

# **Prospects of Energy Production from Lignocellulosic Biomass, Solar Photovoltaic and Hybrid Systems**

*Thesis submitted in partial fulfillment of the requirements for the degree of*

**Doctor of Philosophy**

by

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**January – 2023**



***Dedicated***

***to***

***my Parents and my Lovely Wife***

***for***

***believing in me***



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**SCHOOL OF ENERGY SCIENCE AND ENGINEERING**  
**INDIAN INSTITUTE OF TECHNOLOGY GUWAHATI,**  
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**STATEMENT**

I do hereby declare that the content embodied in this thesis entitled *“Prospects of energy production from lignocellulosic biomass, solar photovoltaic and hybrid systems”* is the result of investigations carried out by me at the School of Energy Science and Engineering, Indian Institute of Technology Guwahati, Guwahati, Assam, India under the guidance of **Prof. Kaustubha Mohanty** and **Prof. Pinakeswar Mahanta**.

In keeping with the general practice of reporting scientific observations, due acknowledgements have been made wherever the work described is based on the findings of other investigators.

**January 2023**

**Sachankar Buragohain**



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**GUWAHATI-781039, ASSAM, INDIA**

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**CERTIFICATE**

This is to certify that the matter embodied in this thesis entitled “*Prospects of energy production from lignocellulosic biomass, solar photovoltaic and hybrid systems*” is the result of investigations carried out by **Mr. Sachankar Buragohain (Roll No. 146151008)** under our supervision, and to be submitted for the award of degree of Doctor of Philosophy to IIT Guwahati. We certify that he has fulfilled all the requirements according to the rules of the institute and this work has not been submitted elsewhere for a degree or diploma.

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## ACKNOWLEDGEMENT

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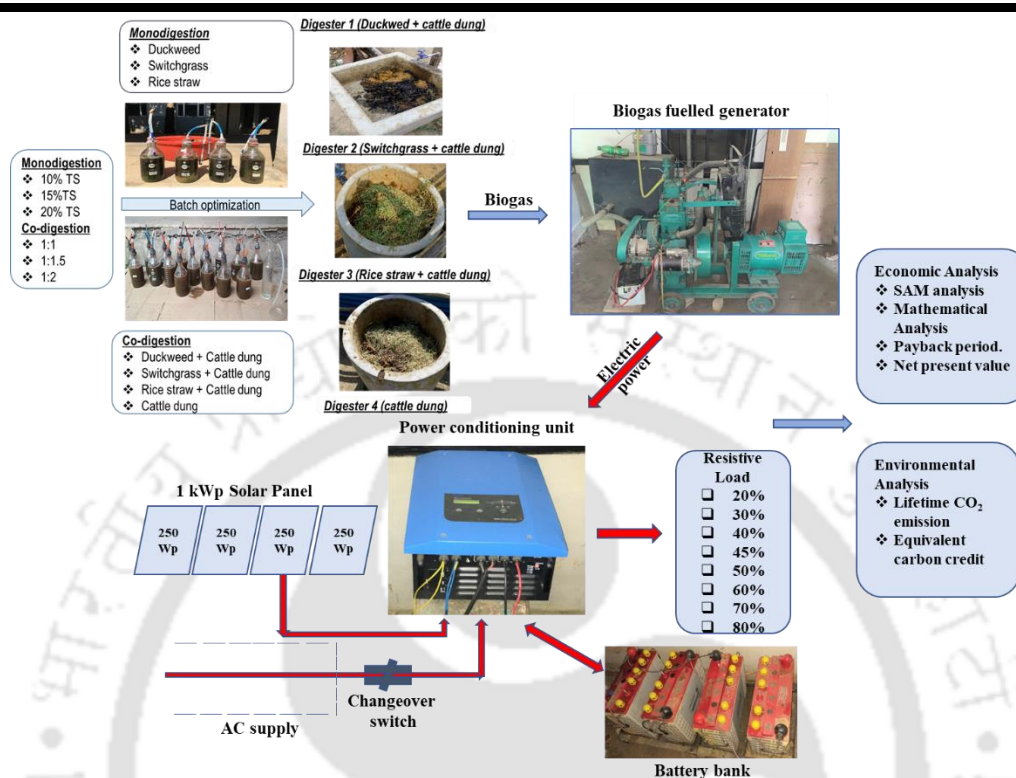
With immense gratitude, I would like to acknowledge the valuable guidance, support, help and encouragement of my supervisor Prof. Kaustubha Mohanty, Department of Chemical Engineering and my co supervisor Prof. Pinakeswar Mahanta, Department of Mechanical Engineering Indian Institute of Technology, Guwahati. I sincerely thank them for being an excellent mentor and teacher throughout my research work. I owe my gratitude to the members of my doctoral committee Prof. Lingaraj Sahoo, Prof. Chandan Das and Prof. Karuna Kalita for their insightful advices and suggestions throughout the research.

My sincere thanks to the Heads of School of Energy Science and Engineering, Prof. V.S. Moholkar and Prof. Pranab Goswami for allowing me to use the Centre facilities in their respective tenures. Special thanks to the Head of Central Instrument Facility (CIF), IIT Guwahati, for providing me the analytical facilities of CIF. I am grateful to all the staff members of School of Energy Science and Engineering for their help during my research work. I would also like to thank all my research group members, Dr. Himadri, Dr Kulbhusan, Dr Ranjeet, Dr Abinash, Dr Sanjeev, Dr Sounak, Santosh, Madonna, Dr Bikashbindu, Pranab, Barasa, Deep, Munmi, Hirakh, for their help throughout my research work. I am also thankful to my colleagues in School of Energy Science and Engineering and my friends for their love and support throughout this period. I would also like to thank the people of Auniati Satra, Amingaon (Guwahati) for providing me the site for carrying out the experiments.

I would like to express my deep sense of gratitude to my parents, my brothers and family for their unconditional love and support towards the completion of my PhD thesis. I extend my sincere thanks to my wife for her constant support and motivation. This journey would not have been possible without them.

**Sachankar Buragohain**

# ABSTRACT



Fossil fuel energy sources have been the primary source of energy and has a major share in meeting the energy demands of the day-to-day activities. However due to constant depletion of fossil fuel sources and low replenishment rate, it has forced mankind to shift its approach towards more renewable and sustainable energy sources. In recent years, all nations have shifted their approach from a fossil reliant nation to a more sustainable and greener approach nations. India being an agriculturally rich country with abundant biomass resources and ample solar radiation for maximum time of the year has invested majorly in biomass and solar. Anaerobic digestion of organic and lignocellulosic biomass has been a major area of research in many parts of this region. Though large-scale anaerobic digestion of organic biomass has already been implemented in some cities, use of lignocellulosic biomass has not been extensively done. The lignocellulosic biomass resources are either dumped in fields or are burned down releasing more carbon dioxide in the atmosphere. Keeping in view the constant

depletion of fossil fuel sources and ever rising energy demand, it is essential that application and feasibility of renewable energy sources at community level is emphasized. The study was thus sub divided into three parts focusing on energy generation from anaerobic digestion, solar photovoltaic and hybrid systems.

The anaerobic mono- and co-digestion of three lignocellulosic biomasses viz. duckweed, switchgrass and rice straw were performed in 1 litre laboratory-scale batch reactors. The initial biochemical methane potential test was performed at three different total solids concentrations (10%, 15%, 20%) and cattle dung to feedstock ratios (1:1, 1:1.5, 1:2) under mesophilic conditions (28–32 °C) for 36 days. Co-digestion of feedstocks at 1:1 ratio yielded better results than other cattle dung to feedstock ratios. Optimized physical parameters were further implemented for a scale-up co-digestion study of biogas potential from 4 m<sup>3</sup> community-size biogas digesters. The investigation was performed for 60 days maintaining a hydraulic retention time of 40 days, and a comparative analysis with mono digestion of cattle dung was also analyzed. Average daily biogas production for digester containing rice straw and cattle dung was 0.36 m<sup>3</sup>/kg-VS, whereas it was 0.34 m<sup>3</sup>/kg-VS and 0.32 m<sup>3</sup>/kg-VS for switchgrass and duckweed, respectively. An overall comparative analysis of the biogas production and its composition for both biochemical methane potential tests and continuous processes are discussed in this work.

The decentralized energy generation from solar photovoltaic systems both in standalone and grid-connected mode at community level was also investigated. A pilot-scale 1 kW photovoltaic system was installed at Auniati Satra near IIT Guwahati for studying the effects of its operating parameters at different load conditions corresponding to the environmental conditions prevalent in Guwahati, Assam (India). The photovoltaic system was subjected to constant electrical load both in standalone mode and grid-connected mode during the daytime at eight different load conditions viz. 20%, 30%, 40%, 45%, 50%, 60%, 70% and 80% and half-hourly data of different parameters like solar insolation, photovoltaic energy, photovoltaic

charge, temperature, and battery capacity were analyzed. Optimum load condition in standalone mode was found to be at 45% – 50% load under normal solar insolation without much burden on the battery bank and can be extended to a maximum load of 70% during the daytime at high solar insolation. In grid-connected mode, load application up to 45% was economically beneficial as less power was utilized from local grid. Though it can be subjected to almost its full rated capacity with input from the ac supply.

The study was further extended to investigate the techno-economic and environmental assessment of a hybrid 1 kW solar photovoltaic plant (having battery backup) and a 3.5 kVA biogas fueled generator. The hybrid system was subjected to constant load conditions from 20% to 80% of the rated power conditioning unit, and energy shared by the combined systems was investigated. At lower loads, the photovoltaic system was sufficient to meet the demand. Whereas at higher loads, energy share from the biogas system was required for meeting the load demand. Economic analysis over a project lifetime of 25 years revealed a high positive net present value of \$1562.15 with a levelized cost of the energy value of \$0.21/kWh for the hybrid system. A comparative financial analysis for the standalone solar photovoltaic system was also performed using the system advisor model. System advisor model analysis resulted in a positive net present value of \$306.45 and a Levelized cost of the energy value of \$0.15/kWh. The environmental analysis revealed a net CO<sub>2</sub> mitigation of 104.59 Tons, equivalent to an earned carbon credit of \$2090.31 from the hybrid system.

This study thus presents a holistic approach for utilization of locally available lignocellulosic biomass for biogas production and integration of bioenergy with solar photovoltaic systems for electricity production.

**Keywords:** Anaerobic Digestion, Solar Photovoltaic, Hybrid systems

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## Abbreviations

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ACoD	Anaerobic co-digestion
AD	Anaerobic digestion
AES	Annual energy saving
ALS	Annual LPG saving
ASEAN	Association of southeast asian nations
BMP	Biochemical methane potential
BF	Biogas fueled
COD	Chemical oxygen demand
CD:FS	Cattle dung to feedstock ratio
C/N	Carbon to nitrogen ratio
COE	Cost of energy
CUF	Capacity utilization factor
$d$	discount rate(= 4.5%)
$d_r$	Degradation rate(= 0.6%/year)
DPP	Discounted payback period
DW	Duckweed
$E_{BF}$	Annual electricity production from BF generator
$E_o$	Annual electrical output from the hybrid system
$E_{L(PV)}$	Annual electricity production from solar PV
$E_{sav}$	Electricity savings from the system
$E_{(sav),t}$	Total electricity savings over project lifetime
$EF_g$	CO <sub>2</sub> emission factor from conventional energy
FC	Fixed carbon
GHG	Greenhouse gas
HES	Hybrid energy system
HOMER	Hybrid optimization of multiple energy resources

HRT	Hydraulic retention time
INR	Indian rupee
IRES	Integrated renewable energy systems
LB	Lignocellulosic biomass
LCC	Life cycle cost
LCOE	Levelised cost of energy
$LPG_{esav}$	LPG equivalent savings from the system
$LPG_{(esav)_t}$	Total LPG equivalent savings over project lifetime
LS	Liquid state
MC	Moisture content
$n$	lifetime of the project(= 25 years)
NPC	Net present cost
NPV	Net present value
$O \& M_t$	Total operation and maintenance cost of the system
OLR	Organic loading rate
$P$	Unit rate of a LPG cylinder (= INR 640)
PCU	Power conditioning unit
PKR	Pakistan rupee
PV	Photovoltaic
PVGIS	Photovoltaic geographical information system
$R$	Per unit rate of electricity (= INR 6.5/kWh)
$RC_B$	Replacement cost of battery banks
$RC_E$	Replacement cost of biogas engine
$RC_t$	Total replacement cost
RF	Renewable fraction
RS	Rice straw
SAM	System Advisor Model

sCOD	Soluble Chemical Oxygen Demand
SDGs	Sustainable Development Goals
SPP	Simple Payback Period
SS	Solid-State
TMY	Typical Meteorological Year
TS	Total Solids
UN	United Nations
UNFCC	United Nations Framework of Climate Change
VFAs	Volatile Fatty Acids
VM	Volatile Matter
VS	Volatile Solids

***Subscripts***

<i>B</i>	Battery
<i>BF</i>	Biogas fueled
<i>BG</i>	Biogas generator
<i>CO<sub>2</sub></i>	Carbon dioxide
<i>E</i>	Engine
<i>esav</i>	equivalent saving
<i>O</i>	Output
<i>PV</i>	Photovoltaic
<i>g</i>	grid
<i>L</i>	Load
<i>PCU</i>	Power conditioning unit
<i>r</i>	rate
<i>t</i>	total

## Symbols and Units

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mm	Millimetre
cm <sup>-1</sup>	Per centimetre
m <sup>3</sup>	Cubic metre
kg	Kilogram
ha	Hectare
mL	Millilitre
L	Litre
W	Watt
kW	Kilowatt
MW	Mega Watt
GW	Giga Watt
°C	Degree Celcius
°F	Degree Fahrenheit
K	Kelvin
A	Ampere
Wp	Watt (peak)
Wh	Watt hour
kWp	Kilowatt (peak)
h	Hour
V	Volt
Ah	Ampere hour
VA	Volt Ampere
kVA	Kilovolt ampere
kWh	Kilowatt hour
tCO <sub>2</sub> (e)	ton of carbon dioxide equivalent
g/L	Gram per litre
L/g	Litre per gram
kg/day	Kilogram per day
L/day	Litre per day
MJ/ton	Megajoule per ton

L/g-VS	Litre per gram volatile solids
mg/L	Milligram per litre
g-VS/L/d	Gram volatile solids per litre per day
g/m <sup>2</sup> /d	Gram per square metre per day
kg-VS/m <sup>3</sup> /d	Kilogram volatile solids per cubic metre per day
kg/m <sup>3</sup> /d	Kilogram per cubic metre per day
mL CH <sub>4</sub> /g-VS	Millilitre methane per gram volatile solids
mL/g-VS	Millilitre per gram volatile solids
L-CH <sub>4</sub> /g-VS	Litre methane per gram volatile solids
L-CH <sub>4</sub> /kg-VS	Litre methane per kilogram volatile solids
L/kg-VS	Litre per kilogram volatile solids
L-CH <sub>4</sub> /g-COD	Litre methane per gram chemical oxygen demand
CH <sub>4</sub> -COD/g-VSS	Methane chemical oxygen demand per gram volatile suspended solids
m <sup>3</sup> /m <sup>3</sup> -d	Cubic metre per cubic metre per day
m <sup>3</sup> /t-VS	Cubic metre per ton volatile solids
m <sup>3</sup> /kg-VS	Cubic metre per kilogram volatile solids
W/m <sup>2</sup>	Watt per square metre
kWh/year	Kilowatt hour per year
kWh/m <sup>2</sup>	Kilowatthour per square metre
kWh/kWp	Kilowatt hour per kilowatt (peak)
h/day	hour per day
kgCO <sub>2</sub> (e)/kWh	Kilogram carbon dioxide equivalent per kilowatt hour
kg/kWh	Kilogram per kilowatt hour
kg CO <sub>2</sub> /MWh	Kilogram carbon dioxide per megawatt hour
kWh/kWp/day	Kilowatt hour per kilowatt (peak) per day

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# Chapter 1

## Introduction, Literature Review and Objectives

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### 1.1. Overview

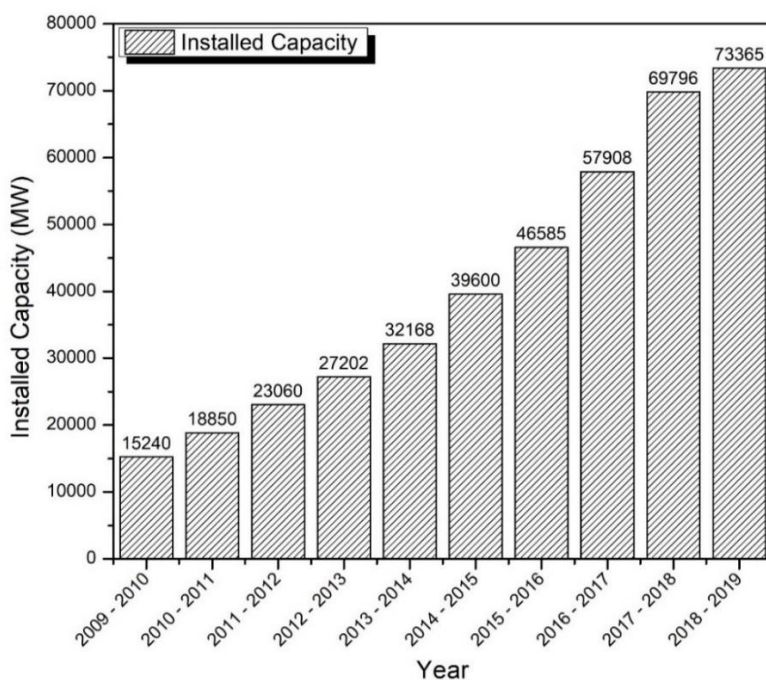
Energy is the basic need for sustenance of humanity in the present-day world and to perform any kind of activity, one has to engage with one form of energy or the other. Energy can primarily be divided into two forms: Conventional and Non-Conventional forms of energy. The present scenario of the world depicts a rapid dissolution of the conventional sources of energy. In contrast, the demand for non-conventional sources has been increasing a huge fold. As such, a shift towards harnessing energy from renewable sources or sources that are sustainable are now majorly focused.

Meeting energy demands from conventional sources is unfeasible and calamitous for nature and is a typical case of a linear economy (Sariatli, 2017). For developing the renewable energy sector, various renewable energy sources such as wind, solar, biomass, hydro, etc., are utilized (Sinsel et al., 2020). Because of the constant rise in fuel prices, countries have shifted their approach towards sustainable energy technologies and environment-friendly methodologies (Gielen et al., 2019). In 2015, the renewable energy segment met 19% of the overall global energy demand (IEA and IRENA, 2017; Yumkella, 2015). As per recent report by IRENA, the share of renewable energy in total final energy consumption would increase from 19% in 2019 to 79% by 2050 (International Renewable Energy Agency (IRENA), 2022). In November 2019, 195-member nations of the United Nations Framework of Climate Change (UNFCCC) signed an agreement to implement renewables. UNFCCC suggested installing

renewables for the reduction of CO<sub>2</sub> emissions and per capita consumption (Santika et al., 2019).

## 1.2. Energy Scenario: India and Global perspectives

In the recent years, various member countries of the Association of Southeast Asian Nations (ASEAN) have made significant efforts in the renewable energy sector and reduced its dependence on fossil fuel sources (Athienitis et al., 2018; Huang et al., 2018). In fact, many nations' governments have shifted their approach towards renewables for ensuring global sustainable development (Madurai Elavarasan et al., 2020). In 2015, the United Nations (UN) had released 17 Sustainable Development Goals (SDGs), out of which SDGs 7 relates to affordable and clean energy and has focused for green energy adoption and limiting GHG emissions (Ikram et al., 2020). All the UN member nations and civil society, research community, policymakers, and stakeholders, have been continuously working towards a common goal to attain sustainable development (Elavarasan et al., 2019). For achieving their renewable energy targets, the countries adhere to the SDGs by forming cooperative structures (Elavarasan et al., 2020b). Apart from the policies, raising awareness in the society about the significance of renewable energy sources is equally essential (Gupta et al., 2010; Kanase-Patil et al., 2011)(Gupta et al., 2010). The growth of renewable energy sources over the past decade in India is shown in Fig 1.1.



**Figure 1.1.** Growth of renewable energy sources over the last ten years (Elavarasan et al., 2020a).

The transition towards renewable energy transmutes vital processes and characterizes a concrete approach to consumption and production (Jochen Markard et al., 2012). Although renewable energy systems' initial capital cost is high, their operation and maintenance costs are low (Tripathi et al., 2016). But with the increase in renewable energy production in many countries, there was a decrease in its production cost (Kim et al., 2017). Moreover, due to the efficient utilization of renewable resources, there were a significant reduction in greenhouse gas (GHG) emissions than conventional sources (Dowaki and Mori, 2005; Schneider and McCarl, 2003).

In the area of non-conventional energy, India is at par with other big economies like China and the United States. On the global arena, India has provided vital pathways for renewable technologies innovation and implementation. It has also acknowledged the importance of renewable energy generation for sustainable and ecological balance (Elavarasan, 2020). According to some researchers, these three countries can significantly contribute two-

thirds of clean energy expansion by 2022 (Panwar et al., 2011). In 2016, global renewable energy generation growth was around two-thirds of its net capacity (~165 GW), of which around 54% was from solar energy generation. It was mainly due to the extensive installation of solar panels throughout the world (Energy Agency, 2019).

In terms of population, India stands at second position after China and has a constant increase in energy demand due to escalation of living style and necessities (Jeslin Drusila Nesamalar et al., 2017). Due to increasing demand, millions of people face electricity shortages and frequent power cuts in some places, which hampers the economic demand. As such, India has shifted its approach towards adoption of renewable energy sources and relies both on conventional and non-conventional resources (Aklin et al., 2016; Balachandra, 2011; Kale and Pohekar, 2012). India aims to reach its energy share from renewable energy sources to 44.4% by 2027 (Laha et al., 2020).

### **India – Agro based renewable energy production**

In India, majority of the population relies on agriculture due to which agriculture sector contributes plays a significant role in the Indian economy. Moreover, a major portion of the Indian sub-continent is covered under forest area and water bodies. As such a huge amount of lignocellulosic wastes are generated from the agricultural fields, forest areas and water bodies. Out of the lignocellulosic wastes available in India, duckweed, switchgrass and rice straw are easily available in the north eastern region of India and as such these three lignocellulosic feedstocks were considered in this study. Rice, being the primary food of the north eastern region, is enormously grown in the fields and as a result huge amount of rice straws are generated in the agricultural fields. These wastes generated are either burnt, or left open for decomposition. On the other hand, switchgrass and duckweeds are enormously available in forest areas, open fields and water bodies, that are left unutilized. It is thus necessary for proper

management of waste and meeting the energy needs of the population. The need for a probable renewable energy source is very prevalent considering the environmental and working conditions of a particular location. India falls under sub-tropical climate conditions with a fair amount of sunlight for maximum time of a year. Thus, solar energy and bioenergy applications can play a significant role in harnessing these resources for overall sustainable development.

Anaerobic digestion (AD) of organic and lignocellulosic substances is another sector that needs significant emphasis on biogas generation and can be utilized as cooking fuel or for power generation. It has been a considerable research area for biogas production, production of high-end organic fertilizers, and electricity generation.

### **1.3. Anaerobic digestion: process overview**

Biogas produced from AD of organic feedstocks is considered as one of the promising bioenergy and an alternative to fossil-based energy due to its numerous innate merits. Due to its immense benefits and eco-friendly waste management approach, AD is widely adopted and implemented in societies over the last century, and thousands of biogas plants are operational worldwide. In the AD process, deconstruction of recalcitrant biomass structures is performed synergistically by the microbes and converted into fundamental components. In a normal AD process, the lignocellulosic components are pounded and fed in an anaerobic bioreactor to convert complex organic matter to energy-rich biogas (Weiland, 2010). AD process though being effective, is energy-intensive and time-consuming, limiting its operation for large-scale production. A study reported that certain biomass might be preferred by certain microorganisms present in AD slurry (Yue et al., 2010). The authors observed that hemicellulose was digested prior to other components in a heterogenous polysaccharide. Methane (CH<sub>4</sub>) can be exclusively produced from hemicellulose by careful adjustment of solid retention time, leaving behind cellulose and lignin. The recalcitrant structure of biomass is

destabilized effectively by the removal of hemicellulose, which allows the cellulose solubilization by commercial enzymes in the downstream process (MacLellan et al., 2013; Yue et al., 2011).

An AD system's economic viability is strongly dependent on CH<sub>4</sub> production from a particular substrate and directly corresponds to its commercialization. Methane yield for biomass can vary significantly between species, geographical location, maturity, etc. (Yang et al., 2013). Biochemical Methane Potential (BMP) test is generally adopted for examination of anaerobic digestibility of organic substrates. The feedstock's composition also plays an essential factor in the CH<sub>4</sub> yield, digester stability, and smooth operation (Amon et al., 2007). It has been reported that CH<sub>4</sub> production from lignocellulosic biomass (LB) with high lignin content is less (Agbor et al., 2011; Alvira et al., 2010).

#### **1.4. Factors affecting the Anaerobic Digestion process**

Performance and stability of an AD system are controlled by various factors such as inoculum quality, organic loading rate (OLR), feedstock to inoculum ratio, C/N ratio, volatile fatty acids (VFAs) production, temperature, pH, hydraulic retention time, trace elements etc. (Luo et al., 2018; TERASHIMA et al., 2009). Some of the essential parameters are described in the subsections below:

##### **1.4.1. Temperature**

Temperature plays a significant role in assessing the physical diffusion, chemical dissociation, and reaction velocity in the AD process (Atelge et al., 2020; Hagos et al., 2017). Optimal temperature is the primary need for an AD system's overall efficiency and stability (Shetty et al., 2017). Typically, temperature ranges for the functioning of AD microorganisms can be subdivided into three groups viz. psychrophilic (10 – 20 °C), mesophilic (30 – 40 °C) and thermophilic (50 – 60 °C) (Kwietniewska and Tys, 2014; Schnürer and Nordberg, 2008).

It has been reported that the growth rate of microbes is high in mesophilic and thermophilic temperature range (Cooney and Wise, 1975; Hagos et al., 2017), which also helps in inactivation of majority pathogenic population (Takedastan et al., 2005). Usually, an increase in temperature improves the metabolic and digestion rate in the AD system. The thermophilic AD system is complex to manage and requires extra energy to maintain high temperature (Hagos et al., 2017). For mesophilic AD system, wide range of microorganisms are involved and it is more stable than thermophilic AD systems (Appels et al., 2008). Thermophilic AD systems are disadvantageous because of poor stability and supernatant quality (Angelidaki and Sanders, 2004). Normally methanogenic microbes are susceptible to hydrolytic and acidogenic microbes (Atelge et al., 2020).

#### **1.4.2. Organic loading rate**

Organic loading rate (OLR) is the amount of volatile solids (VS) fed per unit volume of the reactor in a continuous AD system (Kwietniewska and Tys, 2014; Tanimu et al., 2014; Yavini et al., 2014). It plays a vital role in the overall AD process as feedstock overloading may lead to digester failure. Many studies have assessed the effect of OLR on digester performance (Tanimu et al., 2014; Yavini et al., 2014) and reported that though a high OLR may increase biogas production rate, it reduces system stability (Li et al., 2013). The biogas yield increases up to an optimum value of OLR, but above this value, biogas yield and degradation of volatile solid (VS) decreases due to excess substrate concentration (Hashimoto, 1986). In a study for AD of rice straw (RS), the authors reported a high volume of methane at 2 g-VS/L/d OLR, whereas, for 1 g-VS L<sup>-1</sup>d<sup>-1</sup> OLR, high specific methane yield and stable operations was achieved (Zealand et al., 2017). Another study reported decreased biogas production at OLR of 8 kg-VS/m<sup>3</sup>/d and suggested an OLR of 6 kg-VS/m<sup>3</sup>/d for co-digestion of RS and cow manure at 1:1 ratio (Li et al., 2015a). A study reported a decrease in biogas production and reduction of methane content to 34% at 12 kg-VS/m<sup>3</sup>/d OLR for co-digestion

of RS and pig manure (Li et al., 2015b).

### 1.4.3. Volatile Fatty Acids and pH

Volatile Fatty Acids (VFAs) are considered the most vital intermediaries formed during the AD system and determine the system's stability and potential (Luo et al., 2018). The major VFAs are acetic acid, propionic acid, butyric acid, lactic acid, and formic acid (Cai et al., 2017; Luo et al., 2018). Its accumulation occurs because of the acids formed during hydrolysis and the acidogenesis stage that the methanogens cannot consume, which results in pH reduction and system failure (Cai et al., 2017; Pore et al., 2016). Its accumulation restricts the methanogenic action that disturbs the AD process (Song et al., 2013). Its accumulation might be due to high metabolic rates of hydrogenic, acidogenic, and acetogenic microbes. A high concentration of VFAs makes the reactor sour and lowers the pH (Pore et al., 2016). For AD, a pH range of 6.8 – 7.2 is favorable, while a pH range of 5.5 – 6.5 is favorable for hydrolysis and acidogenesis, and methanogenesis is around 7.0. But inhibition of methanogens may occur for pH less than 6.6 (Schnürer and Nordberg, 2008; Shetty et al., 2017). The fall of pH is generally buffered due to the formation of bicarbonates during methanogenesis. Also ammonia formed during the process controls the superfluous VFA accumulation (Abdel Daiem et al., 2018). A balanced pH in the AD system can be obtained by the addition of  $\text{NaHCO}_3$  and  $\text{NaOH}$  (Ye et al., 2013).

### 1.4.4. Carbon to Nitrogen ratio

The carbon to nitrogen (C/N) ratio is another important parameter for the AD system's smooth functioning and stability (Li et al., 2018). It is an essential parameter in terms of substrate characterization (Atelge et al., 2020). In general, the C/N ratio should be in the range of 20 – 30 for favorable operation of AD (Chandra et al., 2012; Kim et al., 2013; Kwietniewska and Tys, 2014), whereas for hydrolysis, C/N ratio of 16 – 45 and for methanogenesis 20 – 30

is recommended (Atelge et al., 2020). It has been reported that the stability of AD process is significantly influenced by C/N ratio (Zhang et al., 2014). It is because an optimal C/N ratio helps in the proper balance of nutrients, maintaining a suitable environment for the growth of microorganisms. An increase in microbial population takes place, resulting in high biogas yield if nitrogen concentration is low, whereas for higher concentrations of nitrogen, ammonia inhibition might occur (Kothari et al., 2014). In general, enhancement of C/N ratio could be attained by co-digestion of organic substrates with animal manure, sewage sludge, and lignocellulosic biomass (Khalid et al., 2011).

In addition to the aforementioned parameters, the AD process also depends on various other factors viz. total solid concentration, type of biomass and the type of process. Some of these processes are discussed below.

### **1.5. Anaerobic digestion based on total solids**

AD process, based on total solids (TS) concentration, can be distinguished into solid-state (SS) having greater than 15% TS and liquid state (LS) having less than 15% TS (Ge et al., 2016; Yan et al., 2015). LS-AD system has been mostly adopted in large-scale systems using waste and animal manure (Brown et al., 2012). This process requires a large amount of water and is easy to maintain and operate. It also produces a high amount of liquid digestate (Brown et al., 2012). This type of digestion is more suitable for feedstock with high moisture content such as animal manure, water hyacinth, etc. In contrast, SS-AD is more suitable for treating biomass having high OLR. It requires less energy for heating, produces a high amount of methane, and generates less wastewater (Li et al., 2011). Feedstock/Inoculum ratio in SS-AD system plays a crucial role in operation (Luo et al., 2018). As the digestate in SS-AD contains low moisture, its transportation and application are relatively convenient than LS-AD digestate (Kim et al., 2013; Riya et al., 2018). Also, SS-AD's starting time is more than LS-AD, and is thus relatively stable than LS-AD (Lianhua et al., 2010). But due to accumulation

of ammonia, VFA and nutrient imbalances, SS-AD may undergo system destabilization (Li et al., 2011).

### **1.6. Anaerobic digestion of lignocellulosic biomass**

Lignocellulosic biomass (LB), with an annual global yield of over 200 billion metric tons per year, is an abundant biomass resource for bioenergy utilization (Kumar et al., 2008). LB, particularly energy crops and Agri residues, is gaining attention worldwide as potential feedstocks for bioenergy production and bioproducts. It primarily comprises cellulose, hemicellulose, and lignin that are closely interlinked, making it a highly recalcitrant and resistant structure. Subsequently, the hydrolysis process becomes difficult and becomes the rate-limiting step (Khanal, 2008).

The major portion is cellulose, produced due to glucose breakdown in hydrolysis (Zhao et al., 2010). Cellulose is a type of biopolymer and has crystalline and amorphous arrangements. While, hemicellulose is an amorphous arrangement of several polymers such as hexose, pentose, etc., and has complicated heterogeneous structure (Martínez-Gutiérrez, 2018). It links cellulose and lignin and imparts rigidity to the overall network (Laureano-Perez et al., 2005). On the other hand, Lignin is an aromatic amorphous heteropolymer that provides plant support, impermeability, and resistivity to microbial attack (Hendriks and Zeeman, 2009; Saha, 2003). Its breakdown is complex due to structural difficulty (Martínez-Gutiérrez, 2018). Some of the thermal and biochemical processes used for converting LB to useful energy are syngas from gasification, biogas from AD, biochar from pyrolysis, and ethanol from biochemical conversion (Abdel Daiem et al., 2018).

LB can be considered an economical and sustainable substrate for processing chemicals, materials, fuels, and heat/power (Pan et al., 2015). Bio-methanation is one such process for the conversion of LB to produce biogas and nutrient-rich digestate (Pore et al., 2016). It can be considered the complete process out of all the fermentation processes (Meng

et al., 2018). The amount of CO<sub>2</sub> and CH<sub>4</sub> is dependent on the oxidation of organic substrate (Rajagopal et al., 2013). The demand for anaerobic conversion of lignocellulosic residues is on the rise because of substrate availability for utilization (Riya et al., 2018). Among the various agricultural residues, rice straw possesses great potential for conversion to biomethane (Pore et al., 2016). Rice straw has been considered the most preferred lignocellulosic substrate for bioenergy production (Mustafa et al., 2017a). However, various factors affect the anaerobic digestion of rice straw. One such factor is its high C/N ratio and its components (cellulose, hemicellulose, and lignin) that makes the substrate recalcitrant to microbes and make the hydrolysis process difficult. These effects can be reduced by adopting some strategies such as co-digestion with high nitrogen substrates, pre-treatment methods that can ease rice straw's complexity.

### **1.7. Anaerobic co-digestion of lignocellulosic biomass**

Co-digestion is the methodology of treating two or more substrates mixed and treated simultaneously (Kwietniewska and Tys, 2014). AD of single feedstock is usually less effective due to acidification of feed material, an inconsistent supply of raw material, absence of trace elements, etc. But these difficulties can be negated by co-digestion of suitable feed material anaerobically (Zhang et al., 2018). It has been reported that the yield of methane in co-digestion is more than in mono-digestion (Jiunn-Jyi et al., 1997; Ye et al., 2013) and is economically beneficial than the adoption of pre-treatment methods (Ye et al., 2013). For optimized digestion of lignocellulosic biomass, co-digestion can be beneficial in utilizing bacterial diversities and nutrients (Babae et al., 2013). Co-digestion of lignocellulosic biomass with various nitrogenous sources such as pig urine (Meng et al., 2018), pig manure (Shetty et al., 2017; Zhang et al., 2015), chicken manure (Mei et al., 2016a), cow manure (Cai et al., 2017), etc. has been beneficial in increasing digestion efficiency and methane production. Co-digestion helps in the enhancement of methane production, balances the C/N ratio when mixed with suitable

co-substrate.

Among the lignocellulosic biomass, duckweed, switchgrass and rice straw are abundantly found in Assam. The utilization of these biomasses in other parts of India has been extensively studied. However, the same has not garnered much attention in the North-Eastern part of India. Various studies have been performed using these lignocellulosic feedstocks and some of the studies are discussed in the subsections below:

### 1.8. Anaerobic digestion of Duckweed (DW)

Duckweed (*Lemnaceae*) is a free-floating aquatic weed native to subtropical and temperate regions. It belongs to a monocotyledonous family of five genera and 37 species (Xu et al., 2012). It is one of the fastest-growing plants with a doubling time of 2 – 3 days under normal growth conditions (Yu et al., 2014). Cheng and colleagues investigated DW production in swine wastewater and reported a growth rate of 0.2 kg dry mass/m<sup>2</sup>/week under normal conditions (Cheng et al., 2002). DW contains organic nitrogen, starch, and free amino acids, which can be utilized as feed for fermentation. One of the major benefits of DW is that it can be used for CO<sub>2</sub> sequestration. It has been reported that an estimated 57.3 – 155.3 tons of CO<sub>2</sub> can be removed from the atmosphere by 1 ha of DW (having a carbon content of 40%) pond in a year (Landolt, 1998).

Recent research has shown the use of biomass yield from DW in wastewater treatment for the production of bioethanol and biogas (Cui and Cheng, 2015; Verma and Suthar, 2015; Xu and Deshusses, 2015). Duckweed has fast growth, high nutrient tolerance levels, and exceptional nutrient uptake ability, for which it has been used for the treatment of wastewaters (Cui and Cheng, 2015; Mohedano et al., 2012). In recent years, *Lemna minor* (DW species) has been reported to be a potent feed for biochar and bio-oil production (Muradov et al., 2012, 2010). DW comprises low lignin and cellulose but has high leaf starch content and high growth rate. As such it is a potent feedstock for biogas production (Cui and Cheng, 2015; Ramaraj and

Unpaprom, 2016; X. Zhao et al., 2014). The liquid digestate after biogas production contains almost all nutrients and can be further utilized for the growth of DW. Ramaraj and Unpaprom evaluated the effect of fermenter temperature on the production of biogas from DW. They performed the experiments in 2 L batch fermenters at ambient, mesophilic (35 °C), and thermophilic (50 °C) temperatures for a digestion period of 45 days. They reported highest biogas production of 10377 mL with a methane yield of 64.47% at mesophilic temperature followed by thermophilic and ambient fermenters (Ramaraj and Unpaprom, 2016).

