

**DEVELOPMENT OF A MODEL FOR INTEGRATED ANAEROBIC DIGESTION,  
SOLAR AND WIND ENERGY SYSTEM FOR RURAL SEMI-ARID AREAS**

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**A THESIS SUBMITTED IN FULFILLMENT OF THE REQUIREMENTS FOR  
THE DEGREE OF DOCTOR OF PHILOSOPHY OF SOKOINE UNIVERSITY OF  
AGRICULTURE; MOROGORO, TANZANIA**

**2021**

## EXTENDED ABSTRACT

The availability of sufficient energy and its efficient use is a primary factor in improving and sustaining the economic and technological development of any community. However, there are several challenges related to access to sustainable energy in the countries of Sub-Saharan Africa (SSA). Inadequate access and connectivity to affordable, sufficient, and clean energy for off-grid rural communities remain a major limiting factor for development. For instance, only 15% of rural communities in SSA have access to electrical energy, which indicates the severity of the problem. SSA countries have initiated efforts to address the challenge. For instance, Tanzania has progressed by increasing access to energy for the rural population from 49.3% to 69.8% from 2016/2017 to 2019/2020. However, the challenge is still far from being addressed; therefore, more efforts are required to address them. Efficient exploitation of renewable energy resources and sources (RERS), which are readily available in most rural communities of SSA, would be ideal for reducing the challenge of limited energy access and connectivity. However, the RERS have not been adequately utilised in rural communities. The major challenge for insufficient use of RERS in rural communities is the high cost and inefficiency of available RESRS technologies. The technology must be affordable and efficient while it generates clean energy from the use of RERS.

Different countries have taken several initiatives to curb the challenge of insufficient use of RERS in SSA. For instance, in Tanzania, a continuous fed fixed dome biogas technology of 4-6 m<sup>3</sup> digester capacity was introduced in rural semi-arid areas of Dodoma under the subsidy scheme. However, the technology had limited adoption because the system was too expensive for low-income communities; also, the system had technical and operational constraints. One of the constraints included difficulties in troubleshooting

faults in the digester system since the digesters were installed underground to reduce their temperature variation. Another constraint was scarce water in the area since a large quantity of water was required to run such systems. Therefore, further research for alternative affordable and efficient renewable energy systems as part of the efforts to reduce energy scarcity was necessary.

Consequently, this study sought to develop a novel integrated anaerobic digestion, solar, and wind energy system, simply the i-SWEAD system. The system generates energy for households in rural semi-arid areas. The system's affordability and efficiency were essential targets to be met. The study was conducted in the Idifu village of Dodoma, Tanzania, as a representative of the semi-arid areas of SSA. Four specific objectives were set and executed to achieve the study aim. These specific objectives were to (i) characterise the available renewable energy-related resources and variation in ambient temperature, (ii) design and test the functionality of the i-SWEAD system, (iii) model the biogas production of the i-SWEAD system, and (iv) conduct a techno-economic appraisal of the i-SWEAD system.

Characterisation of the available renewable energy-related resources and the ambient temperature was done in the following manner. Firstly, the cow dung samples were collected from the study site and analysed in the laboratory to determine their chemical and compositional properties using proximate and ultimate biomass analysis methods. Secondly, solar irradiance, wind speed, wind direction, and ambient temperature were measured using a weather station installed at the study site. It was found that the available cow dung contained essential qualities (volatile matter of  $744.3 \pm 53.2$  g/kg of dry matter and a Carbon Nitrogen ratio of 19.3) for biogas generation. Also, the amount of solar energy (solar insolation of above 4.5 kWh/m<sup>2</sup>/day for seven months in a year) and wind

energy (average annual wind speed of 4.69 m/s at 4 m hub height with predominant wind direction from North East) were adequate. However, the ambient temperature variation was  $\pm 4.04^{\circ}\text{C}$  within a day, which poses a challenge for adopting a biogas generating unit installed on or above the ground without heat insulation features. Therefore, the design of the i-SWEAD system must consider the limitation in temperature variations.

As a result, the i-SWEAD system was designed to meet the functional requirement of producing biogas and electricity. An anaerobic digestion system was designed and resulted in an Adapted Batch-Fed Anaerobic Digestion (ABFAD) system to curb limitation in biogas clogging; then, the ABFAD system was integrated as a sub-system of the i-SWEAD system. The ABFAD system was tested separately to check if it adequately addressed the challenges of biogas clogging; also to establish its functional curves useful for the system operating status indication. The results revealed that the system had addressed those challenges and some other conventional biogas generation systems' challenges. The data collected for pressure, pH, and dissolved oxygen during the testing of the ABFAD system were useful in developing their functional characteristic curves.

Similarly, the i-SWEAD system was tested for its functionality. The results showed that the system had an average biogas yield of  $0.077 \text{ m}^3/\text{kg}$  of fresh cow dung ( $0.343 \text{ m}^3/\text{kg}$  of cow dung dry matter) and methane content of  $48.57 \pm 2.15\%$ . Also, it had a biogas production rate of  $0.54 \text{ m}^3/\text{m}^3$  of digester in a day. The i-SWEAD system kept its digester temperature variation within  $1.28^{\circ}\text{C}/\text{day}$ , which is tolerable to biogas microbes. Despite the adequate performance of the i-SWEAD system, further analysis would make it robust for adoption and upscaling. In that sense, modelling biogas production of the i-SWEAD system becomes the core of its success in reaching a broad community.

An Artificial Neural Network (ANN) modelling technique was used to model the biogas production of the i-SWEAD system. The method was chosen because of its robustness, and since the anaerobic digestion processes are non-linear, the ANN modelling technique fits well. The ANN technique was used to generate six predictive models for the i-SWEAD system. The models were evaluated to choose the best model, which can adequately predict biogas production in the i-SWEAD system. The data used for training the model and testing its performance were solar irradiance, wind speed, ambient temperature, digester temperature, hydraulic retention time, and biogas volume. Data were separated into two sets to train the model (75% of the data) and test the model (25% of the data) using a random method. The model predictive power was evaluated using the Absolute Model Predictive Accuracy (AMPA). It was found that the chosen model among the six predictive models generated, i.e., Model4, was robust with the AMPA value of 99% for the i-SWEAD system. Therefore, the model gave the required predictive accuracy in this study, implying that it can be adopted in decision making. Thus, the ANN technique proved to be useful in building an appropriate model for the i-SWEAD system's biogas generation prediction. Both the technique and the model are recommended for utilization.

Furthermore, it was necessary to conduct the techno-economic appraisal of the i-SWEAD system to check if the system was efficient and affordable for the low-income communities in semi-arid areas. Comparison was made to the ABFAD-solar system to check if the i-SWEAD system was more efficient and affordable. The total energy generated per year was quantified for both systems. It was found that the i-SWEAD system produced higher energy (267 kWh/year) than the ABFAD-solar system (239 kWh/year). The i-SWEAD and ABFAD-solar systems had the same digester size (0.24 m<sup>3</sup>), same solar PV module rating (20 Wp), while the i-SWEAD system had an additional wind

turbine with the power rating of 54 Wp. The i-SWEAD system's capital investment was TZS 1 136 000.00 or €<sub>2017</sub> 494.00, while the capital investment of the ABFAD-solar system was TZS 971 240.00 or €<sub>2017</sub> 422.00 meaning that the latter is cheaper. However, the Internal Rate of Return (IRR) analysis shows that the i-SWEAD system had an IRR value of 16.6%, while that of the ABFAD-solar system was 10.4%. Therefore, the i-SWEAD system was found to be more economical than the ABFAD-solar systems. The costs of both i-SWEAD and ABFAD-solar systems are within the affordable range based on the National Bureau of Statistics (NBS) of Tanzania. However, given the advantage of the total energy production and value of IRR, the i-SWEAD system can be considered a better option.

The system is technically and economically justifiable as an efficiently feasible and affordably viable project useful for contributing to energy accessibility, based on its detailed techno-economic assessment results. Therefore, the system is novel, adequate, and worthy of being promoted for adoption and upscaling after training users on how to operate and test it in low-income communities of SSA's rural semi-arid areas.

**DECLARATION**

I, **Yusto Mugisha Yustas**, do at this moment declare to the Senate of the Sokoine University of Agriculture that this thesis is my original work done within the period of registration and that it has neither been submitted nor being concurrently submitted in any other Institution.

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(PhD Candidate)

\_\_\_\_\_  
Date

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\_\_\_\_\_  
Date

\_\_\_\_\_  
Prof. S. D. Tumbo  
(Supervisor)

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Date

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## ACKNOWLEDGEMENTS

Almighty God, thank you!

The support and assistance of many people contributed immensely to accomplish this study. I would candidly like to convey my appreciation to the following people involved in this study in one way or another.

Eng. Prof. V. C. K. Silayo and Prof. S. D. Tumbo, my supervisors of the Department of Engineering Sciences and Technology, Sokoine University of Agriculture (SUA), supervised me throughout the study. Their tireless efforts to guide, encourage, and mentor me made working with them a source of relief and strength in acquiring new knowledge and broadening my vision on handling research issues as a PhD student. I am very grateful for their limitless responsiveness.

I am incredibly indebted to Trans SEC Project – *‘Innovating Strategies to Safeguard Food Security Using Technology Transfer: A People-centred Approach’* for financial support, which fully enhanced this study in monetary terms. Heartfelt gratitude to project coordinators Prof. Khamaldin Mutabazi of the School of Agricultural Economics and Business Studies, SUA, Dr Stefan Sieber and Dr Frieder Graef of the Centre of Agricultural and Landscape Research (ZALF), Müncheberg, Germany, for their support. I am very thankful to Dr Klaus Meissner, Dr Hans Oechsner and Prof. Joachim Müller of the University of Hohenheim (UoH) for introducing to me the state of the art technologies on renewable energy and agricultural mechanisation during my studentship at the UoH. Dr Goetz Uckert and Dr Hannes Koenig of ZALF are on this list for encouraging me to accomplish this study. Also, I thank SUA Management for offering me a study leave, which was vital for this study, and bear with me when I needed their support.

My cordial thanks go to Ms Damalis Mgube, a Trans-SEC project beneficiary living in the Chinyika sub-village of Idifu, for her unconditional support of this study. She offered her residency and a piece of land for hosting activities related to this study. I am grateful to the administration of Idifu village in Chamwino, Dodoma, Tanzania, for offering a peaceful atmosphere to work in their village. The Agricultural Research Institute staff at Hombolo, Mr Leon Mrosso, Mr Elirehema Swai, Ms Devotha Mchau, and Mr Fadhili Mbagu, were accommodating in coordinating with the administration of the Idifu village on key logistical issues during my study.

My gratitude goes to all my fellow students funded by the Trans-SEC project. Thank you for your supportive contribution and friendship. I am deeply indebted to Dr Hadija Mbwana, Dr Jacob Kaingo and Dr Edmund Mutayoba for sparing their precious time to proofread the manuscripts related to this study.

I also wish to extend my sincere appreciation to all the Department of Engineering Sciences and Technology (DEST) staff members at SUA for shaping critical issues regarding this study. I want to mention Mr Robert N. Msafiri for his colossal support during handling workshop issues early and late to set up experiments for this study. Additionally, I am thankful to Dr Proches Msigula, Mr Denis Olgen and Eng. Dr Festo Richard, who introduced to me deep learning modelling issues, assisted in setting instrumentation and measuring systems, and installing a weather station in Idifu, respectively. Again, I thank Eng. Dr Festo, for introducing to me the state of art skills of outstandingly and quickly organising research's ideas. Also, I thank Prof Geoffrey Mrema for his assistance to impart me the skills of advanced English language writing for research matters.

All staff members of the Soil Water Management Research Programme at DEST, SUA are also acknowledged for their support, encouragement and handling of administrative matters. For laboratory work related to this study, it is essential to mention the tireless effort made by both Animal Science and Soil Science Laboratory teams at SUA. All other researchers whose publications were reviewed have been acknowledged by listing them under the reference sections.

In a unique, candid and memorable way, my heartfelt thanks are due to my wife Monica, my daughters Imelda alias Kankiza and Klezensia alias Kokutensa, my son Adom alias Kamuwamaka, my mum Imelda Kutensa, my aunt Anna Mulokozi Choggo. Others are my younger sister Alifredina Felix, young brothers Mulokozi Felix and Merixedec Paulo, my brother in law Saimon Ndaki Mathew as well as my elder brother Mbaissa Yustas Mulokozi. Also, my cousin and cousin in law, Mr & Mrs Stanley Kahwegere are very well appreciated. They all gave me their genuine support for the whole period of this study.

Almighty God, bless you all.

## **DEDICATION**

In loving memories of my late father Athanael Yustas Mulokozi, the late Mzee Felix Maruka Barongo, my late uncle Yafesi Bayona, and my late grandfather Festo Ndwemeile Bayona.

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Yustas, Y. M., Silayo, V. C. K., and Tumbo, S. D. (2018). Characterisation of Cow Dung, Weather factors for Developing the Integrating Renewable Energy System. *(To be submitted to the Journal of Renewable Energy)*.

Yustas, Y. M., Silayo, V. C. K., and Tumbo, S. D. (2018). Adaptation of Anaerobic Digester for Effective Degradation of Cow Dung for Clean Energy in Rural Semi-Arid Areas. *(To be submitted to the Journal of Bioresource Technology)*.

Yustas, Y. M., Silayo, V. C. K., and Tumbo, S. D. (2019). Designing of an Integrated Solar, Wind Energy and Anaerobic Digestion (i-SWEAD) System for Energy in Rural Semi-Arid Areas. *(To be submitted to the Journal of Renewable Energy)*.

Yustas, Y. M., Silayo, V. C. K., and Tumbo, S. D. (2019). Artificial Neural Network (ANN) model for Integrated Solar and Wind Energy with Anaerobic Digestion (i-SWEAD) System biogas production prediction. *(To be submitted to the Journal of Resources, Conservation and Recycling)*.

Yustas, Y. M., Silayo, V. C. K., and Tumbo, S. D. (2019). Techno-Economic Appraising of Integrated Solar and Wind Energy with Anaerobic Digestion (i-SWEAD) System for Energy in Rural Semi-Arid Areas *(To be submitted to the Journal of Applied Energy)*.

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**LIST OF ABBREVIATIONS AND ACRONYMS**

AAT	Ambient air temperature
ABC	Stands for initials of analysis of a range of items that have different levels of significance. It has no long form.
ABFAD	Adapted batch fed anaerobic digestion
AD	Anaerobic digestion
ADS	Anaerobic digestion system
AHP	Analytical hierarchy process
AMPA	Absolute model predictive accuracy
ANN	Artificial neural network
ANNs	Artificial neural networks
BMBF	German Federal Ministry of Education and Research
BMZ	Germany Federal Ministry for Economic Cooperation and Development
BPNN	Back-propagation neural network
BV3hr	Biogas volume collected in three hour
C/N	Carbon Nitrogen ratio
CAMARTEC	Centre for Agricultural Mechanisation and Rural Technology
CD	Cow dung
CH <sub>4</sub>	Methane
CO <sub>2</sub>	Carbon dioxide
CSP	Concentrating solar power
DC	Direct current
DEM	Design engineering and management

DEST	Department of Engineering Sciences and Technology
DL	Data logger
DM	Dry matter
DMA	Decision matrix analysis
DO	Dissolved oxygen
DPP	Discounted payback period
DT	Digester temperature
Dv_D	Percent deviation
FAO	Food and Agriculture Organization
GHEs	Greenhouse effect structure
HAWT	Horizontal axis wind turbine
HDPE	High-density polyethylene
HOMER	Hybrid Optimisation Model for Electric Renewables
HRT	Hydraulic retention time
HSAD	High solid anaerobic digestion
ICS	Improved cooking stove
ID	Identification number
IRES	Intended integrated renewable energy system
IMP	Current at maximum power
IPS	Iron pipe size
IR	Infra-red
IRR	Internal rate of return
ISC	Current at short circuit
i-SWEAD	Integrated solar and wind energy with anaerobic digestion

ITC	Investment tax credits
LAD	Liquid anaerobic digestion
LPG	Liquidified petroleum gas
MAPE	Mean absolute percentage error
MC	The moisture content
MIGESADO	<i>Miradi ya Gesi ya Samadi Dodoma</i> ; simply translated as Dodoma Biogas Projects
MNRC	Ministry for Natural Resources Canada
MSE	Mean square errors
N	Nitrogen
NBS	Nation Bureau of Statistics
NGOs	Non-Governmental Organisations
NH <sub>4</sub> -N	Ammonium Nitrogen
NNE	North-North East
NPV	Net present value
NSE	Nash-Sutcliffe Efficiency or model efficiency
O&M	Operation and maintenance
OC	Organic Carbon
OES	Outdoor encasing structure
ON	Organic Nitrogen
PD	Percent deviation
pH	Hydrogen ions
PMI	Plus-minus and interesting
PTC	Production tax credits
PV	Photovoltaic

PWM	Pulse width modulation
R <sup>2</sup>	Coefficient of determination
REA	Rural Energy Agency
REF	Rural Energy Fund
REN21	Renewable Energy Policy Network for the 21st Century
RH	Relative Humidity
RMSE	Root mean square error
RMSS	Residual mean sum of squares
SHCS	Solar Heat Collection and Storage
SN	Serial Number
SNV	Schweizerische Normen-Vereinigung (Swiss Association for Standardization),
SPP	Standardised power purchase
SR	Solar radiation
SUA	Sokoine University of Agriculture
SWOT	Strength, Weakness, Opportunity and Threat
T	Hydraulic retention time
TLCC	Total life cycle cost
Trans-SEC	Innovating Strategies to Safeguard Food Security Using Technology and Knowledge Transfer: A People-Centred Approach
TZS	Tanzanian shillings
UGT	Umwelt-Geräte-Technik
UoH	University of Hohenheim
USD	United States Dollar
VAWT	Vertical axis wind turbine

VM	Volatile matter
VMP	Voltage at maximum power
VOC	Voltage at open circuit
WB	Water and Black-sheet
WS	Wind Speed
ZALF	Germany Centre of Agricultural and Landscape Research

## LIST OF SYMBOLS AND UNITS

Symbol	Description	Unit
$A$	It is the year(integer), in which the cumulative present value of cash flows from investment exceed the initial cost;	-
$A_{D3}$	Rectangle top exposed area of the D3	$m^2$
$A$	Rotor swept area perpendicular to the direction of airflow, i.e. $\frac{1}{2} \pi R_{wt}^2$	$m^2$
$A_{yr}$	Time taken by the system to generate $E_{Syst}$	h
$Bd_f$	Final biogas energy density	$MJ/m^3$
$Bd_i$	Initial biogas energy density	$MJ/m^3$
$CD_{ac}$	Amount of cow dung excreted by adult cattle in a day	$kg.adult-cattle^{-1}.day^{-1}$
$CD_{min}$	Minimum potential amount cow dung collected per day	$(kg.day^{-1})$
$CF^t$	Cash flow at the end of period $t$ ,	TZS or €
$C_p$	Power coefficient based on Betz limit (it was assumed to be 40%)	%
$C_w$	Rating of IL bulb of wind sub-system	W
$C_{pv}$	Rating of the LED bulb of the PV unit	W
$c$	Characteristic wind speed or scale factor at the study site	m/s
$CumPVCF_{(A-1)}$	Cumulative present value of the cash flows from investment at the end of the year $A-1$	TZS or €
$C_{bio}$	Cumulative total amount of biogas in $m^3$	$m^3$

	produced by the system	
$C$	Cumulative volume of biogas collected in RT from the digester	$m^3$
$d$	Discount rate as per financial regulation body of a country	%
$DEM_c$	Design engineering and management cost of the system	TZS
$DPP$	Discounted payback period	years
$d_k$	Degradation rate of hybrid's energy sub-system $k$ per year (%), $k = 1, 2, 3, \dots$ ,	%
$d_s$	Degradation rate of the hybrid's solar energy sub-system per year	%
$D_{i-SWEAD}$	Volume of the i-SWEAD system's digester, which was $0.24 m^3$	$m^3$
$E_{av-cook}$	Biogas thermal energy available per day from the system	kWh/day
$e$	Exponential function	-
$E_{HV-bio}$	Energy density or heating value of biogas	$MJ/m^3$
$E_k$	Energy generated by hybrid's energy sub-system $k$ other than wind or solar in year $n$ ,	kWh
$E_{pv}$	Annual electrical energy generated by the solar PV unit	kWh
$E_{we}$	Electrical energy generated by wind sub-system	kWh or Wh
$E_s$	Energy generated by hybrid solar energy sub-system in year $n$ ,	kWh
$E_{syst}$	Energy generated by the system	kWh

$E_{ES}$	Solar energy flux received daily by D3	kWh
$E_{biogas}$	Total biogas energy produced in a year	MJ/year or kWh/ year
$E_{wt}$	Wind energy which was harnessed by the wind turbine	kWh
$F_{nk}$	Fuel costs of hybrid's energy sub-system $k$ other than wind or solar in year $n$ ,	TZS or €
$F(v)$	Probability of events of the wind speed equal to or above annual average wind speed, at the study site, i.e. $P(v \geq v_m)$	-
$F_{\%CH_4}$	Conversion factor between biogas energy density and methane content	MJ/m <sup>3</sup> / %CH <sub>4</sub>
$HRT$	Hydraulic retention time, i.e. or T or RT	day
$H_{bio-cook}$	Availability of the system in hours per day for household cooking purpose	hours/day
$h_d$	Average daily hours of bright sunshine in a month; it was 9 hours at the study site for each month.	hours (h)
$H_d$	Heat gained by System3's digester from both solar PV unit and wind sub-system	kW
$IRR$	Internal rate of return	%
$ITC_n$	Investment tax credits in year $n$ ,	TZS or €
$I$	Annual average insolation or peak sun hours (h) at the study site	kWh/m <sup>2</sup> /day
$I$	Monthly average insolation	kWh/m <sup>2</sup> /day
$I_c$	Capital cost committed before the start of energy	TZS or €

	generation	
$i_c$	Interest rate on the capital cost committed, i.e. $I_c$ to a hybrid system for 100% debt	%
$k$	Shape parameter (dimensionless).	-
$k$	Constant of proportionality of <b>RT</b> and <b>C</b> .	day/m <sup>3</sup>
$Ld_{DEM}$	Labour cost for design, engineering and project management	TZS/man-hour
LCoE	Levelized cost of energy	TZS/kWh or €/kWh or \$/kWh
$N$	Analysis period or lifetime of the project	years
$NPV$	Net Present value	TZS or €
$O_n$	Operation and Maintenance costs in year $n$	TZS or €
$P_1$	Initial pressure at time two	kPa
$P_2$	Final pressure at time one	kPa
$P_{ac}$	Percentage of adult cattle in the herd of the cattle	(%)
$P_{CD_c}$	Percentage of cow dung collected based on the type of grazing system of cattle.	(%)
$P_{pv}$	Power rating of the solar PV module	W
$P_{syt}$	Peak wattage of the system	kWp
$PTC_n$	Production tax credits in year $n$	TZS or €
$P_{wg}$	Rated power of electricity generator actuated by wind turbine	kW or W
$Pr_{v_{existing}}$	AD systems' biogas production rate	m <sup>3</sup> /m <sup>3</sup> of digester in a day
$P_{i-SWEAD}$	Performance of the i-SWEAD system biogas production based on the existing systems biogas	%

	production rate	
$Pr_v$	Biogas production rate of the i-SWEAD system	$m^3/m^3$ of digester in a day
$P_{wt}$	Power harnessed by the wind turbine	W
$PVCF_{(A)}$	Present value of net cash flow in the year $A$ ;	TZS or €
$P$	Pressure recorded	kPa
$Q_{flow-bio}$	Optimum biogas flow rate of 0.4 $m^3/h$	$m^3/h$
$r$	Radius at cross-section tyre torus	m
$R_{wt}$	Rotor radius, i.e. A length from the hub to the tip of the blade (for this study, it was 0.81 m)	m
$R$	Torus radius	m
$Sr_a$	Monthly average solar irradiance based on recorded daily data in the specific month at the study site	$W/m^2$ or $kW/m^2$
$T_{DEM_{kwp}}$	Design, engineering and project management number of hours per kWp	man-hour/kWp).
$t$	Indicates any particular period (integer)	-
$T_h$	Variable value of T in hours	hours or h
$T_{hc}$	Total number of cattle in the study area	-
$T_d$	Variable value of T in days	day
$t$	Time in hours, $t$ (h), of collecting biogas volume	h
$v_m$	Average wind speed at 4 m hub height at the study site,	m/s
$V_{i-SWEAD}$	Total volume of biogas collected within hydraulic retention time,	$m^3$

$V_{P2}$	Final volume of biogas at a pressure of time two	$m^3$
$V_{P1}$	Initial volume of biogas at a pressure of time one	$m^3$
$V$	Volume of biogas collected in time $t$	$m^3$
$V_p$	Volume of biogas in the torus butyl tube	$m^3$
$v_0$	Wind speed measured at anemometer height $Z_0$ ,	(m/s)
$v$	Wind speed to extrapolated at the height $Z$ ,	(m/s)
$V_{biogas}$	Total biogas volume collected in a year	$m^3/\text{year}$
$X$	Any data value from a dataset of $X_{i, i=1,2,3, \dots}$	Any unit
$X_{max}$	Maximum values from a dataset of $X_{i, i=1,2,3, \dots}$	Unit of $X_i$
$X_{min}$	Minimum value from the dataset of $X_{i, i=1,2,3, \dots}$	Unit of $X_i$
$\hat{X}$	Normalised value	-
$Z$	Height given	m
$Z_0$	Reference height of the anemometer	m
$\alpha$	Proportionality symbol	-
$\alpha$	The power-law exponent depending on the surface roughness	-
$\rho_{e_{biogas}}$	Biogas energy density	$MJ/m^3$
$\rho_a$	Density of air (it was assumed to be $1.26 \text{ kg/m}^3$ )	$\text{kg/m}^3$
$\sigma$	Standard deviation of wind speed values from mean wind speed	m/s
$\pi$	Phi =3.1415926.	-
$\eta_{pve}$	Efficiency of converting electricity from Solar PV module into heat energy by use of 1 W Light Emitting Diode (LED) bulb	%
$\eta_w$	Efficiency of converting electricity wind turbine	%

	into heat energy using 6 W Incandescent Light (IL) bulb	
$\eta_{pv}$	Efficiency of polycrystalline solar PV module and it was taken as 13%	%
$\tau_{cov}$	Transmittance of fibre transparent top cover of OES, which was assumed 0.8	-
$\%CH4_f$	Final methane content	%
$\%CH4_i$	Initial methane content	%

## CHAPTER ONE

### 1.0 General Introduction: Study Contextual and Thesis Organisation

#### 1.1 Background Information

Unsustainable and unreliable access to energy is a global challenge for most developing countries (Oyedepo, 2014; Hirmer and Guthrie, 2017; Zubi *et al.*, 2017). This challenge has persistently been acute in rural semi-arid Sub Saharan Africa (SSA) compared to other regions. The Sustainable Development Goal (SDG) Number seven (7) stresses the availability of affordable, clean, and modern energy for all (McCollum *et al.*, 2017). On the contrary, the SSA region has abundant renewable energy-related resources, which could be used to reduce the acuteness of the problem (Ikejemba *et al.*, 2017; Bishoge *et al.*, 2018). These resources are either underutilised or inefficiently utilised (Bishoge *et al.*, 2018). Several efforts have been made to curb these challenges. These efforts include formulating the energy policy, strategies and programmes that insist on increasing renewable energy in the total energy consumption mix (Teske *et al.*, 2017). Also, among other efforts are promoting the application of renewable energy (Barry *et al.*, 2011) and expanding renewable energy-based energy products and services market shares in the energy sector (Williams *et al.*, 2018).

