installed the solar PV plant of 51 MW capacity. The Solar PV panels are mounted above the tea shrubs and it does not affect the growth of tea and make effective use of land. This plant consists of 197, 800 dual glass solar PV modules and the annual production is estimated as 80,000 MWh. Also, it mitigates the emission of 80,000 tonnes of CO_2 into the atmosphere [27]. In 2011, the installed capacity of the small hydro power plants in Kenya is 31 MW. The Kenya Tea Development Authority and private tea estates such as James Finlay and Brooke Bond own 11% of the small hydro power plants to complement the electrical energy requirements in tea industries. After their successful implementation in 2011, the Kenya Tea Development Authority planned to install more small hydro power plants of 21 MW capacity [28]. These are all some of the initiatives taken by the tea plantations and industries to utilize the renewable energy resources in their vicinity. In this section, details of various renewable energy technologies and their importance to meet the demand for electrical and thermal energy in tea plantations and industries are discussed.

5.1. *Utilization of biomass for heat requirement in tea plantation and industry*

In tea plantations and industries, there are three different types of biomass wastes, namely shade tree waste, garden waste, and tea waste from industry. Biomass can be converted into heat and electricity by using various conversion techniques. There are four ways to convert biomass into useful energy and as shown in Fig. 3. Biomass can be converted into gaseous fuels such as methane, hydrogen, and carbon monoxide and liquid fuels such as ethanol and methanol. Biomass cogeneration is the modern technology to produce heat as well as electricity by employing a gas turbine that drives the generator which produces electricity. The waste heat from the turbine is utilized by placing a heat exchanger to produce the hot air to supplement the energy demand of withering and drying. Cogenerators may tend to improve the energy usage by 80% and achieves 33–38% efficiency for electricity generation only. The cogenerators utilize 15–35% of less fuel to produce the same amount of electricity and heat as compared with the conventional method [29].

Biomass energy conversion techniques have certain demerits because of variations in the raw material (size, mass, and energy density), moisture content, and intermittent supply. To overcome this drawback, hybrid biomass/fossil fuels may be used in which fossil fuels may be used to provide the required heat during intermittent supply [30]. The most conventional method of obtaining heat from biomass is combustion. The chemical energy of biomass is converted into heat by a series of chemical reactions when the biomass is burnt. The efficiency of the combustion process depends on the biomass and amount of oxygen in the air supplied for the combustion [31].

The total bioenergy potential is the sum of biomass waste from the field, shade tree, and processed waste from the industry. The industrial tea waste data collected for six years from 2008 to 2013 in various locations at Assam are shown in Fig. 4. Based on the details given in Tables 10–12, the biomass potential in tea plantation and industry is calculated as ~3.504×10^{10} kWh. By considering the least conversion efficiency of biomass to thermal energy is 52%, the availability of thermal energy is estimated as 1.822×10^{10} kWh [32]. Hence, it accounts for 59% of the thermal energy requirement of the tea industries [33].

The energy potential of tea waste from industry and garden is estimated to be 4.47×10^7 kWh and 1.86×10^{10} kWh respectively in 2013. The comprehensive energy utilization in the tea industry was estimated as 2.24×10^9 kWh [34]. The least energy conversion efficiency of biomass to electrical energy was taken as 25% [29]. Based on the energy demand and available bio-energy potential, it is estimated that 83% of energy could be supplemented by biomass waste from the tea industry [34].

A survey and analysis of prospects of bioenergy potentials and their usage for tea industries were conducted in the Northeast region in India. Based on the study, it was found that using bamboo as feed material for the gasification process, a supplement to process heat and electricity could save $1771.18 per year. Assessment was performed on the paddy fields nearby tea industries. If tea industries could use paddy straw by direct firing system would save $14431.90 and also it could save the usage of diesel by 20% could save $196.78 [35]. The energy consumed at different stages of tea production processes in industries at Assam was calculated for 100 kg are shown in Fig. 5. It is vivid that drying consumed the maximum thermal energy and the production cost of thermal energy is about $0.10. The thermal energy of 49.75 kWh and 497.53 kWh respectively are required for withering and drying process and electrical energy of 5.54, 8.63, 6.23 and 3.95 kWh are required for withering, maceration, drying and grading process respectively [36]. In Sonitpur district (Assam, India) a lab scale experiment was conducted with hybrid renewable energy system which constitutes the solar air heater and biomass gasifier. The results showed that it assisted the conventional drying system in the tea industry by reducing the usage of fossil fuels and emission of the CO_2 into the atmosphere. The solar air heater contributes to the heating system during day time from 9:00 a.m. to 2:00 p.m. for a sunny day and producer gas is yielded from various biomass such as Indian timbers, branches of shade trees and waste from tea plants. The payback time for the hybrid renewable energy system was around one and half years [37]. The Kenyan tea development agency constitutes 5 lakh small growers and 66 tea factories. The challenges in Kenyan tea industries are high production costs, variations in market prices, persistent change in weather and spending more cost on energy. The continual increase in oil prices forces tea industries to use firewood for thermal production demand. Energy consumption impacts negatively in Kenyan tea industries. Since most of the money from the revenue was spent on electricity and firewood. Kenyan tea industries normally use 50 lakh kg of firewood to produce 432.4 million kgs of tea

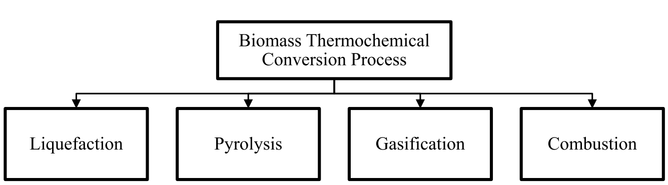

Fig. 3. Primary thermochemical conversion process of biomass [29].

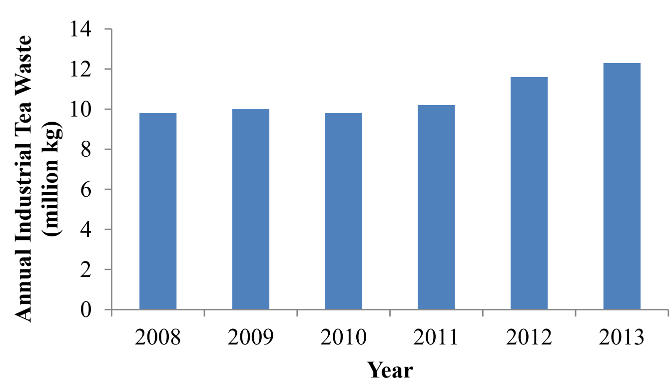

Fig. 4. Trend of industrial tea waste from 2008 to 2013 [34].

Table 10
Energy availability of garden tea bush waste.

Parameters	Value
Area of Tea plantation in India, 2014–2015 (in ha)	563980
Spacing between rows (in m)	1.05
Spacing between bushes (in m)	0.70
Area of the bush (m^2)	1.05 × 0.70 = 0.735
Bush/area (ha)	13605
No. of bushes	7.7×10^9
Field waste/bush/year (wet matter basis) (kg)	2.5
Field waste/bush/per year (dry matter basis) (kg)	1.05
Total field waste (dry matter basis) (kg)	8.085×10^9
Calorific value/kg of garden tea waste (kWh/kg)	4.302
Total energy production from garden tea waste (kWh)	3.478×10^{10}

Table 11
Energy availability of industrial tea waste.

