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Design concept and configuration of a hybrid renewable energy system for rural electrification in India through BioCPV project

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Abstract*:The quality of life of a community in a country largely depends on the per capita energy consumption. In developing countries the gap in the quality life of the urban and rural areas is severely affected by the lack of electricity in the rural areas. A large part of the rural area in India is still not connected by grid due to economical and geographical reasons. Decentralised power plants are the only option for electrification to those areas and renewable energy power plants are the most suitable option. However in current scenario the renewable energy power plants have challenges regarding the continuous supply of electricity over a day and year due to the diurnal and seasonal variation of the availability of resources. One way to solve this problem is to store the electrical energy generated; however storage leads to further challenges. The BioCPV project addresses these issues of continuous supply of electricity over the day and year by a smart integration of the different renewable technologies. The project focuses on the technological development and also sustainable development of the rural community through the energy use. One of the objectives of the project is to develop highly efficient solar, biomass and hydrogen energy technologies for rural application and to integrate these technologies. This will be the first even such kind of integration of these three renewable technologies. These technologies will be integrated with an intelligent control system for continuous supply of electricity from this kind of self-sustained renewable energy power plant. The sustainable development targets providing better environment for education, healthcare, opportunities of employment and quality lifestyle through the energy uses. The research output of the project will be demonstrated with a small scale BioCPV power plant in Kaligunj and Pearson-Pally village, approximately 200km west of Kolkata, India. The rural community of these areas will be benefited from this project for a sustainable development; while 45 households will be provided electricity. A load profile for the 45 households and the community services of the locality has been estimated to design the BioCPV system configuration.*

Keywords: Hybrid renewables, rural electrification, CPV

1. INTRODUCTION

The economic growth of a country is directly related to the per capita energy consumption and for a developing country like India the energy has become an inevitable requirement for development [1]. According to the data of census 2011, Government of India, 878 million (~80% of total population) lives in 638,000 villages, out of which 80,000 villages are without grid connected electricity supply [2]. Apart from the livelihood, power is also required for small-scale local industries in rural areas in India, which contributed significantly to the economic development. The geographical diversity and lack of proper infrastructure has become a barrier for the grid connection to the rural areas. So only the grid supply or the large-scale power generation cannot fulfil the India's future energy demand. Decentralised hybrid power plants with different renewable technologies can be the most efficient, cheap and sustainable options for rural electrification [3, 4]. The integration of different renewable technologies can complement each other to avoid energy storage requirement and at the same time intelligent integration control mechanism can enhance overall system efficiency. A hybrid renewable energy technology has been proposed with the integration of solar, biomass and hydrogen energy in a rural village in the eastern part of India.

2. BIOCPV SYSTEM DESIGN CONCEPT

Sustainable development of the rural areas with the renewable energy to bridge the gap between the urban and rural community is the key objective of the project. Sustainable renewable energy supply with the locally available energy resources can lead to the better life style in terms of healthcare, education, energy, economics and communication. The eastern part of India is rich in both solar irradiation and biomass resources [5, 6]. Due to the geographical location there is enormous solar irradiation and because of a remote area there is a lot of potential to use the biomass and waste resources which remains unused. In some semi urban areas with large community residential buildings massive food waste can be collected to generate biogas through anaerobic digestion. Monthly average of daily solar radiation shows that well designed CPV system will be sufficient to supply the required power to the community during the day time; however hybrid technologies will be the efficient way to realise the sustainable energy generation. A well estimated CPV system combined with intelligent energy storage will also eliminate the battery requirement. Generating hydrogen (and storing) during the daytime with the unused energy generated from CPV system can be an efficient integration of two renewable technologies. The energy demand during the day time in rural areas is very less than the peak demand during evening hours. During the peak demand, energy generated from the biogas can be combined with the hydrogen energy to supply the demand. The parasitic losses within the system will be compensated by recovering of the waste heat and efficient use of it in different technologies. The specification of the different renewable technologies needs to be configured based on daily load demand of the locality considering the seasonal variation of the load.