Additionally, introducing renewable energy education from secondary education to tertiary levels (Kandpal and Broman, 2014; Wenderott, 2016), an increase of funding of renewable energy projects (Wawa, 2012; Bishoge *et al.*, 2018; Okoko *et al.*, 2018; Grimsby *et al.*, 2016) and implementing several small to large projects of renewable energy systems (Bishoge *et al.*, 2018) sum up the efforts in question. However, there is a limitation of adopting technologies that address the challenge of unreliable energy accessibility. The cause of low adoption includes the costs of accessing the technology

since most of the rural communities in SSA are low-income smallholder farmers. Also, difficulty in operating these technologies due to several associated factors. For instance, some technologies require a large amount of water, while in these areas, water is scarce (Jørgensen, 2009; Li *et al.*, 2011b; Wawa, 2012). Another factor is that some systems are complicated for users to troubleshoot systems' faults (Rajendran *et al.*, 2012; Oloche *et al.*, 2017; Afridi and Qammar, 2020).

Integrated renewable energy systems, which function by exploiting a combination of several renewable energy sources and resources, have gained grounds in complementing energy supply, where other conventional energy systems are not meeting energy demand in rural areas (Castellanos *et al.*, 2015; Khoury *et al.*, 2016; Maheshwari and Ramakumar, 2016). Also, they are useful in off-grid areas, where there are several renewable energy resources but the systems available only use one type of resource. Those systems, which use one type of resource, may not be feasible or sufficient to address an unreliable energy accessibility problem (Szabó *et al.*, 2016). Renewable energy sources and resources are temporal and spatially specific (Krioukov *et al.*, 2011). Therefore, energy systems depending on those sources and resources must be optimally designed for their reliability and sustainability of energy generation while considering the resources temporal and spatial specificity.

Consequently, developing integrated renewable energy systems, which address SDG 7 and its objectives, is paramount. The systems are relevant, particularly to communities living in rural semi-arid areas found in most tropical developing countries. The energy in these communities is needed to cook and power electric and electronic gadgets (Hirmer and Guthrie, 2017; Zubi *et al.*, 2017). These needs are common to most of the rural areas of semi-arid SSA, including Tanzania. Therefore, providing affordable and reliable energy to these communities ensures their access to energy supply. Thus, a system needs to be

developed to generate clean energy for households in rural semi-arid areas. This system must be affordable, efficient, reliable, and sustainable in addressing the challenge related to access to clean energy.

This study was conducted to address the challenges of limited energy accessibility and underutilisation of energy resources in rural semi-arid areas. The study site of Idifu village, located in Dodoma, Tanzania, was chosen as a representative of semi-arid areas because of its problems of energy accessibility and underutilisation of energy resources. In general, Tanzania is one of the countries in the SSA region, striving to meet SDG Number seven (7) targets by 2030. The targets include, among others, the following:

- a) Equal access to affordable, reliable, and modern energy services.
- b) An increased stake of renewable energy in the total global energy needs and
- c) Expansion and upgrading of energy infrastructure and technologies and enhancement of the supply of contemporary and viable energy services to all communities in emerging nations.

Tanzania has the National Energy Policy, which was amended in 2015. The policy stresses the increase of renewable energy in the total national energy consumption mix (Sarakikya *et al.*, 2015; Teske *et al.*, 2017). However, communities in rural semi-arid areas face numerous challenges related to access to energy. The population annual growth rate of 2.7% (NBS, 2017) mismatches the growth in energy generation from the grid. As a result, there are challenges, which include rapid deforestation from a minimum of 130 000 ha/annum (1990-2000) to 372,816 ha/annum (1995-2010) due to, among other factors, the search for energy through charcoal making and unsustainable firewood collection (Kashaigili *et al.*, 2013). Underutilisation of crop residues and animal wastes in energy production, while there is insufficient access to electricity, is another limitation that needs

to be addressed (Felix and Gheewala, 2011; Wawa, 2012; NBS, 2018).

The government of Tanzania, through various cross-cutting policies, strategies and programmes, has initiated the use of renewable energy technologies as part of the implementation of the mitigation measures. For instance, in 1975, a biogas technology initiative was established in Tanzania (Grimsby *et al.*, 2016). Also, Tanzania is implementing her energy policy, which among other things, strengthens the use of renewable energy to increase the total energy consumption mix. Dodoma Biogas Projects (MIGESADO) in Dodoma, in collaboration with Tanzania's centres, i.e. Domestic Biogas Programme at the Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC), promoted the use of biogas throughout the country (Wawa, 2012; Grimsby *et al.*, 2016). The Swiss Association for Standardisation (SNV) is among the Non-Governmental Organisations (NGOs), which have been promoting the application of renewable energy across the country and regions (Barry *et al.*, 2011). Also, local and international renewable energy-based companies are significantly expanding their market shares in the energy sector in Tanzania (Williams *et al.*, 2018). However, they are still facing stiff competition from non-renewable energy sources like fossil fuels (Jacob, 2017).

Renewable energy education has been introduced in the curriculum of public and private education institutions from secondary education to tertiary levels worldwide (Kandpal and Broman, 2014; Wenderott, 2016). Tanzania public universities, for example, the University of Dodoma and University of Dar es Salaam, have introduced degrees related to renewable energy and technology at a level of Bachelor and Masters, respectively. Other Tanzania's universities, for instance, the Sokoine University of Agriculture at its Department of Engineering Sciences and Technology, conducts research and training at both undergraduate and postgraduate levels in the field of renewable energy resources and

technology, the current PhD study inclusive. Note that several small to large projects of renewable energy systems have been implemented in Tanzania (Bishoge *et al.*, 2018). It is envisaged that graduates of these fore mentioned higher learning institutions would support implementing these projects and others to be introduced in the future.

The fore described trends about renewable energy in Tanzania are more or less like what has been happening in the East African region for countries like Kenya, Uganda, Rwanda, and Ethiopia (Ikejemba *et al.*, 2017). All this information gives an insight into the vital relevance of using renewable energy systems and the attention paid to it by Tanzania and the region.

## **1.2 Adoption Challenges of Renewable Energy Systems in Semi-Arid Areas of Tanzania**

In Tanzania, biogas technology, one of the renewable energy technologies in the rural semi-arid areas of central Tanzania, was introduced through the government research centre, i.e. CAMARTEC and NGOs such as MIGESADO (Wawa, 2012; Grimsby *et al.*, 2016). The technology was an underground installed fixed dome biogas plant operated by feeding continuously with a mix of water and cow dung at a ratio of one to one (Wawa, 2012). The adoption of the technology was associated with several drawbacks: difficulties in troubleshooting its faults like leakage, use of large amounts of water (in semi-arid water is scarce), tedious operation, and high initial capital outlay for acquiring it. However, cow dung as feedstock for the plant was abundantly available in those areas as communities are involved with crop farming and cattle keeping.

Furthermore, the application of small solar energy-based Photovoltaic (PV) systems (less than 100W) as alternative energy generating systems has increased in rural semi-arid

areas. The increase of application of the systems was enhanced through the renewable energy business community, development partners and government participation. These systems are applied to meet households' lighting and rarely mobile phone charging needs (Klasen and Mbegalo, 2016). However, they may not suffice the household energy need, especially for cooking, which is a vital domestic activity in the household. Hardly, up to 20 Wp solar PV models are used while cooking activity needs a tremendous amount of energy (Scheid *et al.*, 2018). For example, cooking one kilogram of the meal with ingredients of rice and beans using a traditional three-stone cooking stove for 27 minutes (Scheid *et al.*, 2018) requires the equivalent heating power of 7800 Wp  $\approx$  3.5 kWh heating energy by considering the conversion factor of 0.27778 kWh/MJ reported by Lilford (2020) and energy density of fuelwood 17.5 MJ/kg reported by Díez and Pérez (2017).

Also, the business community, development partners and government have been involved in the installation of large-sized solar photovoltaic systems (above 100 W) for powering rural health centre facilities and for water pumping in irrigation schemes (Parida *et al.*, 2011; Bishoge *et al.*, 2018). Solar heating systems are, in most cases, limited to water heating in public institutions and very few privately owned buildings in small centres in rural areas. Mostly, the communities in rural semi-arid areas exploit solar radiation for crop drying using sun drying, which is not efficient.

Another renewable energy-based system adopted in rural semi-arid areas is wind energy conversion systems (Bishoge *et al.*, 2018). The most widely applied wind energy system used in rural semi-arid areas is the windmill technology, which is used for water pumping, as it is a high torque system (Rathore *et al.*, 2018). The wind turbine technology is used for electricity generation as it is a high-speed system (Ebhotu and Inambao, 2016). Rural semi-arid areas are potential areas for electricity generation using wind turbines due to

having favourable ground physical features allowing unhindered wind blowing in most cases. Some sites in these areas have been spotted to install large capacity wind turbines (Bishoge *et al.*, 2018). On the other hand, communities in these areas involved in crop production use wind to separate crop produce and residues by winnowing (Scheid *et al.*, 2018). Limited information is available on small-sized wind turbines to be applied to generate electricity ready for use in households of rural semi-arid areas.

Generally, the challenges associated with adopting biogas technology, solar energy systems, and wind energy systems in rural semi-arid areas are evident; however, they have not been adequately addressed. This situation calls for a search for more robust means of countering these challenges. Renewable energy systems are among the candidate systems, which can offer energy generation sustainably. It should be noted that renewable energy resources, e.g. wind and solar energy resources, are intermittent, as they are weather depended. Therefore, envisaged robust renewable energy systems must integrate these sources to ensure it is reliable and sustainable for energy generation.

### **1.3 Justification of the Study**

The problem of limited energy access in rural semi-arid areas of developing countries is evident and acute; however, efforts put forward have not adequately addressed the challenge. On the contrary, there are abundant resources and sources that can be harnessed to address the problem of limited energy access. Such sources and resources, which are abundant and can be found almost in any location of semi-arid areas, include wind, solar and biomass. However, the limitation in technology remains a significant challenge to harness these sources and resources adequately. Efforts done so far have established various technologies that utilise the resources and sources individually or in combination.

Different systems have been developed to use the combination of these abundant sources and resources; however, most of them have rarely combined solar, wind and biomass as one system. There is evidence that shows the existence of systems with solar-wind (Subrahmanyam *et al.*, 2012), solar-biogas (Karimov and Abid, 2012) wind-hydro (Sirasani and Kamdi, 2013) and solar-wind-diesel generator systems (Kazem *et al.*, 2017). These systems, which are known as integrated renewable energy systems, minimise unreliable energy supply caused by intermittence of weather-related renewable energy resources and sources (Mishra *et al.*, 2014). However, technological or costs challenges associated with these systems limit their up-scaling and out-scaling (Wawa, 2012; Subrahmanyam *et al.*, 2012).

Therefore, this study aimed at contributing to the efforts of addressing the problem of limited energy access (development gap in the energy sector) and underutilisation of resources and sources of energy by designing a system that will integrate wind, solar and biomass energy resources to generate biogas and electricity (scientific gap) sustainably. The system to be designed must be efficient and affordable to limited income communities in rural semi-arid areas to allow adoption and up-scaling.

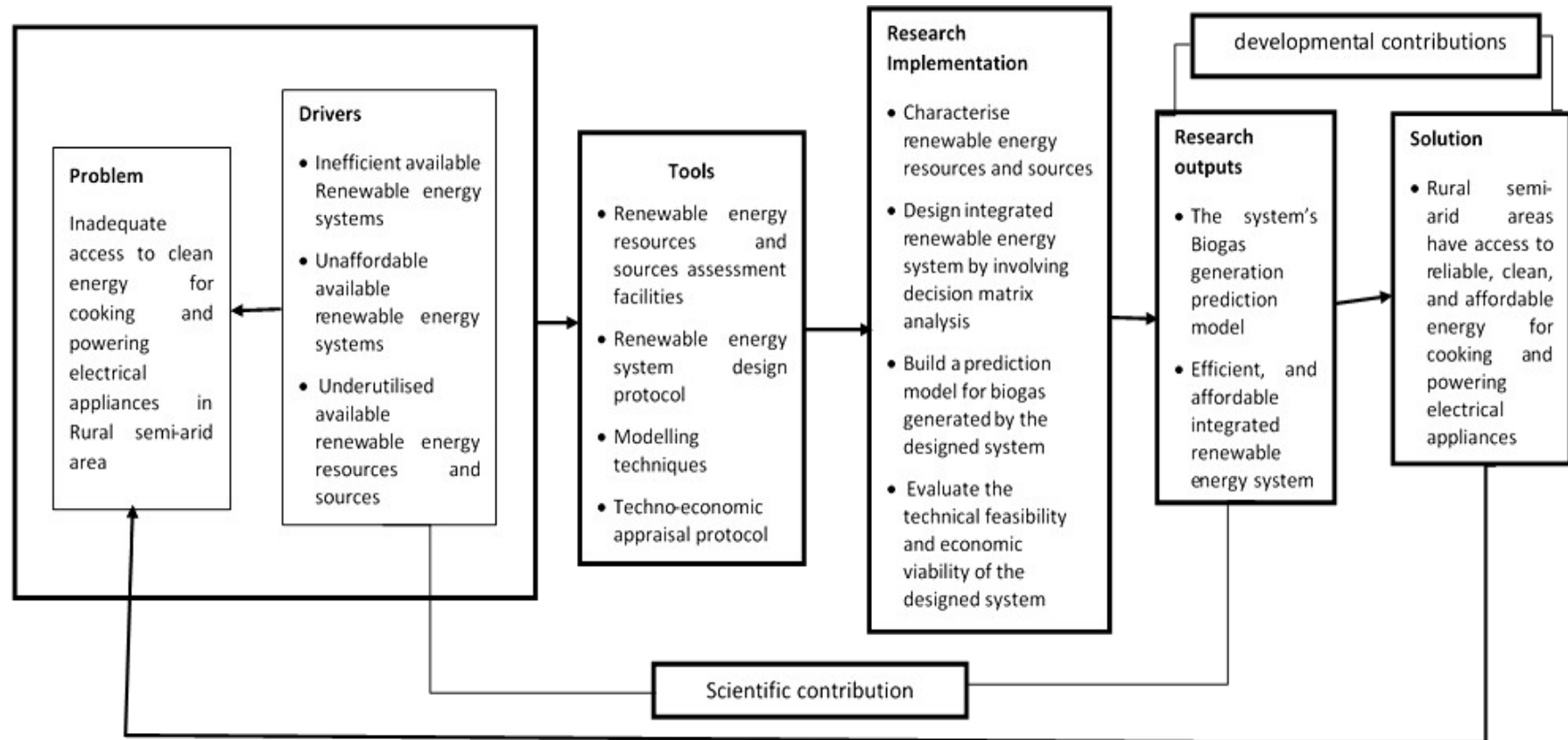
#### **1.4 The Aim and Conceptual Research Framework of the Study**

This study aimed at addressing issues related to energy challenges, which rural semi-arid areas' dwellers are facing. Also, the study considered the potentiality and constraints of the existing biogas technologies and other renewable energy systems. Furthermore, the constraints related to stable anaerobic digester temperature at a constant level for biogas production and the system's electricity have been considered.

The Conceptual Framework is a graphical or another narrative form of presentation of key variables, factors or concepts and their relationship among each other, which have been or

have to be studied in the research (Chetty, 2015). Figure 1.1 shows the interlinkage of factors and concepts considered to seek a solution of inadequate access to clean energy for cooking and powering of electrical appliances in rural semi-arid areas using a research approach. Figure 1.1 also shows the determinants of the problem, which are in the table entitled as Drivers. The arrow from this box indicates that items in that box are among the causes of the problem. Then, tackling the problem in scientific research, a number of tools are required. The nature of the problem at hand impact the choice of tools to be used, as indicated by an arrow from a box hosting problem and drivers to the tools' box. The tools applied in this study are shown in the Tools' box.

Furthermore, the tools available determine the means of implementation of the research to address the problem. In this study, four major research work packages were involved, and they are shown in a box entitled Research Implementation in Figure 1.1. The research outputs box in the same figure presents the products of the study, which include a biogas prediction model and the integrated renewable energy system. The products are the results of the research implementation. These products contribute to the solution towards ensuring communities in the rural semi-arid areas have access to reliable, clean and affordable energy. Research outputs make scientific and developmental contributions by bridging the gap based on the drivers and adding one solution for curbing inaccessibility to energy in rural semi-arid areas, respectively. Therefore, the solution is linked to the problem by an arrow.



**Figure 1.1: Conceptual research framework**

## **1.5 Objectives of the Study**

### **1.5.1 Overall objective**

The overall objective of this research was to develop a model of an integrated renewable energy system, which includes anaerobic digestion, solar and wind energy to produce energies for rural semi-arid areas.

### **1.5.2 Specific objectives**

These specific objectives were to:

- a) characterise the available renewable energy-related resources and variation in ambient temperature,
- b) design and test the functionality of the integrated Solar and Wind Energy with Anaerobic Digestion (i-SWEAD) system,
- c) model the biogas production of the i-SWEAD system for facilitating prediction of the system performance,
- d) conduct a techno-economic appraisal of the i-SWEAD system.

## **1.6 Materials and Methods**

The description of the study site, the definition of concepts and a brief description of the data collection and analysis are given in the subsequent sub-sections. The detailed information on the methodology to undertake this study is given in the individual chapters addressing specific objectives.

### **1.6.1 Description of the study site**

The study site was Idifu village in Chamwino district, Dodoma, Tanzania. The village is shown in Figure 1.2 and Appendix 1 of this thesis. The site is geographically located around the point coordinate with values of 6°26'35" S, 35°58'06" E. Chamwino district

represents the semi-arid climate where considerable insufficient energy for households' purposes is evident. It has one rainfall season with an average of 350-500 mm per annum and is characterised by the prevalence of high food insecurity.



**Figure 1.2: Location of the study site**

**Source: (Silungwe *et al.*, 2019)**

The community in Idifu village and others in the neighbouring areas face several constraints, including inadequate access to sustainable and reliable energy. Inhabitants of the Idifu village are agro-pastoralists, who grow pearl millets and keep cattle under the half-stable system. Cattle are grazed in the village and neighbouring communities' fields and kept in the kraal during the night. The food system is mainly cereal-based, with pearl millet as the preferred staple (Mutabazi, 2013).

The village was a beneficiary of the interventions of the Trans-SEC (Trans-SEC – *Innovating Strategies to Safeguard Food Security Using Technology and Knowledge Transfer: A People-Centred Approach*) project of introducing upgrading strategies for the improvement of community livelihood, especially on food security-related issues as reported by Mwinuka *et al.* (2015). One of the strategies and a basis for this study was related to the beneficial conversion and utilisation of agricultural and animal waste for useful energy and materials availability.

### **1.6.2 Definitions of concepts**

The main concepts and approaches applied in the study are consequential from various types of disciplines, explicitly, engineering sciences, technology, and socioeconomics. The concepts include renewable energy resources, engineering design process, artificial neural network, techno-economic assessment, systems integration, household, and semi-arid area. Definitions of these concepts, as used in this thesis, are given.

*Renewable energy resources* are described by Ellabban *et al.* (2014) as renewable energy resources or sources, which continually replenished by nature and derived directly from the sun (such as thermal, photochemical, and photo-electric). Also, they are indirectly derived from the sun (such as wind, hydropower, and photosynthetic energy stored in biomass) or brought from other natural movements and mechanisms of the environment (such as geothermal and tidal energy). They do not include fossil fuels, waste products from fossil sources, or waste products from inorganic sources.

*The engineering design process* is a methodical series of steps that engineers use in creating functional products and processes. The process is highly complex and iterative - a part of the process often needs to be repeated many times before another one can be

considered - through the part(s) that get iterated. The number of such cycles in any given project may vary (Edwards, 2003).

*Artificial Neural Network (ANN)* is an interconnected group of nodes, similar to the vast network of neurons in the human brain. It can be presented in many ways using available knowledge and technology. In the modelling field, the ANN techniques can simulate or predict a process, which is complex and does not obey linear regression or similar phenomena (Sewsynker-Sukai *et al.*, 2017).

*Techno-economic assessment* is a methodology framework for analysing the technical and economic performance of a system, project, process, product or service. It usually combines process modelling, engineering design and economic evaluation (Chandel *et al.*, 2014; Lauer, 2008).

*Engineering systems integration* is a process of unifying or combining optimally factors affecting the systems in question (Langford, 2016).

*Household* is defined as a group of people who live together in the same house or compound and share the same housekeeping arrangement and are catered for as one unit (Randall and Coast, 2015). Households in rural areas directly rely on their immediate environment and their skills to obtain the daily requirements of life, such as food. These households use available resources to meet energy demand for cooking food and powering electrical and electronic gadgets of their members.

*The semi-arid area* is a land of marginal crops production potential, quick maturing cereals, and carrying natural vegetation of *Acacia-Themeda* association but including dry *Brachystegia* woodland. It is a potentially productive grazing area, limited by bush

encroachment, leached soils, inadequate water and tsetse fly infestation (Pratt and Gwynne, 1977).

### **1.6.3 Data collection**

The collection of data was done for making a base to meet the objectives of the study. The objectives were based on assessing renewable energy resources and sources, conceptual designing, experimental testing of components of the system and the system itself. Also, they aimed at building and assessment of the developed system's biogas generation prediction model and techno-economic appraisal of the system.

The assessment of renewable energy resources and sources included characterising fresh cow dung properties and renewable energy weather-related factors. Data collected using the methodology recommended by Peters *et al.* (2003) were cow dung's total Nitrogen, Ammonium nitrogen ( $\text{NH}_4\text{-N}$ ), pH, dry matter (DM) or total solids and volatile matter (VM), while Organic Carbon was determined using the methodology developed by Moberg (2001). Solar radiation, wind and ambient air temperature data were collected using a weather station installed at the study site.