Parameters	Value
Annual tea production in India, 2014–2015 (in million kg)	1197
Industrial processed waste (in million kg)	23.94
Calorific value (kWh/kg)	5.012
Energy potential (kWh)	11.999×10^7

to supply the essential thermal energy for withering and drying process. Later, the briquetting techniques were developed to enhance the combustion efficiency. The moisture content of less than 15% is used as raw materials for making briquettes. In case the boilers in tea industry run on 50:50 ratio of briquetted wood and firewood, it resulted in 25% saving in cost of firewood procurement. The firewood in tea industry is completely replaced by briquetted wood, it would result in 50% savings in production cost. The cost of one kg of firewood is $0.1 and briquetted wood is $0.05 [38].

Table 12
Energy availability of shade tree waste.

Parameters	Value
Total tea plantation area in India (ha)	563980
Shade/cover tree/area (m^2)	13.7 × 13.7 = 187.69 (medium covering, square)
Cover tree/area (ha)	54
Cover tree waste/tree/year (dry matter basis) (kg)	5
Total Cover tree waste (dry matter basis) (kg)	3.0455×10^7
Calorific value/kg of cover tree waste (kWh/kg)	4.555
Total energy production from cover tree waste (kWh)	1.387×10^8

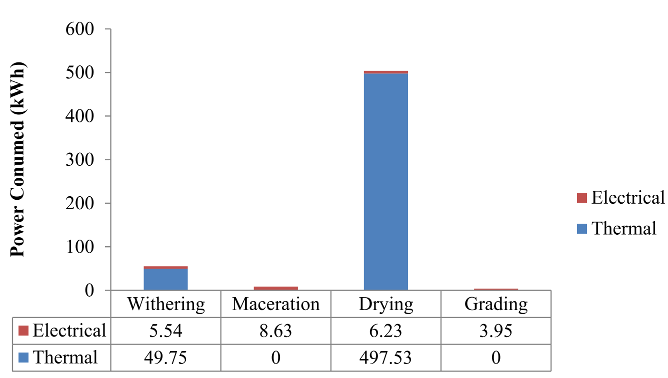

Fig. 5. Power consumption versus Process [36].

5.2. Utilization of solar energy for heat and electricity requirement in tea plantation and industry

As discussed earlier, electricity is required for irrigation in tea plantations and to operate the machinery in most of the operations in tea industries. Thermal energy (heat) is required for withering and drying processes in the tea industry. The electricity may be produced using solar photovoltaic (PV) systems and heat may be produced using solar thermal collectors.

5.2.1. Solar thermal collectors: heat demand

In solar thermal collectors, the solar irradiation incident on the absorber surface is converted into heat and it is transferred to the working fluid (heat transfer fluid). The heat carried by the heat transfer fluid (HTF) can be used to meet the energy demand in the withering and drying processes. The different types of solar thermal collectors and their indicative temperatures are represented in Table 13. The thermal energy requirement in the withering and drying processes could be meet out by the solar thermal collector. The specific thermal energy consumption for withering is 5.6 MJ/kg at 35 °C and drying is 11 MJ/kg in the range of 90 °C - 160 °C. To supplement the thermal energy requirement, a study was conducted by using flat plate solar collectors. The results revealed that 25–34% of fuel could be saved in the drying process and it could be used for re-firing of graded tea without an auxiliary source [39]. An experimental study on the drying of green tea leaves was conducted with the help of a solar-assisted drying system. The moisture content of freshly plucked tea leaves was 87% and it has to be reduced to 54%. The flow rate of air was fixed at 15.1 m^3/min and auxiliary heater was used as additional support to ensure that the inlet temperature does not allow it to fall below 50 °C. Under clear sky conditions with the mean solar radiation value of 567.4 W/m^2 and an ambient temperature of 27–34 °C could able to maintain the temperature of air in drying chamber in the range of 55–60 °C and the drying system was operated for 12 h a day. This contributes 56.3% of the thermal energy requirement in the tea industry [40].

Based on the design of the solar thermal collector, it produces excess heat during noontime due to higher solar insolation as compared to the demand of the withering and drying processes. The excess heat collected from the solar thermal collector may be stored in the buffer thermal energy storage unit and it can be used during cloudy and non-sunshine hours. The different types of thermal energy storage are depicted in Fig. 6. A roof-integrated solar collector and storage unit was developed and examined. During day time, a solar thermal collector is used to deliver the hot air and excess heat is stored in the storage unit. During cloudy or at night time, the heat stored in the storage unit was used to meet the process heat demand [41]. The schematic diagram of the integrated solar heating system with the storage unit is shown in Fig. 7. Low temperature sensible heat storage or latent heat storage system may

Table 13
Types of solar thermal collectors.

Configuration	Collector Type	Absorber Type	Concentration Ratio	Indicative Temperature Range (°C)
Stationary	Flat plate collector	Flat	1	30–90
	Evacuated tube collector	Tubular	1	50–160
	Compound parabolic concentrator	Tubular	1–5	60–240
Single Axis	Parabolic trough	Tubular	60–90	60–390
	Linear Fresnel	Tubular	50–170	150–450
Two-axis tracking	Parabolic dish	Point	100–1000	100–900
	Central receiver	Point	100–1000	300–900

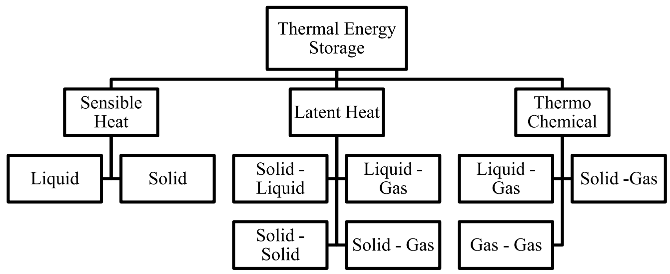

Fig. 6. Classifications of thermal energy storage [43].

be preferred as a storage unit due to its low cost and high storage density [42].

The thermal energy required for withering and drying could be accomplished by the evacuated tube solar thermal collector and it could deliver the outlet temperature in the range of 90 °C to 160 °C. Considering the mean sunshine radiation is 7–8 h per day and the thermal energy could able to supply during off time by thermal energy storage techniques. The most preferred methods for storing thermal energy are pebble bed, hot water storage, compressed hot air storage, and other sensible heat storage techniques.

5.2.2. Solar photovoltaic system: electricity demand

In the solar photovoltaic (PV) system, the PV panel converts the incident solar irradiation directly into DC electricity [41]. The charger controller is used to draw out the power produced from the PV panel and send it to the battery followed by an inverter. The inverter is used to convert the DC electricity from battery to AC electricity for end use applications in tea gardens and industries [39]. The electricity production from the Solar PV system is illustrated in Fig. 8. In off-grid areas, the irrigational requirement could be met out by deploying a suitable solar PV water pumping system. This could save the requirement of fossil fuels for diesel pump set in tea estates.