A few studies have also assessed DW's co-digestion with other substrates such as dairy waste and swine manure (Henderson et al., 2012; Triscari et al., 2009). Henderson and co-workers reported a significant increase in methane yield for anaerobic co-digestion of manure with the addition of 2% to 3% DW in comparison to mono digestion. An increase in methane production was attributed to the presence of micro and macronutrients in DW tissues and changes in C:N ratio (Henderson et al., 2012). Huang and co-workers investigated the co-digestion of DW and swine manure at 1:1 ratio and reported higher biogas yield and chemical oxygen demand (COD) conversion rates than mono-digestion of swine manure (Huang et al., 2013). Clark and Hillman reported an increase in biogas yield of 44% after the addition of DW to chicken manure in semi-continuous lab-scale anaerobic digesters (Clark and Hillman, 1996). Ren and co-workers investigated the effect of hot alkali pre-treatment for AD of duckweed and sludge at different substrate to inoculum ratios. They reported a cumulative gas yield of 2963 mL during co-digestion of both the substrate, which was 11% higher than the single substrate. Moreover, maximum biogas production of 3309 mL was achieved at 1:1 substrate to inoculum ratio. After alkali pre-treatment of duckweed, an increase of 8% methane yield was also achieved (Ren et al., 2018). Gaur and co-workers investigated the anaerobic co-digestion of untreated and pretreated DW with waste activated sludge (WAS) at different DW:WAS ratios viz. 70:20, 60:20, 50:20, 40:20 and 30:20 under mesophilic conditions. Total CH<sub>4</sub> yield ranged

between 60 – 468 mL CH<sub>4</sub>/g-VS and 9 – 76 mL CH<sub>4</sub>/g-VS for pretreated and untreated, respectively. A maximum CH<sub>4</sub> yield of 468 mL CH<sub>4</sub>/g-VS was obtained for the DW:WAS ratio of 50:20 (Gaur et al., 2017a). Some other studies on anaerobic digestion of duckweed are shown in Table 1.1.



**Table 1.1.** Literature review table on anaerobic digestion of duckweed

Feed	Operating conditions	Results obtained	References
Duckweed (DW) + Water Hyacinth (WH)	<ul style="list-style-type: none"> <li>▪ DW:WH ratio of 1:0, 7:3, 1:1, 3:7 and 0:1 on dry basis.</li> <li>▪ First order kinetic model was fitted with experimental biogas yields.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal co-digestion ratio for DW:WH</li> <li>▪ From the experimental analysis – 7:3</li> <li>▪ From the mathematical models – 1: 1.</li> </ul>	(Ogunwande et al., 2018)
Duckweed (DW) + Poultry manure (PM)	<ul style="list-style-type: none"> <li>▪ Batch and semi-continuous mode.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Improvement of microbial succession.</li> <li>▪ Peak methane was achieved after 15 days for duckweed addition compared to 40 days without duckweed.</li> </ul>	(Clark and Hillman, 1996)
Duckweed (DW)	<ul style="list-style-type: none"> <li>▪ Simultaneous yield of ethanol fermentation and anaerobic digestion of duckweed at Substrate to Inoculum ratio of 0.5:1 and 1:1.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Bioethanol yield – <math>0.41 \pm 0.03</math> g/g.</li> <li>▪ Highest biomethane yield – <math>390 \pm 0.1</math> mL-CH<sub>4</sub>/g-VS added at 1:1 S/I ratio.</li> <li>▪ 51.2% higher yield than non-fermented DW.</li> </ul>	(Calicioglu and Brennan, 2018)
Duckweed (DW) + Waste activated sludge (WAS) + Inoculum–acclimatized anaerobic granular sludge (AAGS)	<ul style="list-style-type: none"> <li>▪ Biochemical escalation of DW (<i>Spirodela polyrhiza</i>) in wastewater and AD of cultivated biomass.</li> <li>▪ DW:WAS:AAGS ratios –. 50:10:40 (S1), 40:20:40 (S2), 30:30:40 (S3), and 100% AAGS (S4) for 35 days.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Methane generation ranges of 3001(S3) – 5491(S1) mL.</li> <li>▪ Methane generation rate were 24.01(S1), 15.13(S2), and 9.55(S3).</li> </ul>	(Gaur and Suthar, 2017)
Duckweed (DW) + Trace elements	<ul style="list-style-type: none"> <li>▪ Absorption of iron, nickel, copper, zinc, cadmium, cobalt and manganese by <i>Azolla pinnata</i> R.br and <i>Lemna minor</i> L.</li> <li>▪ Subsequent utilization of harvested biomass for biogas production.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Lead, zinc, cobalt and copper showed toxicity in the AD process.</li> <li>▪ High biogas production rate at low concentrations of cadmium and nickel and vice versa.</li> </ul>	(Jain et al., 1992)
Duckweed (DW) +	<ul style="list-style-type: none"> <li>▪ Varying concentrations of duckweed were</li> </ul>	<ul style="list-style-type: none"> <li>▪ Increase in methane yield on addition in the</li> </ul>	(Triscari et al.,

Feed	Operating conditions	Results obtained	References
Dairy manure (DM)	<p>added to dairy manure slurries.</p> <ul style="list-style-type: none"> <li>▪ Mesophilic temperature – 35°C</li> <li>▪ Observation period of 20 – 40 days.</li> </ul>	<p>range of 0.5 to 2% (duckweed dry mass).</p> <ul style="list-style-type: none"> <li>▪ Total gas production at &gt;2% duckweed were not observed.</li> </ul>	2009)
Duckweed (DW)	<ul style="list-style-type: none"> <li>▪ DW harvested from a swine wastewater treatment system.</li> <li>▪ Feed for biohydrogen production.</li> <li>▪ Effect of pre-treatment and fermentation conditions.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Mild acidic thermal pre-treatment (1% H<sub>2</sub>SO<sub>4</sub> at 85 °C for 1 h) was more effective than individual treatments.</li> <li>▪ Acid-pretreated fermentation – 75 mL H<sub>2</sub> production per gram of dry duckweed in 7 days.</li> <li>▪ H<sub>2</sub> concentration – 42%</li> </ul>	(Xu and Deshusses, 2015)
Duckweed (DW) and others	<ul style="list-style-type: none"> <li>▪ BMP test of different animal manure, slaughterhouse waste and plant residues</li> </ul>	<ul style="list-style-type: none"> <li>▪ Methane production from Duckweed – 340 NL CH<sub>4</sub>/kg-VS Lawn grass – 220 NL CH<sub>4</sub>/kg-VS Water spinach – 110.6 NL CH<sub>4</sub>/kg-VS</li> </ul>	(Cu et al., 2015)
Duckweed (DW) and Water hyacinth (WH)	<ul style="list-style-type: none"> <li>▪ Application of DW and WH in pilot-scale wastewater streams.</li> <li>▪ Time period – more than 1 year.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Total nitrogen recovery rates of Duckweed and water hyacinth were same (0.4 g/m<sup>2</sup>/d).</li> <li>▪ Total phosphorus (TP) recovery rate of DW (~0.1 g/m<sup>2</sup>/d) was slightly lower than WH.</li> </ul>	(Y. Zhao et al., 2014)
Duckweed (DW) and Food waste (FW)	<ul style="list-style-type: none"> <li>▪ AD of raw DW, Residual DW, FW, waste Sorbent and Inoculum were assessed for different combinations of feedstock.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Highest specific biogas yield of 0.16 L/g of organic carbon was observed in case of residual DW (33.3%), inoculum (33.3%), food waste (33.3%)</li> </ul>	(Chusov et al., 2021)

## 1.9. Anaerobic digestion using switchgrass

Switchgrass (SG) (*Panicum virgatum L.*) is a perennial grass indigenous to the US and Canada and is a potent bioenergy crop for biofuel production (Kiesel et al., 2017). It requires minimal pest control and fertilization and is an excellent feedstock for AD (Parrish and Fike, 2005). It can produce a high amount of digestible organic matter, which can be utilized for sustained biogas production (Thamsiroj et al., 2012). It has been considered a suitable energy grass for biofuel production. In the US, Canada, and China, research on SG began from the year 1980s with an emphasis on bioconversion to ethanol. In European countries, it started in the year 1998 (Lewandowski et al., 2003). However, minimal emphasis has been given to the production of biogas from SG. SG primarily comprises of lignocelluloses and sugars that are trapped in the components of lignocellulose material. Breakdown of these polymers into sugars requires cost-intensive pre-treatment to improve the hydrolysis stage aiding in the production of ethanol (Kim and Kim, 2014; Service, 2010). However, in the AD of SG, methane production is done from a wide range of compounds, including sugars, and has a far more tolerant capacity (Jin et al., 2014; Molinuevo-Salces et al., 2012). As such, SG may be considered a prominent feedstock for biogas production in addition to ethanol production. However, due to certain limitations, such as nitrogen deficiency, which disrupts the AD process due to excessive VFA production, it can hinder the AD process (Molinuevo-Salces et al., 2012). In general, co-digestion with a buffer substrate is commonly adopted for improving the pH and stability of the process.

Jin and co-workers investigated the co-digestion of SG and biosolids under similar working conditions as US digesters. They found that powdered or ensiled SG could be easily digested with sewage biosolids under typical American digester conditions. A total solid concentration of 4% resulted in a good yield of methane with an energy conversion efficiency of 74%. However, fine grinding of SG is energy-intensive, which escalates the cost (Jin et al.,

2012).

Ahn and colleagues performed the AD of three different mixtures of animal manure (dairy, poultry, and swine) and SG at 15% TS concentration under thermophilic conditions in 1 L reactors. Highest VS removal of 52.9% was obtained in swine manure, while VS removal of 20.2% and 9.3% was obtained for poultry and dairy manure, respectively. The digestion experiments were conducted for 62 days and highest methane production of 0.337 L-CH<sub>4</sub>/g-VS was obtained for swine manure. In contrast, 0.002 L-CH<sub>4</sub>/g-VS and 0.028 L-CH<sub>4</sub>/g-VS were obtained for poultry and dairy manure, respectively (Ahn et al., 2010).

Frigon and co-workers investigated the anaerobic co-digestion (ACoD) of switchgrass and bovine manure (20% wet mass fraction). They compared it with manure's mono digestion in two 6 L lab-scale anaerobic digesters for 130 days. Hydraulic retention time (HRT) of 37±6 days and VS load of 2.4±0.6 kg/day and 2.6±0.6 kg/day were undertaken, respectively. Total VS reductions of 25% and 39% and methane production of 1.18±0.18 and 2.19±0.31 L/day were obtained for the respective digesters (J. C. Frigon et al., 2012).

Zhao and colleagues investigated the effect of ensiling SG with different additives viz. *L. brevis* (LBr), xylanase (X), and *L. brevis* + xylanase (LBr + X). An increase of 33.59% methane yield was obtained for silage SG in comparison to raw SG. Moreover, an increase in methane yield of 8.72%, 13.08%, and 17.41% was obtained for X, LBr, and LBr + X respectively in comparison to silage SG (Zhao et al., 2017).

Hamed M. El-Mashad performed the batch anaerobic digestion of four feedstocks viz. SG, *Spirulina platensis* algae, Mixture 1 (87% SG and 13% *S. platensis*) and Mixture 2 (67% switchgrass and 33% *S. platensis*) at 35 °C and 50 °C. Respective methane yields of 127, 355, 143, and 198 mL/g-VS were obtained for 35 °C after 40 days of digestion. And methane yield of 167, 358, 198, and 236 mL/g-VS was obtained for 50 °C, respectively. Kinetic study of methane production was also investigated using four first-order models: exponential,

Gompertz, Fitzhugh, and Cone, of which Cone model had the best fit (El-Mashad, 2013).

Sheets and co-workers investigated the effect of total solids (TS) and air exposure on SS-AD of SG under mesophilic ( $36 \pm 1$  °C) and thermophilic ( $55 \pm 0.3$  °C) conditions. There was no significant effect of limited air exposure in the methane yield. Higher methane yield of 102 – 145 L-CH<sub>4</sub>/kg-VS added was obtained in the thermophilic SS-AD process, and methane yield of 88 – 113 L-CH<sub>4</sub>/kg-VS was obtained for the mesophilic process (Sheets et al., 2015).

A comparative analysis of few other studies is also cited in Table 1.2.



**Table 1.2.** Literature review table on anaerobic digestion of switchgrass

Feed	Operating conditions	Results obtained	References
Switchgrass (SG)	<ul style="list-style-type: none"> <li>▪ Pilot-scale 2-stage digester.</li> <li>▪ OLR – 2.5 kg/m<sup>3</sup>/d.</li> <li>▪ Days of operation – 340.</li> <li>▪ Modeling study using ADM1 model</li> </ul>	<ul style="list-style-type: none"> <li>▪ CH<sub>4</sub> reduction – 455 to 363 L-CH<sub>4</sub>/kg-VS at OLR increase from 2 to 2.5 kg-VS/m<sup>3</sup>/d.</li> <li>▪ ADM1 model revealed system failure due to inhibition of acetogenesis, leading to the formation of VFAs.</li> </ul>	(Thamsiroj et al., 2012)
Switchgrass (SG) + Sewage sludge (SG)	<ul style="list-style-type: none"> <li>▪ Effect of alkaline pre-treatment under mild heat conditions (100 °C or 212 °F).</li> <li>▪ Batch and continuous study.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Pre-treatment enhanced digestion of coarse-ground (<math>\leq</math> 0.78 cm particle size) switchgrass.</li> <li>▪ Energy conversion – around 63%.</li> <li>▪ Optimal NaOH concentration – 5.5% (wt/wt alkaline/biomass) with a 91.7% moisture level.</li> </ul>	(Jin et al., 2014)
Switchgrass (SG) + Sewage sludge (SSD)	<ul style="list-style-type: none"> <li>▪ BMP test under mesophilic (35 °C) conditions.</li> <li>▪ SSD:SG ratios – 100:0, 80:20, 60:40, 50:50, 40:60, 20:80, and 0:100 based on VS.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Maximum methane production – 272.06 mLCH<sub>4</sub>/g-VS at 40:60 mixing ratio.</li> <li>▪ Modified kinetic models revealed synergetic effect on the biogas production.</li> </ul>	(Ciggin, 2016)
Switchgrass (SG) + Coastal Bermudagrass (CBG)	<ul style="list-style-type: none"> <li>▪ Microwave-based alkali pre-treatment.</li> <li>▪ Immersion of biomass in dilute alkali reagents.</li> <li>▪ Microwave radiation – 250 W</li> <li>▪ Residence time – 5 to 20 min.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Sodium hydroxide was the most effective alkali reagent for microwave-based pre-treatment.</li> <li>▪ For SG – 82% glucose and 63%, xylose yields.</li> <li>▪ For CBG – 87% glucose and 59% xylose yields.</li> </ul>	(Keshwani and Cheng, 2010)
Switchgrass (SG)	<ul style="list-style-type: none"> <li>▪ Effect of steam explosion after impregnation with calcium hydroxide or dilute sulphuric acid on SG for simultaneous production of ethanol and methane.</li> </ul>	<ul style="list-style-type: none"> <li>▪ For ethanol production, Lime showed great potential</li> <li>▪ For higher methane yield, acid addition showed great potential.</li> </ul>	(Capecchi et al., 2016)
Switchgrass (SG)	<ul style="list-style-type: none"> <li>▪ Different pre-treatments – milling, temperature, sonication, alkalization</li> </ul>	<ul style="list-style-type: none"> <li>▪ Higher methane production – 256.6 ± 8.2 mL/g-VS for fresh SHS after mulching, alkalization, and</li> </ul>	(J.-C. Frigon et

Feed	Operating conditions	Results obtained	References
	<ul style="list-style-type: none"> <li>Applied on both winter harvested SG (WHS) and summer harvested SG (SHS):</li> </ul>	<ul style="list-style-type: none"> <li>autoclaving.</li> <li>Methane production – 139.8 mL/g-VS for WHS after grinding with alkalization and autoclaving.</li> </ul>	al., 2012)
Switchgrass (SG)	<ul style="list-style-type: none"> <li>Mesophilic methane production from SG harvested at three stages of development viz. mid-summer, late summer, and early fall</li> </ul>	<ul style="list-style-type: none"> <li>With crop maturity, specific methane yields decreased from 0.266 – 0.309 L-CH<sub>4</sub>/g-VS in mid-summer to 0.191 – 0.250 L-CH<sub>4</sub>/g-VS in early fall.</li> <li>25% more methane for two-cut strategy compared to the one-cut strategy per hectare.</li> </ul>	(Massé et al., 2010)
Switchgrass (SG)	<ul style="list-style-type: none"> <li>Effect of microwave pre-treatment of SG.</li> <li>Response surface analysis.</li> </ul>	<ul style="list-style-type: none"> <li>Only temperature had a significant effect on solubilization level.</li> <li>sCOD/tCOD ratio – 9.4% (at 90 °C) to 13.8% (at 180 °C).</li> <li>BMP assays – no significant effect on methane yield after microwave pre-treatment.</li> </ul>	(Jackowiak et al., 2011)
Switchgrass (SG) + <i>S. platensis</i> algae	<ul style="list-style-type: none"> <li>Biomethane and ethanol production from single and mixed substrates.</li> </ul>	<ul style="list-style-type: none"> <li>High gross energy production – 6774 MJ/ton in the form of biomethane from untreated SG.</li> <li>Energy production – 3904 MJ/ton in the form of ethanol.</li> </ul>	(El-Mashad, 2015)
Switchgrass (SG) + Dairy manure	<ul style="list-style-type: none"> <li>ACoD of dairy manure and SG at different mixing ratios viz. 4:0, 3:1, 2:2, 1:3 and 0:4 based on total solids (TS)</li> </ul>	<ul style="list-style-type: none"> <li>Formation of VFAs and system failure for mono digestion of SG at more than 4% TS.</li> <li>Co-digestion showed better-buffering capacity with an optimal mixing ratio of 2:2 and 39% higher production than mono digestion.</li> </ul>	(Zheng et al., 2015)

### 1.10. Anaerobic digestion using Rice straw

Rice straw (RS) is produced as a byproduct while cutting paddy plants for grain harvesting. Depending on the cultivation method, RS constitutes 40% – 60% of the gross weight of paddy. It has been reported that approximately 1.35 tons of RS are obtained for each ton of grain harvested (Kadam et al., 2000). RS has been considered one of the most preferred feedstocks for bioenergy production (Mustafa et al., 2017b). AD of RS has been a probable approach for renewable energy production despite its high recalcitrant nature and C/N ratio (Forster-Carneiro et al., 2008). However, these limitations can be negated by adopting co-digestion with substrates having high nitrogen content and pre-treatment methodologies (Mothe and Polisetty, 2020). Luo and co-workers investigated the coupling of LS-AD and SS-AD for RS and cow dung (CD). LS-AD was applied for CD, and SS-AD was applied for RS with inoculums obtained from the LS-AD process. OLR of 10 kg-VS/m<sup>3</sup>/d was possible for the LS-AD process with a specific methane yield of 225.2 mL CH<sub>4</sub>/g-VS. In SS-AD, an optimal substrate/inoculum (S/I) ratio of 0.9 was obtained, which was further utilized for continuous SS-AD reactor with an OLR of 2.17 kg-VS/m<sup>3</sup>/d (feed interval = 2 weeks). A maximum specific methane yield of 216.13 mL CH<sub>4</sub>/g-VS was attained from it (Luo et al., 2018).

Mei and co-workers investigated the effect of OLR on ACoD of RS and chicken manure (CM) under mesophilic conditions. Seven OLRs viz. 3.0, 3.6, 4.2, 4.8, 6.0, 8.0, and 12.0 kg-VS/m<sup>3</sup>/d at RS:CM ratio of 1:1 was utilized. The authors reported average specific biogas production of 380 L/kg-VS and recommended an optimum OLR of 4.8 kg-VS/m<sup>3</sup>/d. They also opined that at higher OLRs, the AD process failed due to ammonia accumulation (Mei et al., 2016b). Many studies have also concentrated on pre-treatment methodologies for the enhancement of biogas production from RS. In one of the studies for AD of alkali pretreated rice straw (RS) at mesophilic temperature range, the highest cumulative biogas production was

obtained at 37 °C, followed by 42 °C, and lowest was obtained at 30 °C (Shetty et al., 2017). For dilute sulphuric acid pre-treatment of RS at 37 °C, 94% COD removal efficiency and CH<sub>4</sub> yield of  $0.346 \pm 0.008$  L-CH<sub>4</sub>/g-COD removed was reported (Cheng et al., 2016). For sodium carbonate pre-treatment of RS at  $37 \pm 2$  °C, a substantial enhancement of digestibility was obtained (Kaur and Phutela, 2016). A comparative analysis of some other studies dealing with AD of RS are shown in Table 1.3.



**Table 1.3.** Literature review table on anaerobic digestion of rice straw

Feed	Operating conditions	Results obtained	References
Rice straw (RS) + Pig manure (PGM)	<ul style="list-style-type: none"> <li>▪ RS:PGM ratio of 0:1, 1:2, 1:1, 2:1, and 1:0.</li> <li>▪ OLRs of 3.0, 3.6, 4.2, 4.8, 6.0, 8.0, and 12.0 kg-VS/m<sup>3</sup>/d.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal ratio – 1:1.</li> <li>▪ Biogas production – 413 L/kg-VS was obtained at an OLR of 3 – 8 kg VS/m<sup>3</sup>/d.</li> </ul>	(Li et al., 2015b)
Rice straw (RS) + Pig manure (PGM)	<ul style="list-style-type: none"> <li>▪ Constant OLR</li> <li>▪ Varied TS contents: 27%, 32%, 37%, and 42%.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Biogas production was stable and high – 564 ± 13 – 580 ± 36 N m<sup>3</sup> t<sup>-1</sup> VS (for TS from 18% – 27%).</li> <li>▪ VFA accumulation – above 27% TS.</li> </ul>	(Riya et al., 2018)
Rice straw (RS) + Cow manure (CM)	<ul style="list-style-type: none"> <li>▪ RS:CM ratio of 0:1, 1:2, 1:1, 2:1, and 1:0.</li> <li>▪ OLRs of 3.0, 3.6, 4.2, 4.8, 6.0, 8.0, and 12.0 kg-VS/m<sup>3</sup>/d.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal ratio – 1:1</li> <li>▪ Specific biogas production – 383.5 L/kg-VS</li> <li>▪ Biogas production rate – 2.30m<sup>3</sup>/m<sup>3</sup>-d at OLR of 6kg-VS/m<sup>3</sup>/d.</li> </ul>	(Li et al., 2015a)
Rice straw (RS) + Pig urine	<ul style="list-style-type: none"> <li>▪ BMP test at F/I ratios – 0.5, 1, 2 and 3 at 55°C and 35-day.</li> <li>▪ Large scale batch test at F/I of 0.5 and 3.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Highest cumulative methane yield – 353.7 m<sup>3</sup>/t-VS at F/I of 0.5.</li> <li>▪ Stable operation between F/I ratio of 0.5 and 3.</li> </ul>	(Meng et al., 2018)
Rice straw (RS) + Kitchen waste + Pig manure (PGM)	<ul style="list-style-type: none"> <li>▪ Different RS:KW:PGM ratios</li> <li>▪ VS added – 54g/L.</li> <li>▪ Mesophilic temperature (37±1°C).</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal RS:KW:PGM ratio was 0.4:1.6:1.</li> <li>▪ Methane content: 45.9 – 70.0%.</li> <li>▪ VS reduction – 55.8%.</li> <li>▪ Biogas yield – 674.4 L/kg-VS.</li> </ul>	(Ye et al., 2013)

Feed	Operating conditions	Results obtained	References
Municipal solid waste (MSW) + Rice straw (RS)	<ul style="list-style-type: none"> <li>▪ MSW:RS ratios of 1:1, 2:1 and 3:1</li> <li>▪ BMP, Sludge activity.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Increase in Biogas and methane (CH<sub>4</sub>) potential of 60% and 57%, respectively for 2:1 MSW:RS ratio.</li> <li>▪ Biochemical methane potential – 0.99 CH<sub>4</sub>-COD/COD<sub>fed</sub>.</li> <li>▪ Sludge activity – 0.50 g CH<sub>4</sub>-COD/g-VSS.</li> </ul>	(Negi et al., 2018)
Urea-ammoniated rice straw (UARS) + food waste (FW)	<ul style="list-style-type: none"> <li>▪ Mesophilic conditions (35 °C)</li> <li>▪ VS added – 6 g/L</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal mixing ratio UARS:FW of 1:3.</li> <li>▪ Methane yield increase – 8.33% than single substrate.</li> <li>▪ Addition of supplements increase methane yield.</li> </ul>	(Zhang et al., 2018)
Sewage Sludge (SS) + Rice straw (RS)	<ul style="list-style-type: none"> <li>▪ RS:SS ratio of 2% and 4%.</li> <li>▪ Mesophilic temperature at (35 ± 1°C).</li> </ul>	<ul style="list-style-type: none"> <li>▪ Biogas yield for 4% increase 6 times that of solo sludge digestion.</li> <li>▪ Highest CH<sub>4</sub> concentration of 60 – 63%.</li> </ul>	(Abdel Daiem et al., 2018)
Rice straw (RS) + Trace elements	<ul style="list-style-type: none"> <li>▪ Effect of addition of trace elements.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Addition of Fe, Mo, Se and Mn – significant VFAs reduction and increase of methane yield.</li> <li>▪ Co and Ni did not improve AD process</li> <li>▪ Highest methane yields – 289.2, 289.6, 285.3, 293.0 mL/g-VS for addition of Fe, Mo, Se and Mn respectively.</li> </ul>	(Cai et al., 2017)
Rice straw (RS) + Sewage Sludge (SS)	<ul style="list-style-type: none"> <li>▪ One-stage system for CH<sub>4</sub> production.</li> <li>▪ Two-stage system for combined production of H<sub>2</sub> and CH<sub>4</sub>.</li> <li>▪ Thermophilic condition.</li> </ul>	<ul style="list-style-type: none"> <li>▪ H<sub>2</sub> fermentation – H<sub>2</sub> yield of 21 mL/g-VS and stable H<sub>2</sub> concentration of 60.9%.</li> <li>▪ CH<sub>4</sub> yield after utilization of post-H<sub>2</sub> fermentation residues – 266 mL/g-VS</li> <li>▪ Stable CH<sub>4</sub> content of 75–80%.</li> </ul>	(Kim et al., 2013)

### **1.11. Pre-treatment methods adopted in the Anaerobic digestion process**

Many studies have stressed the enhancement of lignocellulosic biomass digestibility by applying various pre-treatment methodologies such as physical, chemical, biological, and mixed/hybrid (FitzPatrick et al., 2010; Takara and Khanal, 2011). Prominent pre-treatment methods such as mechanical milling, acid or base treatment, steam explosion, ammonia fiber explosion, etc., have been adopted to disrupt the complex structure of biomass. Application of these methodologies increases the porosity, removes hemicellulose and/or lignin, and reduces the overall crystallinity facilitating the overall conversion process to bioenergy and bioproducts (Agbor et al., 2011; Monlau et al., 2013). However, many of these methodologies are unfavorable due to various environmental and economic considerations (Agbor et al., 2011; Alvira et al., 2010; Kumar et al., 2009; Monlau et al., 2013; Shrestha et al., 2008). In this study, pre-treatment methods have not been adopted to keep the AD process simple and economical.

### **1.12. Digestion of lignocellulosic biomass: challenges**

One of the major challenges in lignocellulosic biomass is producing high energy content biomass that can be converted easily to  $\text{CH}_4$ . Besides, the complex structure of lignocellulosic biomass hinders its digestibility and production of  $\text{CH}_4$ . Thus, for increasing  $\text{CH}_4$  yield, an increase in crop area for increasing biomass yield is necessary. Biomass yield can be improved by selecting suitable biomass with enhanced photosynthetic efficiency, better response to input utilization, and resistivity to pests and disease (SIMS et al., 2006). Thus, harvesting of crops should be done at an appropriate maturity stage so that the production of  $\text{CH}_4$  is done without intense adoption of pre-treatment techniques.

Moreover, the lack of a suitable design digester to treat high solid content feedstock hinders the digestion of lignocellulosic biomass. Also, proper management for digestate utilization and effluent needs to be developed. The digestate typically comprises a high amount of

nitrogen and trace elements, which requires treatment before being discharged into the environment. A combination of microalgae and AD has been recently developed for the utilization of effluent nutrients by algae. Lipids harvested from such algae can be used to produce biodiesel, and residues could be utilized as a feed in an anaerobic digester for production of methane.

In addition to energy harvested from the AD of organic and lignocellulosic substrates, energy harvested from solar photovoltaic systems plays a significant role in India's overall energy share. Solar Photovoltaic (PV) systems are collectors that convert solar energy to usable form, i.e., electrical energy. Based on the connection procedure, Solar PV systems are subdivided into three forms viz. standalone solar PV systems, grid-connected PV systems, and hybrid systems.

### **1.13. Standalone solar PV systems**

Standalone PV systems are decentralized systems that produce power independently and are not connected to the utility grid. It is suitable for places where grid penetration is not feasible, and solar intensity is optimal. These are preferably installed in remotest places where there is no utility grid (Kaundinya et al., 2009). PV system harvest energy from sunlight and converts it into usable electrical energy. This varies from other forms of energy such as solar thermal or concentrated solar power (CSP). A PV system typically comprises solar cells, PV module, mounting structure, inverter, battery, and charge controller. The charge controller and inverter are presently replaced by one unit called a Power conditioning unit (Bose, 2017). In 2015, record growth of 50 GW of solar installations was made, resulting in a total global installed capacity of 227 GW. Numerous numbers of solar projects were implemented for the electrification of distant and electricity deprived areas. And various schemes and subsidies were launched to install PV systems at public, private organizations, and residential buildings (Goel and Sharma, 2017).

Branker and co-workers made a critical review on the performance of solar PV systems based on LCOE. The authors reported that PV systems proved to be economically beneficial and achieved grid parity in some strategic locations (Branker et al., 2011). Barsoum and colleagues made a comparative assessment on biomass and standalone solar system's performance separately using HOMER. The authors reported that the standalone biomass system was economically beneficial than the standalone PV system because of its low LCOE and high efficiency (Barsoum et al., 2008). Ibrahim and colleagues investigated the sizing and algorithmic modelling of a standalone PV/Battery system in Malaysia. They obtained the optimal sizing ratio for PV and battery as 1.184 and 0.613, respectively, with an LCOE value of \$0.447/kWh (Ibrahim et al., 2015). Ma and co-workers investigated the performance analysis of a standalone PV system in Hong Kong and observed a reduction in its output with increased cell temperature. Actual array output of 3.08 kWh/kWp-day was observed against an estimated output of 4.94 kWh/kWp-day (Ma et al., 2013). Akikur and colleagues made a critical review of standalone solar PV and hybrid energy systems utilized for electrification of off-grid locations in different parts of the world. They reported that solar energy is economically beneficial and cost-competitive for load situations far from the grid. They also opined that addition of other energy sources with solar PV systems makes it more reliable and cost-effective (Akikur et al., 2013). A few other studies relating to standalone solar PV systems are discussed in Table 1.4.

**Table 1.4.** Literature review table on standalone solar PV systems

System	Operating conditions	Results obtained	References
Standalone PV system in New Delhi.	<ul style="list-style-type: none"> <li>▪ 2.32 kWp</li> <li>▪ Four weather conditions – clear, hazy, partially cloudy, and fully cloudy.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Overall energy generation of 1293 kWh/year.</li> <li>▪ System efficiency – 4.8%.</li> <li>▪ Inverter efficiency – 95.6%.</li> </ul>	(Chel and Tiwari, 2011)
Standalone PV system in Europe	<ul style="list-style-type: none"> <li>▪ Simulation study for some cities.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Fluctuation in solar radiation affected its reliability and system costs</li> </ul>	(Kaplani and Kaplanis, 2012)
Standalone PV system in Nepal	<ul style="list-style-type: none"> <li>▪ Feasibility of installation for remote area</li> </ul>	<ul style="list-style-type: none"> <li>▪ PV system was cost-intensive in connection to urban areas.</li> <li>▪ Monetary outcomes should be undermined for rural solar PV electrification projects.</li> <li>▪ Social and environmental aspects need to be emphasized.</li> </ul>	(Bhandari and Stadler, 2011)
Standalone renewable energy systems in China	<ul style="list-style-type: none"> <li>▪ Impact of standalone renewable energy systems in the livelihood and economy of 531 rural households.</li> <li>▪ Integration of lifecycle costing and GIS methodologies.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Off-grid systems were economically beneficial and reliable in comparison to conventional generator sets for meeting rural energy demands.</li> </ul>	(Byrne et al., 2007)
Standalone PV system in India	<ul style="list-style-type: none"> <li>▪ 110 kWp standalone rooftop PV system.</li> <li>▪ Performance analysis using Sunny Design, SAM and BlueSol.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Total annual energy output delivered to the grid – 1927.7 kWh.</li> <li>▪ Annual specific yield – 931.6 kWh.</li> <li>▪ Energy production from BlueSol software was comparable with other software results.</li> </ul>	(Shukla et al., 2016)
Standalone PV system in Australia	<ul style="list-style-type: none"> <li>▪ Feasibility analysis.</li> <li>▪ Software tools – HOMER and HYBRIDS to compare diesel generator-only, PV-only, and PV/diesel hybrid technologies.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Hybrid diesel/RES provided lowest NPC with an RF of 76%.</li> <li>▪ NPC and GHG reductions – 50% and 65% respectively compared to the diesel generator-only.</li> <li>▪ Payback time of the hybrid RES is 4.3 years.</li> <li>▪ Wind energy conversion systems (WECS) more economical than photovoltaics for large-scale operations.</li> </ul>	(Dalton et al., 2008)

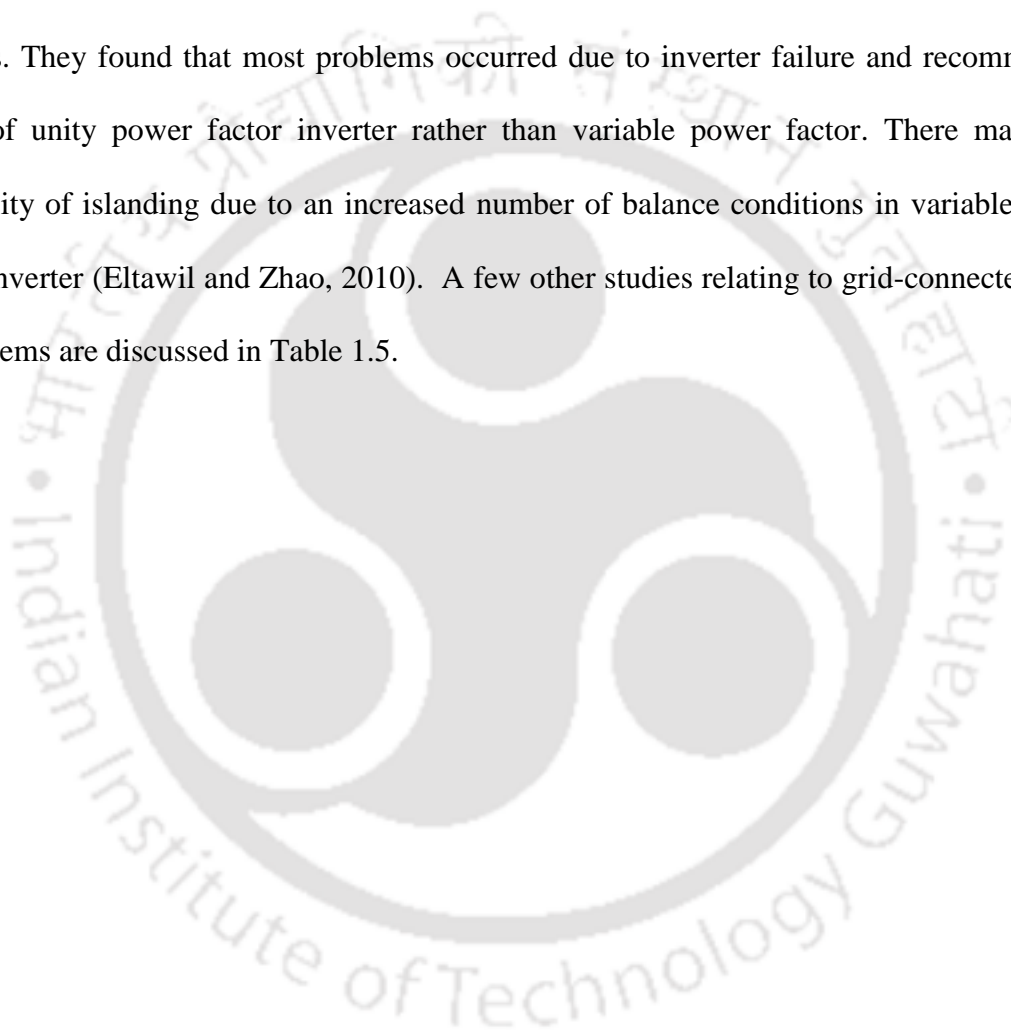
System	Operating conditions	Results obtained	References
Standalone PV system in Pakistan	<ul style="list-style-type: none"> <li>▪ Feasibility analysis for a residential household in Pakistan.</li> <li>▪ Sizing of the components.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Peak power – 1928 Wp</li> <li>▪ Area of PV modules – 12.85 m<sup>2</sup>.</li> <li>▪ Capacity of battery backup – 9640.5 Wh.</li> <li>▪ Size of charge controller – 56.65 A.</li> <li>▪ Size of inverter – 1020 W.</li> <li>▪ LCC of the system – PKR. 457,306.</li> <li>▪ Unit electricity cost – PKR. 14.8/kWh.</li> </ul>	(Ghafoor and Munir, 2015)
Standalone PV system in Egypt	<ul style="list-style-type: none"> <li>▪ Optimal design of standalone solar PV-battery system (BS) for irrigation in an isolated region using HOMER.</li> <li>▪ Two different metrics – net present cost (NPC) and energy cost (EC).</li> </ul>	<ul style="list-style-type: none"> <li>▪ Optimal PV system – 75 kW.</li> <li>▪ Battery system – 32 units Trojan L16P.</li> <li>▪ Converter – 28 KW.</li> <li>▪ NPC – \$109,856.</li> <li>▪ EC costs – \$0.059/kWh.</li> </ul>	(Rezk et al., 2019)
Standalone PV system in Delhi, India	<ul style="list-style-type: none"> <li>▪ Proposed a scheme for utilization of standalone PV system for greywater recycling system and household electric load.</li> <li>▪ Compared the system and design with conventional system.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Proposed system design was economical and saving of 203\$ compared to conventional system.</li> <li>▪ 14,721.5 gallons per year of water saved for the residential level.</li> </ul>	(Prajapati and Fernandez, 2020)
Standalone PV system in Kenya	<ul style="list-style-type: none"> <li>▪ Analysis using PVGIS software.</li> <li>▪ Survey assessment.</li> <li>▪ Economic analysis.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Average daily solar insolation – 5.42 kWh/m<sup>2</sup>.</li> <li>▪ Average energy consumption in a household – 1.278 kWh/day.</li> <li>▪ LCC, ALCC, and COE of \$ 3081, \$ 215\$, and 0.461/kWh for a 20-year lifetime.</li> </ul>	(Odhiambo et al., 2020)

#### 1.14. Grid-connected PV systems

Grid-connected PV system refers to decentralized PV systems connected to the main electricity grid or a local grid. This system is ideal for locations close to the grid or places where solar energy is insufficient to meet the energy demand. Besides, for surplus energy generation from the PV system, excess energy can be injected back into the grid. Grid-connected systems offer reliable electrical systems operation, as seasonal load variations and insufficient supply during bad weather conditions can be taken care of from the grid (Kaundinya et al., 2009). Adaramola did the techno-economic analysis of an 80-kW grid-connected PV system in Nigeria using HOMER. The project was economically viable with an LCOE value of \$0.103/kWh and an overall energy share of 40.4%. The author reported that dependency on diesel generators and GHG emissions could be reduced by the installation of solar PV systems (Adaramola, 2014). Sharma and Chandel (Sharma and Chandel, 2013a) did the performance assessment of a 190 kWp grid-connected Solar PV plant in Punjab. They evaluated the reference yield, final yield, and performance ratio of the system and reported value in the range from 2.29 – 3.53 kWh/kWp-day, 1.45 – 2.84 kWh/kWp-day and 55 – 83% respectively. Also, an average annual energy yield of 812.76 kWh/kWp with a system efficiency of 8.3% was reported. Mondol and colleagues did the performance analysis of a 13 kWp roof-mounted grid-interactive PV system based on daily, monthly and yearly analysis over three years period. They reported an average annual PV, system, and inverter efficiencies of 7.6%, 6.4%, and 75%, respectively. And average monthly AC performance ratios of 0.60, 0.61, and 0.62 were obtained during the three years (Mondol et al., 2006). Tarigan and co-workers did the techno-economic analysis of a 1 kWp grid-interactive PV system in Indonesia. They found that the basic electrical loads of a household were easily met by the system. Moreover, 1 MWh/year of grid injection power with a performance ratio of 72% and CO<sub>2</sub> reduction of 1296 kg was reported in the study. The system had a payback period of 17.6 years

(Tarigan et al., 2015). Pundir and colleagues investigated the performance assessment of a grid-connected solar PV system in IIT Roorkee. They reported that electricity generation cost from the system without subsidy was INR 8.50/kWh with a performance ratio and capacity factor of 63.68% and 8.77%, respectively. The system would have a payback period of 7.5 years with an annual reduction of 2464 tCO<sub>2</sub> equivalent (Pundir et al., 2016).