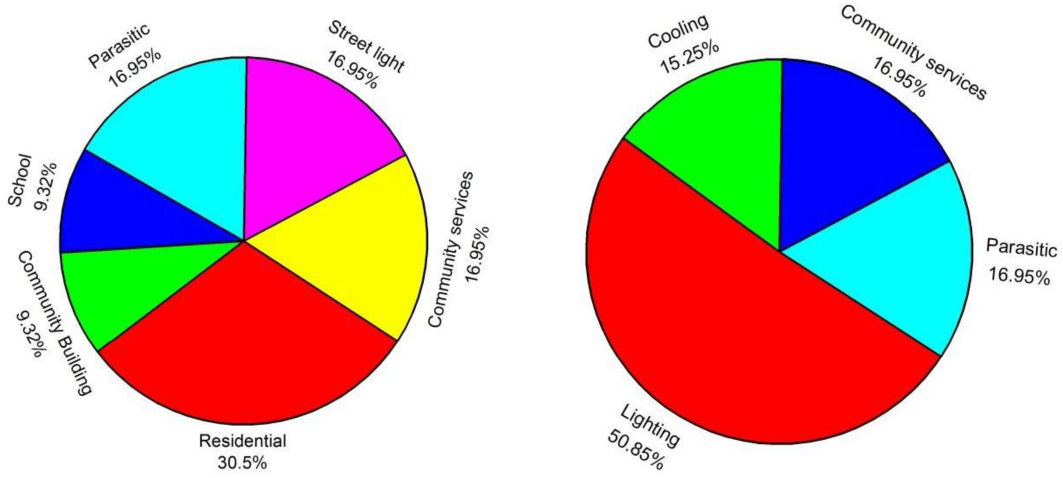
3. THE LOCATION AND THE DAILY LOAD DEMAND

Two rural villages Kaligunj and Pearson-Pally without the grid have been chosen to supply electricity through the BioCPV system by setting up a mini grid within the locality. The Kaligunj – Pearson Pally is a remote village in Bolpur-Sriniketan Block of Birbhum district in Paschim Banga, India. The village is comprised of 170 households with a population of approximately 800. All the families in the village are below poverty line as per the Government of India norms. Out of the total population 52.8% are women and sixty-four are children. The average income of each household is approx. INR 2500/- per month (£33/month). The basic facilities such as drinking water and sanitations are not available which leads to an unhygienic life-style. The houses are typical Indian village houses made up of bamboo or wood and mud. There is a basic health centres in the village; however for any better medical facility villagers have to travel up to 5 km by a non-metalled road, which is not safe especially during rainy seasons. A survey has been carried out to estimate the load demand of the households, including the communal building, schools and the load requirements for community services. The survey also includes the villagers' requirements for sustainable development with the focus on the renewable technologies; the generation of employment; efficient use of the food waste, waste biomass; health and hygiene. Based on the survey, 45 households has been chosen and the load profile has been estimated. Considering the structure of the house and life style of the rural India two lamps per household is considered. Electric fans are only considered in the communal building and in school taking into account of the scale of the project. 1kW energy has been estimated for the community services including the telephone charging stations, refrigerator in health centre etc. 20 street-light have also been considered within the locality. Table.1 shows the load considered for different sector and for different applications. The load of the component is considered based on the ratted power of the commercially available items.

Table.1Load estimation of the Kaligunj and Pearson-Pally village

User Load							
	Lighting		Lighting Load (W)	**Cooling (Fans)**		Cooling Load (W)	Total Load (W)
	Nos	Load per Item (W)		Nos	Load per Item (W)		
Domestic (45 Household)	2	20	1800	0	0	0	1800
Street Light	50	20	1000	0	0	0	1000
Community	5	20	100	9	50	450	550
School	5	20	100	9	50	450	550
Parasitic							1000
Community Services (Mobile Phone Charging station etc.)							1000
Total Load							5900

The major part of the load is for lighting in the 45 households, which is equivalent to the 30.5% of total load demand. The load demand for streetlight and the community services are each of 16.95% of the total demand, which is equivalent to 1kW each. Figure.1 shows the relative load demand of different utility sectors and the relative load demand of different applications.



(a) (b)

Figure.1 Relative load distribution with respect to the (a) utility sector (b) application

Based on the survey, the load profile for summer and winter season has been estimated, since the load demand varies significantly during different seasons as shown in figure.2 (a & b). It is found that the maximum load demand in during 18:30 – 22:00 hours during summer and during 16:30 – 22:00 hours during winter. However the peak load during summer and winter are not equal. During summer the peak load is 5.8kW, whereas during winter it is only 5.5kW. The demand in the communal building and community services lasts from 8:00hrs to 22:00hrs, whereas the streetlight will be operated during the overnight to protect the villagers from anti-social activities.