Solar water pumping works with the aid of PV panels that converts turns light energy into electrical energy to pump the water. The electricity produced from PV panels is supplied to a DC or AC motor that lifts the water from the well for irrigation. The three parameters namely power, flow, and pressure are used to set the size of the solar pump. The elevation difference between the water source and the tea field determines the work to be done by the pump [44]. The schematic diagram

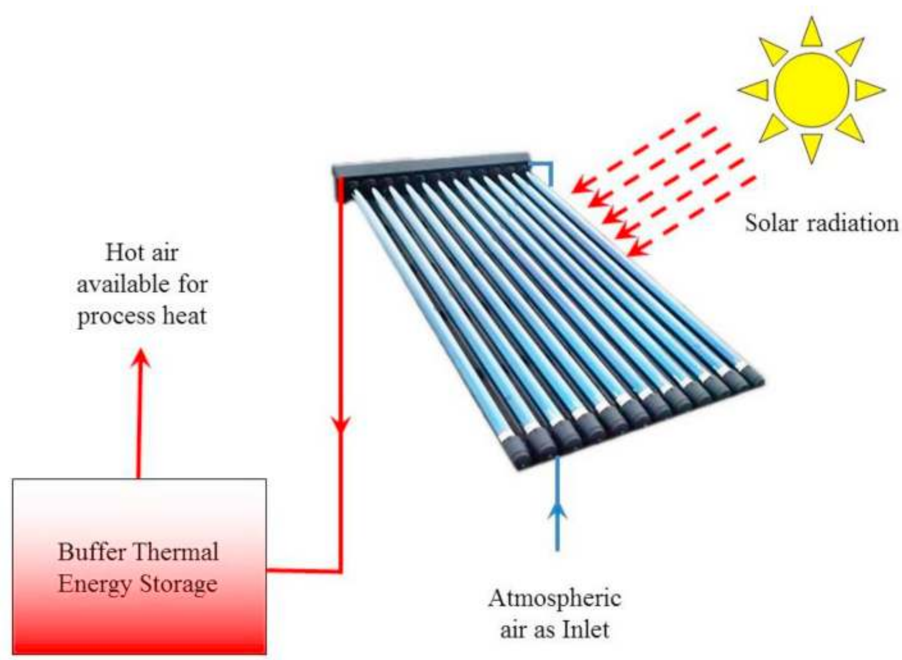

Fig. 7. Solar heating system with thermal energy storage [39].

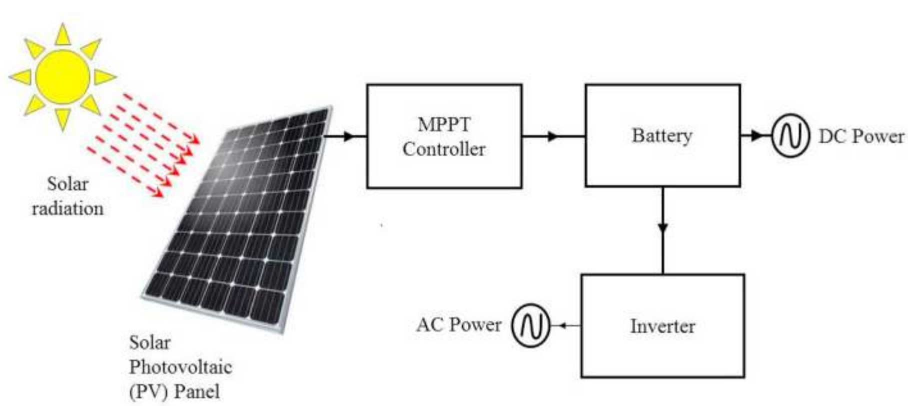

Fig. 8. Schematic solar PV system for electricity production [43].

of solar water pumping with maximum power point tracker (MPPT) is shown in Fig. 9.

5.3. Employment of wind energy system for electricity requirement in tea garden and industry

The uneven heating of atmosphere causes the temperature gradient at the earth's surface which results in the flow of air or formation of wind. The kinetic energy of the wind gets converted into mechanical energy using blades, thus rotates the rotor. The rotor is connected to the gearbox through a shaft and gearbox is connected to a generator to produce electricity. The block diagram of the wind turbine energy generation system is shown in Fig. 10.

A comparative study is conducted on different sizes of windmills 150, 250 and 600 kW in different hub heights of 20, 30, 40, 50 and 60 m. The cost of electricity was found to be 0.044 $/kWh, 0.042 $/kWh and 0.039 $/kWh respectively for 150, 250, and 600 kW wind turbines at 50 m hub height. The capacity factor of the wind turbine was varying between 28 and 45% and it is high for smaller wind machines as compared with larger wind machines [46]. Wind energy is a promising source if exact site selection would be made. Even in places with low potential of wind, once the exact location could have been identified to install the wind turbine, and then wind energy would be harvested in a profitable manner [47]. The feasibility study of the installation of a wind turbine at different altitudes of wind speed was conducted. The levelised cost of electricity (LCoE) and net present value (NPV) were found to be 0.0618 $/kWh and 0.0786 $/kWh respectively. The study concludes that a wind farm composed of 10 units of each 5 MW wind machine could save emissions of 31876 tonnes of CO_2 per year [48]. It is clear from Fig. 11, the tea industries in Southern India at an altitude of 50 m, have the possibility of harnessing wind energy. The exploration and employment of wind energy nearby tea gardens could be a supplement or fulfill the electricity need in the tea garden and industry.

5.4. Exertion of hydro power plant for electricity requirement in tea plantation and industry

In hydropower plants, the potential energy of the water is converted into electrical energy. The schematic diagram of this hydropower plant is shown in Fig. 12. Micro hydropower plants are suitable for producing power up to 200 kW in the remote areas where the electric grid is not available. There are a lot of potential areas in the hill station, canals are flowing with minimal height. The micro hydropower plant is suitable for small scale industries located in remote areas [50]. The main advantage of having a micro hydropower plant is providing better efficiency as compared with other renewable energy technologies of the same size. The variation of hydro energy sources is easily predictable. The main limitation of installing a micro hydropower plant is the site selection and

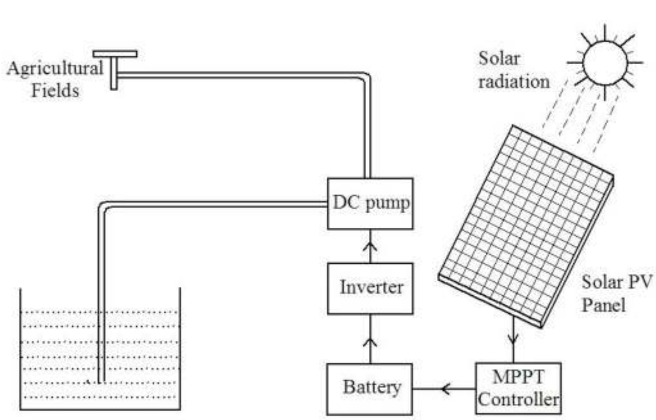

Fig. 9. Solar water pumping with MPPT system.

transmission of produced power to the end use applications/electricity grid [51].