The weather station consisted of Pyranometer for solar irradiance measurement, which was connected to a UGT data logger (DL 389); the Seeeduno Stalker microcontroller connected with an anemometer and wind vane for collecting wind speed and wind direction data, respectively. Also, the weather station included the UGT data logger (DL 386), which was coupled with a Type-K thermocouple temperature probe for ambient temperature data collection. Weather data were collected from November 2016 up to January 2018 at the study site.

The conceptual designing, experimental testing of components of the system and the system itself involved the data collection done according to experimental setups that are described in Chapter Two through to Chapter Five of this thesis. Instrumentation and measurements included in these tasks were Micro Footprint Dissolved Oxygen (DO) and Micro Footprint pH monitoring sub-system with pH and DO circuits of Version 4.0 (*Atlas-Scientific.com*) for measuring DO and pH values of systems substrates. Also, Ultrasonic biogas flow meter Version BF-2000, with a flow range of 0.025 – 4.000 m<sup>3</sup>/h, methane (CH<sub>4</sub>) measurement range of 30-100% and temperature measurement range from -20°C to 60°C were used for measuring of CH<sub>4</sub> content and piping system temperature.

Furthermore, the temperature inside the outside encasing structure, which was enclosing the biogas digesters, was measured using the thermo-element type K connected to VOLTCRAFT DL111K temperature data logger with Serial Number 15 120 153. The temperature values inside digesters were measured using the type K thermocouples connected to UGT 386 temperature data logger and thermo-element type K connected to VOLTCRAFT DL111K temperature data logger with Serial Number 15 090 497. The secondary data on monthly average solar irradiation (insolation) and wind speed of Dodoma, Tanzania, were collected from Solar Electrical Handbook (Boxwell, 2017) and Ret-Screen Plus Analysis Software (Ganoë *et al.*, 2014) and applied in this study. Simgas pressure gauge, encased in plastic material with a measuring range of 0 - 16 kPa (*www.simgas.com*), was used to measure the system's pressure.

On establishing the cut-in wind speed of the i-SWEAD system wind component, the wind speed was measured using an anemometer (TESTO416, SN. 02238844 with the accuracy of 0.01 m/s). Moreover, time measurement of the electricity conversion into heat process and the temperature was done using a mobile phone stopwatch and the thermometer (Eco

Scan Series Thermocouple thermometer, SN. 884436 with the accuracy of 0.1°C) was used to measure temperature level based on heat generated after converting electricity from the wind turbine.

The model's predictive data of the developed system's biogas generation for assessing the model was generated using R-software (Gunther and Fritsch, 2010). Finally, techno-economic appraisal of the system involved collecting primary data from the list of prices of items and activities encountered during systems fabrication and secondary data from the literature.

#### **1.6.4 Data analysis**

Analysis of data collected for this study was done as described herein. Daily solar radiation measurements were used to determine the hourly average solar irradiance ( $\text{W}/\text{m}^2$ ) and monthly average solar insolation ( $\text{kWh}/\text{m}^2/\text{day}$ ). The formula proposed by Wald (2007), which is Equation 2.1 in Chapter Two of this thesis, was employed for calculating the monthly solar insolation. Data obtained by Equation 2.1 was reserved for verification purposes as the secondary data were reliable because of being collected for an extended period.

Wind speed data were transformed, averagely, from 30 minutes' intervals into one-hour interval mode. The transformed wind speed data were used to determine hourly and monthly average, maximum and minimum wind speeds. Wind direction data were used to generate wind roses, which show the predominant wind blowing directions at the study site. Wind speed in metres per second ( $\text{m}/\text{s}$ ) at a given level of height in metre ( $\text{m}$ ), from reference height in metres ( $\text{m}$ ), with known wind speed in  $\text{m}/\text{s}$  above ground, was computed using the Power law formula explained by Jancewicz and Szymanowski (2018).

Extrapolation of wind data was done for 4 m wind turbine hub height. Ret-Screen Plus wind data of Dodoma was used for cross-checking the validity of wind data collected at the study site. The ambient temperature data were used to determine both hourly and monthly average, maximum and minimum temperature at the study site. The analysis of these data was achieved using the data analysis function of Microsoft Excel Version 2013.

Decision Matrix Analysis (DMA) methods applied by Kaena (2012), Olabanji and Mpofo (2014) and Salonen and Perttula (2005) was used to select the best working principles during the system's designing. Dissolved Oxygen (DO), pH, methane content, and average pressure values from designed systems testing were computed using the data analysis function of Microsoft Excel Version 2013. Also, Microsoft Excel was used to generate graphs of analysed parameters' values against time following the recommendation of Mélard (2014) that the software is one of the reliable software after being improved in 2010 by the software owner. The owner improved the software based on criticism raised by statisticians regarding the previous version of the same software.

The volume of the biogas collected was derived from regression Equation 4.3, which is in Chapter Four of this thesis. The procedure used to obtain the equation is well described in Sub-section 4.2.6 (iv) of the same chapter. Electrical and heat energies generated by solar PV unit and wind sub-system as well as the power of the wind turbine were determined using the data analysis procedure given in Sub-section 4.2.6 (v) of Chapter Four in this thesis.

The artificial Neural Network (ANN) model was developed to predict the measured biogas generated by the i-SWEAD system; its performance was analysed using statistical measures. Those measures include averaged mean cross-validation error (mean-cv.error),

a per-cent deviation (Dv\_D), i.e., PD, and Nash-Sutcliffe efficiency or model efficiency (NSE) (Cadenas and Rivera, 2009; Rajapaksha *et al.*, 2015). Other measures were the coefficient of determination ( $R^2$ ), Residual Mean Sum of Squares (RMSS) and absolute model prediction accuracy (AMPA) (Donoso-Bravo *et al.*, 2011). The R Software (R-Core-Team, 2018) codes shown in Appendix 8 were used to analyse the mean-cv.error, PD, and NSE values. The data analysis function of Microsoft Excel Version 2013 was used to analyse the  $R^2$ , RMSS and AMPA values. Also, the visual format analysis of the model performance was done by plotting measured test data and model-predicted result data against the sampled observation numbers (test data) using the data analysis function of Microsoft Excel Version 2013. Section 5.2 of Chapter Five of this thesis explains how data analysis was done on this matter.

The analysis of the techno-economic performance of the i-SWEAD system was done using a simplified techno-economic assessment approach. Factors considered in the appraising are related to the functionality, costs, and financial matters of the i-SWEAD system. The approach and detailed descriptions of the factors used in assessing the i-SWEAD system are provided in Section 6.2 of Chapter Six of this thesis.

## **1.7 Organisation of the Thesis**

This thesis has seven chapters. The first chapter is a general introduction providing introductory issues related to the justification of the use of integrated renewable energy systems and associated technologies, renewable energy resources and sources for meeting the energy demand in the community. It also highlights the relevance of newly developed integrated solar and wind energy with an anaerobic digestion system for producing energy for rural households in the semi-arid areas. This chapter gives the overall theme of the thesis. It contains the description of key concepts and the relationship of the publishable

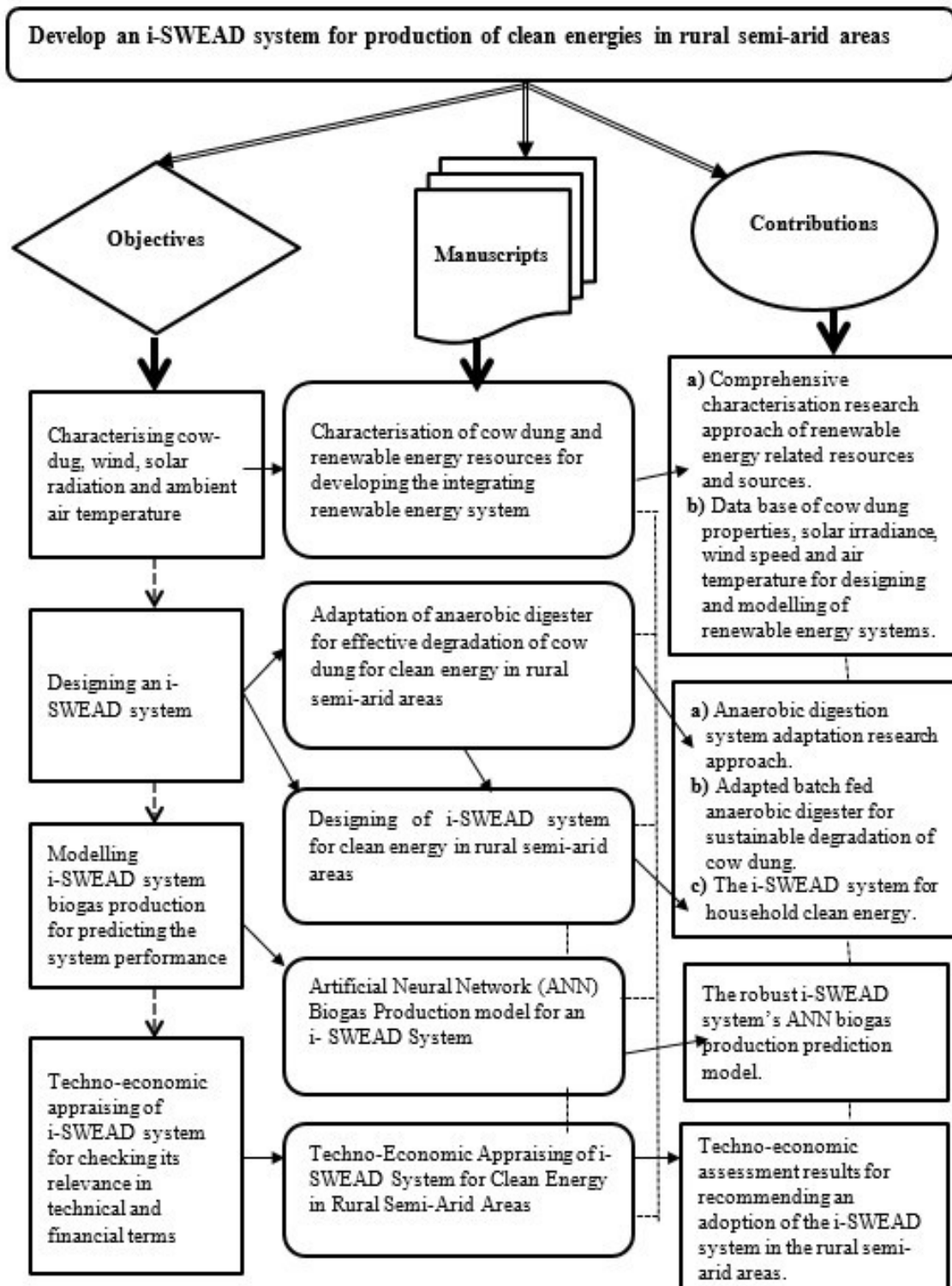
manuscripts and their contributions towards the main objective. Also, the chapter describes the methodology used to collect and analyse data.

All five publishable manuscripts emanating from this study are correspondingly presented in Chapter Two through Chapter Six of this thesis. The first manuscript entails information on how specific objective one of this study has been met, while the second and third manuscripts describe specific objective two. The fourth and fifth manuscripts respectively give the details of how specific objectives three and four of this study have been met.

The seventh, which is the last chapter presents the overall conclusions and recommendations. It focuses on the contribution of the i-SWEAD system to address the limited energy access in rural semi-arid areas affordably and efficiently. Recall that the i-SWEAD system is based on renewable energy resources and sources available in rural semi-arid areas. It is in this chapter a case is built for the award of the PhD degree.

### **1.8 Connection of Research Manuscripts and Their Contribution**

Figure 1.3 presents the connection between the research manuscripts for this study. The figure illustrates how the five manuscripts narrate fundamental contributions to generalised knowledge and critical scientific debates. These manuscripts were systematically written and presented to deliberately inform and benefit one another to accomplish the general objective of this study.



**Figure 1.3: Linkage and contribution of research manuscripts to the general objective of the study**

**1.9 References**

- Afridi, Z. U. R., and Qammar, N. W. (2020). Technical challenges and optimisation of biogas plants. *Chemical Biology Engineering Reviews* 7(4): 119-129.
- Barry, M. L., Steyn, H. and Brent, A. (2011). Selection of renewable energy technologies for Africa: Eight case studies in Rwanda, Tanzania and Malawi. *Renewable Energy* 36(11): 2845 – 2852.
- Bishoge, O., Zhang, L. and Mushi, W. (2018). The potential renewable energy for sustainable development in Tanzania: A review. *Clean Technologies* 1(1): 70 – 88.
- Boxwell, M. (2017). Solar electricity handbook. [<http://solarelectricityhandbook.com/solar-irradiance.html>] site visited on 19/03/2018.
- Cadenas, E. and Rivera, W. (2009). Short term wind speed forecasting in La Venta, Oaxaca, Mexico, using artificial neural networks. *Renewable Energy* 34: 274 – 278.
- Castellanos, J. G., Walker, M., Poggio, D., Pourkashanian, M. and Nimmo, W. (2015). Modelling an off-grid integrated renewable energy system for rural electrification in India using photovoltaics and anaerobic digestion. *Renewable Energy* 74: 390 – 398.
- Chandel, M., Agrawal, G. D., Mathur, S. and Mathur, A. (2014). Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city. *Case Studies in Thermal Engineering* 2: 1 – 7.
- Chetty, P. (2015). *Developing a conceptual framework*. [online] Project Guru.

Available at: [<https://www.projectguru.in/developing-conceptual-framework-in-a-research-paper/>] site visited on 20/01/2021.

Díez, H. E. and Pérez, J. F. (2017). Physicochemical characterization of representative firewood species used for cooking in some Colombian regions. *International Journal of Chemical Engineering*, 2017. [<https://www.hindawi.com/journals/ijce/2017/4531686/>] site visited on 25/10/2020.

Donoso-Bravo, A., Mailier, J., Martin, C., Rodríguez, J., Aceves-Lara, C. A. and Wouwer, A. V. (2011). Model selection, identification and validation in anaerobic digestion: A review. *Water Research* 45(17): 5347 – 5364.

Ebhota, W. S. and Inambao, F. (2016). Design basics of a small hydro turbine plant for capacity building in sub-Saharan Africa. *African Journal of Science, Technology, Innovation and Development* 8(1): 111-120.

Edwards, K. L. (2003). Designing of engineering components for optimal materials and manufacturing process utilisation. *Materials and Design* 24(5): 355 – 366.

Ellabban, O., Abu-Rub, H. and Blaabjerg, F. (2014). Renewable energy resources: Current status, future prospects and their enabling technology. *Renewable and Sustainable Energy Reviews* 39: 748 – 764.

Felix, M. and Gheewala, S. H. (2011). A review of biomass energy dependency in Tanzania. *Energy Procedia* 9(2): 338–343.

Ganoë, R. D., Stackhouse Jr, P. W. and DeYoung, R. J. (2014). *RET Screen Plus Software Tutorial. Technical Report*. Screen International Clean Energy Decision Support Centre, Ottawa, Canada. 42pp.

Grimsby, L. K., Gulbrandsen, L., Eik, L. O., Msalya, G. and Kifaro, G. C. (2016). The prospect of biogas among small-holder dairy goat farmers in the Uluguru Mountains, Tanzania. *African Journal of Food, Agriculture, Nutrition and Development* 16(1): 10723 – 10737.

- Gunther, F., and Fritsch, S. (2010). neuralnet: Training of neural networks. *The R Journal* 2(1): 30-38.
- Hirmer, S. and Guthrie, P. (2017). The benefits of energy appliances in the off-grid energy sector based on seven off-grid initiatives in rural Uganda. *Renewable and Sustainable Energy Reviews* 79: 924 – 934.
- Ikejemba, E. C., Mpuan, P. B., Schuur, P. C. and Van Hillegersberg, J. (2017). The empirical reality and sustainable management failures of renewable energy projects in Sub-Saharan Africa. *Renewable Energy* 102: 234 – 240.
- Jacob, T. (2017). Competing energy narratives in Tanzania: Towards the political economy of coal. *African Affairs* 116(463): 341 – 353.
- Jancewicz, K. and Szymanowski, M. (2018). *The Relevance of Surface Roughness Data Qualities in Diagnostic Modeling of Wind Velocity in Complex Terrain: A Case Study from the Śnieżnik Massif (SW Poland)*. In *Geoinformatics and Atmospheric Science*. Springer, New York. 136pp.
- Jørgensen, P. J. (2009). *Biogas-Green Energy. Planenergi and Researcher for a Day*. Faculty of Agricultural Sciences, Aarhus University. 34pp.
- Kaena, N. P. A. (2012). Guideline for choosing the best alternative solution for engineering academic projects. *Proceeding of the 2<sup>nd</sup> International Conference on Mechanical and Industrial Engineering - Engineering Innovations for Sustainable Development*. 16-17 February, 2012. Naura Springs Hotel, Arusha, Tanzania. pp. 218 – 227.
- Kandpal, T. C. and Broman, L. (2014). Renewable energy education: A global status review. *Renewable and Sustainable Energy Reviews* 34: 300 – 324.
- Karimov, K. S. and Abid, M. (2012). Biogas digester with simple solar heater. *IIUM Engineering Journal* 13(2): 109-119.

- Kashaigili, J. J., Mdemu, M. V., Nduganda, A. R. and Mbilinyi, B. P. (2013). Integrated assessment of forest cover change and above-ground carbon stock in Pugu and Kazimzumbwi forest reserves, Tanzania. *Advances in Remote Sensing* 2(1): 1 – 9.
- Kazem, H. A., Hamood, A. S., Al-Badi, A. S., Busaidi, A. and Miqdam. T. C. (2017). Optimum design and evaluation of hybrid solar/wind/diesel power system for Masirah Island." *Environment, Development and Sustainability* 19(5): 1761-1778.
- Khoury, J., Mbayed, R., Salloum, G., Monmasson, E. and Guerrero, J. (2016). Review on the integration of photovoltaic renewable energy in developing countries - Special attention to the Lebanese case. *Renewable and Sustainable Energy Reviews* 57: 562 – 575.
- Klasen, S. and Mbegalo, T. (2016). The impact of livestock ownership on solar home system adoption in the northern and western regions of rural Tanzania [<http://hdl.handle.net/10419/148393>] site visited on 03/02/2019.
- Krioukov, A., Goebel, C., Alspaugh, S., Chen, Y., Culler, D. E. and Katz, R. H. (2011). Integrating renewable energy using data analytics systems: challenges and opportunities. *Institute of Electrical and Electronics Engineers Data Engineering Bulletin* 34(1): 3 – 11.
- Langford, G. O. (2016). *Engineering Systems Integration: Theory, Metrics, and Methods*. CRC Press, Florida, USA. 406pp.
- Lauer, M. (2008). *Methodology Guideline on Techno Economic Assessment*. ThermalNet Meeting, Vienna. 25pp.
- Li, Y., Park, S. Y. and Zhu, J. (2011b). Solid-state anaerobic digestion for methane production from organic waste. *Renewable and Sustainable Energy Reviews* 15(1): 821 – 826.

- Lilford, E. (2020). Climate, thermal coal and carbon. *Resources and Environmental Economics* 2(1): 126-135.
- Maheshwari, Z. and Ramakumar, R. (2016). *Smart Integrated Renewable Energy Systems for Rural communities. In Power and Energy Society General Meeting*. Institute of Electrical and Electronics Engineers, Boston, USA. pp. 5pp.
- McCollum, D., Gomez Echeverri, L., Riahi, K. and Parkinson, S. (2017). Ensure access to affordable, reliable, sustainable and modern energy for all. [<http://pure.iiasa.ac.at/id/eprint/14621/1/SDGs-interactions-7-clean-energy.pdf>] site visited on 20/6/2018.
- Mélard, G. (2014). On the accuracy of statistical procedures in Microsoft excel 2010. *Computational Statistics* 29(5): 1095 – 1128.
- Mishra, S., Panigrahi, C. K. and Kothari, D. P. (2014). Design and simulation of a solar–wind–biogas hybrid system architecture using HOMER in India. *Ambient Energy* 37(2): 184 – 191.
- Moberg, J. P. (2001). *Soil and plant analysis manual. Revised Edition, the Royal Veterinary and Agricultural University*. Chemistry Department, Copenhagen, Denmark. 133pp.
- Mutabazi, K. D. (2013). *Identifying, Defining and Typologizing FVC and Upgrading Strategies*. Sokoine University of Agriculture, Morogoro, Tanzania. 57pp.
- Mwinuka, L., Schneider, I., Maeda, C., Mutabazi, K. D., Makindara, J., Graef, F., Sieber, S., Swai, E., Mbwana, H. and Swamila, M. (2015). Comparing stakeholder views for mutual acceptable food value chain upgrading strategies in Tanzania. *African Journal of Agricultural Research* 10(12): 1376 – 1385.
- NBS (2018). *National Environment Statistics Report*. Tanzania Mainland, Dar es Salaam, 186pp.
- Okoko, A., von Dach, S. W., Reinhard, J., Kiteme, B. and Owuor, S. (2018). Life cycle

- costing of alternative value chains of biomass energy for cooking in Kenya and Tanzania. *Journal of Renewable Energy* 3939848: 1 – 12.
- Olabanji, O. M. and Mpofu, K. (2014). Comparison of weighted decision matrix, and analytical hierarchy process for design of reconfigurable assembly fixture. *Procedia Centre d'Insertion et de Réinsertion Professionnelle* 23: 264 – 269.
- Oloche, B., Ozigi, I. I., Adeyemi, K. and Ikpe, E. (2017). Construction and Leakage Detection of a Dome-Type Biogas Digester in a Village at Abuja, Nigeria. *FUOYE Journal of Engineering and Technology* 2(1): 27-31.
- Oyedepo, S. O. (2014). Towards achieving energy for sustainable development in Nigeria. *Renewable and Sustainable Energy Reviews* 34: 255 – 272.
- Parida, B., Iniyar, S. and Goic, R. (2011). A review of solar photovoltaic technologies. *Renewable and Sustainable Energy Reviews* 15(3): 1625 – 1636.
- Peters, J., Combs, S. M., Hoskins, B., Jarman, J., Kovar, J. L., Watson, M. E., Wolf, A. M. and Wolf, N. (2003). *Recommended Methods of Manure Analysis*. Publication No. 3769. Cooperative Extension Publishing, Madison, USA. 55pp.
- Pratt, D. J. and Gwynne, M. D. (1977). *Rangeland Management and Ecology in East Africa*. In AGRIS, Hodder and Stoughton, London-UK. 320pp.
- Rajapaksha, A. U., Vithanage, M., Ahmad, M., Seo, D. C., Cho, J. S., Lee, S. E., Lee, S. S. and Ok, Y. S. (2015). Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar. *Journal of Hazardous Materials* 290: 43 – 50.
- Rajendran, K., Aslanzadeh, S., and Taherzadeh, M. J. (2012). Household biogas digesters —A review. *Energies* 5(8): 2911-2942.
- Randall, S., and Coast, E. (2015). Poverty in African households: the limits of survey and census representations. *The Journal of Development Studies* 51(2): 162-177.
- Rathore, P. K. S., Das, S. S. and Chauhan, D. S. (2018). Perspectives of solar photovoltaic water pumping for irrigation in India. *Energy Strategy Reviews* 22: 385-395.

- R-Core-Team (2018). R: A language and environment for statistical computing. Package *utils* version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria. [<https://www.R-project.org>] site visited on 20/2/2019.
- Salonen, M. and Perttula, M. (2005). Utilization of concept selection methods: A survey of Finnish industry. *Proceeding of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. 24-28 September, 2005, Long Beach, California, USA. pp. 527 – 535.
- Sarakikya, H., Ibrahim, I. and Kiplagat, J. (2015). Renewable energy policies and practice in Tanzania: Their contribution to Tanzania economy and poverty alleviation. *International Journal of Energy and Power Engineering* 4(6): 333 – 341.
- Silungwe, F. R., Graef, F., Bellingrath-Kimura, S. D., Tumbo, S. D., Kahimba, F. C., Lana, M. A. (2019). Analysis of Intra and Interseasonal Rainfall Variability and its effects on Pearl Millet Yield in a Semi-arid Agroclimate: Significance of Scattered Fields and Tied Ridges. *Water* 11(3): 1-17.
- Scheid, A., Hafner, J., Hoffmann, H., Kächele, H., Sieber, S. and Rybak, C. (2018). Fuelwood scarcity and its adaptation measures: an assessment of coping strategies applied by small-scale farmers in Dodoma region, Tanzania. *Environmental Research Letters* 13(9): 095004-095015.
- Sewsynker-Sukai, Y., Faloye, F. and Kana, E. B. G. (2017). Artificial neural networks: An efficient tool for modelling and optimization of biofuel production (A mini review). *Biotechnology and Biotechnological Equipment* 31(2): 221 – 235.
- Sirasani, K. and Kamdi, S. Y. (2013). Solar wind hydro hybrid energy system simulation. *International Journal of Soft Computing and Engineering (IJSCE)* Volume-2, Issue-6, ISSN: 2231-2307, 500-503.