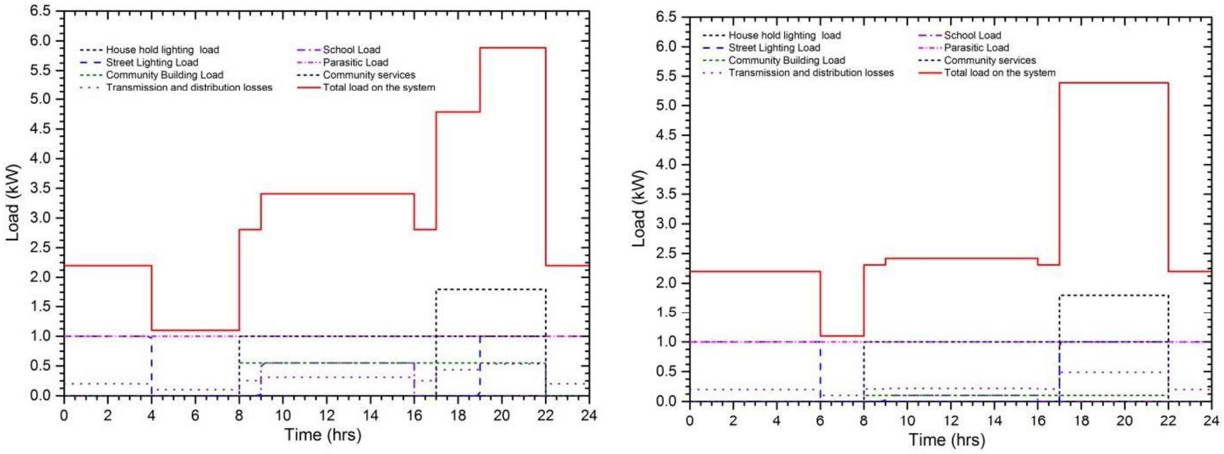


Figure.2 Diurnal load profile of the different sector of the village during (a) summer season (b) winter season

4. SYSTEM CONFIGURATION AND SPECIFICATIONS

The BioCPV configuration is designed to achieve an efficient renewable energy system with a state of the art integration mechanism to incorporate different renewable technologies. While the BioCPV system integrates highly efficient CPV, Anaerobic Digester and Hydrogen storage system to generate electricity, it also increases the overall efficiency of the integrated system by using an automated control mechanism and proper use of the low grade waste heat generated during the process. The detailed BioCPV system configuration is shown as a block diagram in figure.3.Taking into account of the load profile and the peak demand of the locality, a CPV system with rated power output 10kW is estimated. The CPV is the core system to ensure enough electrical power to supply and to store energy by producing hydrogen. CPV system has to dissipate significant amount of thermal energy while generating electricity, which also can be used in other technologies whenever required through a thermal storage system. The multijuncation solar cells that are in market come with ~40% electrical conversion efficiency while used with a high concentrating system [7]. So the rest of the 60% of the solar energy incident on the solar cell is converted into heat and can be extracted. So a maximum of 15kW thermal energy can be extracted from the 10kW (electrical) CPV system and can be used or stored as per the requirement.