Micro-hydro technology is a potential technique to harness the hydro energy available in smaller capacity i.e. Small rivers, streams, etc. It does not require a large reservoir to rotate the turbine. The output power of the turbine depends upon the head and water flow rate. The choice of turbine mainly depends on the pressure head and water flow rate. The impulse turbine is suitable for high head and low flow rate. Reaction turbine is suitable for medium and low head and high flow rate [53,54]. The classification of turbines used in the hydropower plant is depicted in Fig. 13. The reaction turbines are the most commonly used in micro hydropower plants [55]. If there is a resource of hydro energy near the tea garden, then micro-hydro power generation may be explored to meet the energy demand of tea garden and industry.

5.5. Economic analysis of conventional and renewable energy systems for tea production

The investigation of economics of the conventional and renewable energy systems such as solar PV, wind turbine, and micro hydropower plant for generating electricity with a fixed output of 150 kW is given below Table 14. The economic investigation of biomass and solar thermal are not discussed in this chapter, because both of them are used to provide only thermal energy requirements for the tea industry.

The levelised cost of electricity (LCoE) is given as [56]:

$$LCoE = C_{FCap} + C_{LOM} \tag{2}$$

The fixed capital cost (C_{FCap}) is given as:

$$C_{FCap} = \frac{C_{Cap}}{PG_{eff}} \tag{3}$$

Effective power generation (PG_{eff}) is given as:

$$PG_{eff} = PG_{gross} - PC_{aux} \tag{4}$$

The levelised operational and maintenance (O & M) cost (C_{LOM}) is given as:

$$C_{LOM} = LF(C_{FOM} + C_{VOM}) \tag{5}$$

The levelising factor (LF) is given by:

$$LF = \left[\frac{(1+i_e)^{lt}-1}{i_e(1+i_e)^{lt}}\right]\left[\frac{i(1+i)^{lt}}{(1+i)^{lt}-1}\right] \tag{6}$$

where d is the discount rate and d_e is the equivalent discount rate with escalation.

$$d_e = \frac{(d-e)}{(1+e)} \tag{7}$$

The fixed O & M (C_{FOM}) is given as:

$$C_{FOM} = \frac{C_{OM}}{PG_{gross}} \tag{8}$$

The variable O & M (C_{VOM}) includes the additional O & M cost other than the fixed O & M and it is given as:

$$C_{VOM} = 0.1C_{FOM} \tag{9}$$

The LCoE for Solar PV, Wind Turbine and Hydro Turbine are calculated as per norms given by Central Electricity Regulatory Commission of India. It is vivid from Table 14, the existing energy sources such as grid electricity, natural gas and diesel generator demands more cost for electricity generation per unit (kWh) as compared to renewable energy resources. Hence the deployment of renewable energy may decrease the cost of electricity generation considerably.

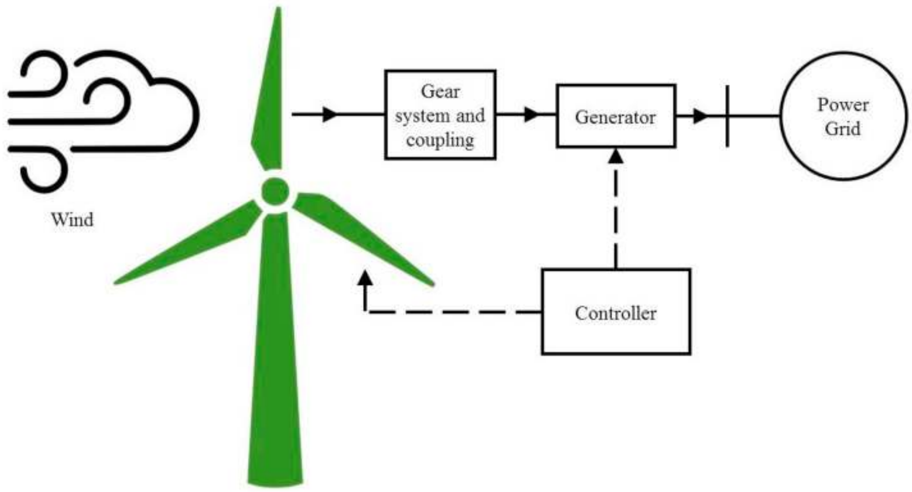

Fig. 10. Block diagram of the wind turbine system [45].