- Subrahmanyam, J. B. V., Alluvada, P., Bhanupriya, K. and Shashidhar, C. (2012). Renewable energy systems: Development and perspectives of a hybrid solar-wind system. *Engineering, Technology and Applied Science Research* 2(1): 177-181.
- Szabó, S., Moner-Girona, M., Kougiyas, I., Bailis, R. and Bódis, K. (2016). Identification of advantageous electricity generation options in sub-Saharan Africa integrating existing resources. *Nature Energy* 1(10): 16 – 140.
- Teske, S., Morris, T. and Nagrath, K. (2017). 100% renewable energy for Tanzania access to renewable and affordable energy for all within one generation. [<http://hdl.handle.net/10453/118647>] site visited on 04/02/2019.
- Wald, L. (2007). Solar radiation energy (fundamentals). *Solar energy conversion and photoenergy systems, edited by Blanco, J and Malato, S, in Encyclopedia of Life Support Systems (EOLSS), Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, pp.UK, [<http://www.eolss.net>], 1.*
- Wawa, A. I. (2012). *The Challenges of Promoting and Adopting Biogas Technology in Semi-arid areas of Tanzania: The Case of Kongwa and Bahi Districts in Dodoma Region*. Thesis for Award of PhD Degree at The Open University of Tanzania. 211pp.
- Wenderott, J. (2016). US and African students unite around materials for sustainable energy at second. *Bulletin* 41(8): 632 – 633.
- Williams, N. J., Jaramillo, P., Campbell, K., Musanga, B. and Lyons-Galante, I. (2018). *Electricity Consumption and Load Profile Segmentation Analysis for Rural Micro Grid Customers in Tanzania*. In 2018 Institute of Electrical and Electronics Engineers (IEEE) Power and Energy Society (PES)/Industrial Application Society (IAS) Power Africa, Cape Town, South Africa. pp. 360 – 365.

Zubi, G., Spertino, F., Carvalho, M., Adhikari, R. S. and Khatib, T. (2017). Development and assessment of a solar home system to cover cooking and lighting needs in developing regions as a better alternative for existing practices. *Solar Energy* 155: 7 – 17.

## CHAPTER TWO

### **2.0 Characterisation of Cow Dung and Weather for the Development of the Integrated Renewable Energy System**

#### **Abstract**

The inefficient use of traditional biomass energy sources for cooking and scarce electricity for powering electric and electronic gadgets are prevalent challenges in most rural areas in the least developing countries. The challenges might be countered by researching mitigating energy systems, which use the locally available sources and resources. The comprehensive characterisation approach of renewable energy-related resources and sources is investigated. This chapter presents a comprehensive characterization approach formulated and the results based on the same approach. The characterisation results include locally available cow dung and weather energy-based resources at Idifu village located in the rural semi-arid area of central Tanzania. A sampling of cow dung at the study site followed by laboratory analyses was done. Solar irradiance, wind and ambient air temperature data were collected using a weather station installed at the study site and analysed. It was found that cow dung available had an average volatile matter of  $744.3 \pm 53.2$  g/kg of dry matter and a C/N ratio of 19.3. The area was found to have average solar insolation of above 4.5 kWh/m<sup>2</sup>/day for seven months a year, an average annual wind speed of 4.69 m/s at 4 m hub-height and the wind blowing predominantly from the direction of North East. Finally, it was found that the area has an ambient air temperature that varies by 4.04°C within a day. The results above indicate that the area has enough renewable energy resources and sources with the requisite quality. The characterisation

approach applied in this study is recommended to researchers and project developers engaged in renewable energy systems assessment and development.

**Keywords:** *biomass; characterise; integrated systems; renewable energy resources; weather*

## **2.1 Introduction**

Poor access to useful energies and their low utilization hinder the sustainable development of any community (Oyedepo, 2014; Mohammed *et al.*, 2013a). Such hindrances may be related to energy resources availability and energy infrastructure for harnessing as well as distributing it to a community. Also, they may be based on a lack of awareness of available energy technology to support access and utilization of energy to a community. The hindrances are handled differently between developed and developing countries (Vandaele and Porter, 2015). This study considered handling these deterrents in developing countries.

Most rural communities lack reliable access to energy for their domestic uses (Mohammed *et al.*, 2013a; Mohammed *et al.*, 2013b). Besides, in households of these communities, a large portion of energy consumption is taken by cooking activities. In contrast, the other is taken by lighting and powering of electrical and electronic gadgets. Moreover, the primary source used to cater for these energy needs is traditional biomass (fuelwood, charcoal and agricultural wastes), which is supported by fossil fuel, solar energy (mainly PVs) and rarely grid connection (Suberu *et al.*, 2013; REN21, 2017). These problems are augmented by low financial capability.

Heavy dependency on traditional biomass as the source of energy and rapid population growth have increased pressure on the dwindling forest stocks in the rural semi-arid areas,

especially in most agro-pastoral communities. Deforestation and land degradation are noted in these areas, for instance, in central Tanzania (Felix and Gheewala., 2011; Wawa, 2012).

Regarding the above-explained hindrances and challenges, several actors have put specific and holistic strategic measures in place, including researchers and policymakers (Bukari *et al.*, 2020; Scheid *et al.*, 2018). These measures aimed at improving availability, accessibility and adoption of energy for all deprived areas in Tanzania and elsewhere with similar conditions (Bekele and Tadesse, 2012; Wawa, 2012). Besides, researchers' works related to the preparatory stages of developing robust and innovative technological systems for the above-stated challenges have been reviewed intensively. Some researchers characterised weather factors and biomass to offer vital information in developing the innovative technological system for energy and other development issues (Zhou and Yang, 2016; Bekele and Tadesse, 2012; Haluschak, 2006; Peters *et al.*, 2003). However, a comprehensive characterisation of renewable energy-related resources and sources research approach has not been investigated.

Weather data may be collected from remotely sensed information systems, meteorological stations and weather stations installed at the micro-scale level, e.g. a village. In most cases, the remotely sensed data is, in coarse spatial resolution, say, 1° x 1° global grid. The coarse spatial resolution does not precisely capture the weather factors' data like wind data at the microclimate level because of topographical features (Suri *et al.*, 2008; Johnston and Matlock, 2011). Meteorological stations are scattered in most of the developing countries but do not cover much of the rural areas. However, weather stations installed at the micro-scale level collect useful and precise data for designing renewable energy systems. In most

cases, they offer high temporal and spatial resolutions data. Nevertheless, with a lack of precise data, the former two data collection means can be considered.

The data collection and characterisation of weather factors and biomass are essential, as their obtained results are essential in designing and modelling the integrated renewable energy system. These systems may involve solar, wind, and biogas technology. Specific primary data needed for the designing and modelling are not readily available in the rural central region of Tanzania at the micro-scale level. The primary data included solar radiation, wind speed, and ambient temperature at the maximum one-hour interval. The one-hour interval enhances the visualization of variation of weather parameters, which influence the performance of renewable energy systems, e.g. biogas plants, solar PV systems and wind turbines. Information on qualities of cow dung for biogas technology in rural semi-arid areas is not available.

Therefore, a vital area of this study was to formulate and apply a comprehensive characterisation approach, which is useful for assessing the quantity and quality of the locally available renewable energy resources and sources. The renewable energy sources are solar radiation and wind, while the resource is cow dung. Assessment results of these resources and sources were intended to be used for developing and modelling the integrated renewable energy system. The system was to be installed at an individual household of rural semi-arid central Tanzania, aiming at producing biogas for cooking under ideal constant temperature and generation of electricity.

This chapter presents a comprehensive research characterization of renewable energy resources and sources approach and the findings based on the same approach. The findings

are comprehensively detailed, and they are useful for developing and modelling the intended integrated renewable energy system (IIRES) installed in rural semi-arid areas of central Tanzania. The IIRES was for countering some of the fore-mentioned energy-related hindrances and challenges in the communities dwelling in rural semi-arid areas.

## **2.2 Materials and Methods**

The study site and comprehensive research characterization of the collected biomass (cow dung) and weather parameters approach at the study site are explained in this section. The approach is detailed in Sub-sections 2.2.2 and 2.2.3. The findings based on the fore mentioned approach are presented and discussed in Sections 2.3 and 2.4.

### **2.2.1 The study site**

The research was conducted at Idifu village located in Chamwino district in the Dodoma region in Tanzania. The study site is described in detail in Chapter One, Subsection 1.7.1. Moreover, the study involved the laboratory analysis of biomass (cow dung). The cow dung sample analysis was done in the laboratories of the Departments of Animal Science and Soil Science and Geology at Sokoine University of Agriculture (SUA), located in Morogoro, Tanzania, 301 km South-East of the study site.

### **2.2.2 Cow dung characterization**

Quantification of potential cow dung minimum amount, which can be collected for biogas generation at the study area, was done. The cow dung amount was estimated using Equation 2.0. The secondary data were used during estimation. The data from Kahimba *et al.* (2015) and Mwinuka *et al.* (2015) showed that the study area has 234 households owning cattle and on average, each household own ten cattle. This makes the total number of cattle in the area to be 2340.

$$CD_{\min} = P_{CD_c} \times CD_{ac} \times P_{ac} \times T_{hc} \dots\dots\dots \text{Eq.2.0}$$

Where  $CD_{\min}$  is the minimum potential amount of cow dung collected per day ( $\text{kg}\cdot\text{day}^{-1}$ );  $P_{CD_c}$  is the percentage of cow dung collected based on the type of grazing system of cattle, it was taken as 60%, (%);  $CD_{ac}$  is the amount of cow dung excreted by an adult cattle in a day ( $\text{kg}\cdot\text{adult-cattle}^{-1}\cdot\text{day}^{-1}$ );  $P_{ac}$  is the percentage of adult cattle in the study area (%), and  $T_{hc}$  is the total number of cattle in the study area (-).

Zhu *et al.* (2020) revealed that 40% of cow dung is lost to the grazing area in semi-arid areas of East Africa when the half-stable grazing system of keeping cattle is used. This system is used in the study area. Also, Zhu *et al.* (2020) reported that adult cattle could produce 25 kg of cow dung and 21 litres of urine per day. Realistic quantification of cow dung amount was based on the assumption that the herd of cattle has 75% of adult cattle. Therefore, the amount of cow dung obtained using Equation 2.0 was the minimum of the total possible amount of cow dung, which can be collected in the study area.

Samples of cow dung for laboratory analysis were collected from 35 households in the study area. The households involved in the purposive survey were selected based on owning at least two cattle. Cattle ownership was depicted from secondary data of baseline survey conducted by Trans-SEC project between January and February 2014 as reported by Mwinuka *et al.* (2015) in the scope area of the project, including the study area.

The household sample size was computed using the online open-source statistical calculator, the OpenEpi-SSPropor version 3 (Sullivan *et al.*, 2009). The input data to the statistical calculator were population size (234 households), hypothesized percentage frequency of outcome factor in the population ( $30\pm 5\%$ ), confidence limits (5%) and design effect factor value (0.3). The researcher set the population size and confidence limits,

while the remaining input data were default set by the calculator. The results obtained from the calculator included the 35 households as the sample size at a 90% confidence level. The sample size was selected, as the confidence level was adequate for this study. The sample size includes at least one household selected randomly from each of seventeen sub-villages of Idifu village (the study site) with ownership of at least two cattle to make a fair representation of the administrative units.

Sampling of cow dung was done as per the sampling technique and procedures of solid manure recommended by Peters *et al.* (2003), which stresses the homogeneity of the sample from the stockpile of cow dung. The homogeneity is ensured by taking ten sub-samples from different locations around the pile at least 45 cm below the surface. The sub-samples are mixed to form a composite sample weighing 450 g, which is then kept in a plastic zip-lock bag after squeezing out entrapped air.

In this study, after sampling, samples were sealed inside a double-walled plastic bag, kept at a temperature below 4°C in a cold conditioned container. Low temperature inhibited the biodegrading of the samples. Then the samples were transferred to the laboratories at SUA in Morogoro within 19 hours. The 19 hours' period is below the maximum holding time of seven days recommended period for samples at 4°C before specific analysis (Peters *et al.*, 2003). The analytical results obtained were compared with published results of samples from feedstock used for biogas technology aiming at checking whether the available cow dung at the study site qualifies to be the feedstock for an IIRES involving biogas production. The physicochemical analyses of the cow dung samples are described in the following subsections.

#### **i. Determination of Organic Carbon (OC) by wet titration**

Organic Carbon determination of cow dung samples was done using the adapted Walkley-

Black chromic acid wet oxidation method (Moberg, 2001). Furthermore, four samples from the same batch were analysed.

## **ii. Determination of Organic Nitrogen (ON) and other cow dung properties**

The Organic Nitrogen (ON) or total nitrogen, ammonium nitrogen ( $\text{NH}_4\text{-N}$ ) and pH of cow dung samples were determined by the standard method illustrated by Peters *et al.* (2003). However, moisture content (MC), dry matter (DM) or total solids, volatile Matter (VM) or volatile solids and ash content were found by use of the standard method described by García *et al.* (2012). The Carbon Nitrogen ratio (C/N) was computed by dividing the values of OC with Organic Nitrogen on a mass basis (Yadav *et al.*, 2013). The four samples from the same batch of cow dung were used to analyse each cow dung property mentioned.

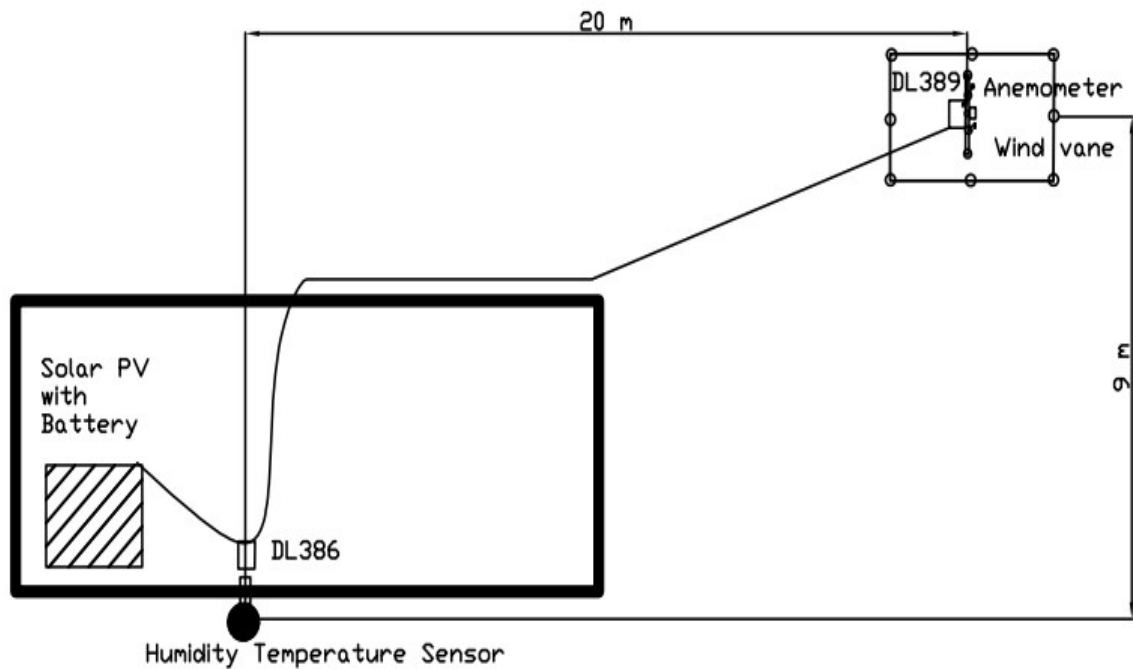
### **2.2.3 Weather parameters characterisation**

The weather parameters considered in this study are solar irradiance, wind speed, wind direction and ambient air temperature. The parameters' data were obtained from a weather station, which was installed at the study site. The data was collected from 1<sup>st</sup> December 2016 to 31<sup>st</sup> January 2018. However, data from 1<sup>st</sup> January 2017 to 31<sup>st</sup> December 2017 was considered, while data out of this range were used for comparison purposes. The weather station for data collection consists of the following devices:

- i. A pair of Umwelt-Geräte-Technik GmbH (UGT) Pyranometer CMP 3 with measuring range of 0.00-2000.00 W / m<sup>2</sup>, sensitivity of 5 - +20  $\mu\text{v}$  / W / m<sup>2</sup>v, & spectral range of 0.31 - 2.8  $\mu\text{m}$ , accuracy of 0.01 W/m<sup>2</sup> and UGT data-logger with designation of DL 389 ([www.ugt-online.de](http://www.ugt-online.de)) set to sample solar radiation values after one hour intervals;
- ii. Seeeduino Stalker Microcontroller Version 2.3 interfaced with a computer by use of Arduino software Version 1.0.5-r5 and set to sample wind speed (m/s) from an

- anemometer with an accuracy of 0.01 m/s and wind direction (degree) from a wind vane with the accuracy of 0.5° at 30 minutes' intervals (Kiobia, 2015), and
- iii. UGT Humidity and temperature (thermocouple Type-K) sensor with Relative Humidity (RH) measuring range of up to 100%, humidity accuracy of  $\pm 2\%$  and temperature measuring range of  $-30.00 - +70.00^{\circ}\text{C}$  with the accuracy of  $0.01^{\circ}\text{C}$ . It is connected with UGT DL 386 data logger. The sensor was set to sample ambient air temperature values at the one-hour interval.

The weather station was powered by a solar PV module (30 Wp) with a backup battery system of 12V- 14Ah. The layout of the weather station is shown in Figure 2.1.



**Figure 2.1: Layout of the installed weather station at the study site**

The detailed procedures for characterising the above weather parameters are illustrated in the subsequent parts of this sub-section.

#### **i. Solar radiation characterisation**

The solar radiation measurements were downloaded from the UGT data logger (DL 389),

cleaned and computed to the hourly average, maximum and minimum solar irradiance daily. The solar irradiance trends from remotely sensed information systems do not differ much from those collected on the ground (MNRC, 2015). Therefore, it was relevant to use the secondary data from a different source to get the monthly average insolation prevailing at the study site. The criteria of choice of secondary data source were that data should have been collected for more than ten years and are immediately freely available online or offline. Two sources were selected based on these criteria. They include Solar Electrical Handbook data and Ret-Screen plus data. On plotting data from these sources, they were overlapping with each other. Therefore, the average value of insolation data from these sources was found and plotted. This average data was taken as insolation data for the study site. The insolation data was checked for validity in terms of the trend using data collected at the study site in the specified period. Wald (2007) described the formula used to convert monthly solar irradiance data, which was collected at the study site, into monthly solar insolation. The formula is shown in Equation 2.1.

$$I = Sr_a \times h_d \quad \dots\dots\dots \text{Eq. 2.1}$$

Where ***I*** is monthly average insolation (kWh/m<sup>2</sup>/day), ***Sr<sub>a</sub>*** is the monthly average solar irradiance based on recorded daily data in the specific month at the study site, and ***h<sub>d</sub>*** is an assumed monthly average daily hours of bright sunshine, i.e. 9 hours, at the study site for each month.

Note that the Solar Electrical Handbook data is based on over 22 years up to 2017 (temporal coverage) to provide monthly (temporal resolution) average insolation. Its spatial coverage is global; the spatial resolution was not given (Boxwell, 2017). RetScreen Plus data is based on the available parameter of insolation on a horizontal surface at

temporal coverage ranging from July 1983 to the near present. Also, it has a daily temporal resolution. Furthermore, its spatial coverage is global, while its spatial resolution is  $1^\circ \times 1^\circ$  (Johnston and Matlock, 2011). The lowest monthly average insolation was set as design insolation for computing the minimum energy harnessed by the solar PV panel. The solar PV unit was intended for solely generating electricity for powering electric and electronic gadgets in the household. Also, the design insolation was used in predicting the amount of heat energy to be collected by other energy systems involving temperature-sensitive microorganisms. The design heat energy collected or designed electrical energy produced by the IIRES's solar PV panel was computed using Equation 2.1(a) with an assumed solar collector area of  $1 \text{ m}^2$ .

$$H_c = 0.67 Y_d \times I \dots\dots\dots 2.1(a)$$

where  $H_c$  is the design heat energy collected or designed electrical energy produced by the IIRES's solar PV panel,  $Y_d$  represents days in a year, i.e. 365 days,  $I$  is the design insolation, and 0.67 is an intuitively assumed factor, which takes care of days in a year when the sun is available to generate solar radiation at the study site; usually, sunshine is guaranteed between April and November (<https://en.climate-data.org/>).

Also, annual heat energy collected was determined using Equation 2.1(a). In this equation, the design insolation was replaced by annual average insolation. The annual average insolation was based on the average values of monthly insolation from secondary data sources. Therefore, characterising solar irradiance was important for designing an IIRES for rural semi-arid areas of central Tanzania, which will involve a solar energy component.

## ii. Wind speed and wind direction trends

The Seeeduino Stalker microcontroller was used to store wind speed and wind direction data from the anemometer and wind vane. Then wind speed data was downloaded, cleaned and transformed, averagely, from 30 minutes' intervals into one-hour intervals. However, wind direction data was not transformed. After that, the transformed wind speed data was used to determine hourly and monthly average, maximum and minimum wind speeds. The Ret-Screen Plus wind speed data source was used for extracting the monthly average wind speed of Dodoma. Dodoma Region is where the study site is located. This data was used for comparison reasons. The monthly average wind speed data was used to compute the annual wind speed at the study site from both sources of data. The Weibull cumulative distribution function (Bidaoui *et al.*, 2019) was used to determine the probability of wind speed events equal to or above the annual average wind speed at the study site using the experimental data. The details of this function and guiding formula are presented in Chapter Four, Sub-section 4.2.6 (v) of this thesis. All data determined were plotted.

Moreover, the wind direction data was used to generate the wind roses, which show the predominant wind blowing directions in monthly and wind speed bins, i.e. wind speed intervals, at the study site. They are expressed in wind speed (m/s) and frequency percentage (%). The anemometer and wind vane were installed at the height of 2.5 m to capture data under the influence of pearl millet canopy (maximum height around 2.5 m) during the cropping season and during off cropping season (Kanyeka *et al.*, 2007). This is because the IRES intended to be installed in the rural semi-arid area of central Tanzania was supposed to include a wind turbine with a hub height of around 4 m.

The hub height is low regarding the 10 metres used to capture the wind measurement data. Also, most of the wind data for wind turbine design is referenced at 10 m high above the ground. However, 4 m hub height was chosen to take the advantage that most of the time

throughout the year, the study site has short grasses, which may not affect the wind regime. Also, the same hub height was assumed to reduce the cost of the system to be installed. The guiding formula was used for the extrapolation of data from 2.5 m to 4 m hub height. The extrapolation formula applied was the power-law based formula. It is represented by Equation 2.2 (Safari and Gasore, 2010). The extrapolation of unknown wind speed ( $v$ ) in m/s at a given level of height ( $Z$ ) in metre from reference height ( $Z_0$ ) in metre with known wind speed ( $v_0$ ) in m/s above ground may be computed by Equation 2.2.

$$v = v_0 \left( \frac{Z}{Z_0} \right)^\alpha \dots\dots\dots \text{Eq.2.2}$$

where  $v_0$  is the wind speed measured at anemometer height  $Z_0$ ,  $v$  is the wind speed to be calculated at the height  $Z$ ,  $\alpha$  is the power-law exponent depending on the surface roughness and was obtained using Equation 2.2a (Bidaoui *et al.*, 2019, Elamouri and Amar, 2008 ).

$$\alpha = (0.37 - 0.088 \ln v_0) / z \dots\dots\dots \text{Eq. (2.2a)}$$

Note that the lowest, highest average monthly wind speed and maximum (gale) wind speed were essential parameters derived from the collected wind speed data. They were useful for conceptual designing of the wind turbine system to generate energy.

**iii. Ambient air temperature trends**

The procedure described in part (i) was used for downloading data from the UGT data logger (DL 386), cleaning and determining both hourly and monthly averages, maximum and minimum ambient air temperature. However, secondary data was not considered for

this case. The ambient air temperature data is vital as temperature influences the biogas microbes' performance to generate biogas in the anaerobic digestion systems (Schnurer and Jarvis, 2010). As the IIRES was supposed to incorporate a unit for anaerobic digestion of cow dung, characterising this weather parameter data at the study site was crucial.