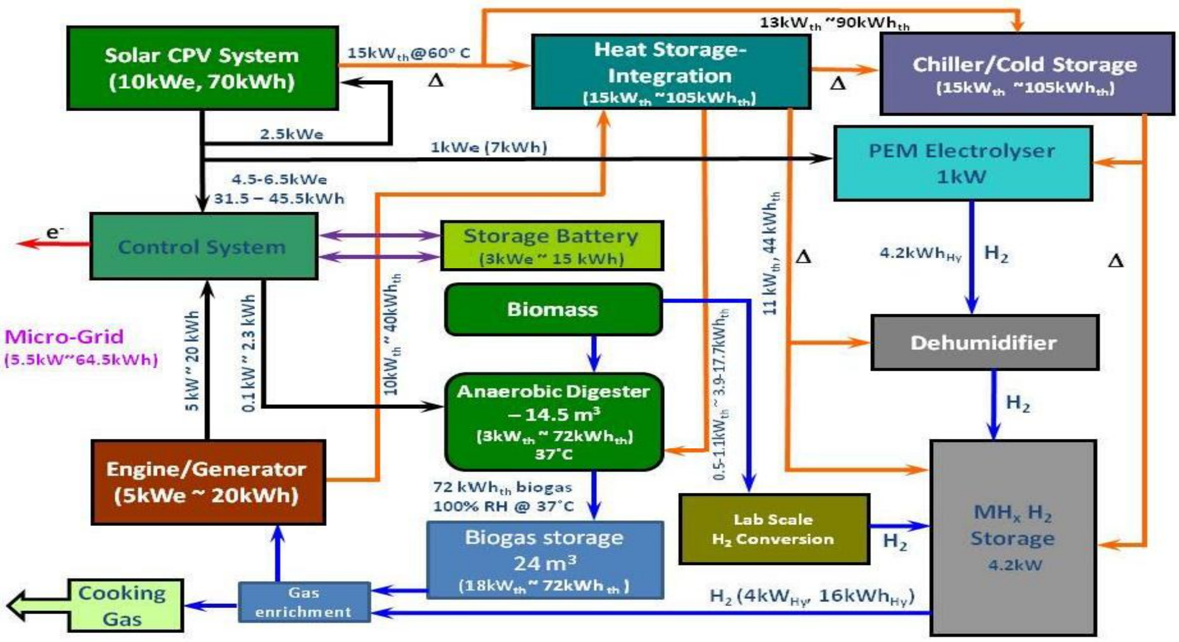


Figure.3 BioCPV system configuration with energy specification of each component

The primary specifications of the CPV, AD and Hydrogen systems are estimated based on the load demand and considering the limitations of the project. The specifications of the CPV system and the digester of the AD system are given in table.2.

The CPV system consists of four CPV units with two axis tracking. Each CPV unit consist of two primary concentrator and receiver. The primary concentrator is parabolic dish with square opening and made up of four sections to achieve an entry aperture area of $9m^2$. The receiver consist of solar cell assemble of 144 solar cells, secondary concentrator (Crossed Compound Parabolic Concentrator (CCPC)) and cooling system. The specifications of the CPV unit are given in table.2.

The digester for the AD system has been designed to meet the requirement of the daily biogas production. The efficient production of the biogas depends on the input of locally available biomass and/or feedstock, atmospheric conditions for the bacteria in the digester and regular maintenance. So the specifications of the digester are maintained for production of sufficient biogas considering all these parameters. The digester design is Continuously Stirred Tank Reactor (CSTR) type with pre-mixing tank.The digester is made of locally available material to reduce the cost.

The input power for the electrolyser is 1 kW from the CPV. The total efficiency of PEM electrolyser is 60 % and it produces about 3 litres of hydrogen per min (180 litres per hour). The total output power from the electrolyser is hydrogen power of 0.60 kW_{Hy}. Further by assuming that the electrolyser will get 1 kW power from the CPV for 7 hours during the day, the total input electrical energy for the electrolyser is 7 kWh_{ele}. With 60 % efficiency for the electrolyser, the total output hydrogen power will be 4.2 kWh_{Hy}, which is equal to 1260 litres of hydrogen.

The hydrogen storage system will be charging mode during the day for 7 hours. The system will absorb 180 litres of hydrogen per hour for 7 hours during the day. The system will desorb hydrogen, when it is required, especially during the night time for 4 hours. The efficiency of the hydrogen storage system will be 90-95 %, depends on the storage properties of the material. Hence the system will release about ~300 litres of hydrogen for 4 hours (1197 litres). 11.2 litres of hydrogen gas is equal to one mole of H, weighs 1 gram. The specification of the hydrogen storage system in the BioCPV system is given in table.3.