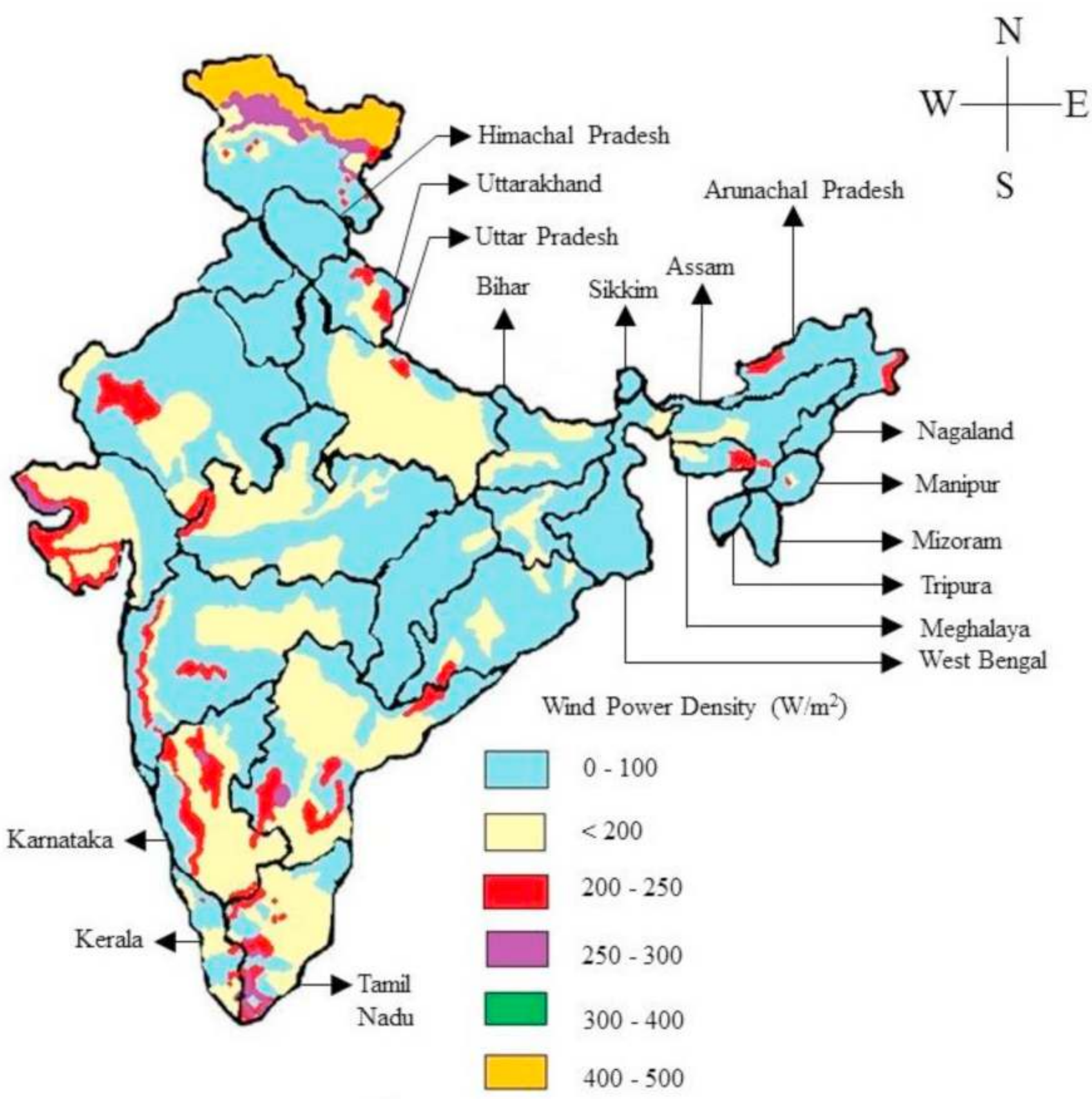

Fig. 11. Wind power potential in tea growing states in India [49].

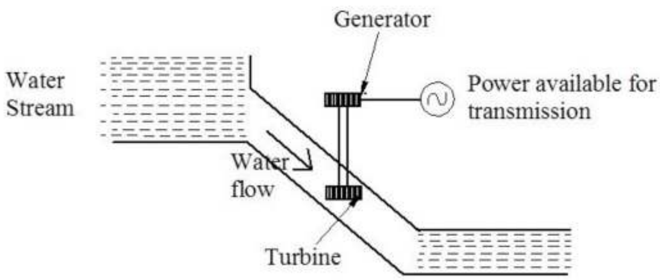

Fig. 12. Schematic of hydropower plant [52].

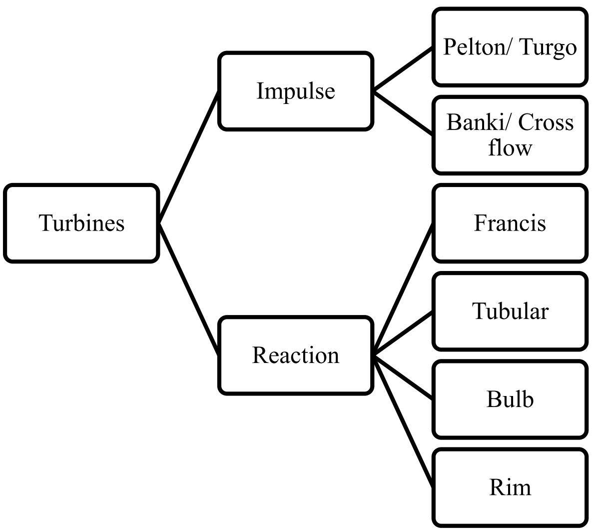

Fig. 13. Classifications of turbines for hydropower plants [55].

6. Practical barriers in utilization of renewable energy sources

There are many practical barriers to utilizing renewable energy sources in the tea industry. For a modern tea industry, environmental protection is a major problem. From the literature review, arbitrary locations in the northeast and southern India are considered as Golaghat, Assam (Latitude: 26.55°N, Longitude: 93.95°E) and Munnar in Kerala (Latitude: 24.25°N, Longitude: 76.85°E) for the analysis of renewable potential throughout the year. The detailed discussion on practical difficulties in the utilization of renewable energy sources in tea plantations and industries are presented in this section.

6.1. Challenges in direct fired biomass combustion for heat generation

Biomass is abundantly available in tea gardens and industries. Poor collection, lack of automobiles for transportation, and improper segregation of tea leaves cause the interruption in the chain supply. This creates a barrier in utilizing the energy from biomass [59]. The harvesting and transportation of biomass is an energy intensive process [60]. The harvested biomass should be stored under shed to protect it from rain, storms, and termites. Otherwise, it is subjected to biological decomposition and the content of biomass gets affected adversely. The moisture content of the stored biomass should be less than 30% for making pellets. The pre-processing of biomass before getting into the combustion chamber is also an energy intensive process. Raw feeding of biomass into the combustion chamber causes slag and formation of ash which stick on the heat transfer tube surface and results in higher thermal resistance. To avoid this, briquetting has been reported as an effective method in the pre-processing of biomass. It consumes thermal energy for drying. The moisture content in briquetted biomass leads to proficiency hindrance in combustion and more ash formation [61].

6.2. Challenges in solar energy systems for heat and electricity generation

The solar irradiance for the Golaghat and Munnar is shown in Figs. 14 and 15. In North-eastern region, factory off-season starts from December to February. Once the main growing period is over in November, the bushes have been given some time to build starch themselves. The Golaghat receives solar irradiance above 600 W/m^2 during solar noon, except in January and December. Hence, the deployment of Solar PV in Golaghat does not provide the energy interruption in working season. From Fig. 15, it is clear that Munnar has a good potential of solar irradiance (above 600 W/m^2) during the solar noon in all months. So, the deployment of Solar PV in Munnar could be a good alternative energy source for grid electricity in tea manufacturing industry.

6.2.1. Challenges in solar thermal collectors for heat generation

The process of heat generation for industrial requirements could be accomplished by deploying suitable solar thermal collectors. Among the solar thermal collectors, to meet the energy demand of the withering and drying processes, the evacuated tube solar collector is more suitable in terms of temperature requirement and economics. Since solar energy is diffused in nature (low energy intensity as compared to fossil fuels), it requires a large space to deploy and become feasible [62]. The diurnal and stochastic nature of solar energy is a major drawback. To mitigate these issues, thermal energy storage is needed to satisfy the thermal needs during cloudy and night time. The thermal energy storage system helps to capture excess energy during noontime and leads to an improvement in overall system efficiency. However, the thermal energy storage system needs additional capital cost to implement the same [63].

6.2.2. Challenges in solar PV power generation

The power output from the solar PV system is not uniform due to the fluctuation in solar irradiation. It strongly depends upon the metrological conditions. The main drawback of using the solar PV integrated with battery and inverter is their efficiency as compared with the conventional power plants. The efficiency ranges from 3 to 7% and usage of charge controller prevents the battery from overheating [64]. Another difficulty of Solar PV is that it is not able to give an immediate response to load demand [65]. The Solar PV is not able to generate power until the faulty component gets replaced/repaired [66]. High initial investment and lack of knowledge about the policies and schemes provided by the government among people is also a hindrance in Solar PV

Table 14
Cost comparison of grid electricity, natural gas, diesel power plants and renewable energy sources such as solar PV, wind, micro-hydro power plants.