## **2.3 Results and Discussion**

Based on the methodological approach explained in Section 2.2, results were obtained as presented in this section. The results include cow dung sample properties and weather parameters.

### **2.3.1 Availability of cow dung and its properties**

Quantification of the amount of cow dung using Equation 2.0 showed that there is a potential availability of a minimum of 26,330 kg of cow dung to be collected per day in the study area. Assuming about 20% biogas is generated from one kilogramme of cow dung and the biogas' density is  $1.15 \text{ kg/m}^3$ , then the available cow dung per day at the study area can generate about  $4,600 \text{ m}^3$  in a day. Also, the cooking stove can be kept on for more than 85 days using the amount of biogas collected in one day. The value of 85 days is derived conversion of a number hours into days by dividing the hours by 24. The number of hours is obtained by multiplying of assumed  $0.45 \text{ m}^3/\text{h}$  biogas flow rate of the cooking stove and the potential biogas amount obtained per day.

The characterisation results of cow dung sample properties revealed that cow dung's volatile matter (VM) and cow dung carbon-nitrogen ratio (C/N) was  $744.25 \pm 53.20 \text{ g/kg}$  of dry matter and  $19.30 \pm 0.56$ , respectively. These properties fall within the ranges of 60% to 89% on a dry matter basis and 15 to 30 for VM and C/N, respectively, which are suitable for feedstock (cow dung) utilized in biogas generation as argued by Weiland

(2010) and Raposo *et al.* (2012). Moreover, other important cow dung parameters characterised, and their results are presented in Table 2.1.

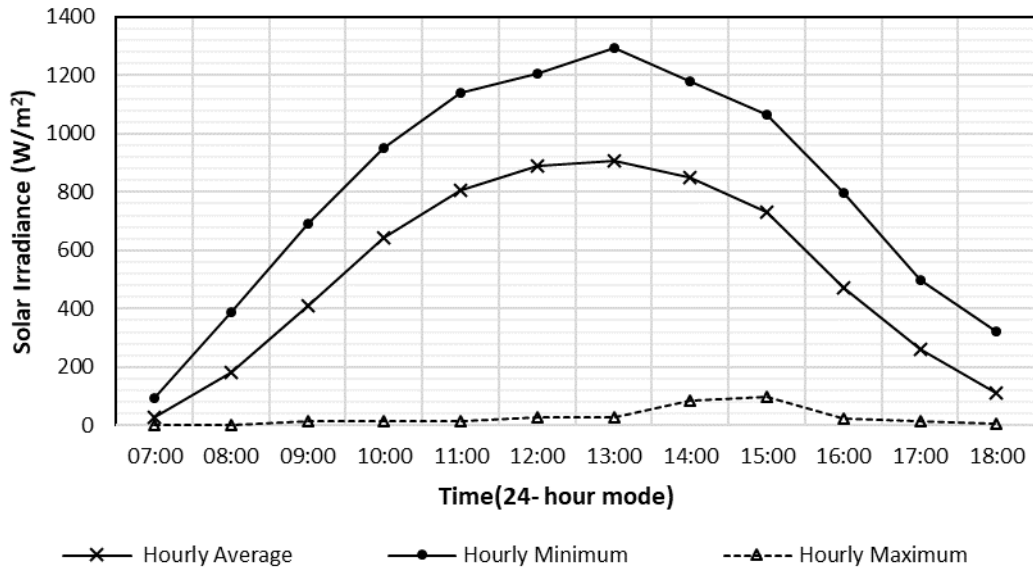
**Table 2.1: Laboratory analysis results of the sampled cow dung**

<b>Property</b>	<b>Amount found</b>	<b>Standard deviation</b>	<b>Number of samples</b>
Moisture content (MC)	77.11 %	0.52%	4
Dry matter (DM)	228.93 g/kg of feed	5.21 g/kg	4
Volatile matter (VM)	744.25 g/kg of DM	53.20 g/kg	4
Organic nitrogen (N)	2.24 % by TKN in DM	0.09 %	4
Ammonium Nitrogen (NH <sub>4</sub> -N)	21.06 % in DM	0.64 %	4
Organic carbon ( C )	43.37 % in DM	2.87%	4
pH	6.90	0.04	4
Carbon Nitrogen ratio (C/N ratio)	19.30	0.56	4
Ash Content	21.20 %	5.35 %	4

The cow dung characteristic results indicate that quality feedstock is available at the study site. The findings justify the establishment of IIRES involving biogas technology in the region.

### 2.3.2 Weather characteristics

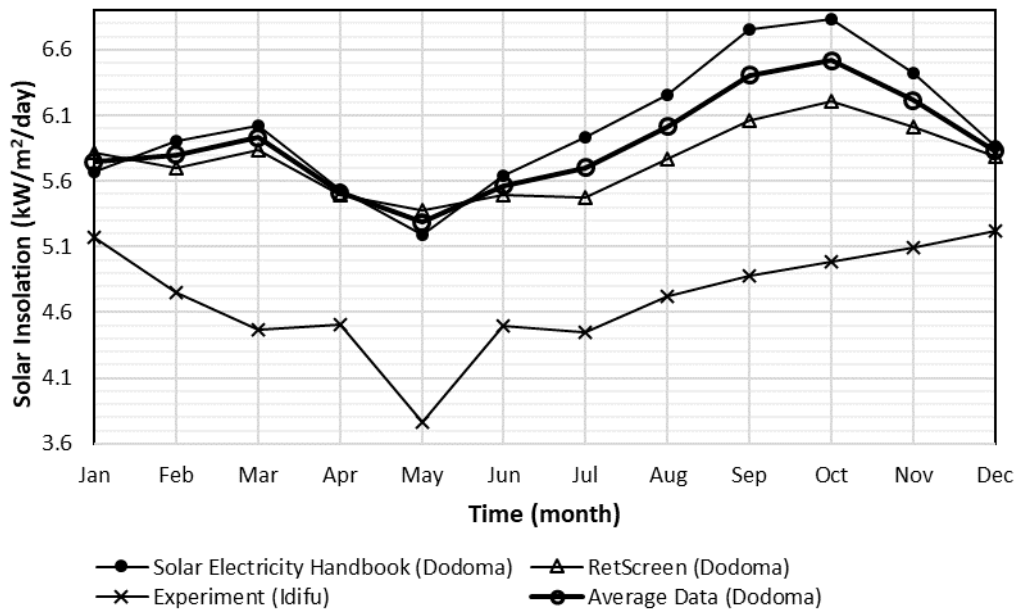
The weather parameters assessed include solar irradiance, wind speed, wind direction and ambient air temperature. The solar irradiance analysis results are presented. The first daily result item consists of hourly average, hourly maximum and hourly minimum solar irradiance, illustrated in Figure 2.2 for the year 2017. This figure shows that the maximum solar radiation values in a day reached 1280 W/m<sup>2</sup> at 13:00 hours; also for five hours, i.e. 10:30-15:30 hours, the maximum solar irradiance was above 1000 W/m<sup>2</sup>.



**Figure 2.2: Hourly average, maximum and minimum solar irradiance for the year 2017**

Besides, the hourly average solar irradiance was above 200 W/m<sup>2</sup> for nine hours on a day, while the hourly minimum solar irradiance was 25 W/m<sup>2</sup> for three hours in a day. However, comparative data of the Dodoma region, from other researchers, on hourly solar irradiance, aggregated daily, were not available.

The second result item includes the monthly average solar irradiation or monthly average insolation based on primary and secondary data, as shown in Figure 2.3. This figure reveals that the monthly average solar insolation was minimum in May for all three sources of experimental, Ret-Screen and Solar Electrical Handbook data with values of 3.76 kWh/m<sup>2</sup>/day, 5.38 kWh/m<sup>2</sup>/day and 5.19 kWh/m<sup>2</sup>/day, respectively. The average solar insolation was 5.29 kWh/m<sup>2</sup>/day. It was based on secondary data sources and taken as the design solar insolation at the study site. The value is found in the curve of Average Data (Dodoma) [ADD] in Figure 2.3.

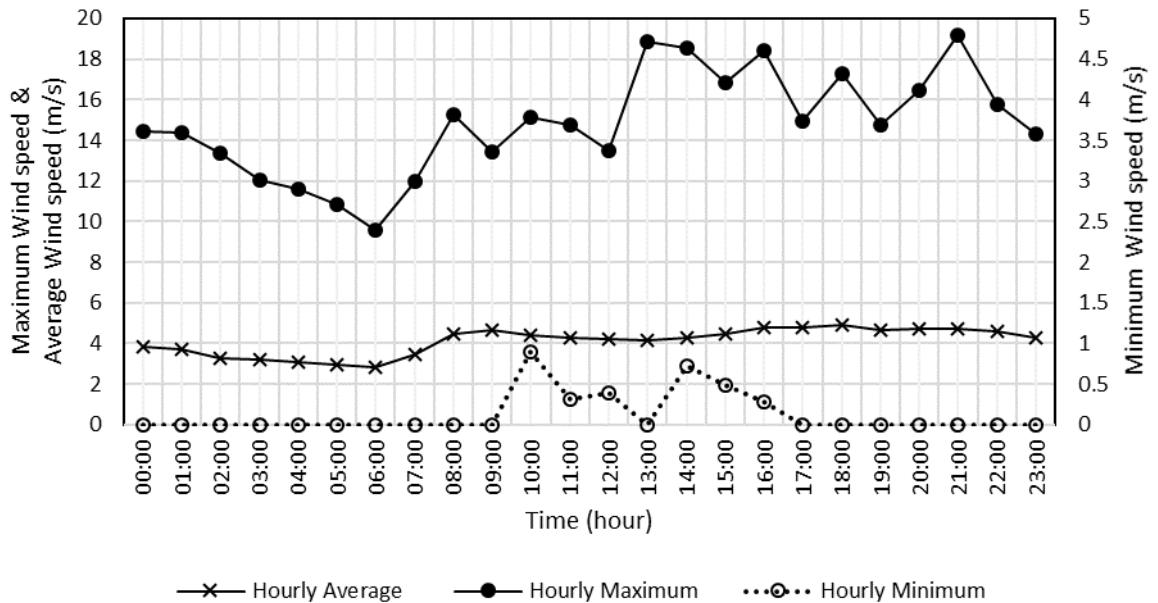


**Figure 2.3: Monthly average solar radiations at the Study site (Jan-Dec 2017)**

The annual average solar insolation based on ADD and experimental data was 5.88 kWh/m<sup>2</sup>/day and 4.78 kWh/m<sup>2</sup>/day, respectively. The difference between these values is almost 23%, which is enormous. This enormous difference is because of the change of computation procedures of monthly average insolation, which produced these values, as explained in Sub-section 2.2.3 (i). The 5.88 kWh/m<sup>2</sup>/day value was taken as the annual average solar insolation of the study site. The revealed information indicates that solar radiation is abundant, and with these values, it can be harnessed.

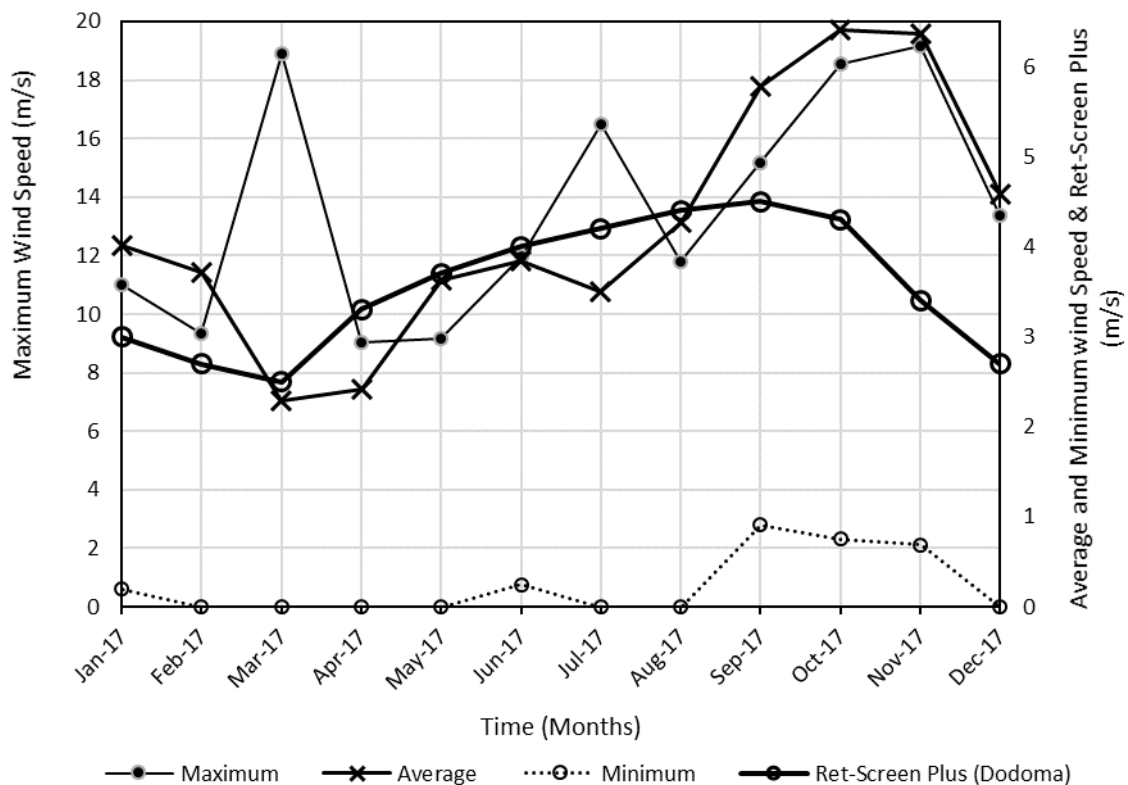
Equation 2.1(a) gives design solar insolation and annual average solar insolation values obtained at the study site. They were used to produce the design heat and average annual heat to be collected at the study site. The design heat and averagely heat collected at the study site were 1.29 MWh and 1.44 MWh. This procedure was adopted to find the designated electrical energy produced by the assumed IIRES's solar PV panel with 1 m<sup>2</sup> and efficiency of 13%. The value obtained was 168.17 kWh.

In the case of wind speed, the hourly and monthly average, maximum, and minimum daily wind speeds are presented in Figures 2.4 and 2.5.



**Figure 2.4: Hourly average, maximum, and minimum wind speed (Jan.-Dec. 2017)**

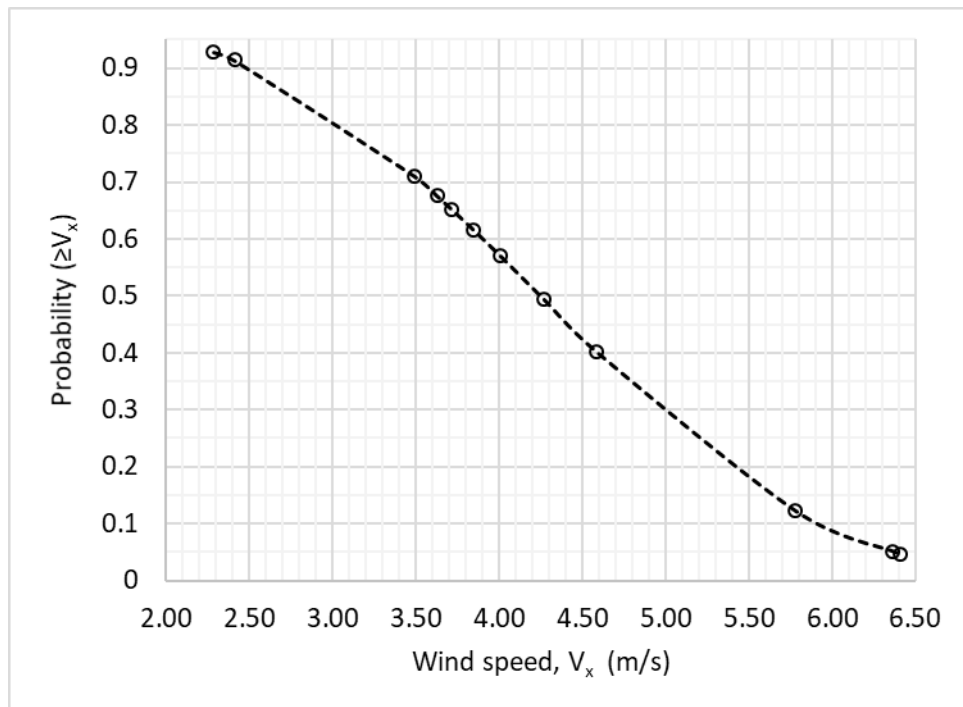
Figure 2.4 shows that the average wind speed was above 4 m/s for 16 hours from 7:30 hours. The maximum wind speed of 19.15 m/s was recorded at 21:00 hours. Also, for some of the days, there was no event of wind speed (0 m/s), i.e. the anemometer was at a standstill for seven hours a day by considering the minimum wind speed values from 9:30 hours to 16:30 hours, except at 13:00 hour. Furthermore, in most cases, the lowest average wind speed of 2.83 m/s was recorded in the morning at 6:00 hours.



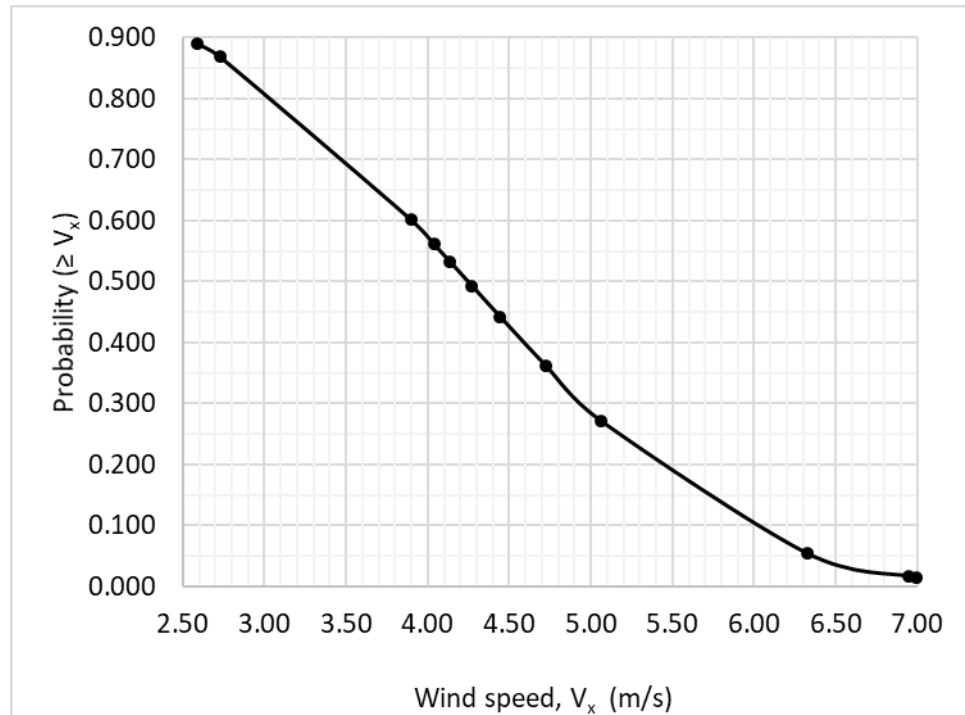
**Figure 2.5: Experimental testing and Ret-Screen Plus monthly wind speed data in 2017**

Figure 2.5 shows that the experimental monthly average wind speed was above 4 m/s from August through December. However, in the same figure, the Ret-Screen Plus wind speed data indicate that wind speed was above 4 m/s in June through October. The gale (wind speed above 16 m/s in this case) occurred in March, July, October and November by referring to maximum wind speed data in Figure 2.5. In some of the days of December through May and July and August, wind speed events of 0 m/s were occurring. Generally, the study site has a predominant wind speed which averagely falls in a range of 4-6 m/s. The lowest average monthly wind speed was recorded in March with a 2.29 m/s value. It is close to that of the Ret-Screen Plus data, which indicated that the lowest monthly wind speed was 2.5 m/s in March. Therefore, it shows that the experimental data are reliable as they fall into the same data trend produced by a proven institution.

The experimental monthly wind speed data were used to extrapolate the monthly wind speed at 4 m hub height. The Weibull cumulative distribution analysis of data at hub heights of 2.5 m and 4 m was done and the results obtained are shown in Figures 2.6 and 2.7, respectively. A cut-in wind speed range of 3.00 - 4.00 m/s is for small wind turbines based on Arnett *et al.* (2013) research work article. Assuming the IIRES will incorporate a small wind turbine with a cut-in wind speed just above 4 m/s, say 4.45 m/s; then from Figures 2.6 and 2.7, the probability of having events of wind speed equal to or above 4.45 m/s at 2.5 m and 4 m hub-height in a year will be the same, which is 0.441. This probability value indicates that the system operating above that wind speed may need to be integrated with other systems for generating energy at the probability value of above 0.5. The 4.45 m/s may be taken as the design wind speed for further engineering design works.