Etwil and Zhao did a critical review on problems associated with grid-connected PV systems. They found that most problems occurred due to inverter failure and recommended usage of unity power factor inverter rather than variable power factor. There may be a possibility of islanding due to an increased number of balance conditions in variable power factor inverter (Eltawil and Zhao, 2010). A few other studies relating to grid-connected solar PV systems are discussed in Table 1.5.



**Table 1.5.** Literature review table on grid-connected solar PV systems

System	Operating conditions	Results obtained	References
Grid-connected Solar PV system in Nigeria	<ul style="list-style-type: none"> <li>▪ Techno-economic analysis of 80 kW grid-connected solar PV system.</li> <li>▪ Optimization using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Annual electricity generation – 331,536 kWh</li> <li>▪ Solar PV share – 40.4%.</li> <li>▪ Levelized cost of energy – \$0.103/kWh</li> </ul>	(Adaramola, 2014)
Grid-connected Solar PV system in Ghana	<ul style="list-style-type: none"> <li>▪ Performance of 5 Solar PV systems with 5 different solar cell technologies.</li> <li>▪ Poly-crystalline (pc-Si), monocrystalline (mc-Si), Copper Indium disulfide (CIS) thin-film, Amorphous Silicon (a-Si), and Heterojunction Incorporating thin (HIT) film.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Total annual energy delivered to the grid – 3133.2 kWh for CIS and 4572.1 kWh for pc-Si.</li> <li>▪ Performance ratio – 48.84% (CIS) to 71.26% (for p-Si).</li> </ul>	(Quansah et al., 2017)
Grid-connected Solar PV system in India	<ul style="list-style-type: none"> <li>▪ Performance analysis of 190 kWp grid-interactive solar PV plant.</li> <li>▪ Prediction of energy using PVsyst.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Final yield – 1.45 to 2.84 kWh/kWp-day.</li> <li>▪ Performance ratio – 55 to 83%.</li> <li>▪ Average annual measured energy yield – 812.76 kWh/kWp.</li> <li>▪ Average annual predicted energy yield using (PVsyst) – 823 kWh/kWp.</li> </ul>	(Sharma and Chandel, 2013b)
Grid-connected solar PV system in Northeast India	<ul style="list-style-type: none"> <li>▪ Feasibility analysis for installation of a megawatt-level grid-connected solar PV plant using PVsyst.</li> </ul>	<ul style="list-style-type: none"> <li>▪ High performance ratio – 0.855 for locations of Guwahati and Gangtok.</li> <li>▪ Lowest LCOE –3.88 INR/unit for Aizawl.</li> <li>▪ Most suitable locations for solar PV installation – Aizawl and Guwahati.</li> </ul>	(Kalita et al., 2019)
Grid-connected solar PV system in Siberia	<ul style="list-style-type: none"> <li>▪ Performance and energy efficiency calculations of a 2-kW rooftop solar PV system depending on the real climate conditions.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Energy efficiency – 10.07%.</li> <li>▪ Annual performance ratio – 93.6%.</li> <li>▪ Annual capacity factor – 12.88%.</li> <li>▪ Energy generated during one-year – 2323.329 kWh.</li> </ul>	(Milosavljević et al., 2015)

System	Operating conditions	Results obtained	References
Grid-connected solar PV system	<ul style="list-style-type: none"> <li>▪ Modeling and simulation of a 3.2 kWp using Matlab/Simulink.</li> <li>▪ Significant error indicators are reported to show the effectiveness of the simulation model to predict energy generation.</li> </ul>	<ul style="list-style-type: none"> <li>▪ I–V characteristic had a good degree of accuracy.</li> <li>▪ Dynamic behavior of the PV system can be evaluated in real working conditions using this method.</li> </ul>	(Chouder et al., 2012)
Grid-connected solar PV system in Hong Kong	<ul style="list-style-type: none"> <li>▪ Performance of a PV system in terms of energy, environmental and financial aspects.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Embodied energy payback period – 8.9 years.</li> <li>▪ Average annual emissions reductions of CO<sub>2</sub>, SO<sub>2</sub>, NO<sub>x</sub>, and particulates – 771, 1.12, 1.03, and 0.054 kg respectively.</li> </ul>	(Li et al., 2012)
Grid-connected solar PV system in southern India	<ul style="list-style-type: none"> <li>▪ Performance of two co-located grid-connected PV systems comprising polycrystalline silicon (p-Si) and copper indium selenium (CIS) arrays were analyzed.</li> <li>▪ Comparative analysis annual experimental data with predicted data using PVsyst.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Annual energy delivered to the grid – 1536.9 kWh (for p-Si) and 1698.4 kWh (CIS PV).</li> <li>▪ Energy yield of CIS array is 7.61% more in comparison to p-Si array</li> </ul>	(Ramanan et al., 2019)
Grid-connected solar PV system in tropical semi-arid climate of India	<ul style="list-style-type: none"> <li>▪ Performance characteristics of 1 MW grid-connected PV system.</li> <li>▪ Degradation of PV plant was quantified using four statistical methods.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Reference yield, final yield, system efficiency, capacity factor, and performance ratio of 4.64 h/day, 6.23 h/day, 11%, 19.33%, and 74.73%, respectively.</li> <li>▪ Degradation rate – 0.27%/year, 0.32%/year, 0.50%/year, and 0.27%/year, respectively, after 50 months operating period.</li> </ul>	(Malvoni et al., 2020)
Grid-connected Solar PV system in Bangladesh	<ul style="list-style-type: none"> <li>▪ Performance analysis of 80 KWp grid-connected solar PV plant.</li> <li>▪ Presented a solar irradiation predict model based on fuzzy logic and artificial neural networks.</li> </ul>	<ul style="list-style-type: none"> <li>▪ Performance of ANN was better than fuzzy logic model by comparing RMSE, R<sup>2</sup> and percentage of accuracy.</li> <li>▪ Accuracy – 97.47% (fuzzy logic model) and 98.78% (ANN model) with actual irradiation.</li> </ul>	(Shuvho et al., 2019)

### 1.15. Hybrid Renewable Energy Systems (HRES)

Typically, HRES comprise mainly of solar, wind, biomass, and hydro. Power generation from these sources is primarily affected by solar irradiation, wind speed, and ambient temperature (Indragandhi et al., 2017; Khatib et al., 2013). As such, integration of multiple energy sources can compensate for the hindrances of variability, unpredictability, and randomness of solar/wind energy (Baños et al., 2011; Iqbal et al., 2014). Hybrid energy systems (HES) has proven to be very beneficial as energy is converted into one form (mainly electricity) and stored in other forms. This can be utilized for varied types of loads, and increased reliability may be achieved (Al-falahi et al., 2017). One energy source's shortcoming is compensated by another when two or more renewable energy sources are hybridized as a single system (González et al., 2015). Thus, obtaining a better efficiency, reliable and better output while lowering the overall cost (Rahman et al., 2014). HES are co-generating units either for the production of power or heat, and their integration can be done using advanced power electronics (Paska et al., 2009). For remote locations, installation of HES instead of a standalone system would be cost-effective, decreasing overall capital and operational expenses and ecological debasement (Khan and Iqbal, 2005)

Hybridization of solar, biogas, and biomass energy systems could recover isolated locations' environmental and economic status. Many studies have reported about the factors highlighting the expense of HES. Various other factors such as system size, cost of energy sources, and system configuration can impact the unit cost of HES (Gupta et al., 2011a, 2011b). Ma and colleagues proposed the setup of an off-grid pumped hydro storage (PHS)-PV hybrid system for meeting the load demand of a remote island considering its system economy (Ma et al., 2015). Das and co-workers discussed the techno-economic feasibility of hybridizing biogas generators and batteries with a PHS-PV system for supplying power to a radio transmitter station (Das et al., 2019). Adaramola and colleagues did the feasibility analysis of

implementing a hybrid energy system for semi-urban and rural areas in Nigeria using HOMER. They found PV/DG/Battery hybrid system to be the most suitable option having an LCOE value from \$0.348/kWh – \$0.378/kWh depending on the interest rate. These costs were comparatively lower than those from using standalone generator systems in the range from \$0.417/kWh – \$0.423\$/kWh (Adaramola et al., 2014). Haghi and co-workers investigated the optimization study of a grid-connected and off-grid system for a small hydro-PV hybrid system in Iran. They found the grid-connected system to be more economical than off-grid system (Haghi et al., 2017). Guo and colleagues performed an overall analysis of the integration of biomass, solar, wind, and geothermal energy. More emphasis was laid on small scale off-grid systems than large scale grid-connected systems. Moreover, they also focused on solar and wind energy (Guo et al., 2018).

Optimal sizing of PV hybrid systems plays a significant role in overall efficiency and optimum output extraction from the system. A review of different traditional methods, modern Artificial intelligence (AI) methods, and usage of simulation tools for sizing of hybrid systems have been reported (Nabipour-Afrouzi et al., 2018; Singh et al., 2016). Fathima and Palanisamy made a critical review of AI methodologies and simulation tools to size microgrid hybrid systems (Fathima and Palanisamy, 2015). Some studies have also reviewed the performance assessment, size optimization, and mathematical modeling of PV-wind battery storage systems (Khan et al., 2018; Mahesh and Sandhu, 2015). Bajpai and Dash made an analysis of sizing methods, modeling components, and energy management of independent HRESs and identified future development trends (Bajpai and Dash, 2012). Bahramara and co-workers made a critical review on the input parameters, modeling of equipment, optimization procedure, sensitivity analysis, and output parameters of HOMER software (Bahramara et al., 2016). A few other studies related to HES are discussed in Table 1.6.

**Table 1.6.** Literature review table on hybrid energy systems

System	Operating conditions	Results obtained	References
Off-grid Hybrid system (PV, wind turbine and diesel generator)	<ul style="list-style-type: none"> <li>Optimization using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>Optimal solution – 500 PV panels (320 W each), 10 kW wind turbine, 25 kW diesel generator, 250 Surrette batteries and 80 kW inverter.</li> <li>Initial capital investment: \$521,078.</li> <li>NPV: \$836,210</li> </ul>	(Haghighat Mamaghani et al., 2016)
Mini-grid Hybrid system in Maldives	<ul style="list-style-type: none"> <li>Presented a design scenario for utilizing renewable energy sources and a diesel generator with a reverse osmosis desalination plant.</li> <li>Simulations were performed using HOMER</li> </ul>	<ul style="list-style-type: none"> <li>Hybrid power system was better both economically and environmentally, compared to the standalone diesel system.</li> </ul>	(Setiawan et al., 2009)
Hybrid (PV)/diesel system	<ul style="list-style-type: none"> <li>Techno-economic feasibility using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>Optimal solution – 60 kW PV array, two units of 50 kW diesel generator, and 12 units of battery.</li> <li>Lower NPC and COE value for 25 years projection period and annual interest rate of 6%.</li> </ul>	(Lau et al., 2010)
Hybrid system in UAE	<ul style="list-style-type: none"> <li>Performance of a standalone solar PV power system with single-axis (horizontal and vertical) and dual-axis solar trackers and a diesel generator (DG).</li> <li>Simulations using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>Best power system architecture – HES with dual-axis solar trackers with renewable fraction (48.55%) and LCOE of 0.25 \$/kWh.</li> <li>Highest GHG emission reduction of 69.6%.</li> </ul>	(Salameh et al., 2020)
Hybrid system in Palestine, Lebanon, and Iraq	<ul style="list-style-type: none"> <li>Analysis of hybridized solar photovoltaic energy using first-hand data.</li> <li>Integrated appraisal of hybrid solar (PV) – diesel systems.</li> </ul>	<ul style="list-style-type: none"> <li>Hybrid PV-diesel systems: - Economically beneficial for Palestine and Lebanon and less promising in Iraq due to its heavily subsidized electricity tariff.</li> <li>Tax exemption on renewable energy components to decrease the initial cost of financing.</li> </ul>	(Harajli et al., 2020)

System	Operating conditions	Results obtained	References
Hybrid off-grid solar PV/Fuel Cell/Diesel Generator system	<ul style="list-style-type: none"> <li>Simulation analysis using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>73% of total energy from solar PV, 24% from fuel cell and 3% from diesel generator.</li> <li>High RF (66.1%).</li> <li>Economically feasible (92 \$/MWh).</li> <li>Eco-friendly (24 kg CO<sub>2</sub>/MWh).</li> </ul>	(Ghenai and Bettayeb, 2019)
Hybrid solar-wind-battery system	<ul style="list-style-type: none"> <li>Optimization of a hybrid solar-wind system with storage using genetic algorithm (GA).</li> <li>Four different cases were evaluated and compared with HOMER results.</li> </ul>	<ul style="list-style-type: none"> <li>Genetic algorithm offers better results than HOMER in terms of cost and reliability</li> <li>Wind turbine size has little impact on system cost.</li> <li>Effect of LPSP on COE remains same after considering the different load demands.</li> </ul>	(Javed et al., 2019)
Hybrid PV-wind-diesel-battery system	<ul style="list-style-type: none"> <li>Viable and optimal solution based on minimum COE and NPC.</li> </ul>	<ul style="list-style-type: none"> <li>Combination of wind energy system, PV, and battery was the best option.</li> <li>COE and NPC of proposed system were equal to \$0.10995/kWh and \$15,039,705 for 25 years.</li> </ul>	(Singh et al., 2017)
Hybrid diesel/PV/wind/battery systems	<ul style="list-style-type: none"> <li>Optimum configuration assessment using HOMER Pro software.</li> </ul>	<ul style="list-style-type: none"> <li>For off-grid systems, COE: 9.3–12.6 ¢/kWh and renewable fraction: 0–43.9%, for PV panel (0–1000 kW) wind turbine (0–600 kW), and battery sizes (1300 kWh).</li> <li>For on grid systems without battery storage, COE: 5.7–8.4 ¢/kWh and RF: 0–53% for the same sizes of PV panel and wind turbine.</li> </ul>	(Baneshi and Hadianfard, 2016)
Hybrid PV/diesel/battery power system in China	<ul style="list-style-type: none"> <li>Techno-economic feasibility using HOMER.</li> </ul>	<ul style="list-style-type: none"> <li>Optimal system – 500 kWp PV arrays, two 1250 kW diesel generators, 600 batteries, and a</li> <li>500-kW sized converter.</li> <li>Lowest total NPC of \$8,162,822 and a LCOE of 0.480 \$/kWh with a renewable fraction of 57%.</li> <li>Significant reduction in emission pollutants.</li> </ul>	(Li et al., 2019)

### 1.16. Biogas hybrid systems

Biogas burns in a similar manner as LPG and CNG leaving behind no smell or residue. Replacement of oil by biogas in internal combustion engines has facilitated solving environmental conditions and emissions (Bhatti et al., 2015). As emission generated from the burning of biogas is already a part of the atmosphere's carbon cycle, it has a minimal carbon footprint (Abbasi et al., 2012). A study successfully demonstrated the hybridization of biomass gasifiers and solar cells to meet primary load demand in distant sites (Kumaravel and Ashok, 2012). Kaur and co-workers presented a hybrid technological solution for small to medium scale energy generation. The study recommended the installation of a 1750 kWp power plant that included a 1000 kW biomass power plant, 400 kW solar PV plant, and 350 kW biogas. The generation cost from the hybrid system was reported to be Rs 5.67/kWh. The cost per unit from the standalone biogas system was Rs 4.2, whereas, from the solar PV plant, it was Rs 22.22. Thus, hybridization of solar energy and biomass offers a viable option for electrification of remote rural areas (Kaur et al., 2016).

Standalone solar or biogas systems that are installed worldwide undergo a lot of operational problems. Solar panels are expensive, and because of the intermittent nature of sunlight, energy could be produced only during the daytime and causes uneven energy generation. Biomass, on the other hand have contains a low amount of ash contents and some pollutants. But the combination of these two sources would augment the generation conditions. As energy generation from biogas and biomass plants can be controlled, they are termed as controlled energy sources while solar PV, which solely depends on the climatic conditions, is an uncontrolled source.

This system's principal advantage is its ability to combine with any heating system such as fan coils, space heating, etc., by replacing conventional heating sources. It acts as a viable and efficient source for a fully renewable-based heating system (Chasapis et al., 2008).

In one of the studies, the authors reported thermal and collector efficiencies of 57% and 63%, respectively, for a co-generation plant of solar and biogas from distillery plant waste. They found that the demand could be met by the supply of biogas coupled with the solar system (Kaushika et al., 2005). It has been reported that the combination of solar and biogas system utilized for heat storage system has proven to be beneficial in lowering the Levelized Cost of Electricity (LCOE) (Servert et al., 2011)

### **1.17. Need for hybridization**

Standalone solar PV system works as mini-grid, which supplies power in locations having consistent access to sunlight. Whereas in places with unsteady and less insolation, the hybrid solar PV system can be an effective electrification approach (Akikur et al., 2013).

Individual drawbacks of solar energy and biomass energy systems are complemented by hybridization (Nixon et al., 2012). Its combination results in decrease of biomass demand, which decreases the demand for biomass cultivation land and improves energy security. The major problem in its combination is the economic disputes compensated by the environmental benefits (Ho et al., 2014; Rahman et al., 2014).

### **1.18. Sizing of hybrid energy systems**

Proper sizing of HRES is very much essential as excessive sizing can increase the initial cost. However, for proper reliability, it is essential for its proper optimization (Al Busaidi et al., 2016). The primary step for an HRES system is to determine the types for integration. Secondly, mathematical models considering grid transmission constraints, energy balance, energy abandonment rate, etc., needs to be established. It is to be noted that for different hybrid systems, objective functions, constraints, and decision variables of mathematical models are different. Subsequently, a suitable sizing methodology is adopted considering the characteristic problem. And finally, the best rating scheme is obtained considering the objective functions.

Various evaluation criteria such as economic, environmental, reliability and social indicators act as tools for the optimization process. Most of the researchers have focused on a single objective considering the system economy. At the same time, many have also focused on multi-objective considering reliability and economy.

### **1.19. Software tools utilized for modelling of Hybrid Energy Systems**

Presently there are various software tools such as HOMER, Hybrid Optimization by Genetic Algorithm (HOGA), HYBRID2, SAM etc. for optimization of hybrid energy systems (Shi et al., 2015).

#### **1.19.1. Hybrid Optimization of Multiple Energy Resources (HOMER)**

HOMER is an optimization tool developed by NREL (US) which focuses on minimizing NPV for optimal capacity of a HRESs system. Its primary input parameters comprise of solar irradiation, wind speed, location, load data etc. (Zhou et al., 2010). Its basic processes includes simulation, optimization and sensitivity analysis (Bahramara et al., 2016). Simulation and optimization phases occur concurrently and the uncertainty or change of input parameters are examined in the sensitivity analysis (Upadhyay and Sharma, 2014). Although it is simpler in nature, the calculation time is increased if number of parameters are increased. Moreover, as the algorithm and mathematical analysis in the simulation process are not visible, it is not intuitive in nature (Khatib et al., 2016). In many studies, HOMER has been incorporated for optimization of off and on grid PV- battery, PV-wind-battery, PV-wind-diesel (Askari and Ameri, 2012; Baghdadi et al., 2015; Bentouba and Bourouis, 2016; Ma et al., 2014; Mandal et al., 2018; Rawat and Chandel, 2013; Yahyaoui et al., 2017) systems. Bekele and Tadesse (Bekele and Tadesse, 2012) utilized HOMER for assessing the feasibility of a small off grid hydro-PV- wind system considering the monthly average runoff, solar radiation, wind speed and load demand. In Algeria, HOMER was utilized for designing a grid connected PV-

wind system (Koussa and Koussa, 2015). The authors reported PV and wind power size of 3 MW and 1.98 MW respectively with an energy production of 24%.

### **1.19.2. Hybrid optimization by genetic algorithm**

HOGA is an optimization software for hybrid system and is developed by the University of Zaragoza, Spain (Zhou et al., 2010). Here GA is utilized for optimizing both single and multi- objective problems and also for adoption of control strategies (Chauhan and Saini, 2014). However, the major drawback of this software is that probability analysis and net measurements are not included in it (Khatib et al., 2016). Cano et al. did the techno-economic analysis of a standalone PV-wind-battery system using HOGA (Cano et al., 2014).

### **1.19.3. HYBRIDS**

HYBRIDS is an application software developed by Solaris Homes. It is based on Microsoft Excel spreadsheet and is utilized for design and evaluation of renewable energy systems. The economic feasibility of a system is estimated in terms of NPV considering daily average load and environmental data for each month of the year. It was developed by Solaris Homes for renewable energy system evaluation and design (Zhou et al., 2010). However, the basic drawback of this system is that it can only simulate one configuration at a time (Chauhan and Saini, 2014)

### **1.19.4. System Advisor Model (SAM)**

SAM is an open-source software developed by U.S. Department of Energy's National Renewable Energy Laboratory (NREL). It is a techno-economic model used for the assessment of performance and financial parameters of renewable energy projects. SAM performs the simulation of various renewable energy systems such as solar PV, wind, biomass power systems etc., and includes a basic generic model for comparative analysis with conventional or other types of systems. The financial model of SAM calculates the financial metrics of

power projects on the basis of cash inflows over a specified analysis period. The financial model uses the system's electrical output calculated by the performance model to calculate the series of annual cash flows. However, the drawback of this model is that it cannot be utilized for modeling of hybrid system containing more than one generating source (Shukla et al., 2016).

### **1.20. Knowledge gaps**

Based on the extensive literature review, it has been observed that lignocellulosic biomass is a suitable source for bioenergy production. It has been observed that the characteristics property of lignocellulosic biomass varies with site locations and environmental conditions. Though many studies are reported on switchgrass for biofuel production, very few studies focused on production of biogas. Moreover, duckweed and rice straw are extensively available in North-East India which can sustainably be utilized for bioenergy generation. Though individual studies have focused on biogas production from these biomass sources, comparative study under similar conditions are not performed.

Study on PV systems has also been done extensively, focusing on performance assessment and economic analysis. Again, mostly modeling and simulation study for hybridization of biogas and solar PV have been presented in most studies. But real-time analysis of PV system and hybrid PV-Biogas system under different loads have not been investigated.

This study thus provides a good insight into the usage of lignocellulosic biomass for bioenergy production. As India's North-Eastern part falls under the sub-tropical climate zone, this study would provide a real-time application of load on solar PV systems and its usability in standalone, grid, and hybrid modes.

### **1.21. Aim and approach**

In many parts of North-Eastern India, certain energy plants such as water hyacinth, water weeds, etc., are abundant in nature, but their potential is still not fully utilized. Moreover,

with the increase in population, there is a tremendous increase in the household and commercial wastes generated regularly. The waste thereby created is either disposed of or incinerated, which creates pollution in the environment. There are various ways of using organic waste and energy crops as a source of energy generation. One such well-established process is the production of biogas by the anaerobic digestion process. Anaerobic digestion is a well-established technology that has gained tremendous attention over the years. It is the process of decomposition of organic matter in the absence of oxygen to form biogas. Biogas is primarily methane ( $\text{CH}_4$ ) and carbon dioxide ( $\text{CO}_2$ ) and a trace amount of hydrogen sulfide ( $\text{H}_2\text{S}$ ) and moisture. It can be used for various heating purposes such as cooking and can also be used in a gas engine to convert the gas to electricity and heat.

There are various parts of this region in which people are devoid of electricity. This region is blessed with ample solar intensity for maximum time of the year, which can be harnessed properly and utilized to overcome the power crisis. In order to meet the continuous increasing demand, it is necessary to focus on harness of power from either a standalone system or a microgrid system at possible sites. One such viable approach can be the integration of electricity generation from biogas and solar PV. This combination can enhance the overall efficiency and reliability of a system with respect to varying and increased load demand.

The present study thus aims to take a holistic and sustainable approach for optimization of lignocellulosic feedstocks like duckweed, switchgrass, and rice straw co-digested with cattle dung for biogas production. The study also analyzes the effects of variable load conditions for a 1 kWp solar PV system in standalone and grid-connected modes. The study further investigates the hybridization of solar PV system with a biogas fueled generator system for electricity generation and its operation under different load conditions. An overall economic and environmental analysis of the hybrid system has also been presented in this study.

## 1.22. Objectives

Based on the extensive literature review, it was observed that though anaerobic digestion is a well-established process, its operation is location and site-specific and more experimentation needs to be done at a large-scale. Moreover, its hybridization with a solar PV system needs further optimization for reliable power supply w.r.t. to environmental conditions and operating parameters. Also, there can be various issues during the synchronization of power generated from the PV system and the biogas generator. Keeping into account the limitations, the following objectives are identified for this research work.

- I. Characterization of lignocellulosic feedstocks viz. Duckweed, Switchgrass and Rice Straw.
- II. Optimization of lignocellulosic feedstocks for biogas production in batch process at different total solid concentration and mixing ratios.
- III. Installation of three 4-m<sup>3</sup> community size digesters at Aoniati Satra, Amingaon (Assam) and implementation of optimized condition obtained in batch process using the same lignocellulosic feedstocks co-digested with cattle dung.
- IV. Installation and experimental investigation of a 1 kWp photovoltaic (PV) system both in standalone and grid-connected mode at different loading conditions.
- V. Investigation of a 3.5 kVA biogas fueled generator and 1 kWp photovoltaic (PV) hybrid connection system at similar loading conditions.
- VI. Economic and environmental analysis of the overall system.

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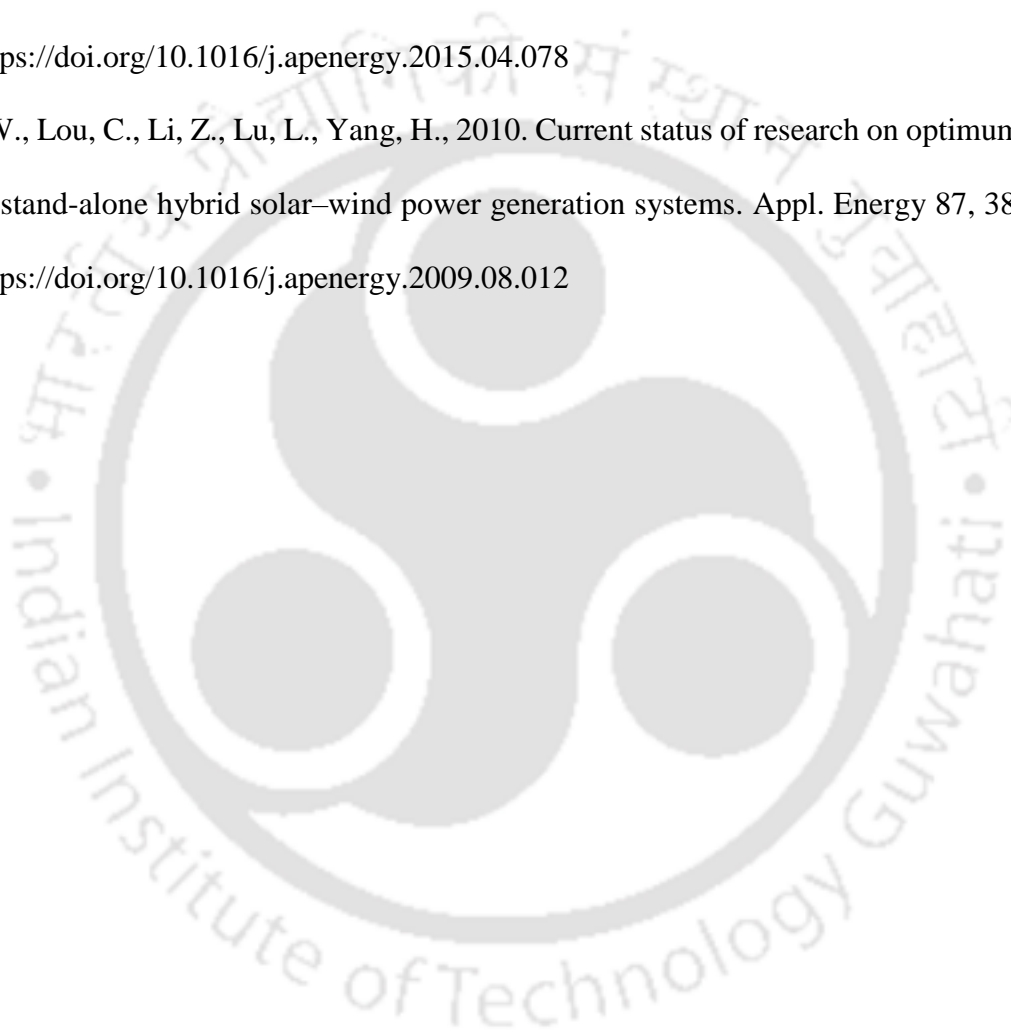
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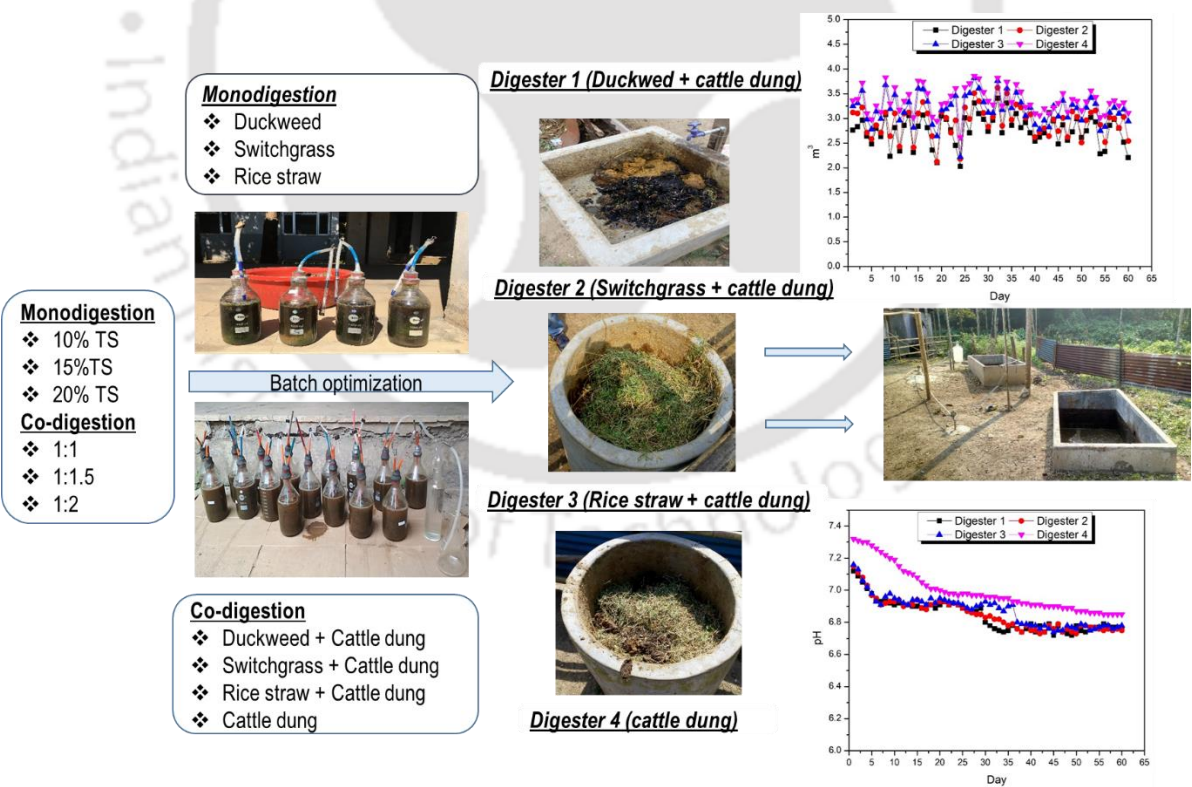
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# Chapter 2

## Biogas production from anaerobic mono- and co-digestion of lignocellulosic feedstock: Process optimization and its implementation at community level



## 2.1. Introduction

In this chapter, anaerobic mono- and co-digestion of three lignocellulosic biomass, viz. duckweed, switchgrass, and rice straw, were performed in 1 litre laboratory-scale batch reactors. The initial biochemical methane potential (BMP) test was performed at three different total solids concentrations (10%, 15%, 20%) and cattle dung to feedstock ratios (1:1, 1:1.5, 1:2) under mesophilic conditions (28 – 32 °C) for 36 days. Co-digestion of feedstocks at 1:1 ratio yielded better results than other cattle dung to feedstock ratios. Optimized physical parameters were further implemented for a scale-up co-digestion study of biogas potential from 4 m<sup>3</sup> community-size biogas digesters. The investigation was performed for 60 days maintaining an hydraulic retention time (HRT) of 40 days, and a comparative analysis with mono digestion of cattle dung was also analyzed. Average daily biogas production for digester containing rice straw and cattle dung was 0.36 m<sup>3</sup>/kg-VS, whereas it was 0.34 m<sup>3</sup>/kg-VS and 0.32 m<sup>3</sup>/kg-VS for switchgrass and duckweed, respectively. An overall comparative analysis of the biogas production and its composition for both BMP tests and continuous processes are discussed in this work.