Energy Source	Capital Cost ($/kW)	Operational and Maintenance Cost ($/kW/Year)	Life Time (Years)	Discount rate (%)	Levelised Cost of Electricity ($/kWh)
Grid Electricity [57]	–	–	–	–	0.337
Natural Gas Generator	36486	1805.79	5	7	0.198
Diesel Generator	33375	2271.21	5	6	0.396
Solar PV [58]	104646	8	20	4	0.039
Wind Mill [58]	158250	40	20	6	0.074
Micro Hydro [58]	197446	47.38	35	8	0.041

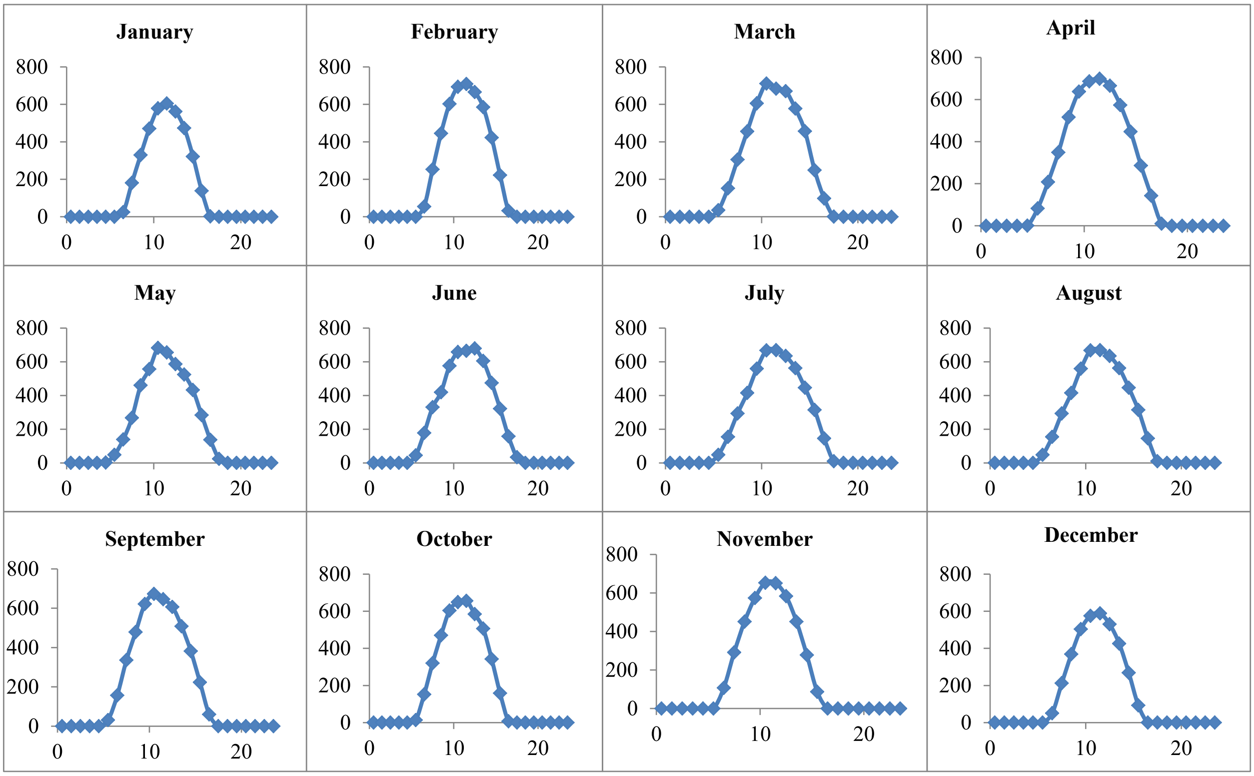

Fig. 14. Solar irradiance in Golaghat, Assam, India [x-axis represents the time in hrs; y-axis represents the solar irradiance data in W/m^2] [74].

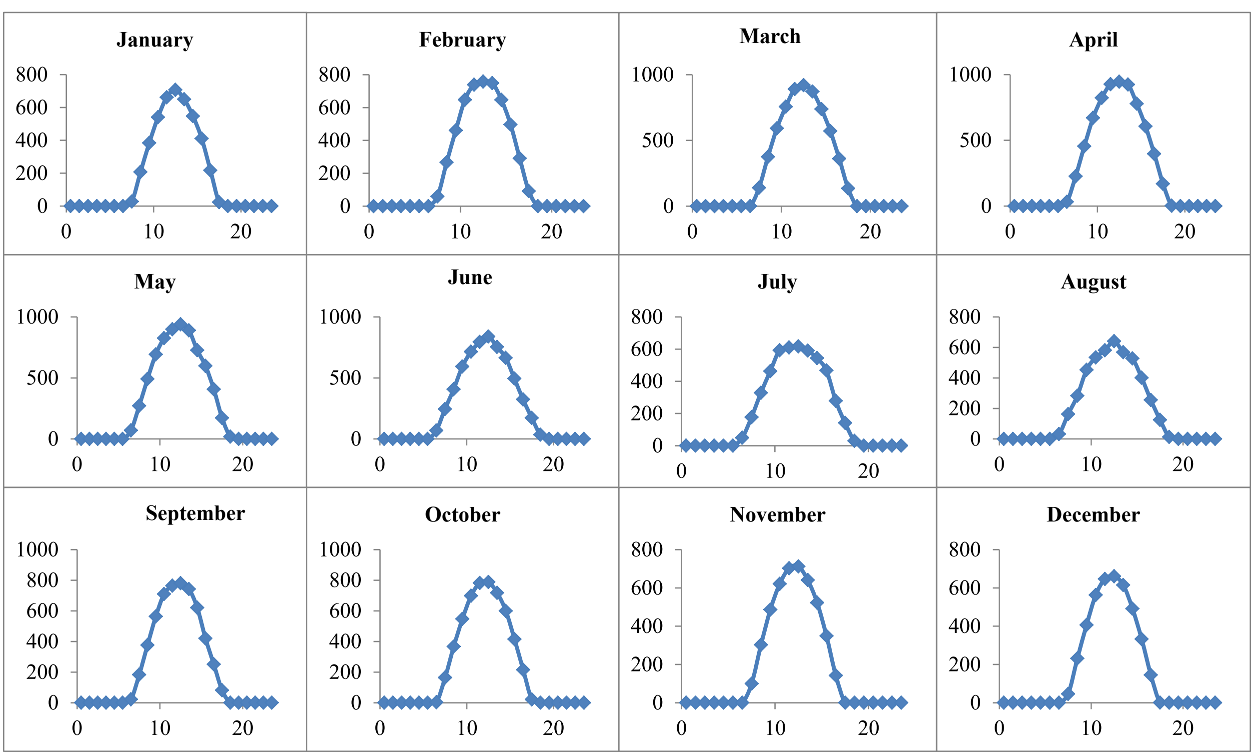

Fig. 15. Solar irradiance in Munnar, Kerala, India [x-axis represents the time in hrs; y-axis represents the solar irradiance data in W/m^2] [74].

deployment. The PV panel and batteries come under e-waste after their lifetime. The disposal and processing of e-waste is a tough task and it adds impacts to the environment [67].