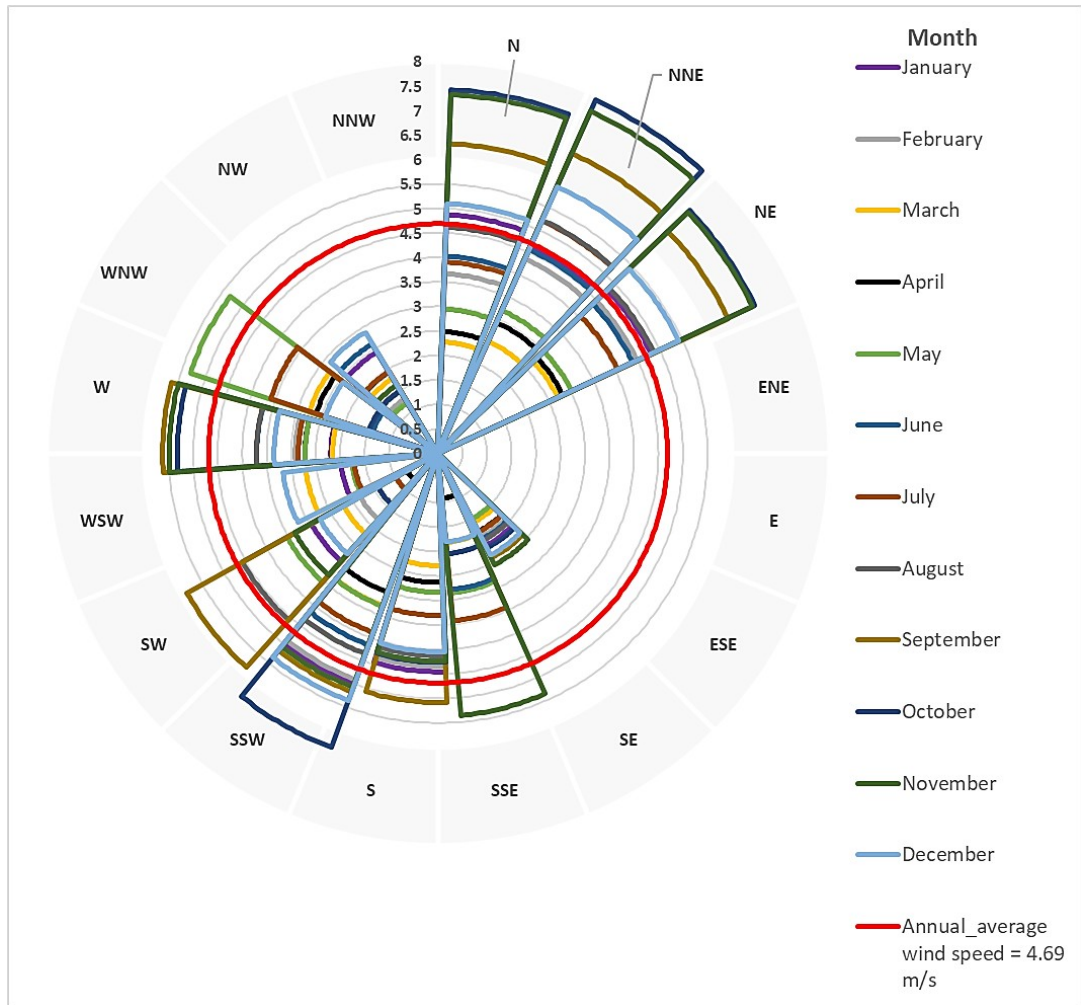
**Figure 2.6: Weibull cumulative distribution analysis results of wind speed at 2.5 m hub height in 2017**



**Figure 2.7: Weibull cumulative distribution analysis results of wind speed at 4.0 m hub height in 2017**

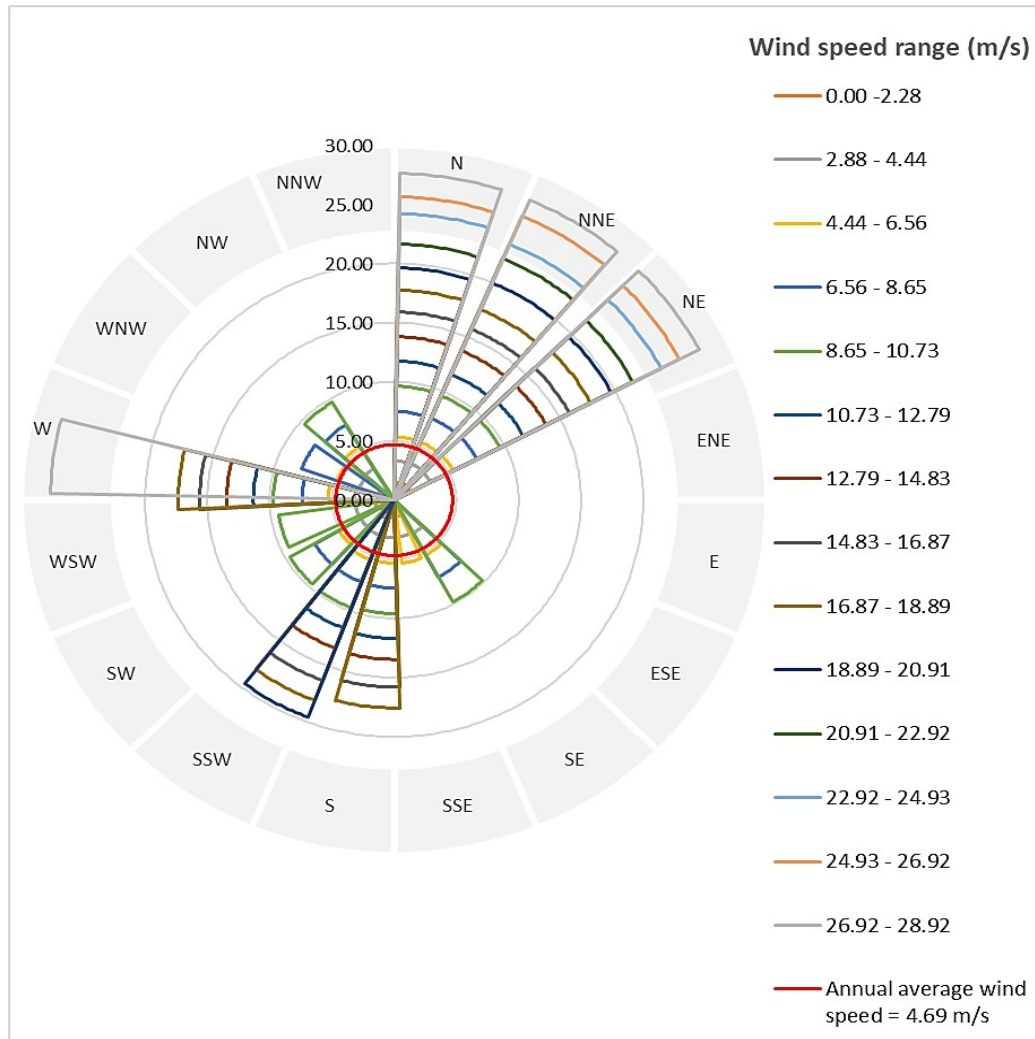
All wind speed data collected in a year at the study site were used to generate the wind roses. The wind roses were derived from the extrapolated wind data at 4 m hub height, referenced from 2.5 m hub height. The wind roses present the wind direction data at the study site.

The average wind speed in a given month and wind speed against the wind direction are presented in Figures 2.8 and 2.9, respectively. The frequencies of wind blowing directions in percentage at a given month and wind bin against wind direction are presented in Figures 2.10 and 2.11, respectively.



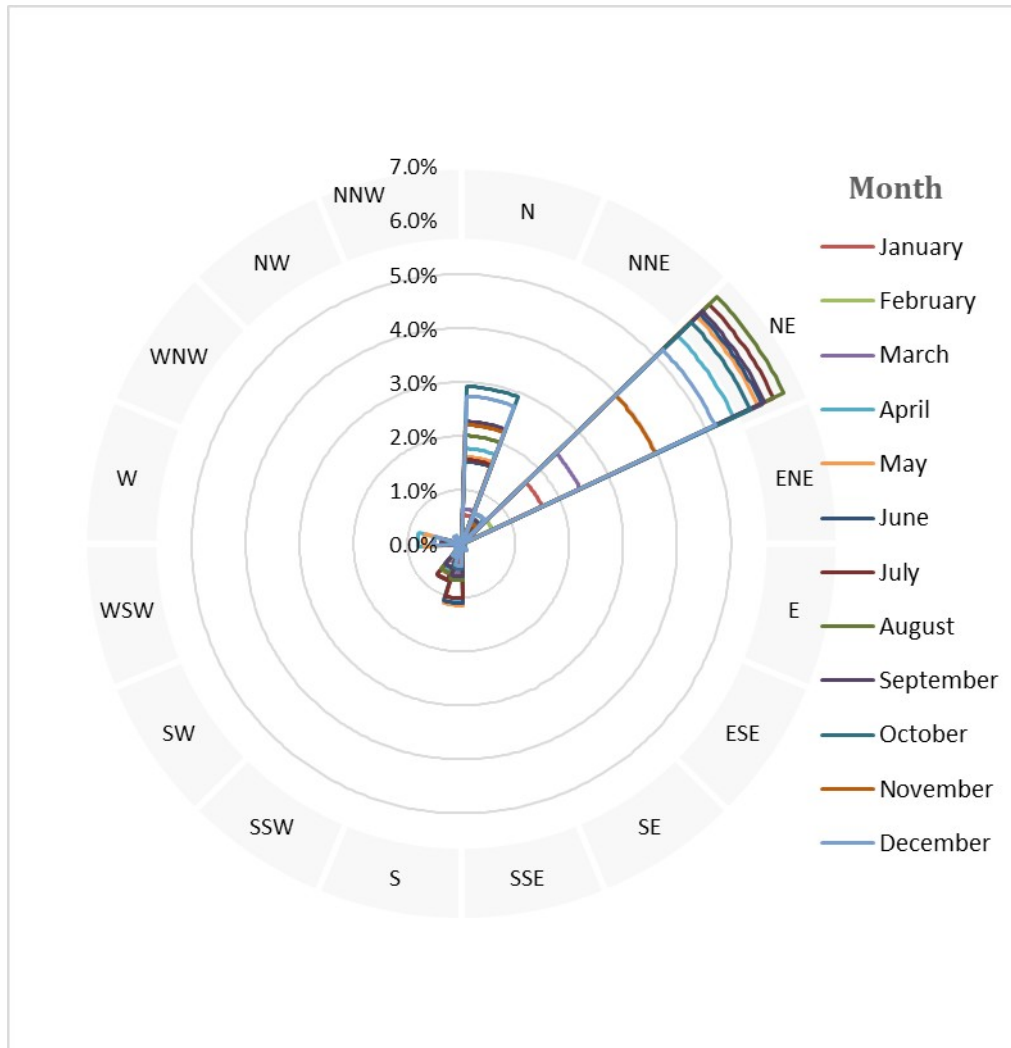
**Figure 2.8: Average wind speeds in a month per wind direction at 4 m hub height in 2017**

Figure 2.5 showed that wind speed is above 4 m/s and high in months June through October. During these months, Figure 2.8 shows that wind was blowing from the ranges of the direction of North (N) to North East (NE) and South (S) to South West (SW), clockwise. Also, it blew from the West (W) direction. The wind speed in these directions at 4 m hub height was blowing at an above annual average wind speed of 4.69 m/s.



**Figure 2.9: Wind speed bin's average wind speed per wind direction at 4 m height in 2017**

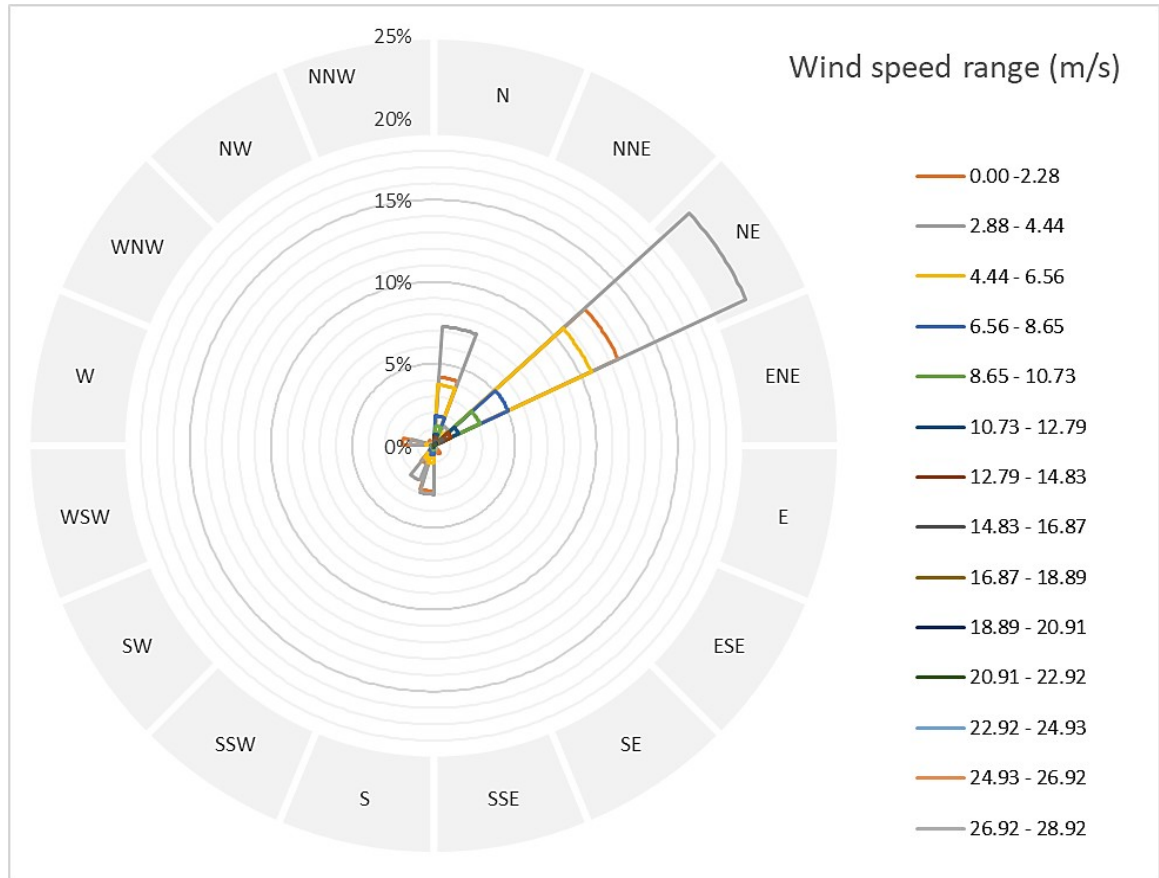
Figure 2.9 shows that the annual average wind speed (4.69 m/s) falls in the wind speed bin of 4.44-6.56 m/s at 4 m hub height. This wind speed bin occurs in the following ranges of directions, clockwise: North (N) to North East (NE) and South East (SE) to South West (SW). Also, from the same figure, the wind blew from the West (W) and West North West (NW) direction.



**Figure 2.10: Monthly wind blowing events' percentage frequency per wind direction in 2017**

The frequency percentage of direction from which wind blows monthly at the study site is presented in Figure 2.10. The figure shows that almost all months' wind predominantly blew from North East (NE) direction followed by the North (N) direction. Other directions in which annually wind blowing frequency is significantly noted are South(S), South-South West (SSW) and West South West (WSW). Figure 2.11 shows a similar trend as that of Figure 2.10 regarding wind directions when considering the whole wind speed bins. However, the wind speed bin of 4.44-6.56 m/s is predominantly falling in the North East (NE) direction, and the wind is blowing from there. This wind speed bin includes the annual average wind speed at 4 m hub height at the study site, as was noted in the previous

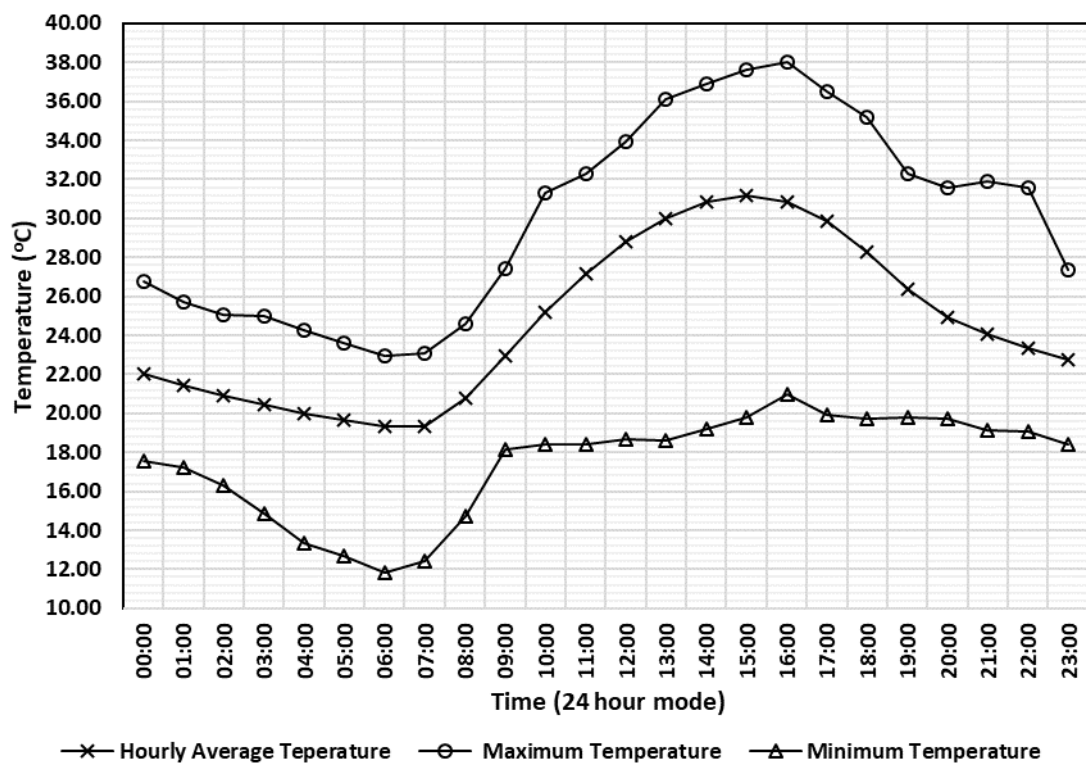
paragraphs. Therefore, for installing the IIRES, which might be affected by wind blowing direction, consideration of the wind speed and direction data is vital.



**Figure 2.11: Wind blowing events' percentage frequency in a wind speed bin per wind direction in 2017**

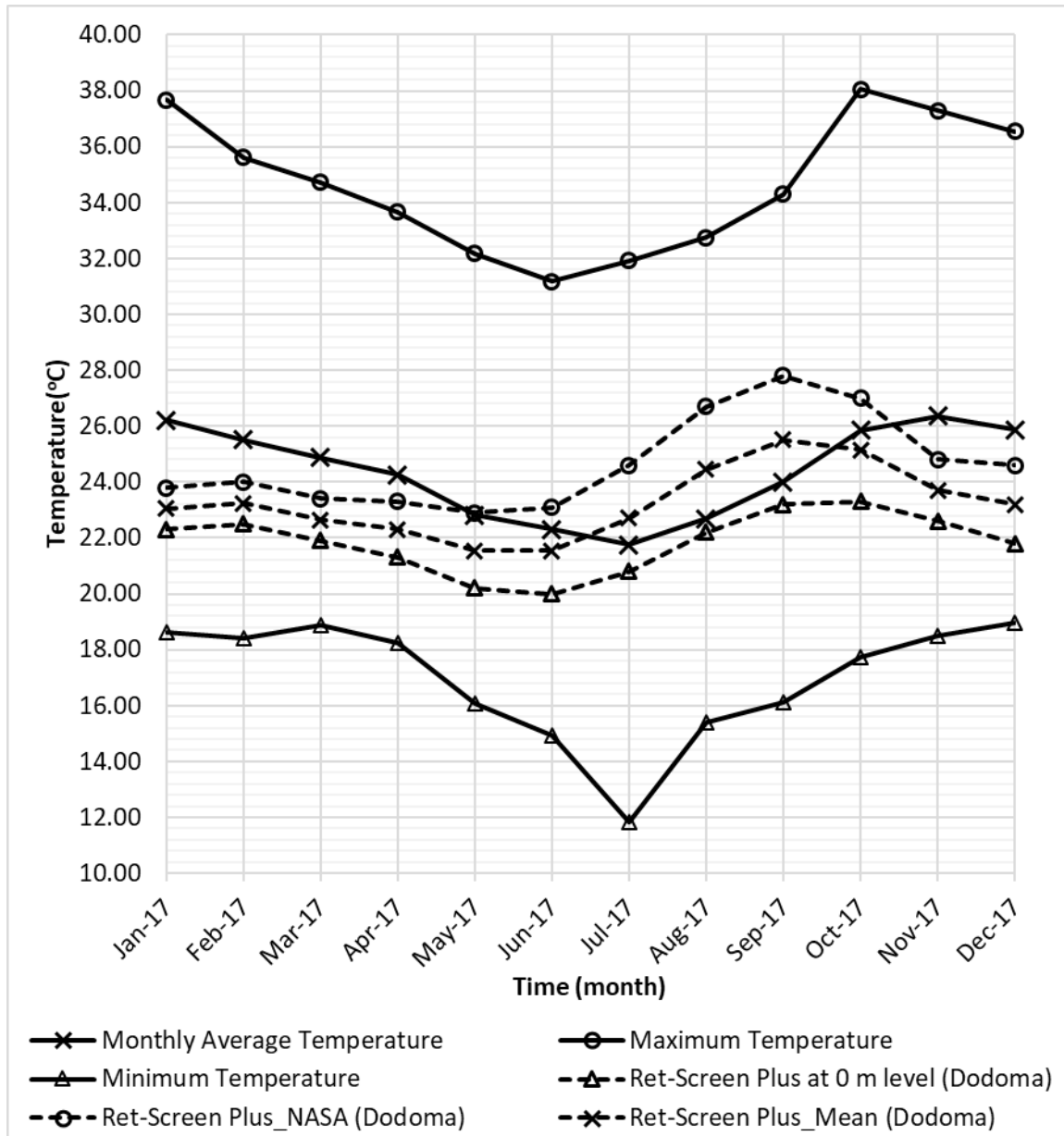
Another weather parameter characterised is ambient air temperature. Characterisation resulted in both hourly and monthly maximum, average, and minimum ambient temperature trends shown in Figures 2.12 and 2.13. Figure 2.12 shows that the maximum ambient air temperature was 38.05°C recorded at 16:00 hours, and the minimum ambient air temperature was 11.82°C recorded at 6:00 hours. For the whole period of collection of data, the average ambient air temperature was 24.71°C, with a standard deviation of 4.04°C within a day. The ambient air temperature was averagely above 24.71°C for ten hours from 10:00 hours through to 20:00 hours. For the same period of ten hours, the

difference between maximum and minimum ambient air temperature values was averagely 13.13°C, with a standard deviation of 3.03°C. The temperature variation at the study site within a day was expressed in the standard deviation that is 4.04°C by considering the average ambient air temperature values for 24 hours.



**Figure 2.12: Hourly average, maximum, and minimum ambient air temperature in 2017**

Additionally, from Figure 2.12, it is depicted that the monthly average ambient air temperature was recorded to be below 25°C from April through September. However, the lowest and highest ambient air temperature values were recorded in July (11.82°C) and October (38.05°C), respectively. Furthermore, the three months of October, November and December had high average, maximum and minimum ambient air temperature records.



**Figure 2.13: Monthly average, maximum and minimum ambient air temperature in 2017**

This trend is similar to the one obtained from RETScreen Plus software for the Dodoma region (Ganoë *et al.*, 2014). However, the RETScreen Plus data shows that ambient air temperature is the lowest of all months in June. The information obtained is useful in planning and developing a renewable energy system that can endure temperature variations and which can be installed on the ground outside the respective household.

The IRES involving biogas technology performs well at a constant temperature ranging from 25°C to 55°C, depending on the state of operating temperature. Therefore, designing the IRES requires a provision for collecting and storing heat at high temperatures during the day to raise the temperature in the morning. This phenomenon would keep the temperature of the biogas digester of the IRES significantly constant. Also, a strategy should be set for operating the IRES during the low-temperature period, which is around July.

#### **2.4 Conclusion and Recommendations**

A comprehensive characterization of the locally available renewable energy resource (cow dung) and sources (weather factors) research approach has been undertaken. The findings reveal that locally available cow dung per day at the study site is abundant (production of 26,330 kg/day), which has the potential of generating a large amount of biogas (4,600 m<sup>3</sup>/day). Also, the cow dung has properties (744.3±53.2 g/kg and the C/N ratio of 19.30), which are suitable for biogas generation. Characterization results show that solar radiation (annual average solar insolation of 5.88 kWh/m<sup>2</sup>/day and solar insolation above 4.5 kWh/m<sup>2</sup>/day for seven months) is an abundant renewable energy source at the study site. This amount of solar energy can be harnessed by any existing solar energy technology.

Moreover, the study site has a predominant wind speed, which falls within the range of 4-6 m/s in a year, while the annual wind speed is 4.69 m/s at 4 m hub height (Figures 2.8 to 2.11). Wind speed is lowest in March (2.30 m/s) and highest in October (6.41 m/s). These data show that the wind speed available at the study site is adequate to transform wind energy into usable energy. Also, wind direction at the study site is predominantly blowing from North East (NE) for almost all months in a year.

Generally, ambient temperature variation is high (±4.04°C within a day) at the study site.

This variation poses a challenge to biogas generation systems installed on or above ground without heat insulation features. The underground installed digesters offer the reduced temperature variation; however, the challenges associated with their default troubleshooting are discouraging, as these challenges were explained in Sub-Section 1.2 of Chapter One of this thesis.

All the above-described findings are useful in developing and modelling energy systems. These systems can involve solar and wind energies and biogas generation units at the study site and nearby areas under similar semi-arid conditions.

Since solar, wind, and biomass (cow dung) are abundantly available with needed quality for generating biogas and electricity, then developing the integrated renewable energy system exploiting these resources to produce clean energy efficiently is an exciting research topic. Therefore, it is recommended that the comprehensive characterisation research approach used in this study be adopted by researchers and project developers engaged in renewable energy systems assessment and development in similar rural semi-arid areas conditions or elsewhere appropriate. Also, it is recommended to consider the means of countering ambient temperature variation if the biogas system has to be installed on or above the ground.

Although rainfall was not characterised, it may affect the grazing of cattle, which produces cow dung and thus feedstock to the digester. Simply, more rainfall gives more cow dung produced while other factors are kept constant, e.g. the health of cattle. Therefore, further research on the relationship between rainfall and the availability of cow dung is a recommended point of research.

## **2.5 Acknowledgement**

The Germany Federal Ministry of Education and Research (BMBF) funded the Trans-SEC project, with Project ID No.: 031A249 A-G, which financed this study. Also, the German Federal Ministry for Economic Cooperation and Development (BMZ) co-financed the project. The above are ushered with gratitude for this vital support. The views expressed in this chapter are purely those of the author and may not in any circumstances be regarded as stating an official position of BMBF or BMZ.