## 2.2. Materials and Methods

### 2.2.1. Feed material and inoculum

Three lignocellulosic biomass viz. duckweed, switchgrass, and rice straw were collected from nearby areas of IIT Guwahati, Assam, India and were utilized for investigation of biogas production potential. Recent research has shown that lignocellulosic biomass should be initially pretreated for enhancement of biogas production. However pretreatment of biomass is energy intensive and is uneconomical (Tu and Hallett, 2019). As one of the primary motive of the study was to maximize the output with minimum energy consumption, the biomass was thus subjected to only mechanical pretreatment for size reduction. For the batch process, the feedstocks were initially dried in oven at 100°C in hot air oven. Size reduction of duckweed

was done by using a mixer grinder. Whereas, switchgrass and rice straw were chopped into even sizes of approximately 10 mm before being fed into the reactors (Zhou et al., 2017). The inoculum used in BMP tests was taken from the anaerobic sludge a biogas plant installed at Auniati Satra, near IIT Guwahati, Assam, India. The biogas plant has been operating for the last seven years and uses cattle dung as feed material. The biogas produced is used primarily for cooking purpose. For assessing the biogas potential from the lignocellulosic feedstock at the community level, three 4 m<sup>3</sup> biogas digesters were installed at the Satra, as shown in Fig. 1. After installation, all the three biogas digesters were initially fed with cattle dung and water mixed in the ratio of 1:1 and kept for 45 days of retention time for inoculum formation. The optimized condition evaluated from the BMP tests was adopted in assessing the biogas production from the feedstocks co-digested with cattle dung in community-size biogas digesters. For the community size digesters, the biomass feeds were initially dried under sunlight and were chopped into pieces for increasing the surface area during digestion.





**Figure 2.1.** Installation of 4 m<sup>3</sup> biogas digesters at Aaoniati Satra near IIT Guwahati (a),(b) Deenbandhu type construction. (c) Feeding of cattle dung for inoculation. (d) Final setup of 4 m<sup>3</sup> biogas digesters.

### 2.2.2. Experimental procedure for the BMP tests

The anaerobic digestion of the lignocellulosic materials was done in 1 L laboratory-scale batch reactors. The reactors were initially inoculated with 30% (v/v) inoculum, and the working volume was kept at 90% (v/v) (Han et al., 2016). These reactors were properly sealed with rubber cork to maintain proper anaerobic conditions. Two outlet pipe was fitted in the cork: One pipe was used to assess the biogas for measurement, and the other was utilized for sample collection. The experiments were performed for each of the feedstock maintaining three different total solids concentrations viz. 10%, 15% and 20%. The optimized total solids concentration from mono-digestion was further optimized for different cattle dung to feedstock ratios (CD:FS) viz. 1:1, 1:1.5 and 1:2. For control operations, reactors were operated with only 30% (v/v) inoculum and water keeping the total working volume of 90% (v/v). The reactors were kept for experimentation under natural sunlight at ambient temperature with temperatures ranging from 28 °C – 35 °C for 36 days. The reactors were shaken manually every 24 h and biogas produced was quantified by the water displacement method. Biogas was collected periodically in Tedlar bags after every five days, and its composition was evaluated using gas chromatography. The experimental matrix for the set of experiments is shown in Table 2.1.

**Table 2.1.** Experimental matrix for the set of batch experiments.

Set	Feed material	Total Solid (TS)		
1	Duckweed	10%	15%	20%
2	Switchgrass	10%	15%	20%
3	Rice straw	10%	15%	20%

Set	Feed material	TS concentration	Mixing ratio		
1	Cow dung + Duckweed	Optimized	1:1	1:1.5	1:2
2	Cow dung + Switchgrass	TS concentration	1:1	1:1.5	1:2
3	Cowdung + Rice straw	concentration	1:1	1:1.5	1:2

### 2.2.3. Experimental procedure for the continuous process

After optimizing the BMP tests, the on-field estimation of biogas potential from the feedstocks was assessed in three 4 m<sup>3</sup> continuous fed biogas digesters installed at Auniati Satra near IIT Guwahati. The Auniati Satra already had a 4-m<sup>3</sup> continuous fed biogas digester entirely operated with cattle dung as feed material and has been solely utilized for cooking. The Satra had a dairy farm that generates a considerable amount of cattle dung and only a portion of it is utilized for biogas generation. Most of the cattle dung are either utilized in farming fields or are left to decompose naturally. Due to the availability of feed material, the site was considered for installing three new 4-m<sup>3</sup> biogas digesters to undertake the co-digestion study of the lignocellulosic feedstocks. The biogas digesters were made of reinforced concrete of the type Deenbandhu model (Kanwar et al., 1994) in which maximum portion of the digester is inside the soil. The biogas digester had a separate inlet and outlet tank connected to the digester through PVC pipes. After the installation, all the digesters were initially fed with 1:1 ratio of cattle dung and water and kept for a retention period of 45 days for inoculum formation. After the retention period, the digesters were utilized for the investigation of co-digestion

experiments. The feedstocks were initially dried in open sunlight and were chopped into even pieces ranging approximately 10 mm. In the first digester (Digester 1), duckweed was co-digested with cattle dung, and in Digester 2 and Digester 3, switchgrass and rice straw were co-digested respectively with cattle dung by maintaining the optimized parameters obtained from the BMP tests. The old digester i.e., Digester 4 was solely fed with cattle dung at similar TS concentrations to make a comparative assessment of the biogas formed. The digesters were fed continuously for 60 days, and daily biogas produced was analyzed from the biogas flow meter installed at the site. An approximate amount of 25 kg (Total solid) with the optimized cattle dung to feedstock ratios (CD:FS) and equivalent amount of water was fed regularly in the individual digesters maintaining an HRT of 40 days. The experiments were performed under mesophilic temperature range and respective biogas yield and composition were analyzed.

#### 2.2.4. Analytical methods

Proximate analysis, i.e., moisture content (MC), ash content, volatile matters (VM), and fixed carbon (FC) of the lignocellulosic feedstock, were estimated according to the standard method (APHA, 2002). Analysis of moisture content was done in triplicates by keeping samples at 105 °C until a constant weight was obtained. Similarly, ash and volatile matters were obtained at 550 °C and 900 °C respectively. The total carbon (C), hydrogen (H), and nitrogen (N) were analyzed by an elemental analyzer (EuroEA3000 Elemental Analyzer) installed at Biotech Park, IIT Guwahati. The soluble chemical oxygen demand (sCOD) of the samples was measured using HACH COD reagents and measured in a DR900 colorimeter (Hach, USA) (Barua et al., 2018). Measurement of volatile solids was done as per standard procedure (APHA, 2002). FTIR analysis of the samples was done using an FTIR spectrometer (Make: Perkin Elmer) from the wavelength range of 4000  $\text{cm}^{-1}$  to 500 $\text{cm}^{-1}$ . To measure the

biomass crystallinity, XRD analysis of samples was carried out at  $2\theta$  values from  $3^\circ - 80^\circ$ . The crystallinity index (CrI) was calculated by using the formulae below (Yao et al., 2018)

$$\text{CrI} = [(I_{002} - I_{\text{am}}) / I_{002}] \times 100 \quad (2.1)$$

Where,  $I_{002}$  refers to the crystalline peak of maximum intensity at 2-Theta ( $2\theta$ ) between  $22^\circ$  and  $23^\circ$ , and  $I_{\text{am}}$  refers to the minimum intensity at  $2\theta$  between  $18^\circ$  and  $19^\circ$ .

The pH measurement of digested samples in both batch and continuous digesters was done using a pH meter (Oakton pH 700 Benchtop Meter). In the batch process, biogas yield was quantified regularly by water displacement technique, and in the continuous process, a biogas flow meter was installed at the site. Biogas composition was estimated by using gas chromatography (Trace GC 1110 EPC) equipped with a thermal conductivity detector. The oven temperature and detector temperature of GC was set at  $45^\circ\text{C}$  and  $180^\circ\text{C}$ , respectively, and helium was used as a carrier gas. Determination of hemicellulose, cellulose, and lignin content of the feedstocks was done by using Fibraplus FES02R Fibre analyzer, which applies the chemistry of the Van Soest method.

## 2.3. Results and Discussion

### 2.3.1. Sample characterization and analysis

Duckweed being an aquatic plant, had a total solids concentration of 4 to 5%, while rice straw and switchgrass constituted more than 80%. Hemicellulose and cellulose concentration lay in a similar range for rice straw and switchgrass; and lignin content was comparatively higher than that of duckweed. The proximate and ultimate analysis of the lignocellulosic feedstocks are reported in Table 2.2. The FTIR and XRD analysis provided in supplementary material shows the presence of cellulose, hemicellulose, and lignin at peaks  $1044\text{ cm}^{-1}$ , which is attributed to C-O stretching for all the three feedstocks. Among the feedstocks, rice straw and switchgrass exhibited a more intense band at this wavelength. Peaks at  $1596\text{ cm}^{-1}$  are

attributed to C=O and C=C stretching, which shows the presence of quinones and lignin in the feedstocks, and rice straw exhibited a more intense band than the other three feedstocks. And small peaks at  $2919\text{ cm}^{-1}$  and  $3284\text{ cm}^{-1}$  are attributed to CH-sp<sup>3</sup> stretching and O-H stretching, which indicates polymers. X-ray diffraction (XRD) analysis determines the crystalline structure, crystallinity index and size of a material. CrI index for rice straw, switchgrass, and duckweed were 33.76%, 22.84%, and 13.81%, respectively.

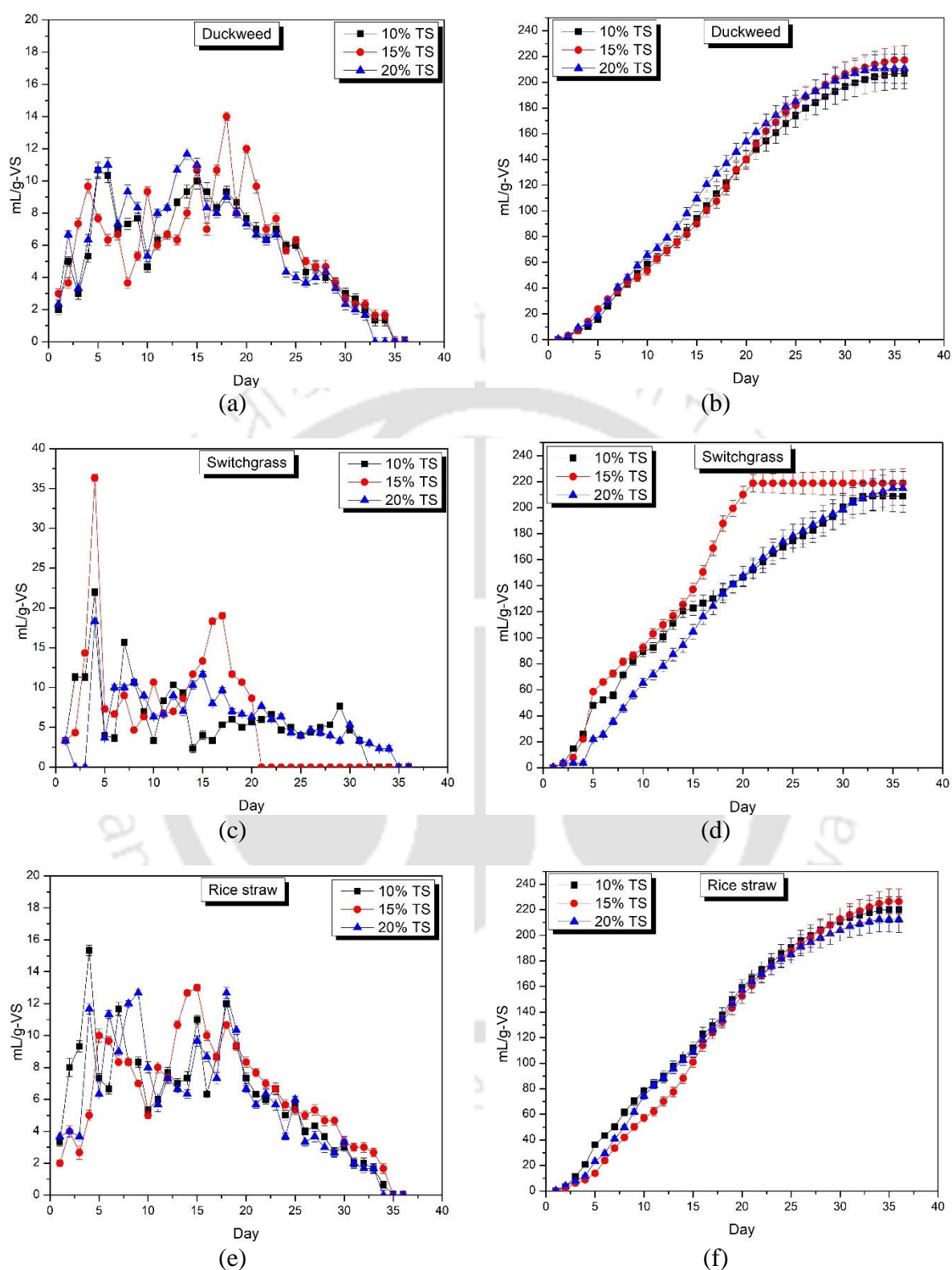
**Table 2.2.** Physicochemical characteristics of the lignocellulosic feed material

Feed Material	Proximate Analysis				Ultimate Analysis			Fibre Analysis		
	MC	Dry basis			C	H	N	Cellulose	Hemi-cellulose	Lignin
		Ash	VM	FC						
Rice Straw	12.04 ± 0.42	13.19 ± 0.61	74.51 ± 0.63	12.30 ± 1.24	38.50	3.50	0.55	29.20 – 34.70	23.00 – 25.90	17.00- 19.00
Duckweed	95.91 ± 0.39	15.52 ± 0.69	74.79 ± 0.43	9.69 ± 1.08	31.21	3.82	3.7	58.00 – 63.20	5.31 – 10.51	4.20 – 10.56
Switchgrass	12.96 ± 1.71	5.34 ± 0.22	78.66 ± 1.29	16.00 ± 1.14	47.80	4.91	1.32	28.00 – 37.20	24.32 – 30.25	19.40 – 24.56
Cattle dung	63.30 ± 0.59	15.79 ± 0.35	69.01 ± 0.72	15.21 ± 0.43	35.30	6.40	1.66	46.00 – 49.20	26.22 – 29.86	20.12 – 22.16

### 2.3.2. Biogas production at different total solids concentrations in BMP tests

Fig. 2.2 demonstrates the biogas production from the three feedstocks at different total solids concentrations analyzed for 36 days. The daily and cumulative biogas produced using duckweed are displayed in Fig. 2.2(a) and (b). The biogas produced initially increased until 16<sup>th</sup> day and then gradually decreased until the 36<sup>th</sup> day. Maximum cumulative biogas produced was seen at 15% TS amounting to  $217.15 \pm 11.20\text{ mL/g-VS}$  compared to  $206.77 \pm 12.19\text{ mL/g-VS}$  and  $210.53 \pm 11.57\text{ mL/g-VS}$  at 10% and 20% TS respectively. Maximum biogas production for duckweed at 10% TS was observed on the 5<sup>th</sup> day, amounting to  $10.67 \pm 0.42\text{ mL/g-VS}$ . At 15% and 20% TS, a maximum of  $14 \pm 0.26\text{ mL/g-VS}$  and  $11.67 \pm 0.33\text{ mL/g-VS}$  biogas was formed on the 18<sup>th</sup> day and 14<sup>th</sup> day, respectively. Fig. 2.2(c) and (d) highlights the biogas produced from switchgrass with maximum biogas production observed on the 4<sup>th</sup> day,

amounting to  $22\pm 0.43$  mL/g-VS,  $36.33\pm 0.41$  mL/g-VS, and  $18.33\pm 0.29$  mL/g-VS at 10%, 15%, and 20% TS respectively. The cumulative biogas production was found to be  $208.77\pm 12.10$  mL/g-VS,  $218.82\pm 11.30$  mL/g-VS, and  $214.87\pm 13.10$  mL/g-VS at the respective TS %. A similar trend was observed in rice straw, and cumulative biogas formation amounted to  $220.10\pm 10.31$  mL/g-VS,  $226.48\pm 9.99$  mL/g-VS,  $212.53\pm 10.10$  mL/g-VS at 10%, 15%, and 20% TS respectively, as displayed in Fig. 2.2(e) and (f). Maximum biogas produced for 10% TS was observed on the 4<sup>th</sup> day, which amounted to  $15.33\pm 0.34$  mL/g-VS. At 15% and 20% TS, maximum biogas production was observed on the 15<sup>th</sup> and 18<sup>th</sup> day, amounting to  $13\pm 0.20$  mL/g-VS and  $12.67\pm 0.34$  mL/g-VS, respectively. A probable cause in the spike of biogas production was the early start of hydrolysis and easy accessibility of degradable organics. (Gaur et al., 2017b). In one of the studies, the influence of total solids concentration on biogas produced from organic portions of municipal solid waste at 10.32%, 9.2%, and 8.4% TS was investigated, and cumulative biogas produced was found to be higher at 9.2% TS concentration (Nair, 2013). In another study, the authors reported higher methane for 5 – 10 % TS than 15 – 20% TS for anaerobic digestion of municipal solid waste with sewage sludge (Ahmadi-Pirlou et al., 2017). The change in TS concentration, as well as feed material, does affect the cumulative biogas production. With the increase in TS concentration, there is a decrease in gas production. It may be probably due to the inhibition of microbes with the rise in TS concentration. It was seen that at 10% and 15% TS concentration, the biogas formation was comparatively higher than at 20% TS and also out of the three feedstocks, cumulative biogas production from rice straw was relatively higher than duckweed and switchgrass.



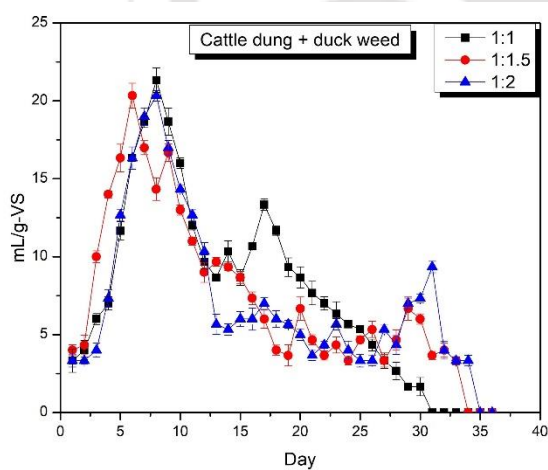
**Figure 2.2:** Daily and cumulative biogas production at different TS concentrations. (a) Daily biogas in mL/g-VS for duckweed. (b) Cumulative biogas in mL/g-VS for duckweed. (c) Daily biogas in mL/g-VS for switchgrass. (d) Cumulative biogas in mL/g-VS for switchgrass. (e) Daily biogas in mL/g-VS for Rice straw. (f) Cumulative biogas in mL/g-VS for Rice straw.

### 2.3.3. Biogas production at different mixing ratios in the BMP tests

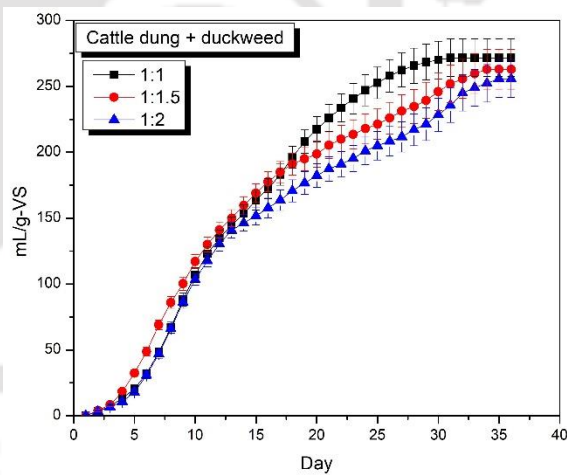
The optimized TS concentration was further used to optimize the feedstock at three different cattle dung to feedstock (CD:FS) ratios viz. 1:1, 1:1.5 and 1:2. Here, 15% TS concentration obtained from the was considered the optimized TS concentration for the investigation. Fig. 2.3 illustrates the daily and cumulative biogas produced at CD:FS ratios viz 1:1, 1:1.5, and 1:2. The daily biogas formation increased significantly in the first week. The maximum biogas produced for co-digestion of duckweed (Fig. 2.3 (a) and (b)) was observed on the 8<sup>th</sup> day for CD:FS ratio of 1:1 amounting to  $21.33\pm 0.78$  mL/g-VS and maximum cumulative production of  $271.67\pm 14.20$  mL/g-VS was observed at same CD:FS ratio. At CD:FS ratio of 1:1.5, maximum biogas produced was observed on the 6<sup>th</sup> day amounting to  $20.33\pm 0.80$  mL/g-VS, and at CD:FS ratio of 1:2, maximum biogas produced was observed on 8<sup>th</sup> day, which too amounted to  $20.33\pm 0.34$  mL/g-VS. Cumulative biogas produced for the two cases respectively was  $263\pm 15.06$  mL/g-VS and  $255.67\pm 14.24$  mL/g-VS. Biogas production for switchgrass (Fig. 2.3 (c) and (d)) at the three-CD:FS ratios showed a similar pattern. Maximum production of  $21.67\pm 0.68$  mL/g-VS was observed on the 6<sup>th</sup> day at 1:1.5 CD:FS ratio. Whereas, highest cumulative production of  $301.71\pm 14.18$  mL/g-VS was observed for 1:1 CD: FS ratio. It was seen that maximum biogas production of  $21\pm 0.78$  mL/g-VS and  $16.33\pm 0.49$  mL/g-VS was observed on the 4<sup>th</sup> day and 7<sup>th</sup> day for 1:1 and 1:2 CD:FS ratio, respectively. For rice straw, maximum biogas was produced on the 8<sup>th</sup> day for 1:1 CD:FS ratio amounting to  $24\pm 0.69$  mL/g-VS. Maximum cumulative biogas production of  $318.33\pm 13.44$  mL/g-VS was also observed for the same CD:FS ratio. Whereas, at CD:FS ratios of 1:1.5 and 1:2, cumulative biogas produced was  $305\pm 15.16$  mL/g-VS and  $275.71\pm 15.54$  mL/g-VS, respectively. The figures show that co-digestion with rice straw resulted in higher biogas production than co-digestion with switchgrass and duckweed.

Moreover, co-digestion of the feedstock yielded better results than the mono-digestion

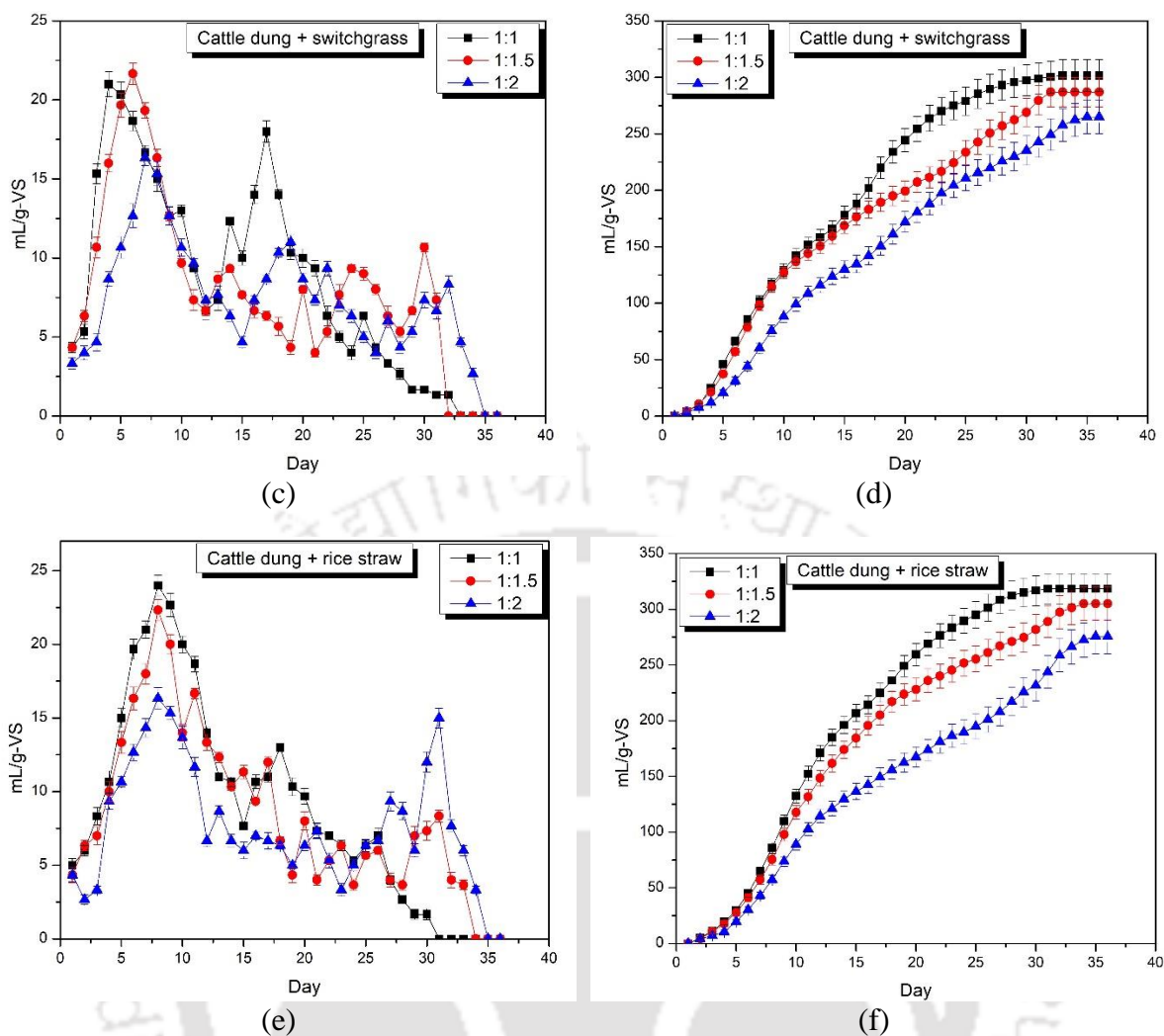
process. In case of duckweed and switchgrass, there was an increase of 21.11% and 31.16% biogas production in co-digestion than mono digestion. Co-digestion with rice straw resulted in an increase of 34.67% biogas production than mono-digestion of rice straw. An increase in biogas during co-digestion was probably due to the addition of cattle dung, which is rich in methanogenic bacteria and helped to enhance the methanogenic reaction. Moreover, the presence of lignin, which inhibits the degradation of feedstock in the mono-digestion process, was compensated by the addition of cattle dung in the co-digestion process. In one of the studies, the authors reported an optimal rice straw to cow manure ratio of 1:1 and obtained average specific biogas production of 383.5 L/g-VS (Li et al., 2015a). Another study reported a biomethane yield of 112 – 139 mL/g-VS for winter harvested switchgrass and 229 – 297 mL/g-VS for summer harvested switchgrass under different pre-treatment conditions (J.-C. Frigon et al., 2012). It can be seen that biogas production obtained in this study is in tandem with prevalent works of literature.



(a)



(b)



**Figure 2.3.** Daily and cumulative biogas production at different 15% TS concentrations and different CD: FS ratios. (a) Daily biogas in mL/g-VS for duckweed. (b) Cumulative biogas in mL/g-VS for duckweed. (c) Daily biogas in mL/g-VS for switchgrass. (d) Cumulative biogas in mL/g-VS for switchgrass. (e) Daily biogas in mL/g-VS for Rice straw. (f) Cumulative biogas in mL/g-VS for Rice straw.

#### 2.3.4. Compositional analysis of gas samples in batch process

The biogas samples were analyzed periodically after every five days, and the percentage of  $\text{CH}_4$  was measured using GC. The percentage of  $\text{CH}_4$  at different TS concentrations and CD: FS ratios are shown in Table 2.3 and Table 2.4 respectively. It was observed that  $\text{CH}_4\%$  for duckweed varied in the range from 40% to 60% at different TS concentrations as well as at different CD: FS ratios. Though there was not much variation in  $\text{CH}_4\%$ , the average  $\text{CH}_4$  content at 10% TS and 15% TS was higher than at 20% TS. Moreover, for the different CD:

FS ratios, the average CH<sub>4</sub>% for 1:1 and 1:1.5 was higher than 1:2. It was observed that with the increase in TS concentration, the percentage of CH<sub>4</sub> decreased, which may be attributed to lower biogas production at 20% TS concentration. The results were similar to the findings of a previous study where an average of 50 to 60% methane content was achieved for codigestion of rice straw with kitchen waste and pig manure (Ye et al., 2013). In switchgrass, the CH<sub>4</sub>% at 10%, 15% and 20% TS varied in the range from 38% to 62%, 47% to 60% and 50% to 54% respectively. It was observed that the average CH<sub>4</sub>% at 15% TS was comparatively higher than at 10% and 20% TS. In case of co-digestion, the CH<sub>4</sub>% varied in the range from 47% to 57%, 53% to 58% and 46% to 52% at 1:1, 1:1.5 and 1:2 CD:FS ratios respectively. The average CH<sub>4</sub>% for 1:1 and 1:1.5 CD:FS ratios were higher compared to 1:2 CD:FS ratio. The lower percentage of CH<sub>4</sub> at 1:2 CD:FS ratio might be due to the inhibition of microbes owing to the formation of volatile fatty acids (VFA). This enhancement in VFA was a result of excess amount of lignocellulosic material being fed in the digesters. Because of which there was lesser biogas production at higher TS concentration resulting in lesser percentage of CH<sub>4</sub>. For rice straw, it was found that CH<sub>4</sub>% varied from 47% to 54%, 46% to 51% and 38% to 55% at 10%, 15% and 20% TS respectively. It could be seen that average CH<sub>4</sub>% at 20% TS and 15% TS lay in a similar range and were comparatively higher than at 10% TS. Moreover, for the different CD:FS ratio during co-digestion, CH<sub>4</sub>% varied in the range from 47% to 58%, 39% to 54% and 47% to 51% at 1:1, 1:1.5 and 1:2 CD:FS ratios respectively. The average CH<sub>4</sub>% at 1:1 CD:FS ratio was higher than other CD:FS ratios. One of the studies reported that higher carbohydrate concentration in substrate resulted in higher methane concentration (50%–60%) (Syaichurrozi, 2018). However, higher fat or protein in substrate resulted in a methane concentration of 75%–90%. The results obtained in the experiments followed a similar trend with the ones reported by other authors (Lianhua et al., 2010; Teghammar et al., 2012).

**Table 2.3.** Percentage of CH<sub>4</sub> at different total solid concentration

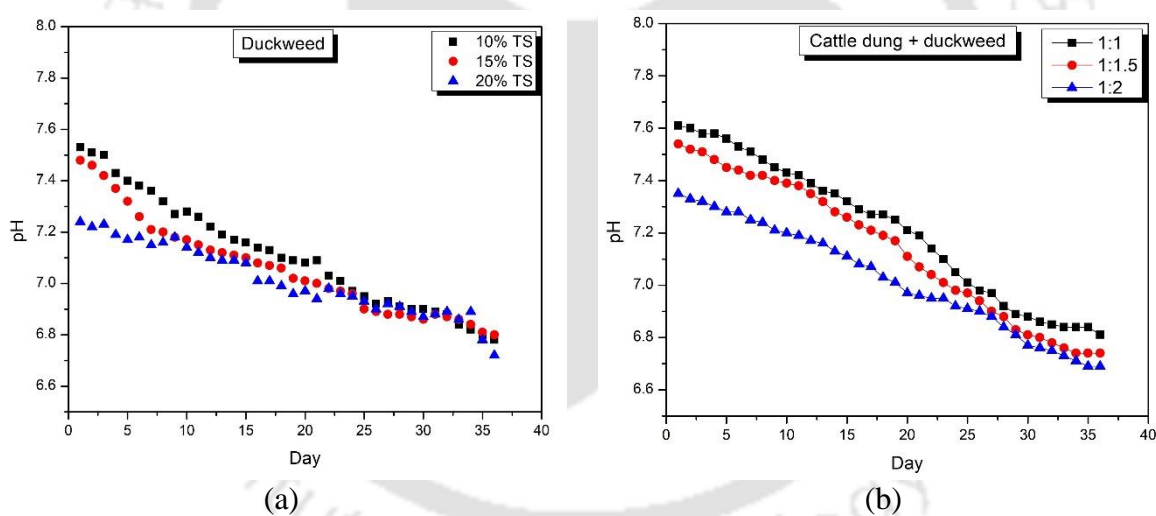
Type of feedstock	Day	% Total solid (TS) of feedstock		
		10% TS	15% TS	20% TS
Duckweed	5	53.32	52.31	52.05
	10	56.06	51.17	44.24
	15	49.20	51.23	45.25
	20	49.47	49.85	40.32
	25	53.60	54.13	45.47
	30	51.77	54.78	49.53
Switchgrass	5	42.56	56.15	51.32
	10	62.23	56.41	52.32
	15	38.03	51.34	54.17
	20	49.80	47.40	50.65
	25	61.17	NA	55.88
	30	59.55	NA	53.71
Rice straw	5	47.40	46.75	38.60
	10	54.45	48.20	52.05
	15	17.54	51.08	51.74
	20	46.80	46.51	50.54
	25	54.48	49.13	50.29
	30	50.30	49.66	55.86

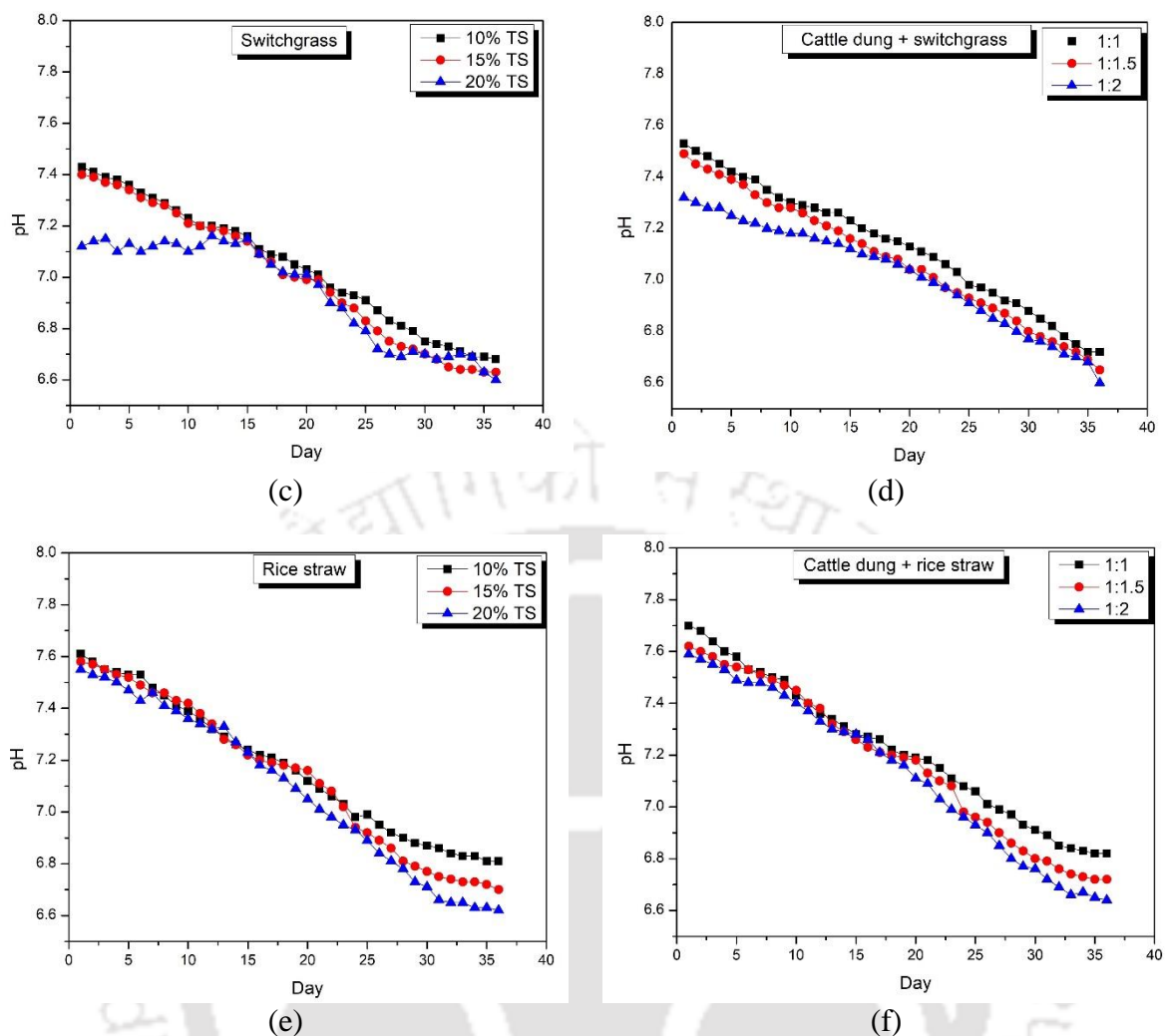
**Table 2.4.** Percentage of CH<sub>4</sub> at different cattle dung to feedstock ratios

Type of feedstock	Day	Cattle dung to feedstock ratio		
		1:1	1:1.5	1:2
Cattle dung + Duckweed	5	57.09	58.92	53.40
	10	56.01	52.34	44.89
	15	53.87	59.58	49.96
	20	44.17	56.67	50.96
	25	55.14	55.19	49.82
	30	54.25	50.87	48.31
Cattle dung + Switchgrass	5	55.68	58.97	52.93
	10	53.02	53.65	48.79
	15	54.72	57.55	47.06
	20	47.68	54.95	52.78
	25	57.50	55.09	48.32
	30	55.39	54.25	46.57
Cattle dung + Rice straw	5	58.44	40.87	48.42
	10	50.11	52.83	51.70
	15	55.95	54.13	48.41
	20	56.96	39.96	50.97
	25	47.87	54.73	48.91
	30	51.47	53.71	47.23

### 2.3.5. Effect of pH on biogas production in batch process

As reported in numerous studies, pH value of 7 is considered ideal for methanogenesis, whereas pH value between 5.5–6.5 is optimal for hydrolysis and acidogenesis (Lin et al., 2011) (Park and Li, 2012). Thus, a pH value of the correct range (6.8–7.2) should be maintained in a single-stage anaerobic system for methanogenic bacteria to reduce the inhibitory effects. Fig.2.4 (a–f) depicts the pH of the reactors measured daily for the three feedstocks (duckweed, switchgrass and rice straw) for mono-digestion as well as co-digestion. There was a uniform decrease in the pH level of all the batch reactors. A possible cause underlying this decrease in pH might be the formation of VFAs during later stages of biogas production. The phenomenon of inhibition in biogas production due to decrease in pH has been validated in earlier studies (Ye et al., 2013).