Table.2 Specification of the CPV system and the digester of AD system

	Parameters	Values
CPV system	Total Installation	10kW
	Number of CPV module	8
	Solar irradiance considered (DNI)	550W/m^2
	Power output of each unit	1.3kW
	Rated voltage of the each unit	216V
	Rated current of the each unit	6amp
	Area of one cell	1 cm^2 (1cm x 1cm)
	Concentration ratio	500X
	Optical efficiency	80%
	Power output of one cell	8.3W
	Area of the cell assembly (receiver) for 1.3kW system (With secondary concentrator)	580cm^2
	The concentrator entry aperture area	7.25m^2
	Opening area of the entry aperture of the primary concentrator dish	2.15m × 2.15m
Anaerobic Digester	Design	STR
	Digestion tank volume	14.7 m^3
	Digestion tank height	2.65 m
	Digestion tank diameter	2.65 m
	Design Hydraulic Retention Time (HRT)	30 days
	Design Organic Loading Rate (OLR)	2.6 kg VS m^{-3} day^{-1}
	Digester operational temperature	37 °C
	Thermal conductivity of tank walls (U)	1 W m^{-2} °C^{-1}
	Pre-mixing tank volume	1.5 m^3
	Pre-mixing tank operational temperature	Ambient

Table.3 Energy specifications of the hydrogen storage system

	Rated energy (kWh_{Hy}) (litres) (grams of H)	Input energy		Output energy		Rated output energy (kWh_{Hy}) (litres)	Efficiency	Total output energy (kWh_{Hy}) (Litres/day) (grams of H)
		Duration (hrs)	Electrical energy (kWh_{Hy}) (litres) (grams of H)	Duration (hrs)	Electrical energy (kWh_{Hy}) (litres) (grams of H)			
Hydrogen storage System	0.60 (180) (16.1)	7	4.2 (1260) (112.5)	4	4.0 (1197) (106.8)	1.0 (300) (26.8)	95 %	4.0 (1197) (106.8)

5. THERMAL ENERGY MANAGEMENT CONCEPT

This thermal energy is distributed to heat storage and to a solar chiller. The solar chiller is used to control the temperature of the metal hydride tank during the hydrogen storing process, since it's an exothermic reaction. A 15kW_{th} heat storage is estimated with a capacity of 105kWh_{th}, considering 7 hours of average sunshine on a day. The heat storage is decided to design with slightly higher specifications not to lose any thermal energy. An efficient solar chiller will be designed with maximum rated power of 15kW_{th}. As shown in figure.3, the chiller is connected to the metal hydride tank and the electrolyser and will operate through the control algorithm to regulate the temperature of these two devices.