## 2.6 References

- Arnett, E. B., Johnson, G. D., Erickson, W. P. and Hein, C. D. (2013). *A Synthesis of Operational Mitigation Studies to Reduce Bat Fatalities at Wind Energy Facilities in North America*. Bat Conservation International. Austin, Texas, USA. pp.38.
- Bekele, G. and Tadesse, G. (2012). Feasibility study of small Hydro/PV/Wind hybrid system for off-grid rural electrification in Ethiopia. *Applied Energy* 97: 5 – 15.
- Bidaoui, H., El Abbassi, I., El Bouardi, A. and Darcherif, A. (2019). Wind speed data analysis using Weibull and Rayleigh distribution functions, case study: five cities northern Morocco. *Procedia Manufacturing* 32: 786-793.
- Boxwell, M. (2017). Solar electricity handbook. [<http://solarelectricityhandbook.com/solar-irradiance.html>] site visited on 19/03/2018.
- Bukari, D., Tuokuu, F. X. D., Suleman, S., Ackah, I. and Apenu, G. (2020), "Ghana's energy access journey so far: a review of key strategies", *International Journal of Energy Sector Management*, Vol. ahead-of-print No. ahead-of-print. <https://doi.org/10.1108/IJESM-02-2020-0008>.
- Elamouri, M. and Amar, F. B. (2008). Wind energy potential in Tunisia. *Renewable Energy* 33(4): 758-768.
- Felix, M. and Gheewala, S. H. (2011). A Review of Biomass Energy Dependency in Tanzania. *Energy Procedia* 9(2): 338 – 343.
- Ganoë, R. D., Stackhouse Jr, P. W. and DeYoung, R. J. (2014). *RET Screen Plus Software Tutorial. Technical Report*. International Clean Energy Decision Support Centre, Ottawa, Canada. 42pp.
- García, R., Pizarro, C., Lavín, A. G. and Bueno, J. L. (2012). Characterization of Spanish biomass wastes for energy use. *Bioresource Technology* 103(1): 249 – 258.
- Haluschak, P. (2006). *Laboratory Methods of Soil Analysis*. Canada-Manitoba Soil

- Survey, Manitoba, Canada. 133pp.
- Johnston, R. Z. and Matlock, M. D. (2011). *Geospatial Climate Data. University of Arkansas*. The Sustainability Consortium, Food, Beverage and Agriculture, Arkansas, USA. 22pp.
- Kahimba, F.C., Mbaga, S., Mkoko, B., Swai, E., Kimaro, A.A., Mpanda M., Liingilie, A. and J. Germer (2015) Rain-fed crop, livestock, and agroforestry systems in Semi-arid and sub-humid Tanzania: A Baseline report, *Trans- SEC Project*, ZALF, Germany, 42pp. [<http://project2.zalf.de/trans-sec/public/media/upload/product/pdf/83905803646d86cb3ba323cdc201860b.pdf>] site visited on 07/06/2021.
- Kanyeka, E., Kamala, R. and Kasuga, R. (2007). *Improved Agricultural Research Technologies Recommended in Tanzania*. Ministry of Agriculture Food Security and Cooperatives, Dar es Salaam, Tanzania. 102pp.
- Kiobia, D. O. (2015). Design and development of a low-cost acoustic device to detect pest infestation in stored maize. [<http://hdl.handle.net/10919/56588>] site visited on 07/06/2017.
- MNRC, Ministry for Natural Resources Canada (2015). *Clean Energy Project Analysis: RETScreen Engineering and Cases*. (3<sup>rd</sup> Edition), Natural Resources, Canada, 77pp.
- Moberg, J. P. (2001). *Soil and Plant Analysis Manual. Revised Edition, the Royal Veterinary and Agricultural University*. Chemistry Department, Copenhagen, Denmark. 133pp.
- Mohammed, Y. S., Mustafa, M. W. and Bashir, N. (2013a). Status of renewable energy consumption and developmental challenges in Sub-Sahara Africa. *Renewable and Sustainable Energy Reviews* 27: 453 – 463.

- Mohammed, Y. S., Mustafa, M., Bashir, N. and Mokhtar, A. S. (2013b). Renewable energy resources for distributed power generation in Nigeria: A review of the potential. *Renewable and Sustainable Energy Reviews* 22: 257 – 268.
- Mwinuka, L., Schneider, I., Maeda, C., Mutabazi, K. D., Makindara, J., Graef, F., Sieber, S., Swai, E., Mbwana, H. and Swamila, M. (2015). Comparing stakeholder views for mutual acceptable food value chain upgrading strategies in Tanzania. *African Journal of Agricultural Research* 10(12): 1376 – 1385.
- Oyedepo, S. O. (2014). Towards achieving energy for sustainable development in Nigeria. *Renewable and Sustainable Energy Reviews* 34: 255 – 272.
- Peters, J., Combs, S. M., Hoskins, B., Jarman, J., Kovar, J. L., Watson, M. E., Wolf, A. M. and Wolf, N. (2003). *Recommended Methods of Manure Analysis*. Publication No. 3769. Coop. Ext. Publishing, Madison, USA. 55pp.
- Raposo, F., De la Rubia, M. A., Fernández-Cegri, V. and Borja, R. (2012). Anaerobic digestion of solid organic substrates in batch mode: an overview relating to methane yields and experimental procedures. *Renewable and Sustainable Energy Reviews* 16(1): 861 – 877.
- REN21 (2017). *Renewable Energy Policy Network for the 21<sup>st</sup> Century. Renewables Global Status Report*. REN21 Secretariat, Paris. 237pp.
- Safari, B. and Gasore, J. (2010). A statistical investigation of wind characteristics and wind energy potential based on the Weibull and Rayleigh models in Rwanda. *Renewable Energy* 35(12): 2874-2880.
- Scheid, A., Hafner, J., Hoffmann, H., Kächele, H., Sieber, S. and Rybak, C. (2018). Fuelwood scarcity and its adaptation measures: an assessment of coping strategies applied by small-scale farmers in Dodoma region, Tanzania. *Environmental Research Letters* 13(9): 095004-095015.

- Schnurer, A. and Jarvis, A. (2010). *Microbiological Handbook for Biogas Plants*. Swedish Waste Management U2009:03, Swedish Gas Centre Report 207, Uppsala, Sweden, 138pp.
- Suberu, M. Y., Mustafa, M. W., Bashir, N., Muhamad, N. A. and Mokhtar, A. S. (2013). Power sector renewable energy integration for expanding access to electricity in sub-Saharan Africa. *Renewable and Sustainable Energy Reviews* 25: 630 – 642.
- Sullivan, K. M., Dean, A. and Soe, M. M. (2009). On Academics: OpenEpi: A web-based epidemiologic and statistical calculator for public health. *Public Health* 124(3): 471 – 474.
- Suri, M., Remund, J., Cebecauer, T., Dumortier, D., Wald, L., Huld, T. and Blanc, P. (2008). First steps in the cross-comparison of solar resource spatial products in Europe. In: *EUROSUN 1st International Conference on Solar Heating, Cooling and Buildings* 7 – 10 October 2008, Lisbon, Portugal. pp. 1 – 10.
- Vandaele, N. and Porter, W. (2015). Renewable energy in developing and developed nations: Outlooks to 2040. *Journal of Undergraduate Research* 15(3): 1 – 7.
- Wald, L. (2007). Solar radiation energy (fundamentals and theory). Solar Energy Conversion and Photoenergy Systems. In; *Encyclopedia of Life Support Systems (EOLSS)*, edited by: Blanco, J. and Malato, S., Developed under the Auspices of the UNESCO, Eolss Publishers, Oxford, UK. 403pp.
- Wawa, A. I. (2012). *The Challenges of Promoting and Adopting Biogas Technology in Semi-arid areas of Tanzania: The Case of Kongwa and Bahi Districts in Dodoma Region*. Doctoral Thesis for Award Degree of PhD at The Open University of Tanzania. 211pp.
- Weiland, P. (2010). Biogas production: Current state and perspectives. *Applied Microbiology and Biotechnology* 85(4): 849 – 860.

- Yadav, A., Gupta, R. and Garg, V. K. (2013). Organic manure production from cow dung and biogas plant slurry by vermicomposting under field conditions. *Recycling of Organic Waste in Agriculture* 2(1): 1 – 21.
- Zhou, K. and Yang, S. (2016). Understanding household energy consumption behaviour: The contribution of energy big data analytics. *Renewable and Sustainable Energy Reviews* 56: 810 – 819.
- Zhu, Y., Merbold, L., Leitner, S., Pelster, D. E., Okoma, S. A., Ngetich, F., Onyango, A. A. and Butterbach-Bahl, K. (2020). The effects of climate on decomposition of cattle, sheep and goat manure in Kenyan tropical pastures. *Plant and Soil* 451(1): 325-343.

## CHAPTER THREE

### **3.0 Adaptation of Anaerobic Digester for Effective Degradation of Cow Dung for Biogas Production in Rural Semi-Arid Areas**

#### **Abstract**

The fixed dome biogas technology was introduced into rural communities of semi-arid areas to counter the energy insufficiency challenge. Constraints, which included high installation cost of the recommended 4-6 m<sup>3</sup> plants, difficulties in troubleshooting leakages for the underground installed plants and large quantities of water required to run such plants, led to low adoption of the technology. Research on alternative technologies for biogas generation has resulted in numerous studies. This paper presents the robust Anaerobic Digestion System (ADS) adaptation research approach and the results of system performance obtained using the same approach. The adapted system seeks to address the fore mentioned constraints. The conventional batch fed anaerobic digester designs were adapted by redesigning and fabricating all of its components using engineering design technique coupled with decision matrix analysis. The adapted batch fed anaerobic digestion (ABFAD) system that is on the ground installed was experimentally tested. Experimental results obtained were analysed, and insights are drawn from them. The ABFAD system has two functional characteristic curves and withstood pressure of 10.8 kPa. During the testing period, the substrate in the ABFAD system was based on feedstock with a dry matter of 228.93 g/kg of feed had Dissolved Oxygen and pH in the range of 8.8-9.0 mg/l and 5.11-5.15, respectively. The biogas produced by the system had a methane content of 52.4%, with a standard deviation of 2.9%. The ABFAD system digester was operating in the mesophilic phase of temperature (24.04°C). The adaptation research approach is recommended for biogas digester

designers. Also, the adapted biogas system is recommended for use in individual households and integration with other renewable energy systems involving wind and solar energy.

**Keywords:** *adaptation; anaerobic digestion; conceptual design; renewable energy system; biogas technology*

### 3.1 Introduction

Biogas generation technology is essential for the sustainable supply of energy to communities and conserving the environment (Surendra *et al.*, 2014; Tumwesige *et al.*, 2014). Due to its nature, the relevance of biogas generation may be very much noticed in rural areas of economically growing countries in most of the sub-Saharan Africa region. In these areas, the rate of insufficiency of energy, especially for cooking, is increasing, although natural gas reserves have been discovered in some of these areas, for instance, Tanzania (Kusekwa, 2011). It is debatable whether the communities will be connected, by a hundred per cent, to the national grid or to natural gas piping systems planned by their governments, for the time being, and soon.

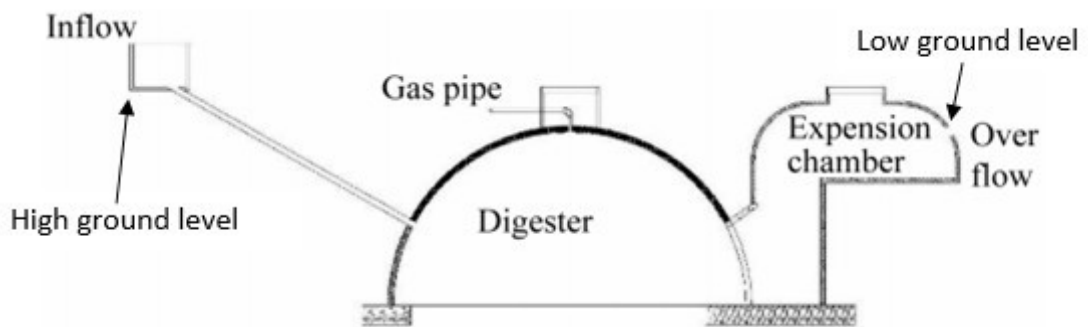
The increase of energy insufficiency in rural areas is due to dwindling forest acreages resulting from an expanded search for fuelwood, which is the traditional source of energy for these communities. Additionally, the dwindling of forests results from enormous pressure exerted on these resources from population growth and the surging expansion of agricultural and pastoral land (Subedi *et al.*, 2014; Ordway *et al.*, 2017). Evidence of this phenomenon is observed in the central regions of Tanzania, which encompass vast rural semi-arid areas. Strategies were devised to counter the challenge while reflecting on the locations and economic level of communities.

Initiatives have been activated to deal with energy insufficiency in semi-arid areas. One of the initiatives was the introduction of biogas production technology. This technology employs microbial degradation of biomass (animal, agricultural, and municipal wastes) under anaerobic conditions. The microbes responsible for the generation of biogas are affected adversely by factors, which include a rapid variation of temperature, more than  $\pm 3^{\circ}\text{C}$  within a day, and heavy chemicals including salts or antibiotics used to treat animals

(Jørgensen, 2009; Pham *et al.*, 2014; Theuerl *et al.*, 2015). The feedstock employed in biogas generation may consist of dry matter of up to 15% wet basis for the liquid state digestion, i.e. liquid anaerobic digestion (LAD) or above 15% wet basis for the solid-state digestion, i.e. high solid anaerobic digestion (HSAD) (Jørgensen, 2009; Li *et al.*, 2011b). The HSAD feedstock requires more massive amounts of inoculum, has a much longer retention time and lacks control over the biological process (Li *et al.*, 2011b). The HSAD feedstock has been reported to produce more biogas and needs less or no water to be added compared to the LAD feedstock; however, they need a large amount of inoculum (Yang *et al.*, 2015).

The central part of Tanzania, the Dodoma region, received biogas technology fed with LAD type feedstock via a subsidy scheme coordinated under a non-governmental organisation, 'Miradi ya Gesi ya Samadi Dodoma' (MIGESADO). MIGESADO is simply translated as Dodoma Biogas Projects (Wawa, 2012). The technology introduced in the region was the continuous fed underground fixed dome digester design ranging from 4 to 6 m<sup>3</sup> in size. The design was a modified Chinese type digester design, mainly known in Tanzania as the Centre for Agricultural Mechanisation and Rural Technology (CAMARTEC) type digester (Mrema *et al.*, 2011; Walekhwa *et al.*, 2009; Garfi *et al.*, 2016; Wawa, 2012). This design is illustrated in Figure 3.1. Also, CAMARTEC has two biogas plant designs, one for humid regions and another for semi-arid areas.

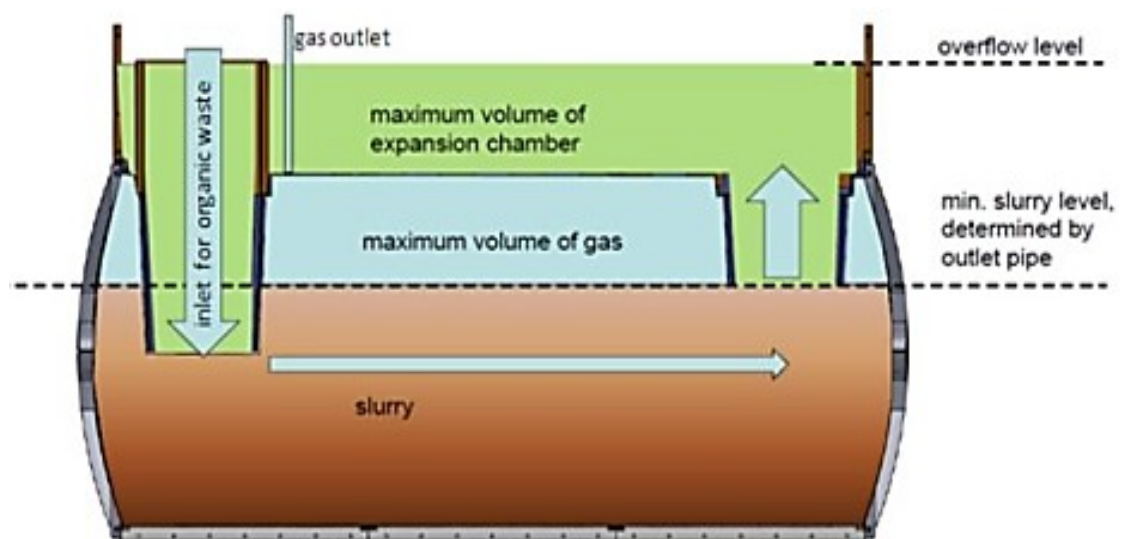
The operation of this type of anaerobic digestion system requires daily feeding with biomass (cow dung) mixed with water, usually at the ratio of one to one. Due to its immense size, large quantities of building materials and intensive labour are involved during its installation. Troubleshooting faults, like leakages, in this type of system is challenging due to being installed subsurface (Oloche *et al.*, 2017).



**Figure 3.1: CAMARTEC Digester design found around the study site**

**Source: (Melinda *et al.*, 2013)**

However, a portable small-sized plastic digester of about 200 litres capacity has been reported by Kusekwa (2011) to be developed at the Dar-es-Salaam Institute of Technology in Tanzania, but its performance and dissemination information is not available. Furthermore, the small-sized biogas system, alias GesiShamba (Figure 3.2), with a minimum capacity of 2 m<sup>3</sup>, was introduced in Tanzania in 2012 by a Netherlands based company, SimGas BV, under a joint venture with Silafrika Company.



**Figure 3.2: GesiShamba system design**

**Source: (WB, 2015)**

The GesiShamba is made of cheap plastic material, making it portable, unlike the conventional biogas plant. It may be scaled up to 25 m<sup>3</sup> at an increment of 1 m<sup>3</sup>. The system is installed horizontally in a dugout trench, then backfilled, leaving its expansion chamber exposed to air. Also, the GesiShamba is a continuously fed system in which the substrates are mixed with some amount of water daily (WB, 2015; Zalma, 2017; SimGas, 2018). As this type of digester needs water daily, it may not be an ideal solution in the rural semi-arid areas, where the availability of water is not guaranteed throughout the year.

Apart from the digester designs mentioned above, there are other types of anaerobic digester designs used in Tanzania and other parts of the world. Among them are the floating drum (India type) digester, separate storage (Sri-Lanka type) digester, and plug flow digesters (Mrema *et al.*, 2011; Rajendran *et al.*, 2012; Zalm, 2017). They are further grouped into batch fed, semi-batch fed, and continuous type digesters based on the mode of operation. The batch type digester for handling HSAD is simple and cheap in design compared to the others, although it has clogging problems (Schnurer and Jarvis, 2010; Kranert *et al.*, 2012).

There are many factors, which affect the efficient production of biogas from anaerobic digesters. These factors include temperature, substrate's pH, Carbon-Nitrogen ratio of feedstock, feedstock loading rate and particle size, hydraulic retention time and additives. The essential and critical factor especially in batch fed anaerobic digesters, is temperature, as it significantly affects the biogas generation and other factors (Masse *et al.*, 2003; Chae *et al.*, 2008; Bond and Templeton, 2011; Adekunle and Okolie, 2015).

The Anaerobic Digester (AD) temperature needs to be kept within 20°C to 45°C for the

mesophilic state. However, increased biogas generation can be attained by keeping the AD at a constant temperature, around 35°C (Yadvika *et al.*, 2004; Rowse, 2011). This range of temperature can be attained in semi-arid regions. The ADs are supposed to be kept at temperature variations approaching less than 0.5°C/day because at this temperature variation, biogas microbes survive optimally (Rowse, 2011; Schnurer and Jarvis, 2010). Usually, biogas microbes can sustain temperature variation of  $\pm 3^\circ\text{C}$ . In rural semi-arid areas, temperature differences may reach 10°C within a few hours. The devising of a simple temperature control system, which may reduce biogas digester temperature variation toward 0.5°C/day, is of paramount importance for sustainable biogas generation.

The biogas generated contains methane ( $\text{CH}_4$ ) content. The  $\text{CH}_4$  is a measure of the quality of biogas (Poulsen and Adelard, 2016). The higher the content of methane in the biogas, the better quality of biogas (Siefers *et al.*, 2010). Abatzoglou and Boivin (2009) and Su *et al.* (2015) have described techniques for biogas quality improvement. The techniques include reducing impurities from biogas. Some of the impurities are Carbon dioxide, hydrogen sulphide, water vapour and ammonia. Auxiliary components of the biogas plant are available for purifying biogas by removing the impurities (Kulkarni and Ghanegaonkar, 2019). The components include water traps and scrubbers filled with water or other organic and inorganic materials like steel wools and activated carbon (Awe *et al.*, 2017).

Additionally, the large size biogas digesters of up to 100 m<sup>3</sup> or more may experience pressures of up to 10 000 kPa (100 bar) that lead to the increased purification of biogas generated by the same systems up to 95%  $\text{CH}_4$  content (Achinas *et al.*, 2017). Useful cheap and straightforward materials for purifying biogas consist of water and steel wools. However, cheap designs of water traps and scrubbers are needed if affordable renewable

energy systems involving biogas technology have to be developed for the low-income communities in rural semi-arid areas.

Domestic small biogas plants of fixed dome or floating drum type, in most cases, operate at low pressure, which may hardly reach 16 kPa. They operate at low pressure because of being open to the atmospheric pressure at the substrate outlet if no clogging is to be encountered in the system (Zalm, 2017). However, for a batch fed anaerobic digester design, which is well sealed and the biogas outlet valve is closed, its pressure may rise above 16 kPa. The biogas flow rate in the low-pressure systems may go as low as 0.025 m<sup>3</sup>/h. This flow rate makes direct application of the system pressure while cooking a challenge. It is because most applied standard cooking facilities operate at a moderate biogas flow rate of 0.45 m<sup>3</sup>/h (Zalm, 2017). The existing AD systems have a biogas production rate of between 0.2 and 0.6 m<sup>3</sup> per m<sup>3</sup> of the digester size. The low production rate is encountered in cold regions, while the high production rate is in warmer regions (Wawa, 2012; Menya *et al.*, 2013).

The semi-arid areas exhibit both hot and cold conditions during the day and night time, respectively. Considering the fore given biogas production rate and the temperature variation in the semi-arid areas, then the AD systems' biogas production rate in these areas was assumed to bear a mean value of 0.4 m<sup>3</sup>/m<sup>3</sup> of digester in a day, i.e. biogas production rate of 0.017 m<sup>3</sup>/h of a given m<sup>3</sup> digester size. This figure was set as the basis for evaluating the performance of the integrated system to be developed. Releasing biogas efficiently at the right time from renewable energy systems was crucial. Therefore, it is justified to invent cheap biogas storage when operating domestic small biogas plants at low pressure and flow rate with due consideration of the prevailing weather conditions in the semi-arid areas.

For ensuring the generation of biogas in an increased quantity and quality, the adaptation

of the digester designs mentioned above has been done by researchers as explained by Yadvika *et al.* (2004), Nasir *et al.* (2012) and Divya *et al.* (2015).

The adaptations include the addition of facilities for mixing and recycling flow of the leachate from and into the substrate inside the digester; adding fixed-film on the surface inside the digester periphery walls, or adding pieces of inert materials (plastics, nylon, and sponge) in the feedstock to increase the contact surface area of biogas microbes' growth and minimizing the abrupt changes of the temperature inside the digesters (Jørgensen, 2009; Yadvika *et al.*, 2004). Furthermore, the digester designs alteration for biogas quality increment and handling may be done by adding auxiliary components like water trap for carbon dioxide gas and water vapour screening, scrubber for hydrogen sulphide trapping, and separate robust biogas storage for releasing the biogas efficiently (Ryckebosch *et al.*, 2011; Muñoz *et al.*, 2015; Kapdi *et al.*, 2005).

Some of these adaptations are expensive as they may need an energy-intensive mixer and pump for substrate mixing and leachate recycling, respectively. Increasing contact surface area for the biogas microbes includes placing films on the periphery of the digester, which is prone to temperature variation if no proper insulation is provided. Also, it is done by adding pieces of inert materials in substrates, which may require extra energy and time for separating them before reusing substrate as bio-fertilizer or the pieces in the same or other batch-fed biogas plants. The auxiliary components for biogas quality improvement and handling are sophisticated and too expensive for the communities in the rural semi-arid areas. The cost of these components is TZS 690 000.00 (€<sub>2018</sub> 300.00) or more for a biogas plant with methane yield in a year of approximately 330 Nominal m<sup>3</sup>/tonne of Volatile Solids (Karellas *et al.*, 2010).

With this background information, the adaptation of the design for addressing the

technical challenges of the existing continuous anaerobic digesters introduced in semi-arid areas and that of the batch fed anaerobic digester is needed. Application challenges related to the adaptations, as explained, necessitate the development of cheap and straightforward but effective and efficient adaptations of biogas digester designs to facilitate sustainable biogas generation. It may be achieved using an engineering methodological approach involving decision-making methods to develop the appropriate intended improved design of the anaerobic digestion system.

There are no on-ground installed small-sized (200 - 1000 litres) anaerobic digesters in the rural semi-arid areas, which address the above stated developmental and research gaps, operating in individual households. Also, small-sized digesters with biogas passage, which eliminates the risk of clogging the biogas outlet, have not been documented. Besides, no literature is available of the small-batch type system describing the ease to release biogas from the interior of substrates of high solid anaerobic digestion, in which mechanical mixing is not feasible. In this study, the adaption of a batch type anaerobic digester, which addresses the fore explained challenges, is considered. The adapted digester is intended for the generation of biogas for cooking.