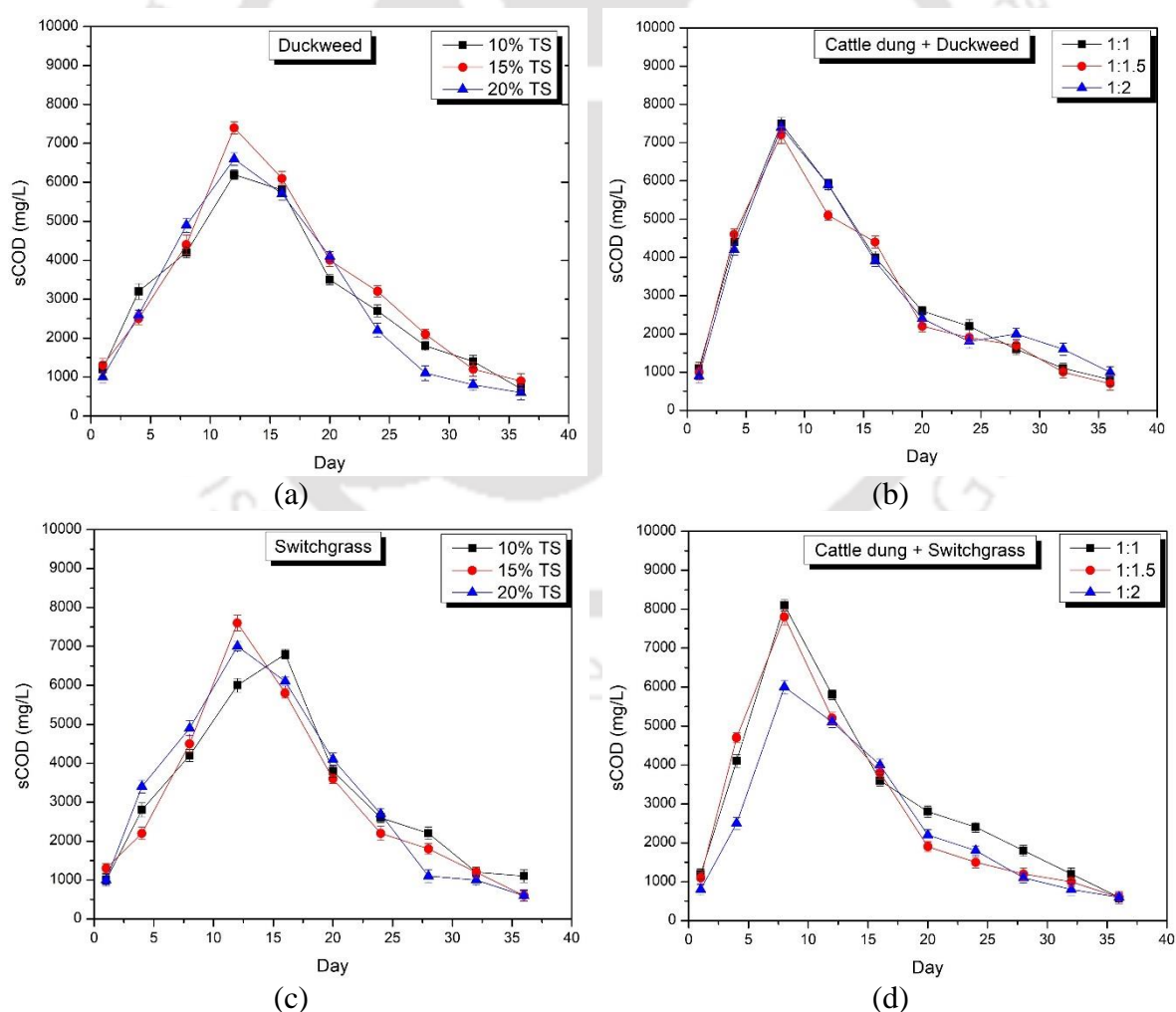


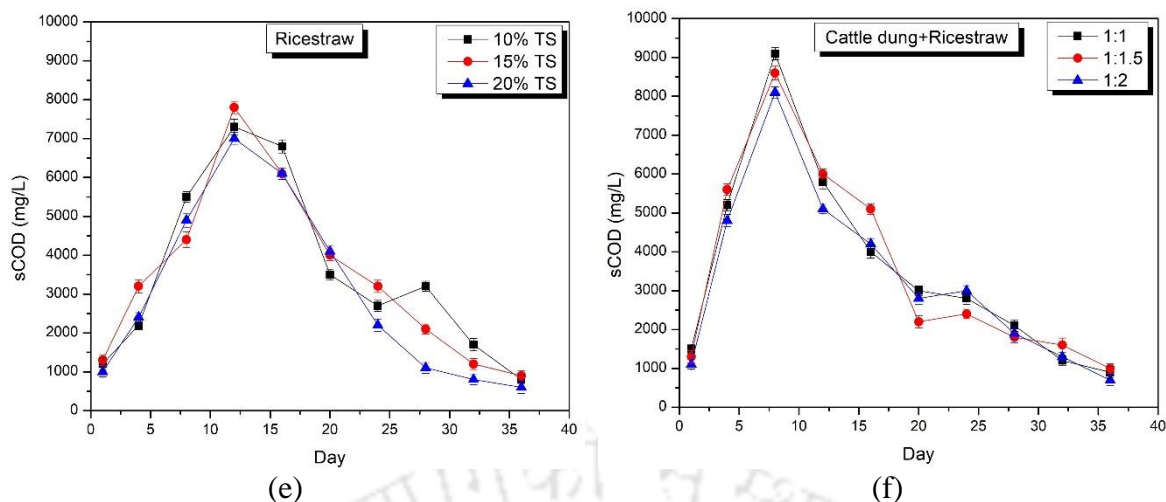
**Figure 2.4.** pH of the reactors at different TS concentrations and CD: FS ratios. (a) pH of the reactors at different TS concentration for duckweed. (b) pH of the reactors at different CD: FS ratio for duckweed. (c) pH of the reactors at different TS concentration for switchgrass. (d) pH of the reactors CD: FS ratio for switchgrass. (e) pH of the reactors at different TS concentration for Rice straw. (f) pH of the reactors at different CD: FS ratio for Rice straw.

### 2.3.6. Effect of sCOD and VS reductions in Batch process

Analysis of samples for sCOD and VS reductions were performed for both mono and co-digestion experiments. The sCOD analysis was carried out after every four days. During the initial period, there was a rise in sCOD concentration. After attaining a maximum value, it started to decrease. An increase in sCOD signifies the availability of soluble organic matter that can be easily converted to biogas. During mono-digestion, as shown in Figs. 2.5(a, c and e), sCOD values initially increased till the 12<sup>th</sup> day, and from the 16<sup>th</sup> day, it started to decrease gradually. Whereas, during co-digestion, as shown in Figs. 2.5(b, d and f), sCOD values

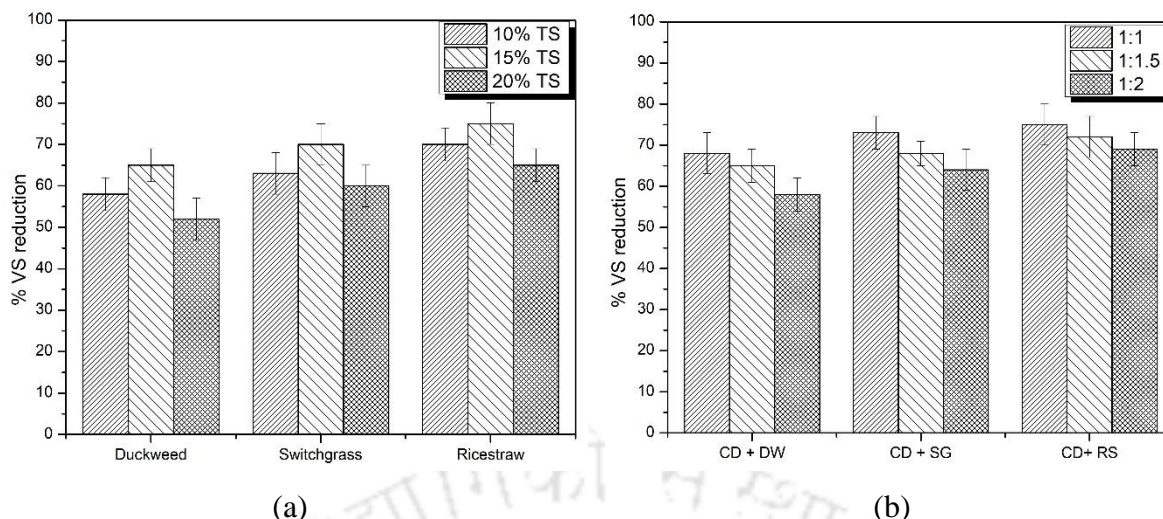
increased till the 8th day, followed by a significant decrease after that. A plausible cause of the higher availability of organic matter in the early stage may be the proper mixing of cattle dung with the feedstock and abundance of methanogenic bacteria in cattle dung, resulting in enhancement of the digestion period. The higher sCOD values during the period resulted in higher biogas production during that period and the same can be seen from the BMP tests. In mono-digestion, maximum sCOD concentration was observed at 15% TS concentration for all three feedstock, and the highest was observed for rice straw. Similarly, for co-digestion maximum sCOD values were observed for 1:1 mixing ratio for all the feedstocks, and the highest was observed for rice straw. These results supported the finding of maximum production of biogas from rice straw in the batch process.





**Figure 2.5.** sCOD of the reactors at different TS concentrations and CD:FS ratios. (a) sCOD of the reactors at different TS concentration for duckweed. (b) sCOD of the reactors at different CD:FS ratio for duckweed. (c) sCOD of the reactors at different TS concentration for switchgrass. (d) sCOD of the reactors CD: FS ratio for switchgrass. (e) sCOD of the reactors at different TS concentration for Rice straw. (f) sCOD of the reactors at different CD: FS ratio for Rice straw.

VS reduction is an indicating factor of organic matter that can be converted to biogas. As seen in Fig. 2.6(a), the highest VS reduction of 65%, 70%, and 75% was observed for duckweed, switchgrass, and rice straw, respectively, at 15% TS concentration during mono-digestion. Low VS reduction at 10% TS concentration for all three feedstocks is a result of limited microbial activity due to lesser availability of organic material. Moreover, 20% TS concentration inhibited the growth of methanogenic bacteria. As VS reduction was found to be highest at 15% TS concentration, co-digestion experiments were performed by maintaining 15% TS. In co-digestion, highest VS reduction of 68%, 73%, and 75% was observed for the respective feedstocks at 1:1 CD:FS ratios as shown in Fig. 2.6(b). CD:FS ratio of 1:1 facilitated proper mixing of cattle dung and feedstock, leading to higher availability of organic matter to the microbial community, thereby leading to higher biogas production. Moreover, a probable cause for lower VS reduction at 1:1.5 and 1:2 CD:FS ratios might be due to inhibition of the microbial growth in presence of higher concentration of feedstock, leading to lower biogas production.



**Figure 2.6.** % VS reduction of the reactors at different TS concentrations and CD: FS ratios.

### 2.3.7. Biogas production at the optimized condition for continuous process

The optimized condition as obtained in the BMP tests, i.e., 15% TS concentration and 1:1 CD:FS ratios, were applied to assess biogas potential from the three 4 m<sup>3</sup> biogas digesters installed at Auniati Satra utilizing the same feedstocks. The old digester was also fed with equivalent amounts of cattle dung with 15% TS concentration for comparative analysis. Fig. 2.7(a) and (b) displays the daily and cumulative estimation of biogas production investigated for 60 days. Digester 1 depicts the biogas production from cattle dung and duckweed with an average biogas production of 2.76 m<sup>3</sup> during the analysis period. And maximum and minimum biogas production of 3.41 m<sup>3</sup> and 2.03 m<sup>3</sup>, respectively, was attained while maintaining almost a constant production level. In Digester 2, containing cattle dung and switchgrass, average biogas production was 2.93 m<sup>3</sup> with maximum and minimum biogas production of 3.62 m<sup>3</sup> and 2.12 m<sup>3</sup>. The biogas production from Digester 3, which contained rice straw and cattle dung, showed a similar pattern as that of Digester 1 and Digester 2, with an average biogas production of 3.19 m<sup>3</sup>. Maximum biogas production of 3.82 m<sup>3</sup> and a minimum of 2.22 m<sup>3</sup> was observed during the period of study. The cumulative biogas production for Digester 1, Digester 2, and Digester 3 were 165.75 m<sup>3</sup>, 175.92 m<sup>3</sup>, and 191.40 m<sup>3</sup>, respectively. The digesters' average biogas yield was 0.32 m<sup>3</sup>/kg-VS, 0.34 m<sup>3</sup>/kg-VS, and 0.36 m<sup>3</sup>/kg-VS, respectively. The results

illustrated in the continuous process complemented the results obtained in the batch process. Also, the cumulative biogas production for rice straw was higher than the other two feedstocks in both cases.

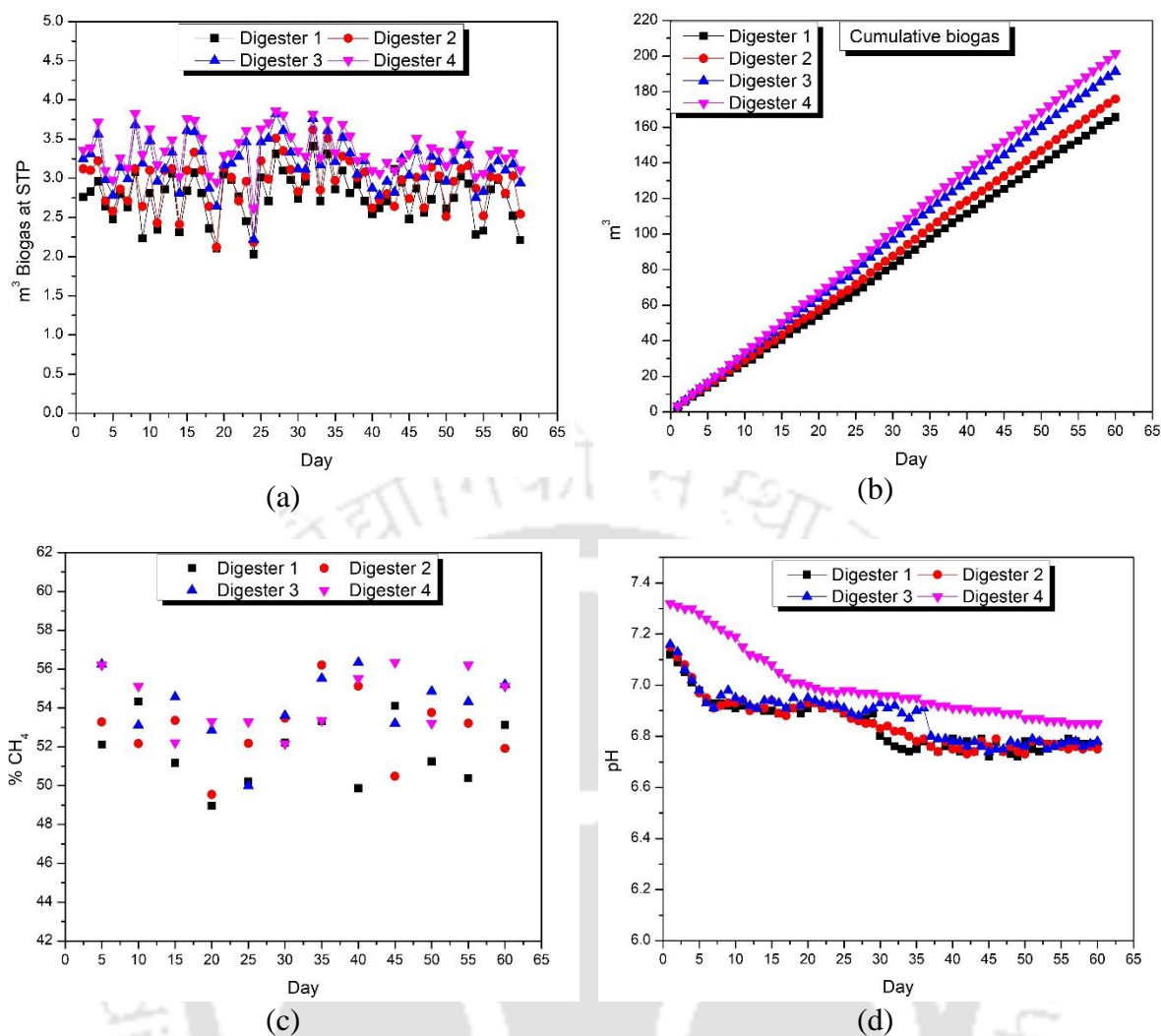
Biogas production from solo cattle dung as represented by Digester 4 had a cumulative biogas production of 201.37 m<sup>3</sup> with maximum and minimum production of 3.86 m<sup>3</sup> and 2.62 m<sup>3</sup>. It can be seen that biogas production from all the three feedstock was comparatively lesser than that with sole cattle dung. Higher production for mono-digestion of cattle dung may be due to more availability of methanogenic bacteria. It can be seen that co-digestion of lignocellulosic feedstock with cattle dung can be a feasible option for optimal biogas production in community size digesters. In one of our previous studies, the feasibility of implementing a 50 m<sup>3</sup> floating drum type community size biogas digester using food waste was reported. The study highlighted the addition of cattle dung for proper balance pH and biogas production (Buragohain et al., 2018). In this study, too, the addition of cattle dung enhanced the biogas production of maintenance of pH. Biogas production from small community size digesters is prevalent in many parts of Europe and the status of the working biogas plants has also been recently reviewed in one of the studies (O'Connor et al., 2021). In another study the authors discussed the various standardized factors and procedures that are to be analyzed in BMP test (Angelidaki et al., 2009). And some of the parameters have also been briefly discussed in the BMP analysis of the present study.

### **2.3.8. Compositional analysis and effect of pH in continuous process**

The compositional analysis of biogas samples from the community level 4 m<sup>3</sup> continuous fed biogas digesters installed at Auniati Satra is shown in Fig. 2.7(c). Biogas was collected in Tedlar bags from the four digesters after every five days to assess the CH<sub>4</sub> and CO<sub>2</sub> composition. The CH<sub>4</sub>% for Digester 1 was in the range from 48% to 54%, maintaining almost a similar CH<sub>4</sub> variation with the other two digesters. For both Digester 2 and Digester 3, CH<sub>4</sub>%

varied in the range of 49% to 56%. Whereas for Digester 4, the CH<sub>4</sub> composition varied in the range from 52% to 56%. It could be observed that there was not much variation in the biogas composition, and all the digesters maintained a uniform CH<sub>4</sub>% during the period of study. Although in Digester 4, CH<sub>4</sub> composition was slightly higher than the other digesters. It might probably be due to a higher amount of methanogens during mono-digestion of cattle dung. Biogas production also maintained a constant level during the experimentation period, which is attributed to cattle dung utilization that helped maintain a constant level of biogas production and CH<sub>4</sub>%. The same trend was also observed from the pH variation of the digestate samples of the digester.

The pH of community-size biogas digesters was analyzed daily for 60 days. The pH of all the four digesters during the study period is shown in Fig. 2.7(d). After the retention period, the digesters had an initial pH in the range of 7.1 – 7.5. As the feeding period started, the pH began to reduce gradually in all the digesters, and after a period of 30 to 40 days, it maintained a constant pH of 6.5–7.0. The pH of the Digester 4 (containing only cattle dung) was slightly higher than the other three digesters. A probable cause might be due to the presence of a higher amount of cattle dung than the other digesters that maintained the pH level. The digested samples' pH reduced gradually in the batch reactors, whereas in the continuous process, it decreased initially, but after stabilization, it maintained a constant level. It occurred mainly due to the regular addition of cattle dung, which compensated for the decrease in pH and maintained a constant level. As pH is an essential factor for efficient biogas production, a pH range of 6.5–7 in the community-size digesters contributed to the constant biogas production.



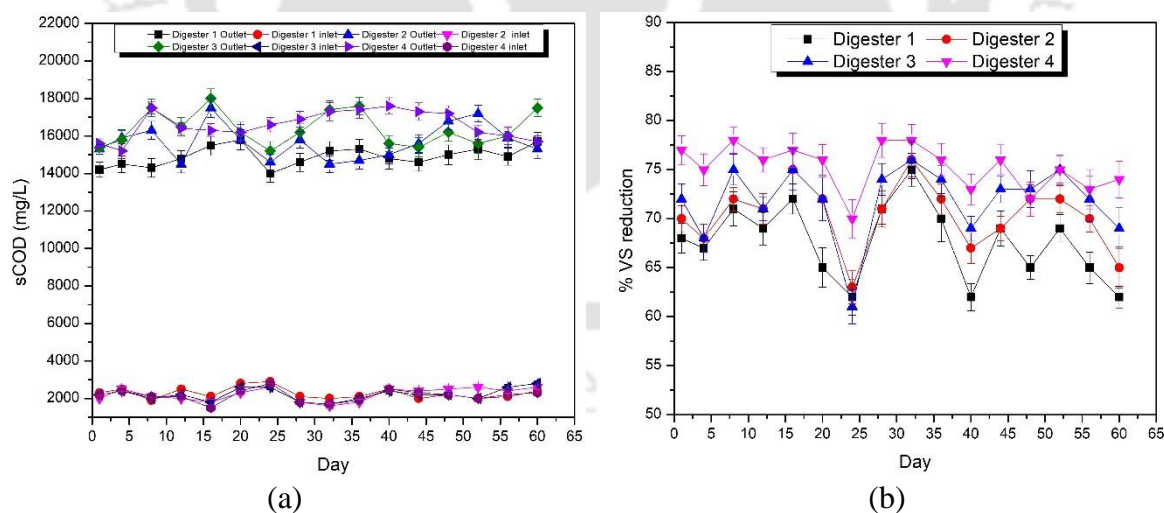
**Figure 2.7.** Different operating parameters of the 4m<sup>3</sup> biogas digesters installed at Aoniati Satra. (a) Daily biogas in m<sup>3</sup> for all the four digesters. (b) Cumulative biogas in m<sup>3</sup> for all the four digesters. (c) % variation of CH<sub>4</sub> of the four digesters. (d) pH variation of the biogas digesters.

### 2.3.9. Effect of sCOD and VS reductions in continuous process

The sCOD removal is an essential parameter for assessing the output characteristics of community size digesters. Analysis of sCOD and VS reductions for the biogas digester's inlet and outlet was analyzed after every four days for all four digesters. The TS concentration and CD:FS ratio was fixed at 15% and 1:1 as obtained from the batch experiments. Higher sCOD removal results in higher biogas production and stability of the digester. Fig. 2.8(a) clearly depicts that the average sCOD removal for all the feedstock was more than 80%, and during co-digestion, the highest was observed in Digester 3 containing rice straw and cattle dung. The

percentage sCOD removal for Digester 4 (containing only cattle dung) was slightly higher than the other digesters due to easily degradable organic matter of cattle dung. In the other three digesters, sCOD removal remained almost constant due to proper mixing and continuous feeding of cattle dung with the lignocellulosic feedstock. Maximum sCOD removal in Digester 3 for co-digestion indicates higher organic matter availability for digestion, resulting in higher biogas production. These results clearly support the findings obtained in batch experiments.

VS reductions in all three digesters maintained a constant level throughout the entire duration of the experiment. As seen in Fig. 2.8(b), the VS reduction for Digester 4 (containing only cattle dung) was comparatively higher than the other three digesters. For co-digestion, VS reduction for Digester 3 (CD+RS) was relatively higher than the other two digesters. Though mono-digestion of cattle dung was better in VS reduction, the combination of cattle dung and rice straw proved to be the most effective in biogas production and VS reduction among the lignocellulosic feedstocks. The results of the continuous process were found to be in tandem with batch process.



**Figure 2.8.** sCOD and % VS reduction of community size digesters.

## 2.4. Conclusion

The present study investigated the biogas production from mono- and co-digestion of three lignocellulosic feedstock viz. duckweed, switchgrass, and rice straw at different TS concentrations. BMP tests revealed an optimum TS concentration of 15% with 1:1 CD: FS ratio. In both BMP tests and community-size biogas digesters, co-digestion of rice straw exhibited maximum biogas production. Under similar operating conditions, mono-digestion of cattle dung showed better performance in the large-scale operation than the co-digestion experiments. Though biogas production from co-digestion of lignocellulosic feedstock is slightly lower than mono-digestion of cattle dung, its utilization can be adopted at community level for proper management and disposal of lignocellulosic material. The results depict an overall comparative analysis of biogas production on both laboratory scale and community level. A similar attempt can be adopted in other developing nations where communities with small dairy farms and ample biomass availability can go for decentralized renewable energy generation.

**References**

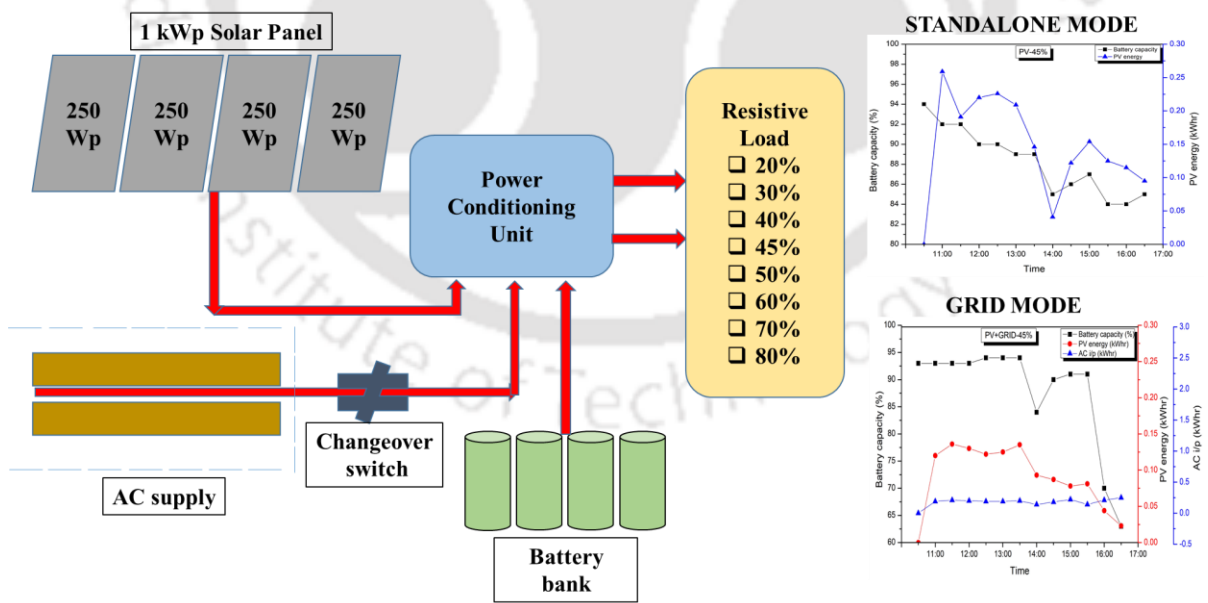
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# Chapter 3

## Experimental investigations of a 1 kW Solar Photovoltaic plant in standalone and grid mode at different loading conditions



### 3.1. Introduction

In this chapter, feasibility of operating of a 1 kWp solar photovoltaic plant at different loads in the environmental conditions of Guwahati, Assam, India was investigated. A pilot-scale 1 kWp photovoltaic (PV) system was installed at Auniati Satra near IIT Guwahati for studying the effects of its operating parameters at different loading conditions corresponding to the environmental conditions prevalent in Guwahati, Assam (India). The PV system was subjected to constant electrical load both in standalone mode and grid-connected mode during the daytime at eight different loading conditions viz. 20%, 30%, 40%, 45%, 50%, 60%, 70% and 80% and half-hourly data of different parameters like solar insolation, PV energy, PV charge, temperature, and battery capacity were analyzed. Optimum loading condition in standalone mode was found to be at 45% – 50% load under normal solar insolation without much burden on the battery bank and can be extended to a maximum load of 70% during the daytime at high solar insolation. In grid-connected mode, load application upto 45% was economically beneficial as less power was utilized from local grid. Though it can be subjected to almost its full rated capacity with input from the ac supply.

### 3.2. Materials and Methods

#### 3.2.1. Installation of 1 kWp photovoltaic system

The PV system comprised of four PV modules each 250Wp (make Tata Solar Power) amounting to a total of 1 kWp. The PV modules were mounted on metal frames on the rooftop of a residential house at Auniati Satra situated in Amingaon near IIT Guwahati (26°11'29"N, 91°43'19"E). The panels comprised an area of 6 m<sup>2</sup>, which were placed at an inclination of 25° facing south direction. Detailed specifications of the panels are shown in Table.1. The panels were connected to a hybrid solar power conditioning unit (PCU) of rating 1 kVA. The PCU has options for priority mode selection where solar was set as first priority, and grid connection was made second. Detailed specifications are given in Fig 3.2. The PCU was connected to a

battery bank comprising of four tubular solar batteries, each of rating 12V, 150 Ah. The detailed specifications are given in Table 3.3. Charging of the battery was done by the power from solar PV in standalone mode and from both solar PV and grid during grid-connected mode. The plant was installed in a wide-open area and was kept away from any obstacles which could cause shading of the PV cells. Solar insolation and temperature data were recorded using a pyranometer (Make: Apogee SP-212) and a digital thermometer respectively. The PV plant setup at the site is provided in the supplementary material.

**Table 3.1.** Specifications of PV module.

<b>Details of PV module</b>	
Manufacturer	Tata Power Solar
Model	TP250
Maximum power at STC ( $P_{max}$ )	250 W
Optimum operating voltage ( $V_{mp}$ )	26.7 V
Optimum operating current ( $I_{mp}$ )	6.74
Dimensions of solar cells (156 X 156 mm)	60
Derating factor	80%
Slope (degree)	25°

**Table 3.2.** Specifications of PCU.

<b>Details of PCU</b>	
Manufacturer	Tata Power Solar
Model	Dynamo Series
Power output (VA)	1000 VA
PCU output AC voltage (V)	230 +/- 5%
Supply power priority	Primary: Grid, Secondary: Battery
Battery charging priority	Solar + Grid
Voltage operation range on AC mains (Vac)	110-270/180-260
PCU status indicators	LED display
Change-over time from AC mains to battery/PV (ms)	<10

**Table 3.3.** Specifications of battery.

<b>Details of battery bank</b>	
Manufacturer	Tata Solar Power
Nominal capacity	150 Ah

Nominal voltage	12 V
Roundtrip efficiency	86%
Maximum depth of discharge	70%

### 3.2.2. Experimental procedure in standalone mode

Solar insolation in a particular area is not constant and changes throughout the day. It is maximum during the daytime and gradually decreases towards the evening. It depends upon various natural and environmental factors, which makes it difficult for a study to be considered as a base point. In this study, the PV system was initially connected in standalone mode, and the load supply was met solely by the PV and battery banks. Eight different constant loading conditions viz 20%, 30%, 40%, 45%, 50%, 60%, 70%, and 80% were employed by applying connected loads present at the residence. The investigations were carried out at different times of the year with medium to high insolation period having an average value of 400 to 600 W/m<sup>2</sup> in the peak hours period was considered as the base point. In standalone mode, energy generated from solar PV was directly supplied to the loads, and extra energy, if generated, was utilized for charging the battery. The energy supplied to the loads was estimated by a static watt-hour meter (make Maxwell India). During experimentation, constant load was applied throughout the day, and corresponding half-hourly variation of different operating parameters viz. PV energy, PV charge, solar insolation, battery capacity, and temperature. were analyzed. The overall effect of different loads and a comparative analysis of the working environmental parameters are presented in this study.

### 3.2.3. Experimental procedure in grid-connected mode

To study the comparative analysis of the effect of grid connection with solar PV, investigation of the PV system in grid-connected mode was also done. In this system, the PCU was set in a condition in which the input supply was fed from both the PV module and local grid i.e., ac supply. The PCU can be configured in a priority mode in which solar PV was set

as first priority and ac supply second priority. In this mode, energy required for supplying the load was first met from solar PV, and if energy required was more, it was compensated from the ac supply. The energy generated from the PV supply and the input energy fed from the ac supply was estimated by watt-hour meters installed at the site. At similar environmental conditions as in standalone mode (described in preceding section), the PCU was subjected to same loading conditions from 20% to 80% load. Investigations were done in a similar manner as in standalone mode by applying constant load throughout the day and analyzing the half-hourly data of different operating parameters viz. PV energy generated, PV charge, solar insolation, battery capacity, temperature, and ac input.

### **3.3. Results and Discussions**

#### **3.3.1. Effect of load and environment on the PV system in standalone mode**

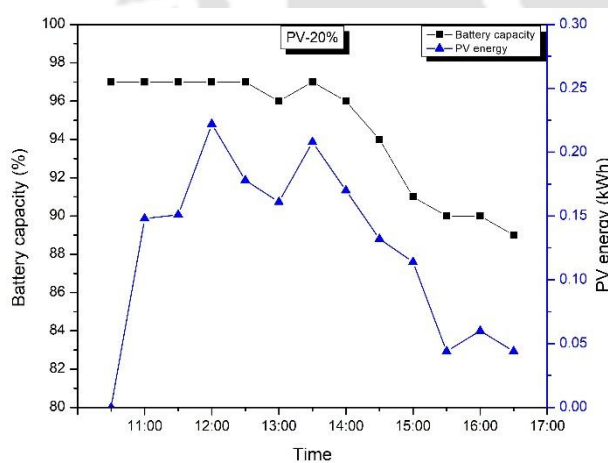
In order to study the effect of load on different working parameters in standalone mode, PV system was subjected to different loading conditions from 20% to 80% by applying constant load during the daytime. The corresponding half-hourly data of various parameters, viz., PV energy generated, PV charge, battery capacity during the period of experiment were analyzed from the panel installed in the PCU. Solar insolation and temperature were also recorded using pyranometer and digital thermometer respectively. The individual analysis of the load impact in standalone mode are described in the succeeding subsections.

##### **3.3.1.1. Effect of 20% and 30% load**

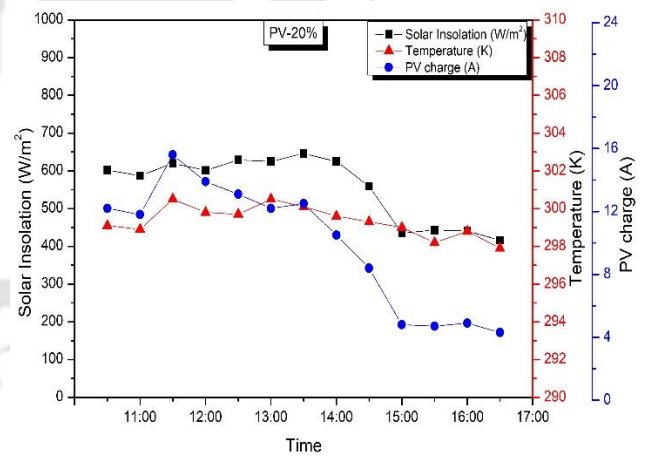
Half-hourly data of different parameters at 20% load are shown in Fig. 3.1(a and b) and 30% load are shown in Fig. 3.1(c and d). Fig. 1(a) depicts the PV energy generation and battery performance at 20% load. Average energy generated during the daytime was 0.129 kWh, with an overall battery discharge percentage of only 9%. It was observed that performance of the battery was not much affected, and load energy required was easily provided by the PV system. Fig. 3.1(b) shows variation of solar insolation ( $\text{W/m}^2$ ), PV charge (A), and temperature (K)

during experimentation. It can be seen that the PV charge varies w.r.t. to solar insolation, and maximum PV charge of 15.6 A was obtained in the morning hours. Average temperature during the experimentation was 299 K. Though energy generation was less during low insolation period, 20% load was easily met by the system.

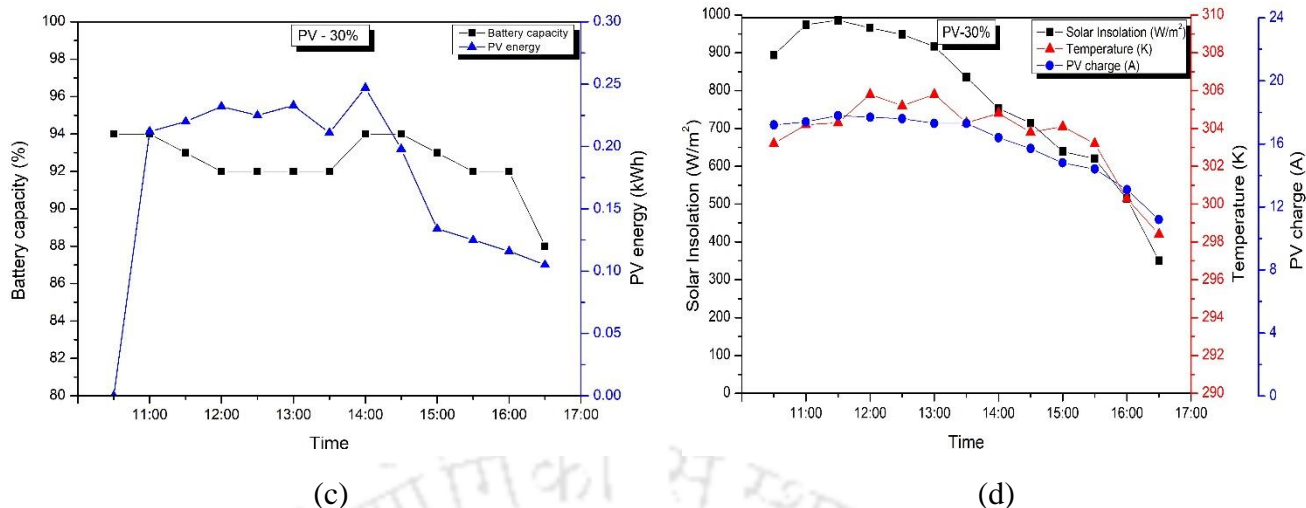
Fig. 3.1(c) depicts the effect of 30% load on different parameters. In this case also it was seen that energy generation from 10:30 – 14:30 h was quite impressive. The battery kept charging when the energy generation was high. The overall battery discharge percentage was only 9%, and average energy generation during the experimentation was 0.181 kWh. As the solar insolation in this case was comparatively higher than that during 20% load application, energy generation was comparatively higher. For 30% load too, energy requirement was easily supplied from the PV system without much burden on the battery bank. The solar insolation, PV charge, and temperature during the experimentation are shown in Fig. 3.1(d). PV charge varied in coherence with solar insolation and temperature. A maximum PV charge of 17.8 A was obtained in the morning period. Average temperature during the whole period was 303 K.