6.3. *Challenges in wind power generation*

The challenges in wind power generation are appropriate site selection, fluctuation in wind speed, and economics of wind turbines for smaller capacity. The life period of the wind turbine is less as compared to the solar PV plant. The lifetime of the wind turbine may be improved by proper maintenance and strategies of the wind turbine [68]. The technical challenges with wind turbines are turbulence, controls, and turbine dynamics [69]. Economics of the wind turbine is mainly affected by the transportation of the wind turbine to the site [70]. Wind turbine also faces many difficulties during erection. It also creates a disturbance to the wildlife by direct and indirect methods. The mortality rate of birds is high in nearby wind turbine areas due to collision with blades. It also gives noise pollution by aerodynamically and mechanically. Visual effects are persuaded by shape, size, and colour of the blades. The wind turbine requires initial expenditure as 80% of the total cost as compared to solar PV power plant [71]. The Fig. 11 shows the wind power density at an altitude of 50 m and huge efforts may be required for installing a wind turbine in northeastern tea growing states. The wind density in the range of 200–300 W/m^2 is obtained in the Western Ghats of southern states such as Tamil Nadu, Kerala and Karnataka. This could be enough for implementing commercial wind turbines. The same locations are considered for the analysis of solar irradiance are taken for wind resources analysis as well. Figs. 16 and 17 shows wind potential for throughout the year at Golaghat and Munnar. It is clear from the Figs. 16 and 17 it shows that there is not enough wind speed for installing a wind turbine.

6.4. Challenges in hydro power generation

The seasonal climatic change gives an impact on water availability. Longer construction period and lack of ability to construct nearby roads are major drawbacks of using micro-hydropower plants [72]. During the summer season, the water flow rate could be drastically reduced in the canals and streams. It could not able to meet up the energy requirement in the summer season [73]. Micro hydropower plants of gravity wheeler are having low rotational speed. It requires a high ratio gearbox to produce the electricity and results in higher capital investment.

7. Research outcomes and future prospects

India is pursuing steady growth in the renewable energy sector. The objective of deploying renewable energy technologies in tea producing sectors is to diminish the usage of fossil fuels and the reduction of CO_2 emission into environment as well as the production cost. The renewable energy technologies also provides employment opportunities to local community and reduce the import of fossil fuels. The lowering of fossil fuel imports also improves the economy of the country. The total tea production for the financial year 2018–2019 in India was reported as 1338 million kgs. If high speed diesel (HSD) was used for overall production of tea in the financial year 2018–2019 and thereby replacing it with renewable energy technologies, it could save a mammoth of 517.80 million kg of carbon emission into the atmosphere. In the tea industry, individual renewable energy technologies such as biomass, solar, wind, and hydro could not able to meet the entire energy demand. Hybrid systems such as a combination of biomass and solar thermal could able to bear the thermal energy requirement. Biomass and solar energy resources are almost available in all tea growing regions. The block diagram of the proposed thermal energy utilization in the tea industry is shown in Fig. 18. The buffer thermal energy storage tank in this proposed diagram is to provides constant thermal energy output. Even though the bio-waste potential is available throughout the year, their conversion efficiency of electrical energy is low due to high moisture and low energy density. The future scope is to focus on the integration of renewable energy sources to completely mitigate the usage of conventional fuels and greenhouse gas emissions from the tea industries. Electrical energy generation by renewable energy system and its utilization in the tea industry is proposed in Fig. 19. The integration of electrical energy storage and control systems with the renewable energy system is to provide constant electrical output to the tea industry processes. Mostly, electrical energy requirement in tea industries may be met by using solar PV systems. In very few locations especially in North-Eastern part of India, the solar radiation may be inadequate from few days to months during winter for generating the desired electricity. In such a case, an alternative renewable energy sources such as biomass,

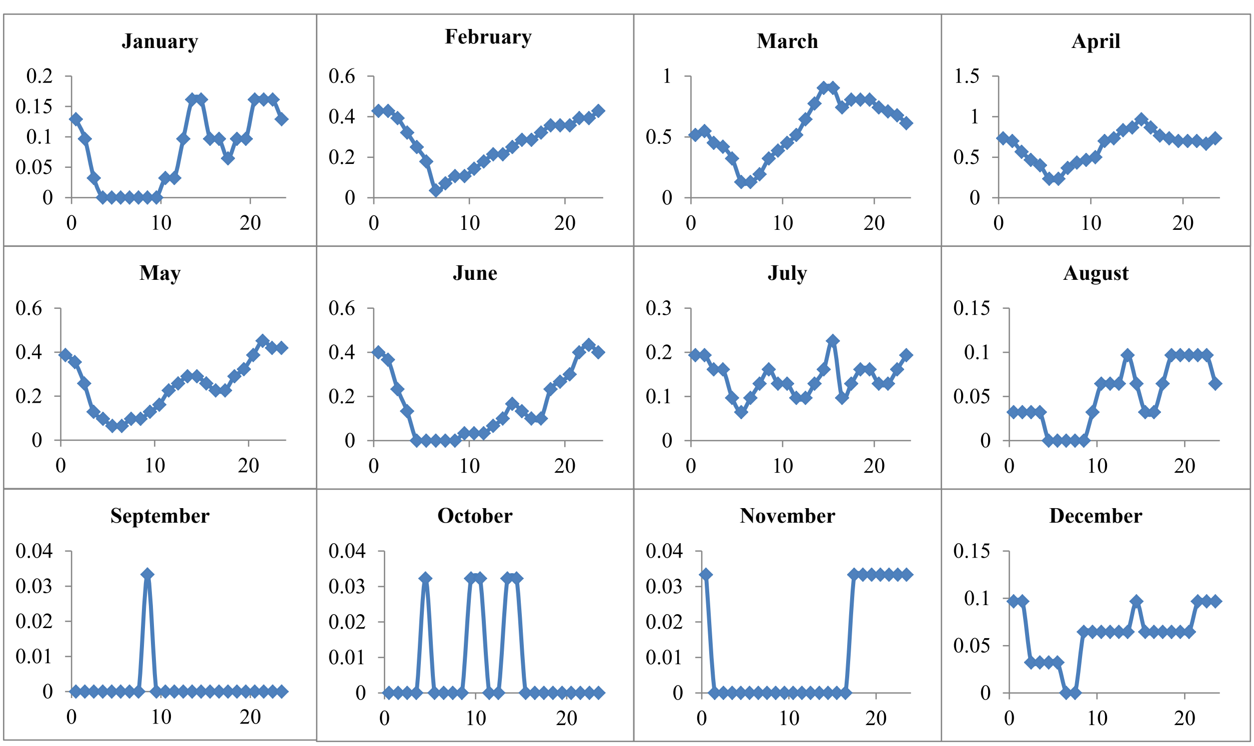

Fig. 16. Wind speed in Golaghat, Assam, India [x-axis represents the time in hrs; y-axis represents the wind speed in m/s] [74].