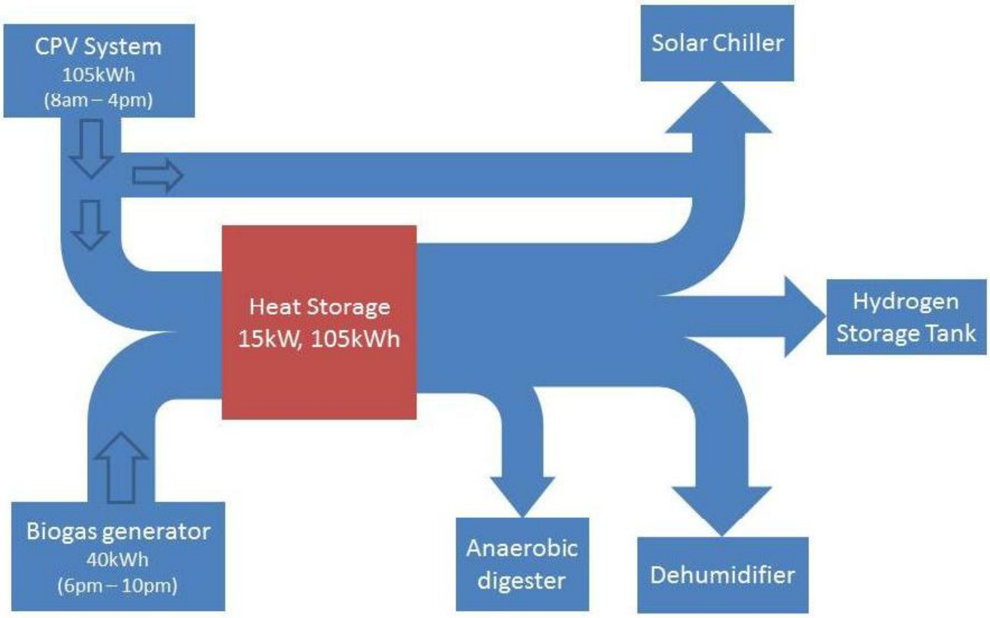


Figure.4 Thermal energy flow diagram of the BioCPV system

To maintain the input thermal energy during low irradiance, heat storage device is also connected to the chiller. The thermal energy in the heat storage can be supplied to the four devices as per the requirement: Chiller, metal-hydride storage tank, dehumidifier and anaerobic digester. The demand of the thermal energy for chiller and metal hydride has already been discussed. Dehumidifier helps in removing the water content in the hydrogen generated by the electrolyser. This results in higher efficiency of the metal hydride storage and increase the life time of the material in the storage tank. The AD system requires thermal energy to prevent thermal shock to the bacteria in the digester. Especially during the winter season while the ground temperature can even go below 10°C, it becomes important to supply the thermal energy to maintain the temperature within operating range (15-40°C) for efficient production of biogas. There is another source of thermal energy in the system; the low grade heat released by the generator while using biogas to produce electricity. $10kW_{th}$ thermal energy has been estimated from the generator, which is equivalent to $40kWh_{th}$ during its 4 hours of operation a day. This thermal energy is feed into the heat storage to use in different time. The thermal energy flow in the BioCPV system is demonstrated in the figure.4.

6. ELECTRICAL ENERGY MANAGEMENT CONCEPT

There are two sources to generate electrical energy: CPV system and electric generator using biogas as fuel. Considering the demand of the locality, the rated power of the CPV and the generator are estimated. A 10kW CPV system is capable of generating 70kWh of electrical energy on a sunny day. However there are few parasitic losses within the CPV units and in the overall BioCPV system, such as tracker, pumps, control units and losses in invertor. There are 4 units of CPV installations with rated power 2.5 kW. Each CPV unit requires 0.5kW power for tracker resulting 2kW loss when the CPV units are in operation. On a sunny day and during off peak hours 1kW power is supplied to the electrolyser to generate hydrogen from water. There are 10 pumps and compressors in the BioCPV system which are operated during the different time of the day and have different operating hours. These compressor and the pumps requires 0.5kW of power which will be supplied from the CPV or biogas generator depending on the time of operation. The power to the pumps used in cooling systems of the CPV system and the heat storage is supplied from the CPV system through control unit. This increases the efficiency of the system. During the overcast condition, while the CPV units are generating minimum power, there is no requirement cooling system as well. In this situation the pumps will be ideal saving significant amount of energy. The control system requires 0.5kW power including the invertor, battery storage and the BioCPV operation control unit. There is a 3kW battery bank with a storage capacity of 15kWh of energy. The requirement of the battery storage is to regulate the supplied power and to use during emergency circumstances. For the evening hours electrical power is generated by 5kW biogas generator. The biogas produced in the AD digester is enriched with the hydrogen to increase the efficiency of the biogas generator. The AD system is designed to produce the amount of biogas sufficient to operate the biogas generator for 4 hours resulting 20kWh of electrical energy. This power is transmitted to the village through the control system. Any shortage of power during the peak hours is compensated or stabilised by the battery bank. Figure.5 shows the electrical energy flow in the BioCPV system.