(a)



(b)



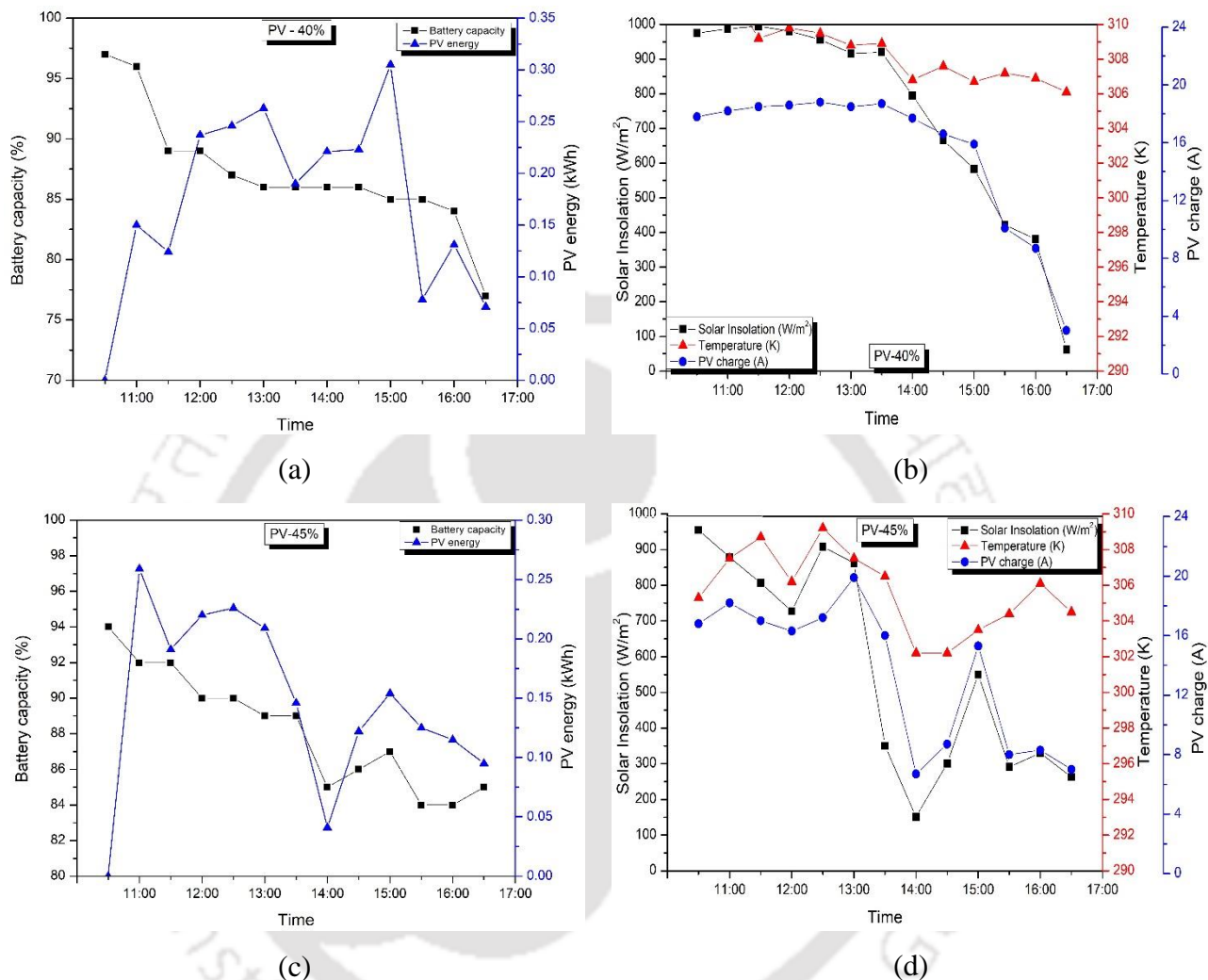
**Figure 3.1.** Half-hourly data at 20% and 30% load in standalone mode. (a) and (c) PV energy and Battery capacity (b) and (d) Solar Insolation, Temperature and PV charge.

### 3.3.1.2. Effect of 40% and 45% load

Half-hourly data of different parameters at 40% load are shown in Fig. 3.2 (a and b). during peak insolation period, battery percentage maintained almost a constant value signifying the fact that load was fully met by the PV system. But after 15:00 h, it gradually started decreasing due to low solar insolation. The overall battery discharged percentage was 25%, and average energy generation during this period was 0.174 kWh. The variation of PV charge, solar insolation, and temperature are shown in Fig. 3.2(b). Maximum PV charge obtained was 18.8 A in peak insolation period. Though temperature maintained almost a constant level throughout the day, maximum solar insolation was observed in the morning period and gradually decreased in the later hours. Average temperature during the period was 308 K. Load of 40% was easily met by the PV system alone without much burden on the battery bank.

The effect of 45% load on the PV system and environmental factors during the experiment are shown in Fig. 3.2(c and d). Energy generation was maximum during the morning period and was low in the afternoon period. Average energy generation during the period was 0.152 kWh. The overall battery discharge percentage was 12%, which signifies that a constant load of 45% was easily met by the PV system. Variation of PV charge, solar insolation, and temperature

during 45% load application are shown in Fig 3.2(d). PV charge varies in a similar way as that of solar insolation, and a maximum PV charge of 19.9 A was obtained when solar insolation was at its peak. Average temperature during the period was 305 K.



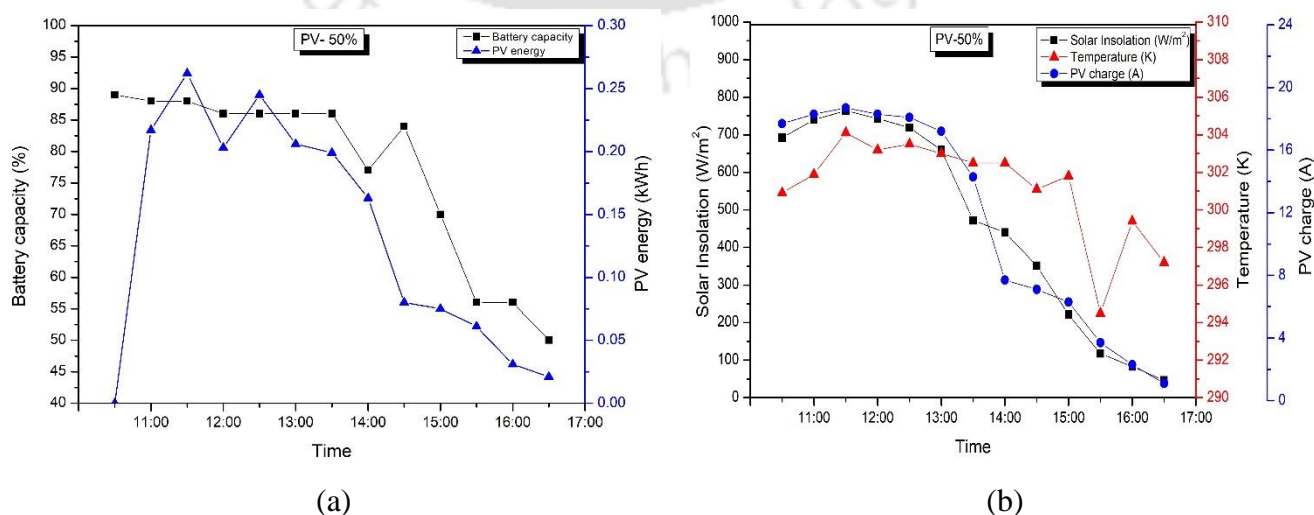
**Figure 3.2.** Half-hourly data at 40% and 45% load in standalone mode. (a) and (c) PV energy and Battery capacity (b) and (d) Solar Insolation, Temperature and PV charge.

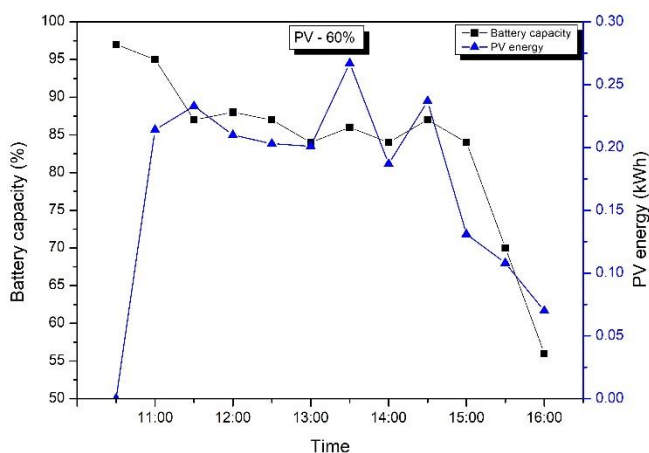
### 3.3.1.3. Effect of 50% and 60% load

Half-hourly data of the various parameters due to application of 50% constant load are shown in Fig. 3.3(a and b). It was observed that the battery initially maintained a minimal discharge till 14:30 h due to high solar insolation at that period. Energy generation during that period also maintained an optimum level with an average value of 0.15 kWh. But after 14:30 h, it drastically reduced as a result of which battery also discharged drastically with an overall

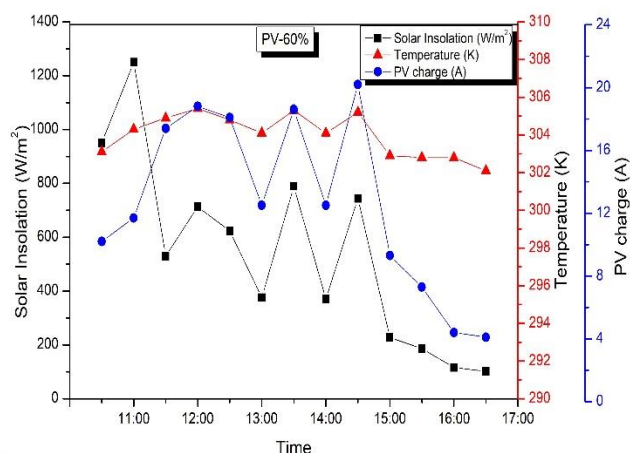
discharge percentage of 39%. In this case, during peak insolation period, the load was easily met by the PV system. But as solar insolation reduced in the evening, energy generation was less and much burden was met by the battery. Solar insolation, PV charge, and temperature during the experimentation period are shown in Fig. 3.3(b). From 10:30 – 13:30 h, solar insolation was at its peak. PV charge maintained a similar variation as that with solar insolation and maximum value of 18.70 A was obtained during peak insolation period with an average temperature of 301 K.

Fig. 3.3(c) depicts the effect of load on the battery performance at 60% load. During the peak insolation period from 11:00 – 15:00 h, the battery percentage maintained a constant level. It was because energy generation was sufficient to supply the load. Though solar insolation as shown in Fig. 3.3(d) fluctuated in a triangular wave pattern, energy generation maintained a constant level. Solar insolation and PV charge were at peak values from 10:30 – 14:30 h and gradually decreased. There was not much temperature variation during the period maintaining an average of 303 K. Average PV energy production was found to be 0.187 kWh, and overall battery discharge was 41%. As load applied was comparatively high, extra energy required for compensating the load was supplied from battery bank. Load burden during daytime was easily met by the PV system. But as solar insolation and energy generation decreased after 14:30 h, much burden was met by the battery, and it discharged significantly.





(c)



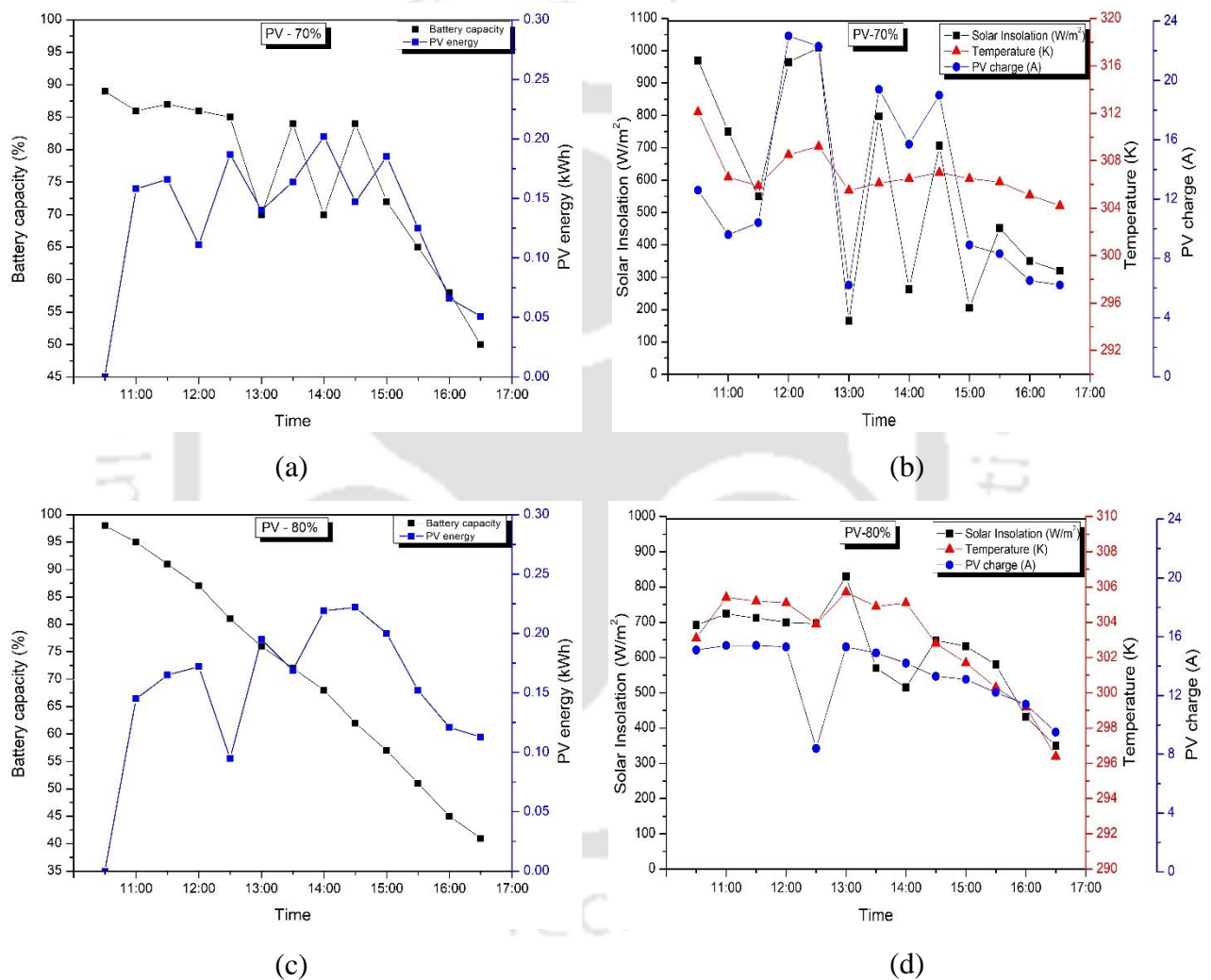
(d)

**Figure 3.3.** Half-hourly data at 50% and 60% load in standalone mode. (a) and (c) PV energy and Battery capacity (b) and (d) Solar Insolation, Temperature and PV charge.

#### 3.3.1.4. Effect of 70% and 80% load

The effect of 70% load on different parameters is shown in Fig. 3.4(a and b). There was a continuous rise and fall of the battery capacity in coherence with energy generation. Initially, the battery capacity maintained a constant value till 12:30 h after which it fluctuated in coherence with energy generation. A similar variation of PV charge, solar insolation, and temperature were also observed during the experimentation period, as shown in Fig. 3.4(b). Fig. 3.4(c and d) highlights the variation of parameters at load application of 80%. From the very beginning, battery discharged significantly, which totalled an overall discharge of 57%. Energy generation was high most of the time, but this was not sufficient for supplying the load, and as such much of the load requirement was met by the battery bank. Average energy generation during the daytime was 0.164 kWh. Though during the daytime the load was met by the PV system, further application of load would have led shut down of PCU leading to failure of load supply. Also, reduction of battery capacity clearly indicates that constant load application of 80% of the rated capacity is not feasible under normal environmental conditions. Solar insolation, PV charge, and temperature data during the experimentation are shown in Fig. 3.4(d). Solar insolation was high in the morning period and gradually decreased towards the

later hours. A maximum PV charge of 15.4 A was obtained during peak insolation period. At 12:30 h, with a decrease in solar insolation and temperature, there was a sudden decrease in PV charge, but it again rises as other parameters increases. It gives a clear indication of the effect of solar insolation and temperature with PV charge. Average temperature during the period was 302 K.



**Figure 3.4.** Half-hourly data at 70% and 80% load in standalone mode. (a) and (c) PV energy and Battery capacity (b) and (d) Solar Insolation, Temperature and PV charge.

Thus from the above subsections, it can be summarized that in standalone mode, a PV system can be subjected to 70% of its full load capacity under normal environmental conditions. But the situation is prevalent only if it is operated during the daytime. Moreover,

up to 45% load, the burden was met mostly by the PV, and less burden was met by the battery bank. In places where a PV system is installed for supplying loads for 24 h, a maximum of 45% load should be applied during the daytime to compensate for the energy requirement during night time. Load application of more than 45% has led to a significant decrease in battery capacity in post noon hours. Load application of  $\geq 80\%$  is not feasible pertaining to environmental conditions in Guwahati. This kind of operating procedure can be implemented in decentralized PV electricity generation where there is no electrical connection, and the system can be designed as per load requirements. Sharma et al.,(Sharma et al., 2020) also proposed a similar load management strategy keeping minimum discharge percentage of battery at 40% and power required for supplying the loads will first be met by PV systems, and extra energy will be utilized for charging the battery. In another study, the author estimated the load forecasting of different load patterns and highlighted the optimum design of a hybrid renewable energy system(Murugaperumal et al., 2020). In all the load conditions used in this study, it was observed that the solar insolation under normal sunny day in Guwahati is sufficient for a PV system to operate at 45% of the rated capacity.

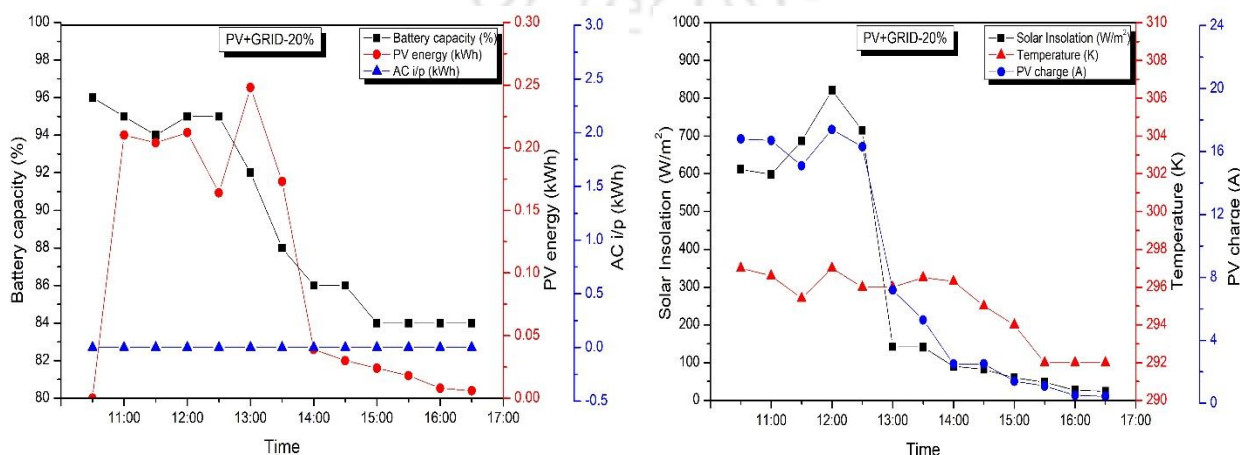
### **3.3.2. Effect of load and environment on the PV system in grid-connected mode**

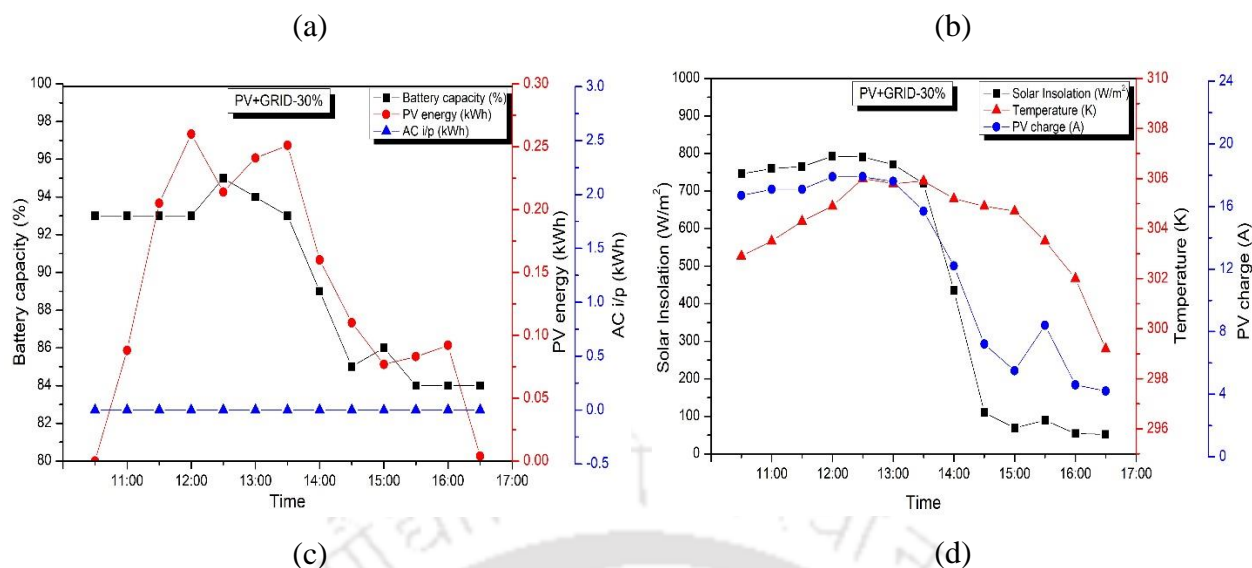
To study the impact of load and environment on a 1 kWp PV system in grid-connected mode, the PV system was subjected to the same loading conditions as in standalone mode. Here the input supply was met from both solar PV and ac supply. The PCU has provisions for two input connections in which one input was fed from solar PV, and the other was from ac supply. In order to analyze the half-hourly variation of different parameters, the PCU was subjected to different loading conditions from 20% to 80% by applying constant load throughout the day.

#### **3.3.2.1. Effect of 20% and 30% load**

The effect of 20% load on battery performance and ac input is shown in Fig. 3.5(a). Battery discharged at a very minimal level of 12%, and energy required for 20% load was

sufficient from PV supply. Battery percentage maintained a constant level in the morning and gradually decreased from the afternoon. This was mainly due to low energy generation and low solar insolation during that period. Though energy generation was less in the afternoon period, 20% load was easily met by the PV system without any supply of ac input. Average energy generation during the experimentation was found to be 0.11 kWh. Fig. 3.5(b) shows the variation of solar insolation, PV charge, and temperature. A maximum PV charge of 17.40 A was achieved in the peak insolation period. The variation of battery percentage, ac input, and PV energy generation at 30% load is shown in Fig. 3.5(c). Battery percentage maintained a constant level from 10:30 – 13:30 h and gradually decreased after that due to low energy generation. Though the energy generation was comparatively less, 30% load was easily met by the PV system, and no ac supply was used during the experimentation period with an overall battery discharge of 9%. Average capacity amount of PV energy generated during the daytime was 0.15 kWh. As electricity generation was comparatively higher than that at 20% load analysis, discharge percentage of battery was comparatively less. Solar insolation, PV charge, and temperature during the experimentation are shown in Fig. 3.5(d). Solar insolation was high during the morning period leading to high energy generation. PV charge does vary in a similar way with solar insolation, and a maximum PV charge of 17.90 A was obtained during this period. Average temperature maintained during the period was 303 K.





**Figure 3.5.** Half-hourly data at 20% and 30% load in grid-connected mode. (a) and (c) Battery capacity, PV energy and AC i/p (b) and (d) Solar Insolation, Temperature and PV charge.

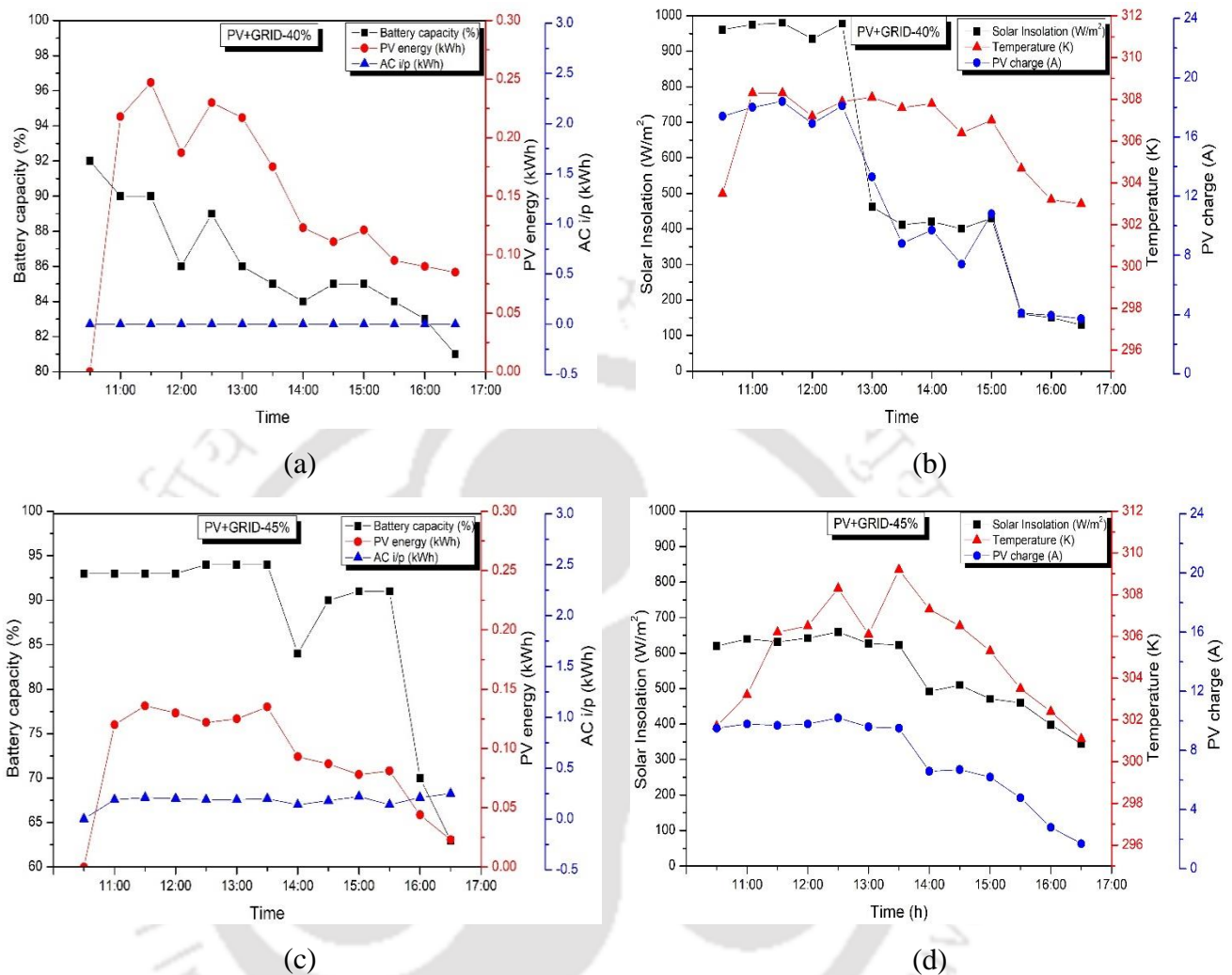
### 3.3.2.2. Effect of 40% and 45% load

Fig. 3.6(a and b) shows the half-hourly variation of different parameters at 40% load. During peak insolation period, energy generation was high, maintaining an average energy generation of 0.16 kWh during the experimentation period. There was no requirement of ac supply, and load requirement was met by solar PV. Battery capacity reduced to an overall percentage of 11%. Maximum solar insolation was observed in the morning time, and PV charge obtained a maximum value of 18.40 A during that period maintaining an average temperature of 306 K.

Fig. 3.6(c) and (d) shows the variation of parameters for load supply of 45%. As load burden was comparatively high, ac supply was required from beginning of the experiment. The overall ac input utilization was 2.32 kWh. Though ac supply was utilized, it was observed that battery capacity degraded from 16:00 h, which resulted in a decrease of an overall 30% discharge.

Moreover, average energy generated during the daytime was 0.10 kWh. The increase in ac supply was because load burden could not be compensated by the PV supply alone, and more energy from ac supply was utilized for compensating the load. Solar insolation was high

from 10:30 –13:00 h and gradually decreased in post noon hours. PV charge and solar insolation showed a similar trend with a maximum value of 10.20 A at peak insolation period.



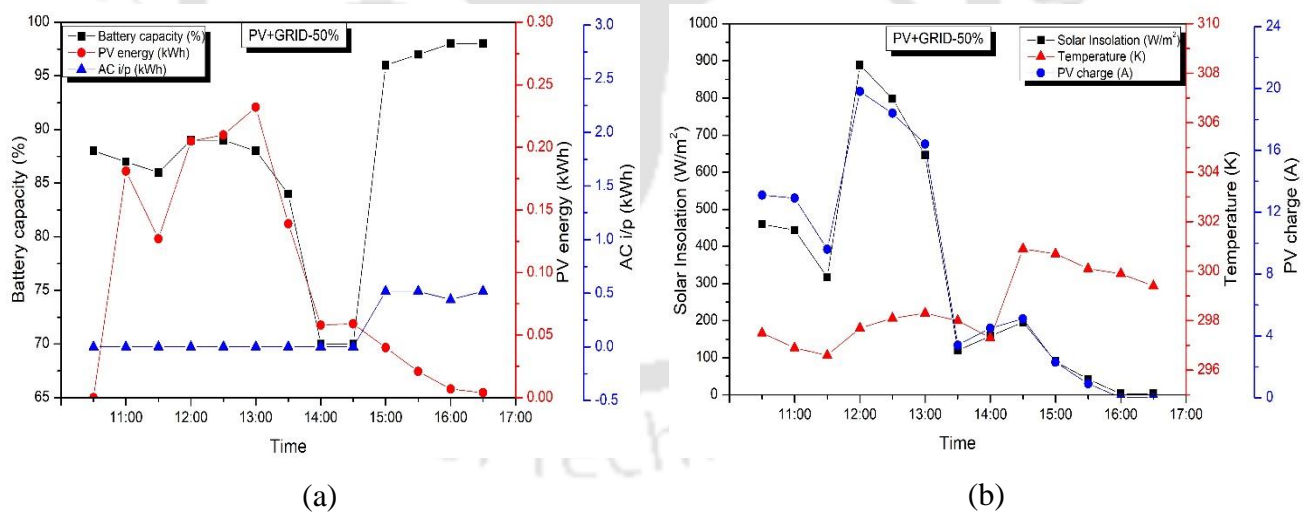
**Figure 3.6.** Half-hourly data at 40% and 45% load in grid-connected mode. (a) and (c) Battery capacity, PV energy and AC i/p (b) and (d) Solar Insolation, Temperature and PV charge.

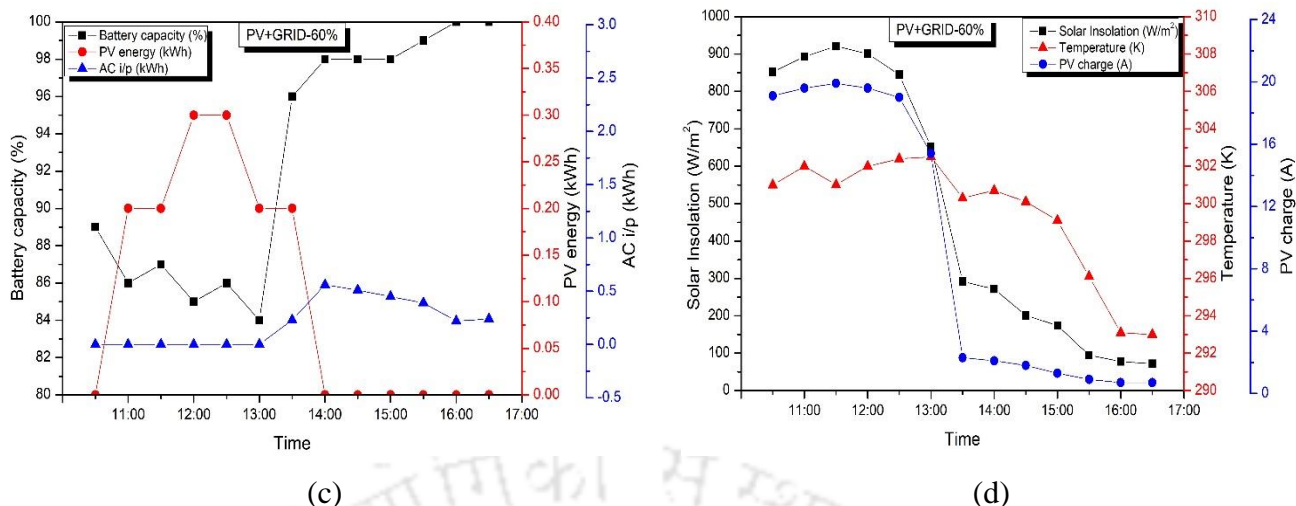
### 3.3.2.3. Effect of 50% and 60% load

Fig. 3.7(a) shows the effect of 50% load on ac input and battery capacity. Battery percentage maintained a constant level till 13:30 h and suddenly decreased significantly at 14:00 h. The sudden downfall of battery percentage was due to low insolation at that period. But as the battery discharged substantially to 70%, it started charging from the ac supply. Average energy generated from PV was found to be 0.11 kWh and total energy supplied from ac supply was 2 kWh. PV charge showed similar variation as solar insolation, and energy

generation was low during low insolation period. A maximum PV charge of 19.80 A was obtained during peak insolation period, and average temperature was 298 K, as shown in Fig. 3.7(b).

Fig. 3.7(c and d) shows the variation of operating parameters at 60% load. It was observed that till 13:00 h, there was no requirement of ac supply, and the battery discharge percentage was less. But there was a rise in ac supply as well as battery percentage after 13:00 h. This was because 60% load was not met by the PV system, and it was compensated from the ac supply. Average energy generation during experimentation was 0.11 kWh. Moreover, solar insolation, as shown in Fig. 3.7(d) was high during the morning period, and there was a sudden drop in the afternoon. A maximum PV charge of 19.90 A was obtained in the peak insolation period. The total ac energy utilized for compensating the loads and charging the battery was 2.60 kWh.