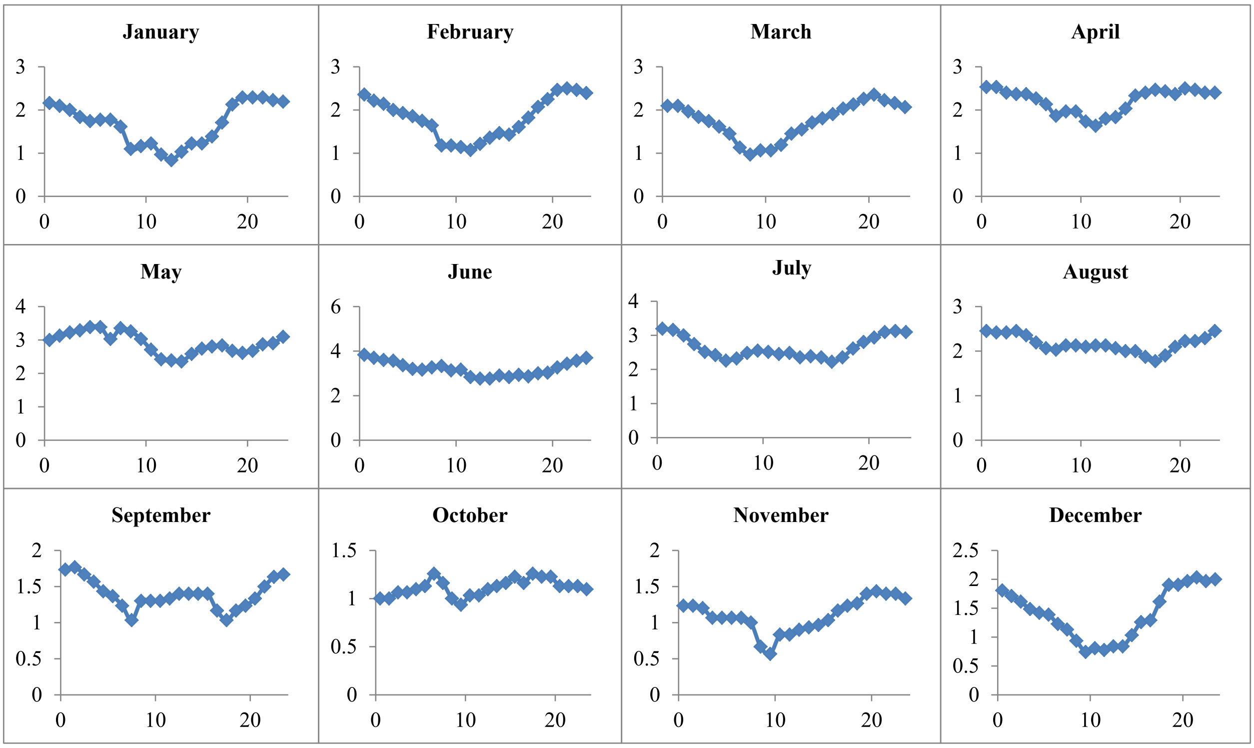

Fig. 17. Wind speed in Munnar, Kerala, India [x-axis represents the time in hrs; y-axis represents the wind speed in m/s] [74].

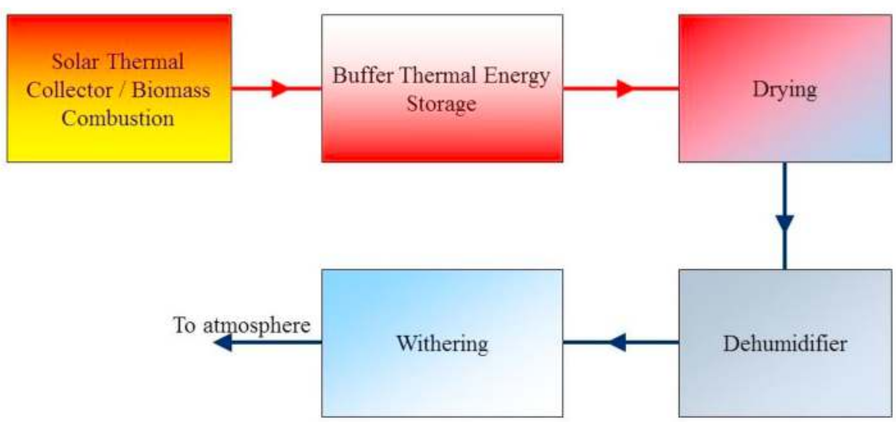

Fig. 18. Block diagram of proposed thermal energy utilization in the tea industry.

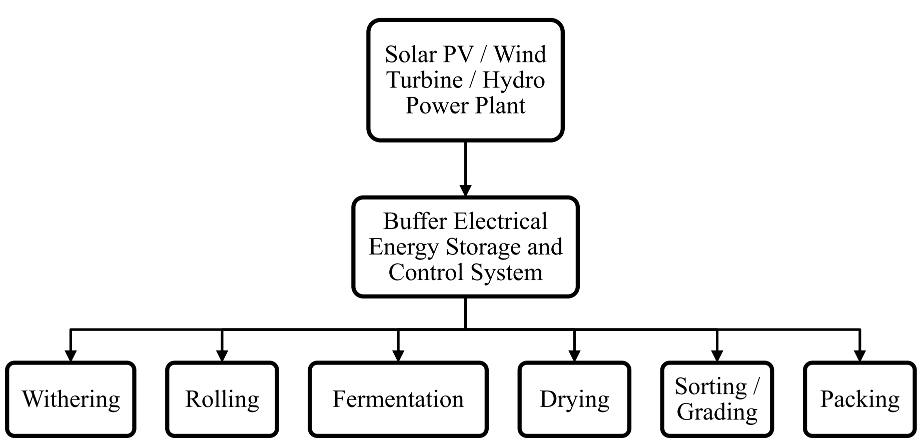

Fig. 19. Block diagram of proposed electrical energy utilization in the tea industry.

micro-hydro may be opted to meet the electrical energy demand.

8. Summary

In this article, the opportunities for renewable energy technologies to encounter the energy demand of tea plantations and industry are discussed. The freshly plucked tea leaves arrived at the tea factory has to undergo several processes to get the final product of tea. The specific thermal and electrical energy consumption is in the range of 4.45–6.84 kWh/kg and 0.4–0.7 kWh/kg of tea respectively. From the estimation of bioenergy waste from industry and garden, it could able to supplement up to 83% of the thermal energy requirement in the tea industry. Evacuated tube solar collectors could able to supply hot air in the temperature range of 90 °C to 160 °C to meet the energy demand of drying and withering processes. The solar-biomass hybrid system could be used to supply the hot air for drying and withering process throughout the day. The hot air from the evacuated tube collector can be stored in thermal energy storage systems to meet the energy requirement during cloudy and non-sunshine hours and minimize the fluctuations. The electricity consumption in the tea garden and industry could able to meet by three different sustainable renewable energy technologies such as solar PV, wind turbine, and micro-hydro power systems based on the availability of resources. Based on the analysis, it is found that solar energy may be the potential energy resource in Golaghat (Assam), and Munnar (Kerala) to satisfy the electricity requirement need as compared to other renewable energy resources. The present review prudently revealed the opportunities and challenges involved in the implementation of renewable energy technologies in the tea gardens and industries. Thus, the global tea sector has to replace the possible practices for sustainable tea production with renewable energy sources that may enhance the productivity, market value, environmental and social aspects to stay competitive. This could able to reduce the production cost of tea and strategies should be embraced to meet up the challenges in global demand for tea in the forthcoming years.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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