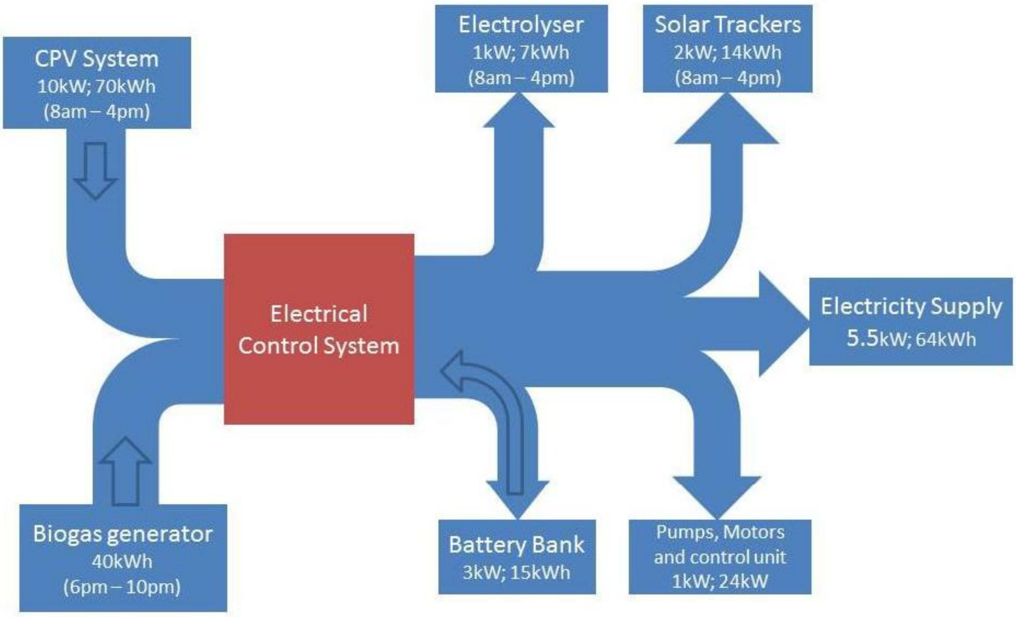


Figure.5 Electrical energy flow diagram of the BioCPV system

7. SOCIO-ECONOMIC BENEFIT OF THE LOCALITY THROUGH BIOCPV PROJECT

The BioCPV project addresses number of socio-economic aspects of the village where the project is to be implemented. Supplying electricity to the household is expected to increase the quality of life and will be helpful for the education of the children. It is expected that with the supply of electric power some small scale handwork industries will be benefitted, as they will be able to work during the night as well. The thrown-away food waste and the biomass used to be thrown away will be used for power generation with a very minimum maintenance cost. In a bigger picture BioCPV is generating power through renewable technologies which reduces the emission of the greenhouse gases. BioCPV is supplying cylinders of hydrogen enriched biogas to use as cooking gas. This will help villagers not to use firewood for cooking purposes resulting healthy lifestyle and reduced carbon footprints.

BioCPV project is expected to improve the socio-economics of the Kaligunj and Pearson-Pally village through this off-grid integrated renewable energy technology concept. The socio-economic benefit through BioCPV project is demonstrated by the figure.6.

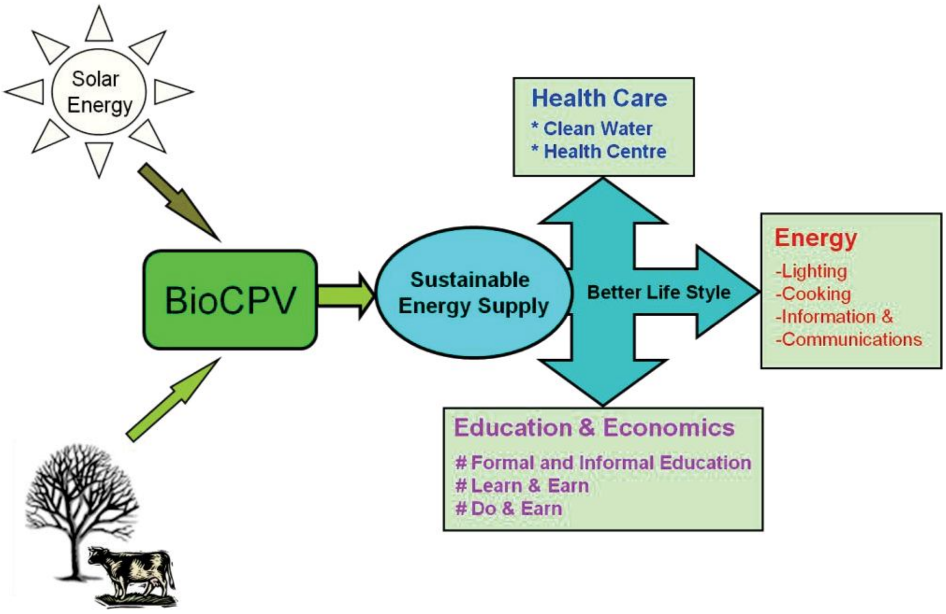


Figure.6 Block diagram representing socio-economic benefits from the BioCPV project

8. CONCLUSION

Rural electrification is a major issue to bridge the urban and rural divisions. The BioCPV project will address this issue with a renewable energy power plants comprise of CPV (concentrating photovoltaics) and biomass system. The load profile of the project location (Kaligunj – Pearson Pally village, West Bengal, India) has been estimated considering the basic power need of the villagers. The basic lighting for the households, community areas and for streets; with cooling facilities in the communal areas have been considered for the initial phase of the electrification. However with the scaling up of the installed capacity of the power plant the energy can be supplied to small scale business and industries as well, which will boost the economics and the life standard of the people in that locality.

8. ACKNOWLEDGEMENT

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