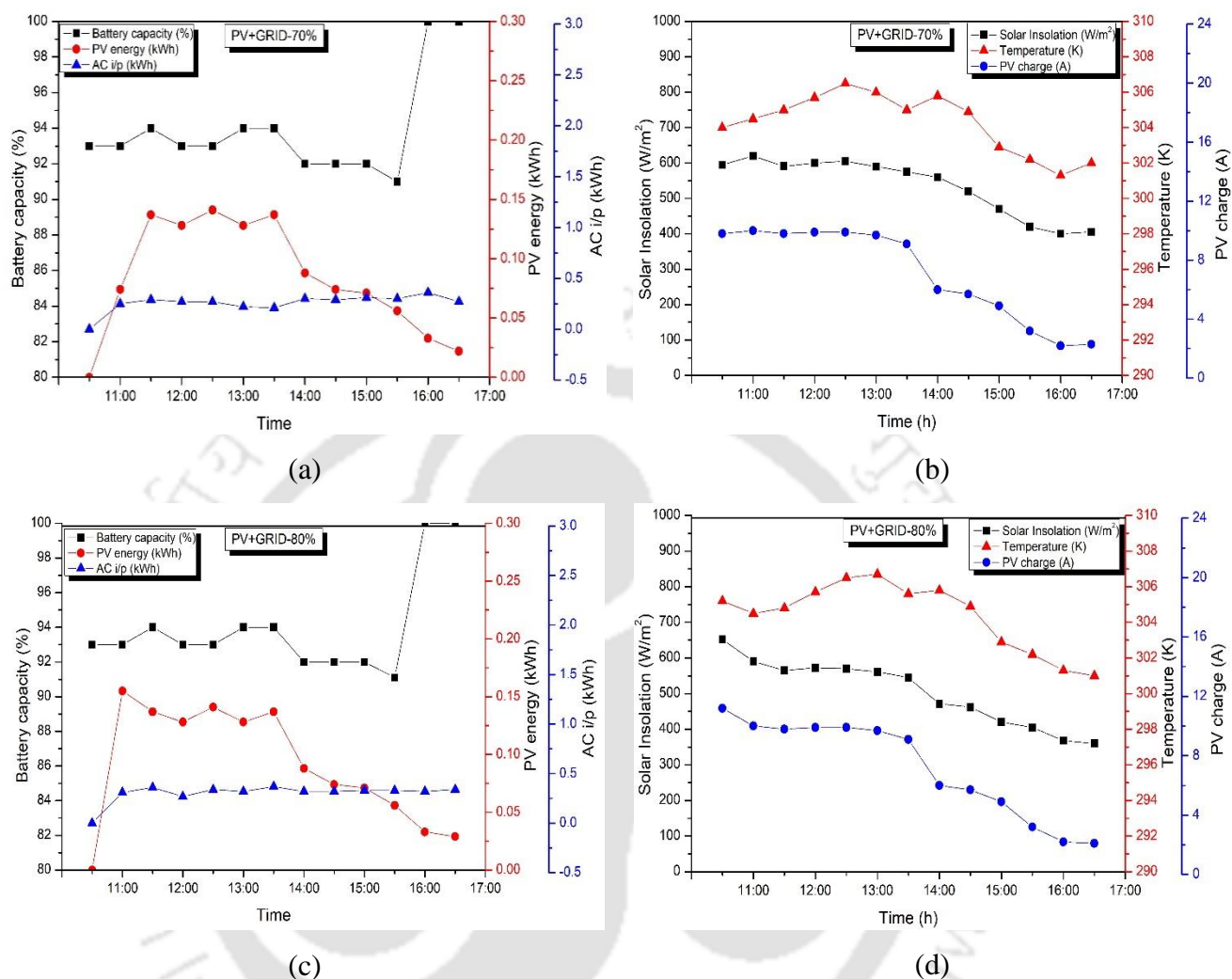
**Figure 3.7.** Half-hourly data at 50% and 60% load in grid-connected mode. (a) and (c) Battery capacity, PV energy and AC (b) and (d) Solar Insolation, Temperature and PV charge.

### 3.3.2.4. Effect of 70% and 80% load

Fig. 3.8 (a and b) shows the variation of different parameters at load application of 70%. As load applied was high, ac supply was required from the beginning of the experiment. And as such total ac input of 3.34 kWh was utilized. Battery capacity maintained a constant level until 15:30 h, after which it charged to 100%. This was reflected in the ac input, which was high at that point. Average energy generation during the period was 0.164 kWh. Solar insolation, PV charge, and temperature variation are shown in Fig. 3.8(b). Though the temperature was high during the period, solar insolation was relatively less. PV charge varied correspondingly with solar insolation. A maximum PV charge of 15.4 A was obtained during the peak insolation period.

Half-hourly data generation of different parameters during application of 80% load are shown in Fig. 3.8(c) and (d). Performance of the battery, ac input, and energy generated from PV is shown in Fig. 3.8(c). As the load applied was high, ac supply was required from the beginning of the experiment. It was evident that the amount of energy required to supply the loads was not met by the solar PV alone. The total ac input during the experimentation was 3.93 kWh. This amount of ac input was used for compensating the load as well as charging the battery to 100%, as can be seen from Fig. 3.8(c). Average energy production during the analysis

was 0.098 kWh. As energy production was also comparatively less than the other analysis, the requirement of ac power was more in this case.



**Figure 3.8.** Half-hourly data at 70% and 80% load in grid-connected mode. (a) and (c) Battery capacity, PV energy and AC i/p (b) and (d) Solar Insolation, Temperature and PV charge.

From the above subsections, it can be summarised that load application from 20% to 40%, the energy requirement was easily met by PV system alone in grid-connected system. This was also evident in standalone mode connections. Though ac supply was connected to PCU, it was not utilized up to load application of 40%. At 45% and 50% load, ac supply required was comparatively less than other loads. But as the load increased, use of ac supply increased, compensating the load as well as charging the battery. It was observed that if the discharge percentage of the battery decreases at a larger rate, it starts charging from the ac

supply. This kind of connection is very much efficient in places where there are provisions of grid supply, and solar energy can be utilized as a co-producer with conventional grid supply. In a similar work, Suganthi et al.,(Suganthi et al., 2019) monitored the real-time analysis of a 300kWp PV grid-connected system and presented a comparative analysis of the energy shared from the local grid and diesel generators.

Considering the environmental conditions prevalent in Assam, solar PV systems can be subjected to its full load capacity in grid-connected mode. As extra energy required will be compensated from the ac supply. Though considering the economic benefits, load application of 45% – 50% in grid-connected mode is much suitable. In India, almost in all residential buildings, either generator is provided, or individual homes have commercial inverters for load supply during shutdown and load shedding. Though the initial cost of a PV system is comparatively higher than the commercial inverter, with subsidy ranging from 30% – 70% by GOI(Manju and Sagar, 2017), PV systems can play a major role in harnessing clean energy. During daytime, when solar insolation is at its peak, maximum energy can be harnessed from solar PV depending on its load requirement. Design of a PV system can be made either according to connected load or peak load. In standalone mode, a load of 45% – 50% of rated capacity can be easily met without much burden on the battery bank. And in grid-connected mode, a PV system can be subjected to almost its full load capacity.

Moreover, energy can also be met from other renewable sources. As a result, reliance on conventional sources would greatly be reduced. It is only at night when solar insolation is nil, energy requirement will be met from conventional sources. A further investigation is under process in order to assess the feasibility of utilizing biogas as fuel for electricity generation in community level.

### 3.4. Conclusions

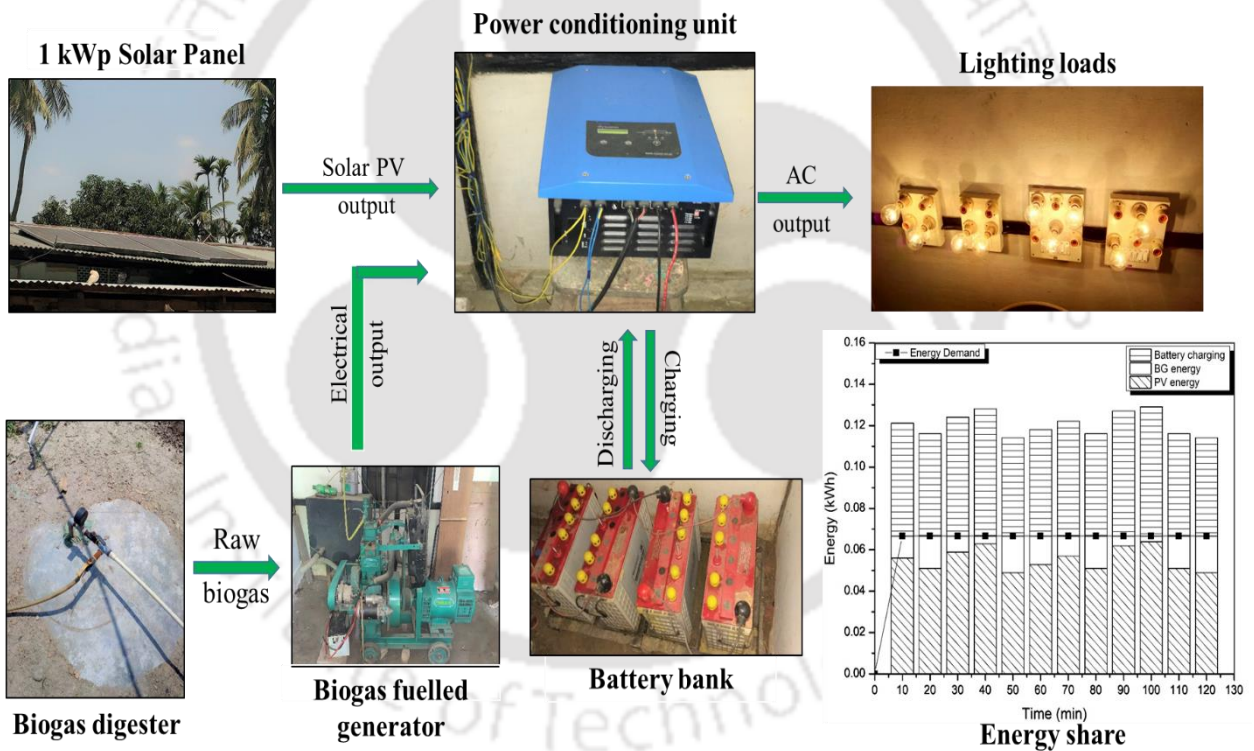
The present study investigated the feasibility of implementing solar PV in both standalone and grid-connected mode for decentralized production of electrical energy. A 1 kWp PV system was subjected to constant loading conditions during the daytime at eight load conditions viz. 20% to 80%. PV system was loaded at different times of the year, considering similar environmental conditions during experimentation. The results showed that in standalone mode, a PV system could be subjected to 70% of its rated capacity during daytime if energy required is to be utilized only during daytime. But if energy required is both for 24 h duration, maximum loading of 45% – 50% can be applied under a normal sunny day without putting much burden on the battery bank. Whereas in grid-connected mode, a PV system can be subjected to almost its full load capacity. This loading procedure can be adopted in cities like Delhi, Mumbai etc. and, in remote places or islands, where there is no electricity production, standalone mode connection with maximum loading of 45% – 50% can be a favourable option. This study should provide a good insight into the operating procedure as well as maximum load application of a PV system in both standalone and grid-connected mode, thereby making it feasible for decentralized energy generation.

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# Chapter 4

## Hybridization of Solar Photovoltaic and Biogas system: Experimental, Economic and Environmental analysis



## 4.1. Introduction

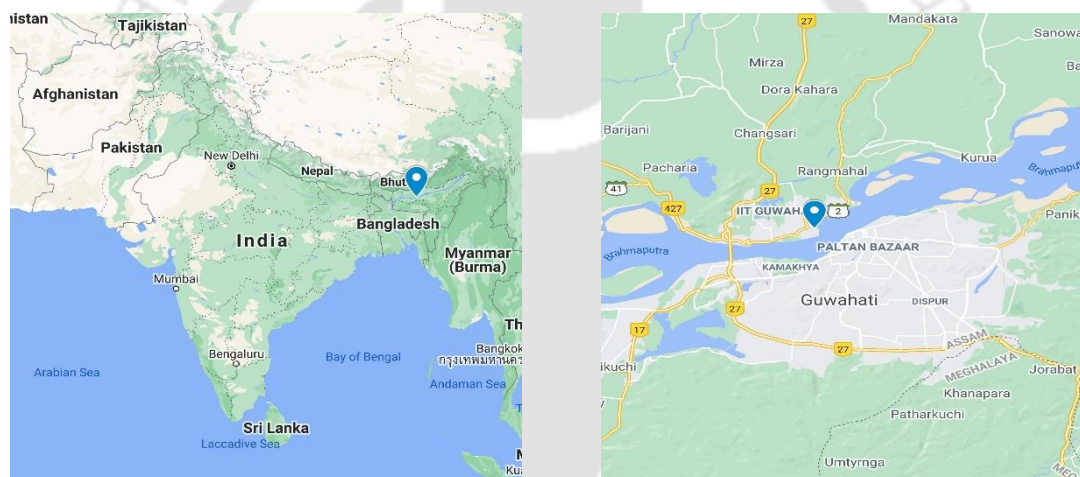
In this chapter hybridization of a 1 kWp solar photovoltaic with a biogas system was investigated. The coupling of renewable energy systems has proven to be advantageous in achieving sustainable and reliable energy generation. In this study, the techno-economic and environmental assessment of a hybrid 1 kWp solar photovoltaic (PV) plant (having battery backup) and a 3.5 kVA biogas fueled (BF) generator was investigated. The hybrid system was subjected to constant load conditions from 20% to 80% of the rated power conditioning unit (PCU), and energy shared by the combined systems was investigated. At lower loads, the photovoltaic system was sufficient to meet the demand. Whereas at higher loads, energy share from the biogas system was required for meeting the load demand. Economic analysis over a project lifetime of 25 years revealed a high positive net present value of \$1562.15 with a Levelized cost of the energy value of \$0.21/kWh for the hybrid system. A comparative financial analysis for the standalone solar photovoltaic system was also performed using the system advisor model (SAM). System advisor model analysis resulted in a positive net present value of \$306.45 and a Levelized cost of the energy value of \$0.15/kWh. The environmental analysis revealed net CO<sub>2</sub> mitigation of 104.59 Tons, equivalent to an earned carbon credit of \$2090.31 from the hybrid system.

## 4.2. Materials and Methods

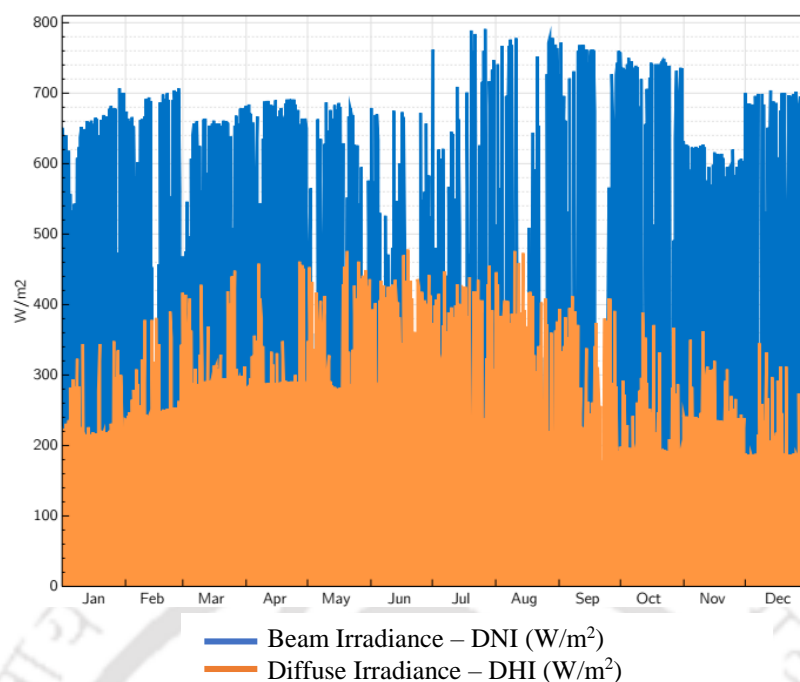
### 4.2.1. Study Area

The study area for installing a 1 kWp PV system and its hybridization with biogas system was considered in Auniati Satra, a place nearby IIT Guwahati (26.15°N, 91.75°E), Assam (India). The Satra has an in-house dairy farm consisting of 14 hybrid cows that provide ample cattle dung to be utilized for biogas production. Various lignocellulosic materials such as duckweed, switchgrass, and rice straw were used as mixed substrates along with cattle dung for anaerobic digestion. The Satra is a religious place that promotes Vaishnavism and Satriya

culture in Assam and has a cluster of people living in different blocks. The setup was installed in one of the blocks, which had the dairy farm. Electricity produced from the hybrid system and biogas produced from the digesters was utilized for cooking purposes by the people residing in this block. It has five permanent members as residents, and on average, 12 - 14 who come to perform religious rituals at the Satra are served one-time food every day. Considering the availability of cattle dung and other lignocellulosic waste, the site was selected to perform experimental studies for the hybrid system. The geographical location of the area on the Indian map is shown in Fig. 4.1. Beam and diffuse irradiance for a TMY, as obtained from SAM, is shown in Fig. 4.2.



**Figure 4.1.** Geographical location of the installation site (Source: Google maps)



**Figure 4.2.** Beam and Diffuse irradiance for a TMY of the site (Source: SAM software)

#### 4.2.2. PV plant description

A 1 kWp PV system with panels mounted on the rooftop in south direction and an inclination of  $25^\circ$  was installed at the site. The PV system consisted of four PV modules of rating  $250 W_p$  each and was free from any shading. The output from the panels was connected to a power-conditioning unit (PCU) of rating 1 kVA. The PCU had slots for four connections and has the facility of priority mode selection. Out of the four slots, two slots were used for input connections from solar PV and other generating units/local grid. The third slot was used for the connection of battery banks, and the fourth one was utilized to provide output supply. The battery banks consisted of four tubular solar batteries each of rating 12 V and 150 Ah. Energy used for charging the battery was utilized from either generating sources or both as per priority mode selection. Detailed specifications of the PV module, PCU, and battery banks are already given in Table 3.1, 3.2 and 3.3 respectively.

### 4.2.3. Biogas system description

The Satra has three 4 m<sup>3</sup> Ferro cement Deenbandhu model biogas digesters. As the Satra has a dairy farm, an ample amount of cattle dung with an average amount of 20 to 25 kg of cattle dung/cow/day was available as feed for the digesters. Moreover, there are numerous lignocellulosic wastes near the location, mainly duckweed, switchgrass, and rice straw that are available, which could be used as co-substrate with cattle dung biogas production. In this study, anaerobic co-digestion of lignocellulosic wastes with cattle dung was used for the production of biogas. An approximate amount of 25 kg of mixed biomass at 1:1 ratio with an equal amount of water was fed in the digesters. Biogas produced from these digesters were inter-connected through pipes, and part of it was utilized for cooking, and part of it was utilized for electricity production. A modified spark ignition (SI) engine already installed in the site was utilized for running a generator of rating 3.5 kVA (make- Prakash) using biogas as fuel.

### 4.2.4. Experimental analysis of the hybrid mode

For the hybrid mode of operation, the output from solar PV and BF generator was connected to the PCU. The PCU was set in priority mode, in which solar was set as the first priority, BF generator was set to second, and the battery storage was set as third. As biogas production depends on various environmental and other factors, biogas formed from the digesters were not sufficient for 24 hours operation of the BF generator. Moreover, a part of the biogas formed was utilized for cooking. As such, the BF generator was operated for 120 min duration, and hybridization study was investigated for that period. For analyzing the share of load by the hybrid system, PCU was subjected to eight different loads from 20% to 80% in a step of 10% increase with the rated apparent power of 1000 VA. The energy utilized for supplying the load as well as for charging of battery from the hybrid system was analyzed after every 10 min for 120 min duration. Two energy meters were connected to the utility for assessing the BF generator's energy and the total energy supplied to the load. One of the energy

meters was connected directly with the loads, and the other was connected with the PCU. As the rating of BF generator was more than the PCU, the output connection from the BF generator was subdivided into two parts. One part was connected directly to the PCU, and the other was connected to some residential loads. This was done to run the BF generator at almost full load capacity. The experimental setup at the site location is provided in the supplementary material. The amount of energy utilized from the BF generator for supplying load and charging was estimated by Eq. (4.1).

$$\text{BF generator units supplied} = \text{Total units supplied} - \text{PV units supplied} \quad (4.1)$$

#### 4.2.5. Economic analysis of the hybrid system

For evaluating the economic criteria, parameters like annualized cost of system (ACS), Levelized cost of energy (LCOE), net present cost (NPC), payback period (PP), internal rate of return (IRR), etc. are considered by various researchers (Chauhan and Saini, 2014; Pal and Bhattacharjee, 2020a). In this study, LCOE, Net present value (NPV), Simple payback period (SPP), and Discounted payback period (DPP) over the project lifetime have been estimated using standard formulas (Mudgal et al., 2019; Pal and Bhattacharjee, 2020b). LCOE, NPC, and NPV are economical tools for a hybrid system, encompassing all recurring and non-recurring costs over the project lifetime. LCOE is the average cost to generate per kWh of electricity from the hybrid system (Mudgal et al., 2019; Pal and Bhattacharjee, 2020a). It is defined as the ratio of total annualized cost of the system over the project lifetime to the system's annual electricity production  $E_L(t)$ . NPC represents the overall values of all costs, including capital cost, running cost, and maintenance cost over the project lifetime, as shown in Eq. (4.2) (Pal and Bhattacharjee, 2020b). The present value of a project considering overall cost and savings incurred over the project lifetime is termed as net present value (NPV). A high and positive NPV value is an absolute indication of a project's viability. Its estimation is done by considering

the future cash inflows and outflows discounted back to the present. Its mathematical interpretation is represented by Eq. (4.3) (Pal and Bhattacharjee, 2020b).

$$NPC_t = IC_t + RC_t + O \& M_t \quad (4.2)$$

Where,  $NPC_t$  - Total net present cost,  $IC_t$  - Total initial capital cost,  $O \& M_t$  - Total operational and maintenance cost

$$NPV_t = E_{sav} + LPG_{esav} - IC_t - RC_t - O \& M_t \quad (4.3)$$

Where,  $NPV_t$  - Total net present value,  $E_{sav}$  - Electricity savings from the system,  $LPG_{esav}$  - LPG equivalent savings from the system

Electricity savings from the hybrid system were estimated by considering the PV system's annual electricity share and predicted generation from the BF generator considering constant generation operating for 2 hours daily. Overall, saving from these systems over a project life of 25 years was estimated by considering the yearly discounted cash flows. Equivalent electricity and LPG savings for the first year was estimated using Eq. (4.4).

$$E_{sav} = (E_{L(PV)} + E_{BF}) \times R \quad (4.4)$$

Where,  $E_{L(PV)}$  - Annual electricity production from solar PV,  $E_{BF}$  - Annual electricity production from BF generator

Overall saving of electricity from both solar PV and BF generator over 25 years project lifetime and considering a degradation rate of 0.6% per year (Kumar et al., 2020; Yadav and Bajpai, 2020) was estimated using Eq. (4.5) (Kumar et al., 2020; Yadav and Bajpai, 2020).

$$E_{(sav)_t} = \sum_{n=1}^{25} \frac{E_{sav} (1 - d_r)^n}{(1 + d)^n} \quad (4.5)$$

Where,  $E_{(sav)_t}$  - Total electricity savings over project lifetime,  $d_r$  - degradation rate,  $d$  - discount rate

Similarly, the equivalent amount of LPG that could be saved from biogas as cooking fuel was estimated using Eq. (4.6). A standard domestic LPG cylinder weighs around 14.2 kg, and price ranges \$8.86 to \$13.62 (\$8.86 – current price in Assam). Overall saving of using biogas as cooking fuel for a project lifetime of 25 years was estimated by calculating the discounted cash flows over the years using Eq. (4.7) (Kumar et al., 2020; Yadav and Bajpai, 2020).

$$LPG_{esav} = Biogas(m^3) \times F \quad (4.6)$$

Where,  $LPG_{esav}$  - LPG equivalent savings from the system,  $F$  - Conversion factor

$$LPG_{(esav)_t} = \sum_{n=1}^{25} \frac{LPG_{esav}}{(1+d)^n} \times P \quad (4.7)$$

Where,  $LPG_{(esav)_t}$  - Total LPG equivalent savings over project lifetime,  $P$  - Unit rate of an LPG cylinder

The total investment cost comprises the biogas digester's capital cost, BF generator, all the PV system components, and other installation costs as given in Eq. (4.8) (Kumar et al., 2020; Yadav and Bajpai, 2020).

$$IC_t = IC_E + IC_D + IC_{PV} + IC_B + IC_{PCU} + IC_O \quad (4.8)$$

Where,  $IC_E$  - Capital cost of biogas engine,  $IC_D$  - Capital cost of biogas digester,  $IC_{PV}$  - Capital cost of panels,  $IC_B$  - Capital cost of battery banks,  $IC_{PCU}$  - Capital cost of power conditioning unit,  $IC_O$  - All other cost such as installing and commissioning

Battery banks have a useful life of 4 to 5 years, and BF generators have a useful life of 7 to 10 years (Pal and Bhattacharjee, 2020b). As such, considering the useful life of battery as 5 years and for BF generator as 7 years, the overall replacement cost of the battery banks and BF generator considering replacement can be estimated by using Eq. (4.10) and (4.11) (Pal and Bhattacharjee, 2020a).

$$RC_t = RC_E + RC_B \quad (4.9)$$

Where,  $RC_t$  - Total replacement cost,  $RC_E$  - Replacement cost of biogas engine,  $RC_B$  -

Replacement cost of battery banks

$$RC_E = IC_E \times \left[ \sum_{n=7,14,21} \frac{1}{(1+d)^n} \right] \quad (4.10)$$

$$RC_B = IC_B \times \left[ \sum_{n=5,10,15,20} \frac{1}{(1+d)^n} \right] \quad (4.11)$$

The operation and maintenance costs over the lifetime of 25 years can be estimated by using Eq. (4.12) (Pal and Bhattacharjee, 2020a).

$$O \& M_t = \frac{IC_{O\&M}}{d} \times \left[ 1 - \frac{1}{(1+d)^n} \right] \quad (4.12)$$

The value of capital recovery factor (CRF) can be estimated using Eq. (4.13), which can be utilized for calculating the LCOE (Pal and Bhattacharjee, 2020a).

$$CRF = \frac{d(1+d)^n}{(1+d)^n - 1} \quad (4.13)$$

$$LCOE = \frac{NPC_t \times CRF}{\sum_{t=1}^{8760} E_L(t)} \quad (4.14)$$

#### 4.2.6. Economic analysis of standalone system using SAM

To make a comparative assessment of the hybrid system with standalone system, the PV watts model in SAM was utilized to assess the standalone system's economic performance. It is an open-source software developed by NREL and enables application of an extensive database of PV system components with varied calculation parameters and selections (Allouhi, 2020). The software has an inbuilt wide range of local resource data. If for a particular co-

ordinate, resource data is not available, it can be downloaded from the National Solar Radiation Database (NSRDB) and added as input parameters. Various input parameters such as design specification of the components of PV system, system costs, electricity rates, and electrical load were simulated in the model. The model's output parameters comprised of NPV, LCOE, payback, capacity factor of plant, load, and generation characteristics (Thakur and Chakraborty, 2019). The current site's monthly load demand with tariff rates as per Assam Power Distribution Company Limited (APDCL) has been incorporated in the model (Electricity and Commission, 2021). SAM performs energy calculations for solar PV energy projects based on system design and installation parameters given as inputs to the model. SAM is an electric energy generation model and accounts for the system performance and financial parameters of either standalone or grid-connected solar PV system to meet the electric load. It performs a time-step simulation of a solar PV system performance and calculates energy generation (Shukla et al., 2016).

#### 4.2.7. Environmental Assessment

The evaluation of the hybrid system's carbon reduction potential was assessed by considering the CO<sub>2</sub> emission and mitigation of both the PV system and the biogas system.

##### **CO<sub>2</sub> Emission**

It represents the total emissions in the production of components of the hybrid system. It has been reported that life cycle CO<sub>2</sub> emissions from polycrystalline silicon modules is taken as 0.053 kgCO<sub>2</sub>(e)/kWh (Kumar et al., 2020; Peng et al., 2013). Annual and lifetime CO<sub>2</sub> emissions of a PV system can be estimated by using Eq. (4.15) and (4.16), respectively (Kumar et al., 2020).

$$CO_2 \text{ emissions per year} = E_{L(PV)}(kWh/ \text{year}) \times LC_{co_2} \quad (4.15)$$

Where,  $E_{L(PV)}$  - Annual electricity production from solar PV,  $LC_{co_2}$  - CO<sub>2</sub> emission factor from the solar PV system

$$\text{Lifetime } CO_2 \text{ emissions} = \sum_{t=1}^n E_{L(PV)}(kWh / year) \times (1 - d_r)^n \times 0.053 \quad (4.16)$$

Similarly, lifecycle  $CO_2$  ( $LCE_{BG}$ ) emission from the biogas system was estimated by considering all individual component's  $CO_2$  emission factors.

### ***CO<sub>2</sub> mitigation***

It is the amount of  $CO_2$  emission that can be reduced due to the equivalent amount of electricity produced from a coal-fired plant as that of the hybrid system. The average  $CO_2$  emission factor from a coal-fired power plant for electricity generation is 0.98 kg/kWh. Due to transmission and distribution losses in India,  $CO_2$  emission factor raises to 1.58 kg/kWh, which is the grid emission factor represented as  $EF_g$  (Kumar et al., 2020; Yadav and Bajpai, 2020). Annual  $CO_2$  mitigation for the hybrid system was evaluated by using Eq. (4.17) (Kumar et al., 2020).

$$\text{Annual } CO_2 \text{ mitigation} = E_o(kWh / year) \times EF_g \quad (4.17)$$

Where,  $E_o$  - Annual electrical output from the hybrid system,  $EF_g$  -  $CO_2$  emission factor from conventional energy

Net  $CO_2$  mitigation over the PV system's lifetime was estimated by using Eq. (4.18) (Kumar et al., 2020).

$$\text{Net } CO_2 \text{ mitigation} = [EF_g - LC_{CO_2}] \times \sum_{t=1}^n E_{PV}(kWh / year) \times (1 - d_r)^n \times 10^{-3} \quad (4.18)$$

And net  $CO_2$  mitigation for the biogas system was estimated using Eq. (4.19) (Kumar et al., 2020).

$$\text{Net } CO_2 \text{ mitigation} = \left[ EF_g \times \sum_{t=1}^n E_{BG}(kWh / year) \times 10^{-3} \right] - LCE_{BG} \quad (4.19)$$

Where,  $LCE_{BG}$  - lifecycle  $CO_2$  emission from biogas system

### ***Carbon credits earned***

A carbon credit is a general term for any tradable license or certificate representing the right to emit one ton of carbon dioxide or the mass of another greenhouse gas with a carbon dioxide equivalent (tCO<sub>2</sub>e) equivalent to one ton of carbon dioxide. Certified Emission Reductions (CERs) are a type of carbon credits issued by the Clean Development Mechanism (CDM) Executive Board for the reduction in emission attained by CDM projects and verified by a Department of Energy (DOE) under the rules of the Kyoto Protocol (Ahhammad et al., 2015).

It is an offset term that assigns a monetary value to the lessening of greenhouse gas emissions. In the international market, one carbon credit is earned on trading 1 ton of CO<sub>2</sub>(e). The price of carbon credits is €16.32/tCO<sub>2</sub>(e) (Kumar et al., 2020). Thus, the earned carbon credits can be estimated by using Eq. (4.20) (Kumar et al., 2020).

$$\text{Earned carbon credits (\$)} = [\text{Net CO}_2\text{mitigation (PV + Biogas)}] \times 16.32 \times 1.22 \quad (4.20)$$

## **4.3. Results and Discussion**

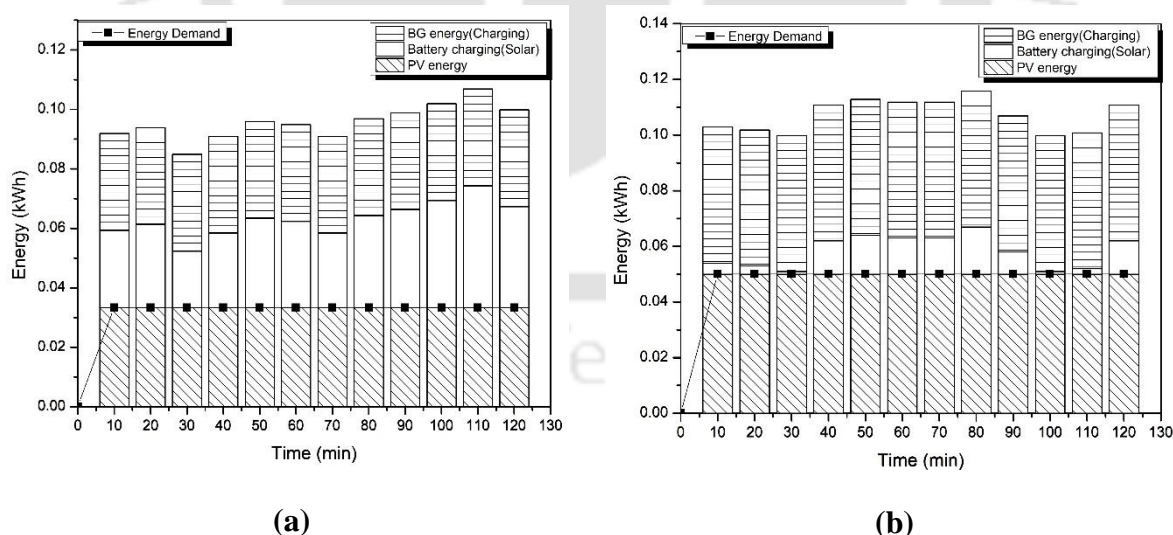
### **4.3.1. Energy share by the hybrid system at different loads**

To investigate the real-time analysis for hybridization of solar PV and biogas energy system, the hybrid system was subjected to constant load from 20% to 80% of rated PCU capacity. Load share by the individual energy systems was estimated from the energy meters and PCU panel. Due to a limit in biogas availability, the BF generator could be operated for a maximum period of 120 min. As such, the combined system's operating parameters were assessed for 120 min operation and at a 10 min interval period. For all the cases, the percentage of battery was first allowed to drain 60%. Lighting loads are then applied to the combined system to assess the energy required to supply the load and charge of battery. The run time for the hybrid system was kept constant to make a comparative assessment of the hybrid system at

different load conditions. Energy share at different load conditions are described in the succeeding subsections.

#### 4.3.2. Energy share at 20% and 30% load

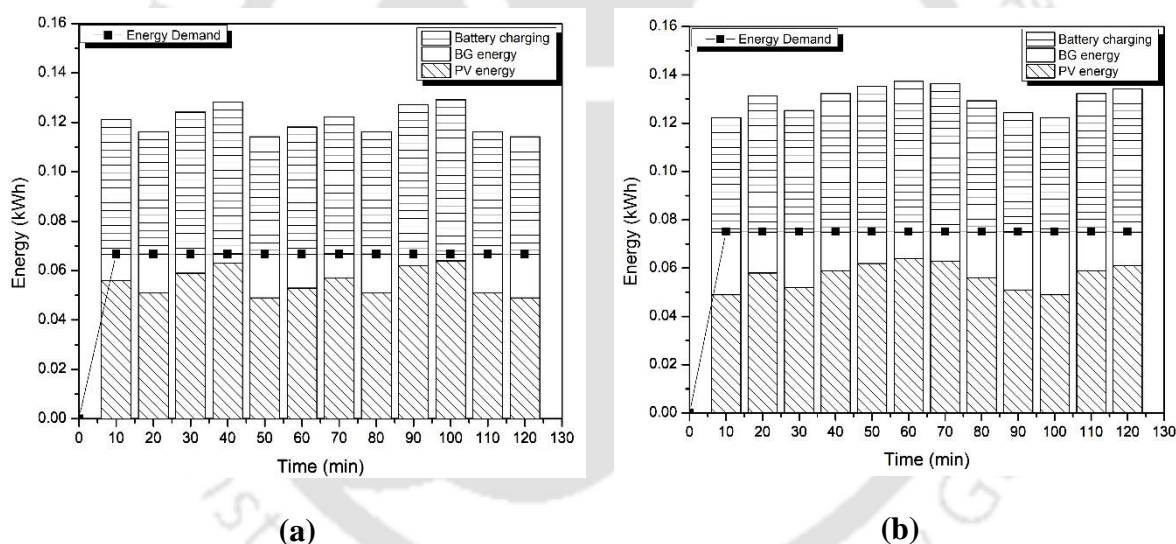
Fig. 4.3(a) and (b) show the PV system's energy share and BF generator on load application of 20% and 30%, respectively. The lower two stacks represent total PV generation during the interval, and the upper stack represents the energy from the BF generator. It was observed that the PV system could easily meet the load demand of 20% and 30%. It is very evident as PV energy generation was comparatively higher than the energy demand. The extra energy generated from the PV system was utilized for charging the battery. Moreover, for charging the battery to 100%, the additional energy required was supplied from the BF generator. The total energy supplied from the PV system was 0.753 kWh and 0.652 kWh at 20% and 30% load, respectively. And, the total energy provided from the BF generator was 0.391 kWh and 0.587 kWh, respectively. As PV energy generation was comparatively low during 30% load, energy sharing for charging of battery from the PV system was less.



**Figure 4.3.** Energy share of the hybrid system at (a) 20% and (b) 30% load.

### 4.3.3. Energy share at 40% and 45% load

Energy share by the PV system and BF generator at 40% and 45% load are shown in Fig. 4.4 (a) and (b). Here the lower stack represents the PV generation during the period, and the upper two stacks represent the energy generation from the BF generator. Total PV energy of 0.665 kWh and 0.683 kWh and total BF generator energy of 0.780 kWh and 0.880 kWh were required to supply the load of 40% and 45%, respectively, and charging of the battery. It was observed that PV energy was not sufficient for both 40% and 45% load, as PV energy generation was less in both cases. As such extra energy was utilized from the BF generator for compensating the load as well as charging of battery. The extra energy produced from the BF generator was utilized to charge the battery from 60% to 100%.

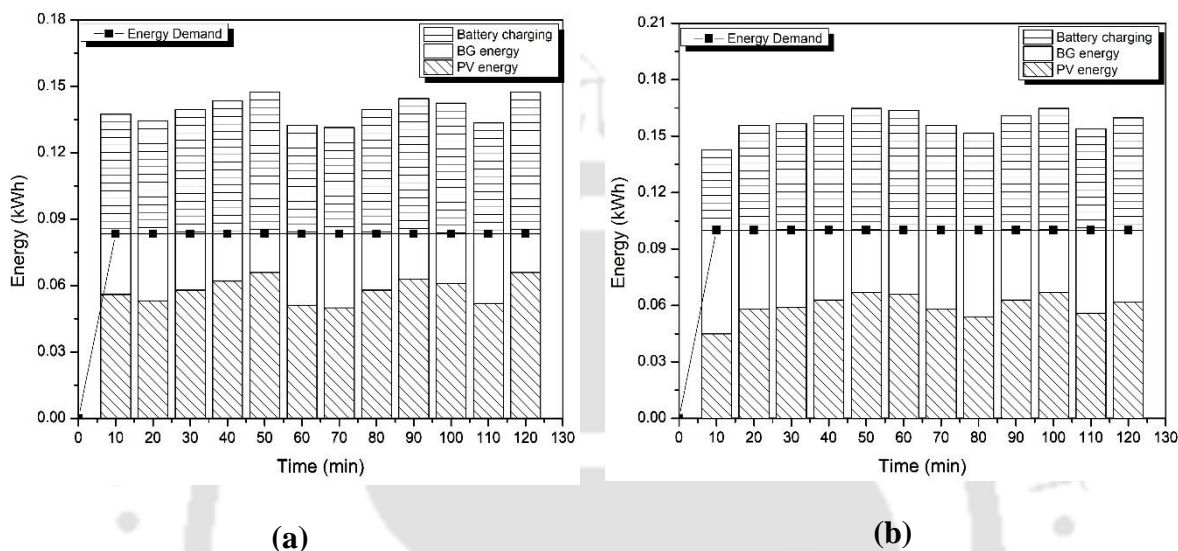


**Figure 4.4.** Energy share of the hybrid system at (a) 40% and (b) 45% load.

### 4.3.4. Energy share at 50% and 60% load

Fig. 4.5(a) and (b) show the hybrid system's sharing of load for supplying the load and charging of battery. In both the figures, the lower stack represents the PV generation, and the upper two stacks represent the energy generation from the BF generator during the experimentation period. As seen from the figures, load demand was not fully met by the PV system. As such, the extra energy required was met by the BF generator. Total PV energy

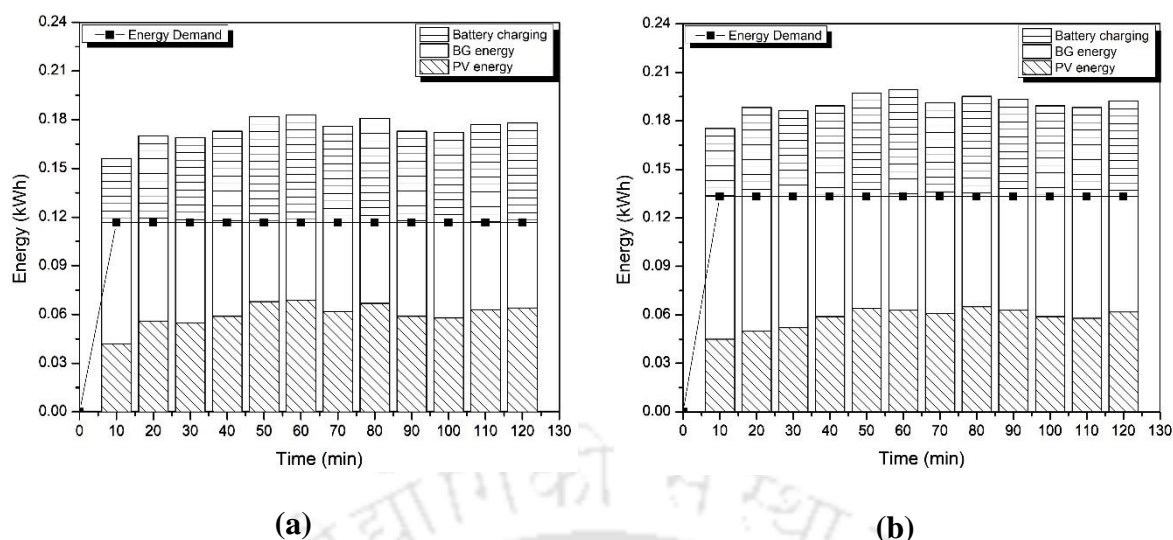
generation of 0.696 kWh and 0.718 kWh were obtained for 120 min at 50% and 60% loads, respectively. And total respective BF generator energy of 0.987 kWh and 1.173 kWh were utilized for compensating extra share of loads and charging of the battery. At 60% load, the BF generator's share of energy for load demand compensation was comparatively higher than at 50% due to an increase of load.



**Figure 4.5.** Energy share of the hybrid system at (a) 50% and (b) 60% load.

#### 4.3.5. Energy share at 70% and 80% load

The energy share of the hybrid system at load application of 70% and 80% are shown in Fig. 4.6(a) and (b). The lower stack represents the PV generation during the 120 min period. The upper two stacks represent the BF generator's energy for compensating the load and charging the battery. As PV energy generated was not sufficient for supplying the load, the energy share from the BF generator for compensating the loads was comparatively higher than the other loads. Total PV energy of 0.722 kWh and 0.701 kWh was generated during the 120 min period for 70% and 80% load, respectively. A total BF generator energy of 1.369 kWh and 1.564 kWh was required to compensate for loads and charge of battery.



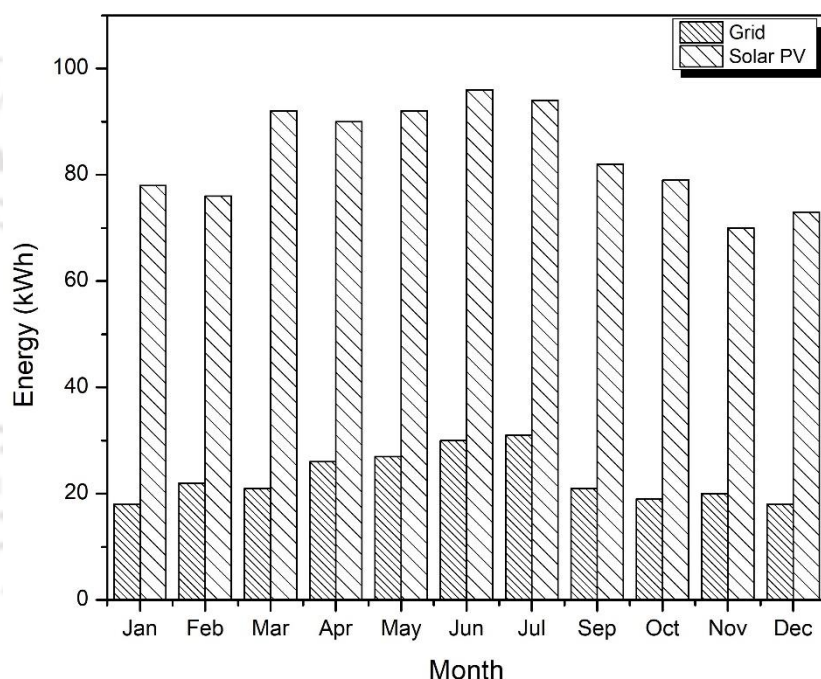
**Figure 4.6.** Energy share of the hybrid system at (a) 70% and (b) 80% load.

In all the cases, it was observed that as solar PV was set as the first priority, load demand was first met by the solar PV, and extra energy generated was utilized for charging of the battery. BF generator supplies only the extra energy that was required for supplying loads and charging of battery banks. In one of our previous studies (Buragohain et al., 2020), load application of 45% to 50% was found to be economically feasible for standalone system, and for grid-connected, PCU could be loaded to its full load capacity. Here we can see that load of 20% and 30%, BF generator energy was utilized for charging of battery only and from 40% load onwards, a part of its energy was utilized for compensation of loads. However, its share at 40% and 45% loads were comparatively less than at higher loads. With the increase of load, the combined system could efficiently operate as the BF generator could supply the extra loads. Here it could be seen that though only a part of BF generator energy was supplied to the PCU and load almost at rated PCU could be easily met by the combined system. It is seen that a combination of two or more sources provides a reliable and uninterrupted power supply.

#### 4.3.6. Energy demand analysis of the site

To analyze the annual energy demand of the location, the site's monthly energy demand analysis was estimated. Under normal conditions, the PV system was connected with the local

grid, and power was delivered from the combination of both these sources. Fig. 4.7 depicts the monthly energy demand profile analysis of the site location in which total energy demand is the summation of PV energy and energy from the local grid. It was observed that in all the months, the load requirement was mostly met by the PV system, and very few amounts were utilized from the local grid for meeting the load demand. This indicated that hybridization of the PV system with BF generator would be beneficial for supplying extra energy that was utilized from the local grid.



**Figure 4.7.** Monthly energy profile of Auniati Satra.

#### 4.3.7. Economic analysis of the standalone system

The feasibility of standalone system was investigated by simulating all input parameters in the SAM model. Overall results obtained from the model are shown in Table 4.1. Simple payback period (SPP) is the time required to recover the money invested in the project. In contrast, discounted payback period (DPP) refers to the number of years after which discounted cash inflows cover the investments made in the project during its lifetime. Components of a

PV system are relatively costly, and as such, electricity cost is high. However, with the decrease in price and increased subsidies, solar PV technology stands at par with conventional energy resources. A PV system's high capital cost has been the major hurdle to its widespread implementation of decentralized energy generation in the community level. It can be seen that the standalone PV system has a positive NPV value of \$306.45 with an LCOE of \$0.15/kWh over its project lifetime of 25 years. Also, a payback period of 16.7 years signifies the viability of the standalone PV system. The yearly load profile as shown in Fig. 4.7 was incorporated in the SAM model, and an estimated yearly saving of \$114.58 was obtained from the system. A recent study reported the techno-economic assessment of standalone solar PV systems with and without battery backup using SAM. The author reported an LCOE of 8 to 10 ¢/kWh (= 0.08 to 0.1 \$/kWh) for the fixed tracking system and 5–6 ¢/kWh (= 0.05 to 0.06 \$/kWh) for single axis and double axis tracking systems (Agyekum, 2021). Another study presented the feasibility of grid-tied solar PV systems using SAM in which an LCOE of 5.75 US cent/kWh (=0.0575 \$/kWh) was reported for a 25.4 MWp PV plant (Mukisa et al., 2019). As the PV system was only 1 kWp size, LCOE of the present system is a bit higher than the above-mentioned works of literature. Economic assessment of the proposed system is beneficial in the implementation of more decentralized PV systems in India.

**Table 4.1.** Parametrics obtained from SAM model for Standalone PV system

Sl no	Metric	Value
1	Annual energy (year 1)	1,298 kWh
2	Capacity factor (year 1)	15.20%
3	Energy yield (year 1)	1,334 kWh/kW
4	Battery roundtrip efficiency	91.05%
5	Battery charge energy from system	67.40%
6	Levelized COE (nominal)	\$0.19/kWh
7	Levelized COE (real)	\$0.15/kWh
8	Electricity bill without system (year 1)	\$139.13

9	Electricity bill with system (year 1)	\$24.55
10	Net savings with system (year 1)	\$114.58
11	Net present value	\$306.45
12	Simple payback period (SPP)	16.7 years
13	Discounted payback period (DPP)	24.6 years

#### 4.3.8. Economic analysis of the hybrid system

The capital cost of all the components of the hybrid system are shown in Table 4.2. The primary components of the PV system comprised of the module cost, battery cost and the PCU cost. Other components such as cables, junction box, circuit breakers etc. are included in the miscellaneous cost. The biogas system comprised of the costs incurred on the construction of digesters and fittings and also of the BF generator. These two costs comprise the maximum portion of the capital cost. To determine the cost-benefit analysis, a project lifetime of 25 years, and a discount rate of 4.5% was considered (Kasaeian et al., 2019; Yadav and Bajpai, 2020). From these initial values, the replacement cost of battery banks and BF generator was estimated using Eq. (10) and (11). The hybrid system's annual energy output was evaluated by addition of annual energy supplied from the PV system (from Fig. 4.7) and predicted yearly energy output from 2 hours/day operation of BF generator. This value was utilized in assessing the Annual electricity saving (AES) from the system. Considering 4 m<sup>3</sup> of biogas that could be utilized for cooking and converting it to equivalent LPG, Annual LPG saving (ALS) was estimated using Eq. (6). It can be seen that though a significant amount of the capital cost is due to the biogas system, the amount of equivalent LPG saving due to it is also higher.

Moreover, a part of biogas utilized for electricity production also adds up to the overall revenue obtained. Thus, a positive NPV value of \$1562.15 with LCOE of \$0.21/kWh as estimated using Eq. (3) and (14) signifies the project's feasibility. Also, the SPP and DPP of 6.45 years and 17 years make the hybrid system much more beneficial than the standalone system. The overall economic parameters of the hybrid system are shown in Table 4.2. In one

of the studies, the LCOE value of Rs 14.94/kWh and Rs 11.40/kWh for on-site and off-site 2.5 MW capacity solar PV was obtained (Chandel et al., 2014). In another study, investigation for hybridization of BF generator, Solar PV, diesel generators, and batteries reported COE and NPC values of \$0.28/kWh and \$612280, respectively (Das et al., 2017). A study also reported COE ranges of \$0.128 to \$0.223/kWh for optimal hybrid systems. The authors suggested an optimal economic system comprising of 150 kW biogas generator, 80.7 kW PV panels, converter, and batteries (Jahangir and Cheraghi, 2020). A techno-economic assessment of grid-connected photovoltaic thermal system with nanofluid has COE of \$0.196/kWh and a payback period of 7 – 8 years (Al-Waeli et al., 2018).

**Table 4.2.** Capital cost of system components for the Hybrid System

Sl no	Particulars (item)	Rating	Nos	Rate (\$)	Capital cost (\$)
1	Solar PV module	250 W <sub>p</sub>	4	\$194.15	\$776.60
2	Tubular Battery	150Ah	4	\$149.87	\$599.48
3	Power Conditioning unit	1000 VA	1	\$506.84	\$506.84
4	Biogas digester	4 m <sup>3</sup>	3	\$435.99	\$1307.96
5	Biogas fueled Engine	3.5 kVA	1	\$1089.97	\$1089.97
6	Miscellaneous	-	-	-	\$136.25

**Table 4.3.** Parametrics of the Hybrid System

Sl no	Metric	Value
1	$IC_t$	\$ 4417.10
2	$RC_t$	\$ 3867.32
3	$O \& M_t$	\$ 1010.14
4	$NPV_t$	\$ 1562.15
5	$CRF$	0.07
6	$LCOE$	\$0.21/kWh
7	$AES$	\$ 280.87

8	ALS	\$ 403.44
9	SPP	6.45 years
10	DPP	17 years

#### 4.3.9. Carbon reduction potential

Environmental benefits from a system play a major role in the overall sustainability of a project. PV system is environmentally friendly than other electrical energy sources (Sharma and Tiwari, 2013). Net CO<sub>2</sub> emission from the PV system was estimated to be 1.25 tCO<sub>2</sub>(e), and net mitigation was estimated to be 35.97 tCO<sub>2</sub>(e). Similarly, for the biogas system, net CO<sub>2</sub> emission of 10.11 tCO<sub>2</sub>(e) was estimated using the individual emission parameters (City of Winnipeg, 2011; Haryanto and Cahyani, 2019) and is shown in Table 5. A net overall mitigation of 68.62 tCO<sub>2</sub>(e) from the biogas system was estimated. CO<sub>2</sub> emission from the PV system is less because it emits very less during its operation. But CO<sub>2</sub> emission from biogas system is large due to CO<sub>2</sub> emission during its operation. The net CO<sub>2</sub> mitigation from the hybrid system was estimated to be 104.59 tCO<sub>2</sub>(e). And the equivalent amount of carbon credits earned was \$ 2090.31. Sharma and Tiwari (Sharma and Tiwari, 2013) obtained net CO<sub>2</sub> mitigation of 61.15 tCO<sub>2</sub>(e) and 62.44 tCO<sub>2</sub>(e) for rooftop and ground-mounted solar PV system of 2.32 kWp, respectively. Jahangir and Cheraghi (Jahangir and Cheraghi, 2020) reported saving 701,958 to 844424 kg/year of CO<sub>2</sub> for different scenarios of HRES. And the implementation of the optimal system would save money up to \$8444. In another study, annual CO<sub>2</sub> mitigation of 421.02 tCO<sub>2</sub>(e) and lifetime CO<sub>2</sub> mitigation of 9801.10 tCO<sub>2</sub>(e) was obtained from a 200 kWp on-grid solar PV system (Kumar et al., 2020). It can be seen that net CO<sub>2</sub> mitigation for the hybrid system is comparatively higher than the standalone systems, and more mitigation is observed in case of Biogas systems.

**Table 4.5.** CO<sub>2</sub> emission calculation of biogas system

Sl. No.	Item	Materials Required	Rate	Total	CO <sub>2</sub> emission rate (value)	CO <sub>2</sub> emission rate (unit)	Total CO <sub>2</sub> emission (kg)
1	Cement	60 bags	50	3000	0.89	kg/kg	2670
2	Chicken mesh (G.I. mesh)	45 m <sup>2</sup> /bundle	9	405	1.91	kg	386.78
3	4 mm MS rod	60 kg	3	180	1.91	kg	343.80
4	6 mm MS rod	6 kg	3	18	1.91	kg	34.38
5	Binding wire	7 kg	3	21	1.91	kg	40.11
6	Sand	4 m <sup>3</sup>	1	4 m <sup>3</sup>	0.01	kg	61.17
7	Stone chips (Jelly)	1.41 m <sup>3</sup>	3	4.23	263	m <sup>3</sup>	1112.49
8	A.C. Pipe 15 cm diameter (feet)	2.743 m	3	8.229 m	2.22		□
9	G.I.pipe 0.0127 m	0.203 m	3	0.609 m	1.91	kg	□
10	Gate Valve	3					□
11	Brass Nipple	3					□
12	Bend pipe	3					□
13	Paint(lit)	7.5					□
14	Biogas Stove	1					□
Total CO <sub>2</sub> emission from components							4648.72
15	Biogas Burning	4 m <sup>3</sup> / day		36500 m <sup>3</sup>	0.12	m <sup>3</sup>	4380
16	Biogas Electricity			54293.75 kWh	.02	kWh	1085.88
Lifetime CO <sub>2</sub> emission							10114.6

#### 4.4. Conclusion and Summary

In the present study, the hybridization of solar PV with biogas was investigated to assess the impact of constant load. This work aims to investigate the actual on-field data of load shared by the individual systems in hybrid mode. For evaluating the feasibility and sustainability of the project, economic and environmental analysis of the combined system was investigated. The popular economic SAM model was also incorporated to compare the hybrid system's financial analysis with standalone system. The primary outcomes obtained from the study are presented below:

- ❖ At the load of 20% and 30%, PV energy share was sufficient for the load supply. At 40% and 45% load, the BF generator energy share was less. Whereas, at higher loads, the BF generator's energy share was comparatively higher than the PV system. It was observed that the hybridization of the two systems provides a reliable and uninterrupted power supply.
- ❖ The mathematical analysis revealed a simple payback period (SPP) and discounted payback period (DPP) of 6.45 years and 17 years, respectively, for the hybrid system. SAM model revealed SPP and DPP of 16.7 years and 24.6 years for standalone system. Positive NPV for both standalone and hybrid systems displayed the viability of the project. SAM model revealed an LCOE value of \$0.15/kWh for the standalone system, whereas, for the hybrid system, the mathematical analysis revealed an LCOE value of \$0.21/kWh.
- ❖ Net CO<sub>2</sub> mitigation of 35.97 tCO<sub>2</sub>(e) and 68.62 tCO<sub>2</sub>(e) was estimated from the PV system and biogas system, respectively, making it 104.59 tCO<sub>2</sub>(e) for the combined system and carbon credit value of \$2090.31.

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# Chapter 5

## Overview and Suggestions for future Work

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### 5.1. Overview

The present thesis has focused on the utilization of locally available resources for biogas generation and integration of the biogas system with solar photovoltaic system for electricity production. An attempt has been made in this thesis for emphasizing on the practical implementation of renewable sources at community level and decentralized electricity production by adopting renewable technology. Though various studies have been made on feasibility of renewable energy technology in other parts of India, its potential in North-Eastern part of India has not been explored much. Moreover, on site assessment of hybridization of two or more renewable energy technologies has been less explored in North-East India. Thus, investigation of bioenergy production using locally available resources and hybridization of bioenergy with solar energy for decentralized production of electricity was investigated in this study. The primary focus of this study was optimization of locally available biomass resources for biogas production. Another aspect of this study was investigation of a 1 kW solar photovoltaic system at different load conditions corresponding to the environmental conditions of Guwahati, Assam (India). The study was further extended for assessing the feasibility of hybridization of bioenergy production and solar photovoltaic system at similar load conditions as in standalone system. A summary of the various chapters in the thesis are presented below:

- ❖ Chapter 1 presents a general introduction on the outline of thesis. A brief description on the Anaerobic digestion process, its operating parameters and previously conducted research works have been presented in this chapter. Various studies performed on

anaerobic digestion and special emphasis on anaerobic mono and co-digestion of duckweed, rice straw and switch grass (Lignocellulosic material that were part of this investigation) have been discussed. Literature review focusing on standalone solar PV system, Grid-connected Solar PV system and Hybrid renewable energy systems has also been discussed.

- ❖ Chapter 2 presents the investigation of biogas production from mono- and co-digestion of three lignocellulosic feedstock viz. duckweed, switchgrass, and rice straw at different TS concentrations. BMP tests revealed highest biogas production at TS concentration of 15% with 1:1 CD:FS ratio. Co-digestion of rice straw exhibited maximum biogas production both in BMP tests and community-size biogas digesters. Under similar operating conditions, mono-digestion of cattle dung showed better performance in the large-scale operation than the co-digestion experiments. Though biogas production from co-digestion of lignocellulosic feedstock is slightly lower than mono-digestion of cattle dung, its utilization can be adopted at community level for proper management and disposal of lignocellulosic material. The results depict an overall comparative analysis of biogas production on both laboratory scale and community level. A similar attempt can be adopted in other developing nations where communities with small dairy farms and ample biomass availability can go for decentralized renewable energy generation.
- ❖ Chapter 3 presents the investigation on feasibility of implementing a 1 kWp solar PV system both in standalone and grid-connected mode for decentralized electricity production corresponding to weather conditions of Guwahati, Assam (India). Load applications in standalone mode revealed that the PV system could be subjected to 70% load of its rated capacity during the daytime in a normal sunny day, however it can be efficiently operated for maximum time period if it is loaded to 45% – 50% rated capacity. Whereas in grid connected mode, the PV system can be subjected to almost its full load

capacity. A good insight into the operating procedure as well as maximum load application of a PV system in both standalone and grid-connected mode has been presented in this chapter.

- ❖ Chapter 4 addresses the techno-economic analysis of on-site application of integrating a 1 kWp solar PV system with a biogas fueled (BF) generator system. Hybridization of both solar PV and BF generator system revealed reliable and uninterrupted power supply. At lower loads, PV energy was sufficient whereas at higher loads, maximum energy required was compensated from BF generator system. Mathematical analysis and SAM analysis revealed a positive NPV for both standalone system and hybrid system reflecting viability of the project. Environmental analysis revealed a net CO<sub>2</sub> mitigation of 35.97 tCO<sub>2</sub>(e) and 68.62 tCO<sub>2</sub>(e) for the PV system and biogas system, respectively, making it 104.59 tCO<sub>2</sub>(e) for the combined system and carbon credit value of \$2090.31.

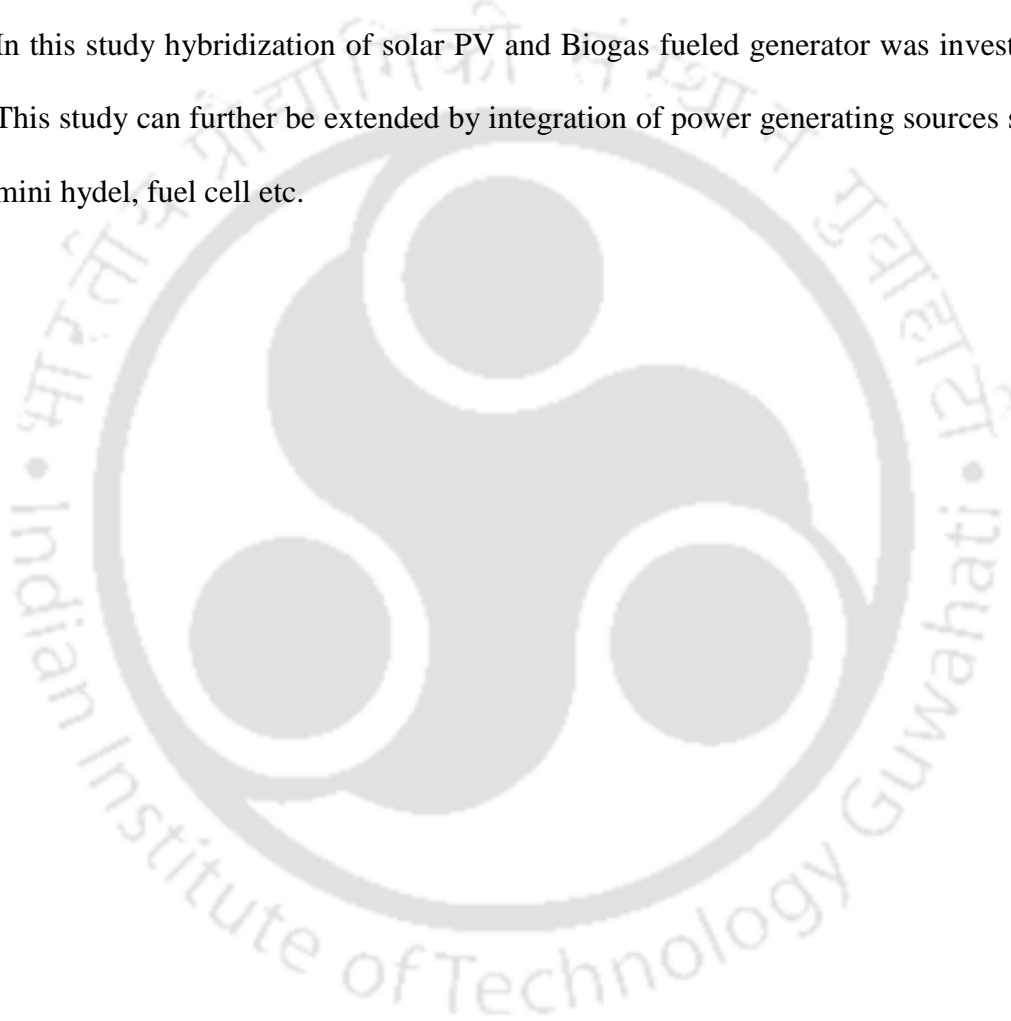
## 5.2. Suggestions for Future work

The present thesis has highlighted the actual on-site operating parameters for biogas production from locally available lignocellulosic biomass resources. The present thesis has given a clear picture on the actual loading capacity of a 1 kWp Solar PV system corresponding to the environmental conditions of Guwahati, Assam (India). This study can further be extended and some suggestions in this regard are as follows:

1. The study on anaerobic digestion can be further extended by using other biomass such as water hyacinth, vegetable and fruit wastes from local markets etc.
2. The study on co-digestion of two or biomass sources with cattle dung have not been investigated in this study. Different combination of these biomass can be investigated for biogas production.
3. In the present study raw biogas was utilized as fuel for operation of the generator. However raw biogas contains hydrogen sulphide, carbon dioxide and water that are

corrosive in nature and might damage the engine parts. As such investigation on purification of biogas could be another aspect that can further be investigated.

4. In the present study solar PV was investigated corresponding to the environmental conditions in Guwahati, Assam (India). This can be extended to different parts of North-East India and a comparative analysis of the load applications can be investigated.
5. Power output for different ratings of Solar PV can also be extended.
6. In this study hybridization of solar PV and Biogas fueled generator was investigated. This study can further be extended by integration of power generating sources such as mini hydel, fuel cell etc.



## List of Publications

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### Journal:

1. Buragohain, S., Mahanta, P. and Mohanty, K., 2021. Biogas production from anaerobic mono-and co-digestion of lignocellulosic feedstock: Process optimization and its implementation at community level. **Environmental Technology & Innovation**, 24, p.101981.
2. Buragohain, S., Mohanty, K. and Mahanta, P., 2021. Hybridization of solar photovoltaic and biogas system: Experimental, economic and environmental analysis. **Sustainable Energy Technologies and Assessments**, 45, p.101050.
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### Conference Presentations:

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Contents lists available at ScienceDirect

Environmental Technology &amp; Innovation

journal homepage: [www.elsevier.com/locate/eti](http://www.elsevier.com/locate/eti)

## Biogas production from anaerobic mono- and co-digestion of lignocellulosic feedstock: Process optimization and its implementation at community level

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### ARTICLE INFO

#### Article history:

Received 21 June 2021

Received in revised form 14 September 2021

Accepted 18 September 2021

Available online 23 September 2021

#### Keywords:

Anaerobic digestion

Biogas

Co-digestion

Community digesters

Lignocellulosic biomass

### ABSTRACT

Anaerobic digestion of lignocellulosic biomass has gained attention in recent years due to its increase availability and productivity. In this study, anaerobic mono- and co-digestion of three lignocellulosic biomass, viz. duckweed, switchgrass, and rice straw, were performed in 1 litre laboratory-scale batch reactors. The initial biochemical methane potential (BMP) test was performed at three different total solids concentrations (10%, 15%, 20%) and cattle dung; feedstock ratios (1:1, 1:1.5, 1:2) under mesophilic conditions (28–32 °C) for 36 days. Co-digestion of feedstocks at 1:1 ratio yielded better results than other cattle dung; feedstock ratios. Optimized physical parameters were further implemented for a scale-up co-digestion study of biogas potential from 4 m<sup>3</sup> community-size biogas digesters. The investigation was performed for 60 days maintaining a hydraulic retention time (HRT) of 40 days, and a comparative analysis with mono digestion of cattle dung was also analyzed. Average daily biogas production for digester containing rice straw and cattle dung was 0.36 m<sup>3</sup>/kg-VS, whereas it was 0.34 m<sup>3</sup>/kg-VS and 0.32 m<sup>3</sup>/kg-VS for switchgrass and duckweed, respectively. An overall comparative analysis of the biogas production and its composition for both BMP tests and continuous processes are discussed in this work.

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### 1. Introduction

Anaerobic digestion is the methodology of decomposing organic substrates in the absence of oxygen and is a well-proven technology for biogas production. It primarily comprises of four steps viz hydrolysis, acidogenesis, acetogenesis, and methanogenesis (Ramaraj and Unpaprom, 2016; Ramaraj et al., 2015). In India, various studies had been carried out for biogas production from different biomass resources. The biomass availability in tropical and sub-tropical regions is comparatively higher than in other regions of the world. India falls under both tropical and sub-tropical climate zone. Most of the tropical countries like Africa, Kenya, Sri Lanka, Papua New Guinea, etc., and many parts of Asia are enriched with abundant biomass resources. These countries are either underdeveloped or still in the developing stage, and the utilization of biomass resources has not been extensively studied. The technology development in these countries and the implementation of renewable energy projects are still under developing stage. Considering these factors, a low-cost,

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Contents lists available at ScienceDirect

## Sustainable Energy Technologies and Assessments

journal homepage: [www.elsevier.com/locate/seta](http://www.elsevier.com/locate/seta)

Original article

## Experimental investigations of a 1 kW solar photovoltaic plant in standalone and grid mode at different loading conditions

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## ARTICLE INFO

## Keywords:

Solar Photovoltaic (PV)  
Standalone  
Grid  
Solar insolation

## ABSTRACT

Decentralized energy generation at community level is the need of the hour for meeting the increasing load demands. A pilot-scale 1 kW photovoltaic (PV) system was installed at Aunlati Satra near IIT Guwahati for studying the effects of its operating parameters at different loading conditions corresponding to the environmental conditions prevalent in Guwahati, Assam (India). The PV system was subjected to constant electrical load both in standalone mode and grid-connected mode during the daytime at eight different loading conditions viz. 20%, 30%, 40%, 45%, 50%, 60%, 70% and 80% and half-hourly data of different parameters like solar insolation, PV energy, PV charge, temperature, and battery capacity were analysed. Optimum loading condition in standalone mode was found to be at 45% – 50% load under normal solar insolation without much burden on the battery bank and can be extended to a maximum load of 70% during the daytime at high solar insolation. In grid-connected mode, load application upto 45% was economically beneficial as less power was utilized from local grid. Though it can be subjected to almost its full rated capacity with input from the ac supply.

## Introduction

Around 1.3 billion of the global population reside in remote areas where administration often cannot provide basic energy facilities [1]. Thus, off-grid power systems are often the only way to meet the energy needs of population residing in such places. Many remote systems, such as radio telecommunication stations and repeater tower stations, are entirely dependent on off-grid power systems [2]. The rapid depletion of fossil fuels worldwide has also made it necessary to reduce dependency on these non-renewable energy resources. One way of accomplishing this is to exploit the enormous potential of renewable energy sources to meet continually increasing demands for energy [3,4]. However, the periodic nature of renewable energy sources is the main issue hindering their rapid implementation. After the outbreak of the world energy crisis in 1973, the world shifted its approach from fossil fuel reliant towards renewable energy generation. Solar energy has been the backbone of almost all the tropical and sub-tropical countries. There has been a constant increase in R&D activities in the field of solar. India too, has invested billions of dollars in the field of solar to mitigate climate change [5]. India lies in the sunny belt of the northern hemisphere between the tropic of cancer and the equator, and various parts

of India are exposed to sunlight all round the year. Solar energy sector is likely to play a key role in decarbonizing India's electricity sector. In order to support the solar energy sector, the Government of India (GOI) has implemented various numbers of policies. Considering the North-Eastern (NE) part of India, only 53% of the rural population has access to electricity and in Assam, only 37% population has access to electricity. It is mainly due to improper infrastructure, road connectivity, and varying weather conditions. GOI has also implemented various schemes for implementing solar energy projects in northeast India [6]. Harnessing solar power is dependent on numerous factors, such as irradiation of the location, amount of daylight hours, and meteorological conditions, such as wind speed, temperature, rainfall or precipitation, humidity, cloudiness, etc. The NE region of India lies in the proximity of the Tropic of Cancer making it a good location for usage of solar energy [7].

Various studies have been carried out to determine the feasibility, viability, financial indicators, and risk factors involved in the implementation of PV electrification systems [8–10]. Ajao et al., 2009 in his work examined the feasibility of a PV system for a location in Nigeria and recommended off-grid PV systems as a viable option for rural communities for the economic development of the society [11].

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<https://doi.org/10.1016/j.seta.2020.100796>

Received 21 April 2020; Received in revised form 19 June 2020; Accepted 24 July 2020  
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Contents lists available at ScienceDirect

## Sustainable Energy Technologies and Assessments

journal homepage: [www.elsevier.com/locate/seta](http://www.elsevier.com/locate/seta)

Original article

## Hybridization of solar photovoltaic and biogas system: Experimental, economic and environmental analysis

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## ARTICLE INFO

**Keywords:**  
Biogas  
Solar PV  
Hybridization  
SAM

## ABSTRACT

The coupling of renewable energy systems has proven to be advantageous in achieving sustainable and reliable energy generation. In this study, the techno-economic and environmental assessment of a hybrid 1 kW solar photovoltaic (PV) plant (having battery backup) and a 3.5 kVA biogas fueled (BF) generator was investigated. The hybrid system was subjected to constant load conditions from 20% to 80% of the rated power conditioning unit (PCU), and energy shared by the combined systems was investigated. At lower loads, the photovoltaic system was sufficient to meet the demand. Whereas at higher loads, energy share from the biogas system was required for meeting the load demand. Economic analysis over a project lifetime of 25 years revealed a high positive net present value of \$1562.15 with a Levelized cost of the energy value of \$0.21/kWh for the hybrid system. A comparative financial analysis for the standalone solar photovoltaic system was also performed using the system advisor model (SAM). System advisor model analysis resulted in a positive net present value of \$306.45 and a Levelized cost of the energy value of \$0.15/kWh. The environmental analysis revealed net CO<sub>2</sub> mitigation of 104.59 Tons, equivalent to an earned carbon credit of \$2090.31 from the hybrid system.

## Introduction

Prior to the Covid-19 pandemic, global energy demand was intensifying at an alarming rate and was expected to grow 12% between the years 2019 and 2030. But due to the pandemic, it is expected to grow between 4 and 9%. It has been projected that by 2030, 80% of the global electricity demand would be met by renewables [1]. India's energy demand is also rising and had a deployment of 84 GW grid-connected renewable electricity capacity by December 2019. India has set a target of achieving 175 GW renewables by 2022 [2]. Though the share of renewable energy sources has increased, full dependence on it has not been fully achieved due to various seasonal and environmental variations. As such, the hybridization of two or more renewable energy sources has gained attention for reliable and uninterrupted power supply [3]. Solar PV and biogas have been considered the most favorable and feasible technological solutions compared to other renewable sources [4]. Because of its complementary nature in some locations, both systems' integration provides a reliable power supply. However, they encounter many problems during operation due to the high capital

cost of PV and the production of pollutants from biogas plants [5,6]. Electricity production from conventional sources accounts for 54% of greenhouse gases (GHG). Thus, renewables' adoption reduces dependency on fossil fuels and helps in mitigating overall GHG emissions [7].

## Background study

Various studies investigated and reported the techno-economic feasibility of PV/Hybrid systems [8–10]. A payback period of 18.37 years and 18.93 years with net CO<sub>2</sub> mitigation of 27.09 tCO<sub>2</sub>(e) and 25.80 tCO<sub>2</sub>(e) was obtained from a 2.32 kWp rooftop and ground-mounted standalone solar PV system [11]. Proper sizing of the biogas section in the hybridization of solar PV and biogas resulted in improved plant capacity factor and efficiency [12]. Rahman et al. (2014) reported the feasibility of implementing biogas and solar PV hybrid system for households having 3–6 cattle [13]. Mudgal et al. (2019) reported NPC and COE values of \$117,095 and \$0.09/kWh, respectively, for a system configuration of 12 kW photovoltaics, 3 kW wind turbine, and 15 kW biogas generator [14]. For hybridization of photovoltaics, biomass, and

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<https://doi.org/10.1016/j.seta.2021.101050>

Received 7 November 2020; Received in revised form 26 January 2021; Accepted 28 January 2021

Available online 28 February 2021

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