Therefore, this chapter presents the adaptation and experimental testing results of the above-ground adapted batch fed anaerobic digestion (ABFAD) system. The adapted anaerobic digester may be integrated into any other renewable energy system for the stable production of useful energy and bio-slurry.

## **3.2 Materials and Methods**

### **3.2.1 The study site**

The study site description is the same as the one given in Sub-section 2.2.1 of Chapter

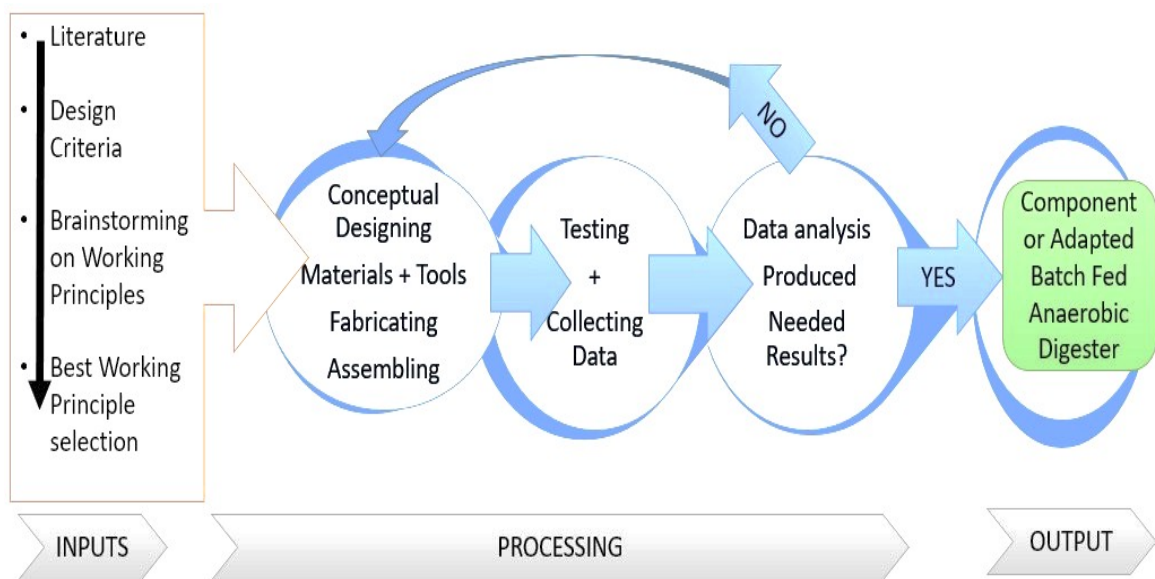
Two of this thesis, with exceptions. The exceptions include the description of the location where some research-related activities were done. Some desk works and preliminary fabrications of the system components were done in the workshop of the Department of Engineering Sciences and Technology (DEST) at Sokoine University of Agriculture (SUA), located in Morogoro, Tanzania, 301 km from the study site. Finally, the final desk work and fabrications were done both on the study site and at the nearest local workshop located 29 km at Mvumi Mission in Chamwino District. A cross symbol indicates the Mvumi Mission in Appendix 2 of this thesis.

### **3.2.2 The research approach**

The research approach used and illustrated in Figure 3.3 employed the adapted engineering procedural and research techniques. These guided the adaptation process of the batch fed anaerobic digester design. Several tasks in the adaptation process were executed in the field rather than in laboratories and workshops of research centres. It involved inputs, processing and output phases. The inputs phase included reviewing the literature on the functionality of various existing designs of digesters, developing design criteria to be met by the intended components or system to be re-designed, synthesising the working principles or concepts as per design criteria, and selection of the best working principle.

The processing phase comprised of the conceptual design of the selected best working principle; fabrication and or assembly of the selected components and or the digester system; experimental testing of the components and or the system while collecting data, and data analysis as well as results interpretation to check whether the components or the system have produced the intended results. It was planned that if the interpretation of the results suggested that the component or system did not fit the intended design, the

processing phase would be repeated. It means the process would be re-done by conceptual re-designing the details of the best-selected working principle, and other steps will follow as before. If the interpretation of the results suggested otherwise, the output phase would be established, and the design passed as the intended design by finalising the finishing of the component or the adapted batch fed anaerobic digester.



**Figure 3.3: Anaerobic digestion system adaption framework**

### 3.2.3 The inputs phase of the adaption framework

After a thorough literature review on the functionality of various digesters' designs and operations (Garfi *et al.*, 2016; Kapdi *et al.*, 2005; Li *et al.*, 2011b; Mrema, 2014; Munoz *et al.*, 2015; Rajendran *et al.*, 2012; Yang *et al.*, 2015), the batch fed anaerobic digestion system was selected to be used. The selection of this system was based on the design simplicity, low cost and ease of operation. However, this system needed an adaptation to offer the intended service of increased quantity and quality of biogas to be generated. The basis of achieving this result was the design criteria explained in this and subsequent subsections and the approach shown in Figure 3.3.

**i. The batch anaerobic digestion system design criteria**

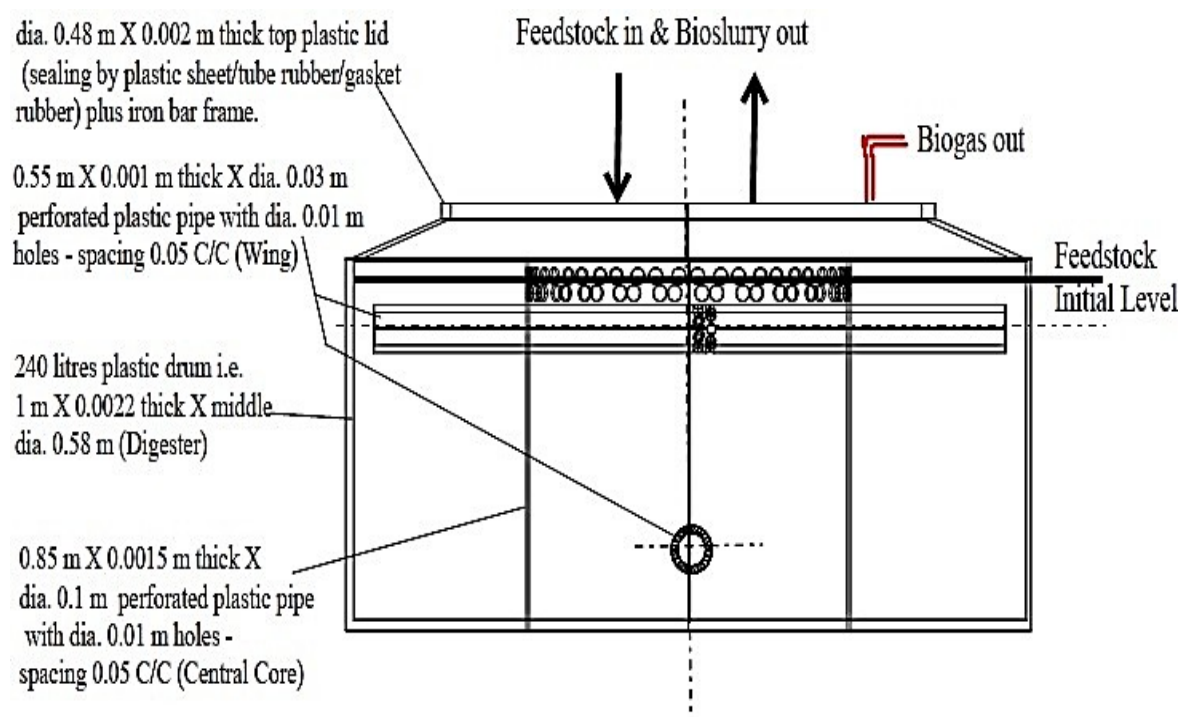
The criteria formulated as a basis for devising the intended system are the ability to withstand the pressure of about 16 kPa; biogas tight seal capacity/airtight sealing by 100%; self-mixing during operation; possible self-leachate re-circulation during operation and increased contact surface area of biogas microbes. The other criteria include easy passage of biogas from the interior of substrates; easy to operate; ensuring no biogas outlet clogging; availability of raw materials locally; less cost involved; more durable and ease of manufacturability.

**ii. Synthesis and selection of best working principle****a) *Synthesis of the working principles***

Working principles were generated for all components of the batch anaerobic digestion system. The components include the digester, the water trap, the scrubber, biogas storage and piping system. The digester working principles generated are shown in Table 3.1. The unscaled drawing in Figure 3.4 illustrates the digester working principle generated with various top cover types.

**Table 3.1: Generated digester working principles**

S/N	Working principle	Volume (litres)	Drum material	Seal used	Other components
1	DWP1	240	Plastic	Plastic sheet and lid	None
2	DWP2	240	Plastic	Tube rubber thread and lid	Sealed central core
3	DWP3	240	Plastic	Flexible plastic tube and lid	Perforated central core and lid
4	DWP4	240	Plastic	2 mm thick gasket rubber and lid	The perforated four-winged central core
5	DWP5	500	Plastic	Screwed top lid	The perforated central core and four wings
6	DWP6	240	Plastic	2 mm thick gasket rubber, lid and 2 mm thick flat bar frame	The perforated four-winged central core

**Figure 3.4: Unscaled drawing of the digester working principle**

The water trap working principles brainstormed are shown in Table 3.2.

**Table 3.2: Generated water trap working principles**

S/N	Working principle	Volume (litres)	Main Part	Important Dimension	Other components
1	WWP1	5	Plastic jerry-can	1 mm thick wall	None
2	WWP2	3	Plastic bucket	1.5 mm thick wall	None
3	WWP3	0.6	IPS Plastic pipe	Length 500 mm and diameter 40 mm	None
4	WWP4	5	Plastic can	0.7 mm thick wall	None
5	WWP5	12	Plastic can	0.7 mm thick wall	None
6	WWP6	10	Plastic bucket	1 mm thick wall	None
7	WWP7	20	Plastic bucket	1 mm thick wall	None
8	WWP8	10	Plastic jerry-can	1 mm thick wall	None
9	WWP9	20	Plastic jerry-can	1 mm thick wall	None
10	WWP10	3	Plastic bucket	1 mm thick wall	Fastening 2 mm thick iron bar frame

The scrubber working principles devised are shown in Table 3.3.

**Table 3.3: Generated scrubber working principles**

S/N	Working principle	Volume (litres)	Main Part	Important Specification	Other components
1	SWP1	0.5	IPS plastic pipe	Length 400 mm and diameter 40 mm (monolithic)	None
2	SWP2	0.5	IPS plastic pipe	Length 400 mm and diameter 40 mm (non-monolithic)	50 mm diameter IPS Connector
3	SWP3	1.5	Plastic bottle	0.5 mm thick wall	None
4	SWP4	1	Plastic bottle	0.5 mm thick wall	None
5	SWP5	2	Plastic jug	1 mm thick wall	None
6	SWP6	1	Plastic jug	1 mm thick wall	None
7	SWP7	0.8	Iron pipe size (IPS) plastic pipe	Length 400 mm and diameter 50 mm (monolithic)	None
8	SWP8	0.8	IPS pipe	Length 400 mm and diameter 50 mm (non-monolithic)	40 mm diameter IPS Connector

The biogas storage working principles thought-of are inflatable plastic bag (BSWP1), inner tyre tube - various sizes (BSWP2) and inflatable plastic bag covered with clothes (BSWP3). The piping system working principles were considered to comprise either one, two or three types of pipe. The percentage of the length of the type of pipe to the total length of the piping system was computed by assuming the piping system having a total

length of 1.7 m without including fittings. The percentages and combinations of types of pipes differentiate the working principles generated. The piping system working principles intuitively generated are shown in Table 3.4.

**Table 3.4: Generated piping system working principles**

S/N	Working principle	Pipe type length percentage to the total length of the piping system			Fittings material types
		Horse pipe (%)	Another Flexible pipe (%)	IPS plastic pipe (%)	
1	PWP1	100	-	-	IPS plastic and galvanised steel
2	PWP2	70	30	-	IPS plastic and galvanised steel
3	PWP3	-	-	100	IPS plastic and galvanised steel
4	PWP4	70	30	-	IPS plastic and galvanised steel
5	PWP5	70	25	5	IPS plastic and galvanised steel

**b) Selection of the best working principle**

Best concept selection techniques are available. They involve Decision Matrix Analysis (DMA)/grid analysis, ABC analysis, Pareto analysis, Analytic Hierarchy Process (AHP) based approach, anonymous voting technique, cost-benefit (CB) analysis, and Failure Modes and Effects Analysis (FMEA). Other concept selection techniques include Plus-Minus and Interesting (PMI) analysis, Kano model, nominal group technique, Sticking dots, and “Strength, Weakness, Opportunity and Threat” (SWOT) analysis (Rebernik *et al.*, 2008; Mardani *et al.*, 2015). The procedure of choosing an appropriate selection technique of the best working principle was based on the following criteria: its simplicity in application, ability to single out one best option, quick sorting of more than three options and diverse application in different disciplines, which include designing of renewable energy systems.

With the fore mentioned procedure, it was found that CB analysis, SWOT analysis and

Kano model are discipline-specific for financial, business, and marketing disciplines analysis, respectively. Also, the ABC analysis is used for prioritising one among the only three options and to control inventories. Furthermore, Pareto analysis uses the 80/20 rule, i.e. only 20% of options influences 80% of the same options. Therefore, it renders the analysis unable to single out one best option. The Analytic Hierarchy Process (AHP) based approach was reviewed and found to be complex to apply. It requires special software tools to perform the calculations, which involve the concept of Eigen-vectors, to get the best option.

The anonymous voting technique was found to be very subjective and based on individuals' opinions. It is mainly appropriate for the early phases of the idea selection process. The FMEA was found to be used to identify potential failure modes, determine their effect on the operation of the product, and identify actions to mitigate the failures (Rebernik *et al.*, 2008). It is complex to apply, as anticipating every failure mode is not possible. The PMI analysis employs finding positive, negative and interesting points of an idea. It was found to be an entirely subjective decision based and the most appropriate for idea screening technique. Another selection technique reviewed was the Nominal Group Technique. It is a useful technique for prioritizing issues, ideas and projects rather than choosing one best option. The Sticking dots analysis was also reviewed and found to be a quick method for determining priorities by voting. It is useful for collecting opinions in early phases rather than the final phase in the idea selection process.

The last idea selection technique reviewed for this study was DMA. The DMA employs evaluating an idea as per criteria, factors, or/and their attributes (Mardani *et al.*, 2015). It is simple and allows quick sorting of options/concepts by identifying their relative strengths and weaknesses. Many application possibilities use DMA in different areas of study,

including that of designing renewable energy systems (Abu-Taha and Daim, 2011). However, the setting of scoring criteria must be done carefully for effective use of the results to be obtained (Rebernik *et al.*, 2008; Abu-Taha and Daim, 2011). Based on this background, the DMA method was opted to be used in this study.

**c) *Application of the DMA method***

The selection of the best working principles was made using the DMA method as per the laid out procedure applied by Kaena (2012), Olabanji and Mpofu (2014), and Salonen and Perttula (2005). In this procedure, the design criteria were assigned weight values based on their importance to ensure the component or the system needed to meet the requirement set. The assignment task of weight to the design criteria was done by experts in renewable energy, system design and mechanical engineering. The selection of experts to participate in the weight values assignment exercise was made intuitively by considering the expert's experience in designing and operating renewable energy systems and machines involving fluid systems. Twenty experts were contacted to participate in this exercise, but only thirteen experts were effectively ready. Therefore, eight renewable energy system developers and five mechanical engineers were involved based on readiness to participate in this task.

The fore-mentioned weight assignment process produced the weight values, in brackets, obtained per design criteria as follows: the ability to withstand the pressure of about 16 kPa (0.21), biogas tight/airtight at 100% sealing (0.4), self-mixing during operation (0.01), possible self-leachate recirculation during operation (0.01), the increased surface area of contact for biogas microbes (0.03), easy passage of biogas from the interior of substrates (0.08), easy to operate (0.1), ensuring no biogas outlet clogging (0.05), availability of raw materials locally (0.04), less cost involved (0.03), more durable (0.02), and easy

manufacturability (0.02).

Moreover, factors with their corresponding rating on Likert factor scale values in the bracket, needed to determine the possibility of the working principles to meet each design criteria were intuitively set as follows: not at all able (1), lowly able (2), moderately able (3), highly able (4), and very highly able (5). Furthermore, the weighted score of the working principles relative to each design criterion was determined as the product of design criteria weight and the rating on Likert factor scale values. Finally, the total weighted score for each working principle was determined by summing up the weighted scores.

Plots of the total weighted score against the working principles were produced. The Working principle with the highest total weighted score was selected as the best and used for conceptual design in the processing phase. However, for those working principles that did not produce conclusive weighted scores, the selection was made based on the testing results interpretation in the processing phase. For instance, this happened when working principles were assigned the same rating of at least 3 for the highly weighted design criterion, which is a design criterion with a weight of more than 0.21.

### **3.2.4 The processing and output phases of the adaption framework**

Conceptual design of the selected working principle was done. Fabrication and or assembly of all the designed components of the anaerobic digestion system were done using materials, equipment and tools that were earlier prepared. Then the experimental testing and data analysis were done, and the obtained results were interpreted.

#### **i. Materials used**

The materials used were fabrication consumables and other items, which included: IPS

plastic pipes of diameter 50 mm, 38mm, and 13 mm; standard plastic pipes of diameter 25 mm and 100 mm; 240-litre plastic drum with a wall of 2.2 mm thick; IPS fittings of sizes ranging from 13 mm to 38 mm diameter; bolt and nuts of N10 (8 mm diameter); flexible tube clamps; a Grade S235JR - 25 x 2 mm flat bar (EU standard); 13 mm diameter flexible water pipes and thread seal tapes. Other materials used were putty sealants, gasket rubbers, plastic sheets, pieces of tyre inner tubes; 2.5 mm square wires and butyl tyre inner tubes of sizes: 8.25- 16, 9-20, and 12-24, all with valves type TR177A and 7.5-15 with valve type TR175A. These tubes were of Korean Standard, made in India based on the specifications provided on their packaging labels. Additional materials were steel wool for hydrogen sulphide scrubbing and cow dung with dry matter (DM) and Carbon Nitrogen ratio (C/N ratio) of 228.93 g/kg of feed (standard deviation of 5.21 g/kg) and 19.30 (standard deviation of 0.56), respectively.

## **ii. Instrumentation and measurements**

All electronic instruments were powered by a Solar PV module with a battery bank. A list of essential instruments and tools used during this study include the following:

- (a) UGT humidity and temperature (thermocouple Type-K) sensor as described in Chapter Two, Section 2.0, Sub-section 2.2.3 (iii) of this thesis.
- (b) Micro Footprint Dissolved Oxygen (DO) monitoring subsystem equipped with the DO circuit of Version 4.0 for hardware and firmware (*Atlas-Scientific.com*), with a full range of DO readings from 0.01 to +35.99 mg/L and the accuracy of  $\pm 0.2$ , set to sample data after 15 minutes' interval,
- (c) Tools used to measure the acidity or alkalinity of the ageing substrate in the digester was Micro Footprint pH monitoring subsystem equipped with a pH circuit Version 4.0 for hardware and firmware (*Atlas-Scientific.com*) and with full range pH reading from 0.01 to 14.00 and accuracy within two significant figures (XX.XX); also set to

sample data after 15 minutes' interval.

- (d) Ultrasonic biogas flow meter Version BF-2000 with a flow range of 0.025 – 4.000 m<sup>3</sup>/h, methane (CH<sub>4</sub>) content percentage to the total volume of the biogas measurement range of 30-100% (accuracy is 0.01%), temperature measurement ranges from -20°C to 60°C (accuracy being 0.01°C), the working pressure of less than 100 kPa and explosion-proof grade of Ex ibiiat4 Gb, and
- (e) Simgas pressure gauge encased in plastic material with a measuring range up to 16 kPa with an accuracy of 0.5 kPa.

Methane content and pressure were measured at the three-hour interval. A simple descriptive data analysis was done by the data analysis function of Microsoft Excel (2013). Microsoft Excel was used to generate graphs from data collected based on Mélard (2014) recommendations as one of the reliable software.

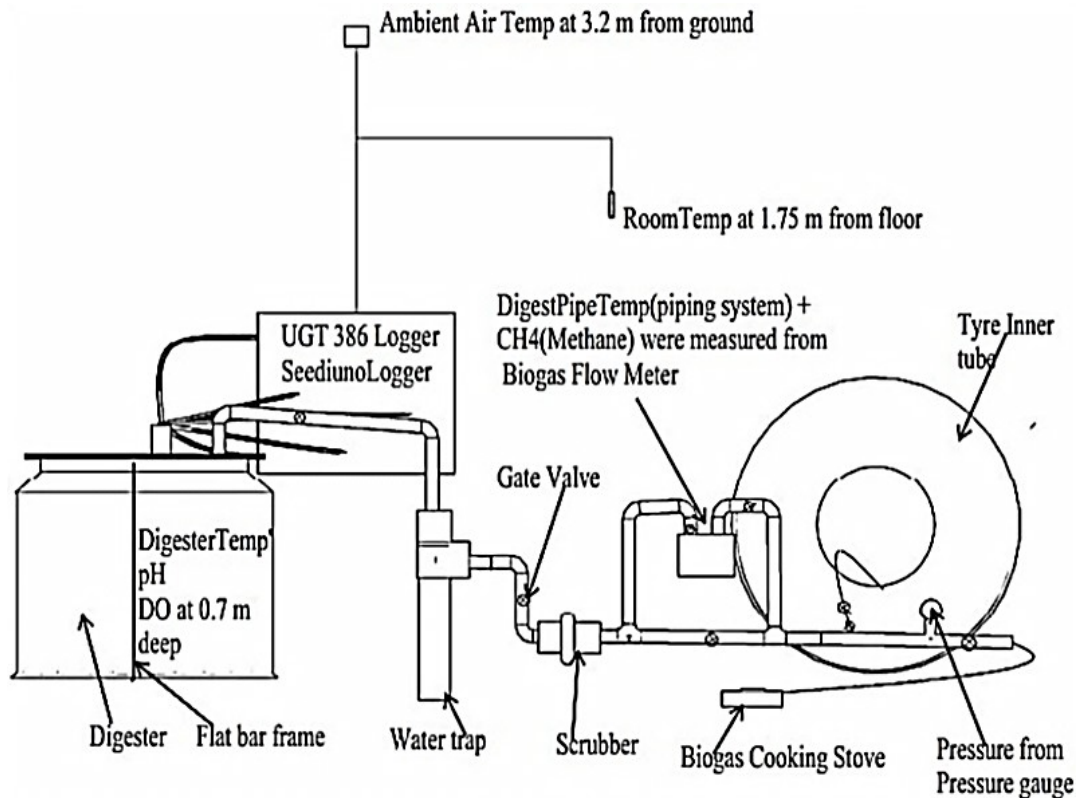
### **iii. Fabrication and testing of the system and its components**

The two conceptual design components were fabricated. These were the digester and piping system. However, other components had more conceptual designs to be fabricated to test their functionality to allow for the choice of the best design option among them before assembling, as no cheap and reliable alternative way to evaluate them was feasible at that particular time and place. For the best option selection purpose, the initial testing was done for the three fabricated conceptual designs of water trap and two conceptual designs for both scrubber and biogas storage. This exercise, as initial testing, was done especially for leakage problems. It was done using a manual hand air pump to fill in air into the fabricated component to a safe pressure of about 8 kPa. The component was then immersed into water or water poured on it to check if there was any sign of leakage. The selected best options were the ones that could resist by 100% the leakage at or above the stated pressure. If more than one option passed the test, then the component's total weighted score was used for selection. Also, if all options failed the test, then another new

conceptual design of the component was considered.

After selecting all the best components needed, then assembling these components forming the batch fed anaerobic digestion system followed. The assembling involved connecting the batch fed digester, water trap, scrubber, biogas storage and biogas cooking stove. The water trap was filled with 140 ml of soft water, and the scrubber was filled with steel wool. Furthermore, instruments were added, including instrumentation for measuring pH, DO, digester temperature, room temperature, ambient air temperature, CH<sub>4</sub> content, pressure and piping system temperature. After feeding the digester with cow dung, probes for measuring pH, DO, and the digester temperature was added by inserting them deep to 0.7 m from the top of the digester and axially 0.1 m away from the central core. The system assembly and experimental setup are illustrated in Figure 3.5.

With an adapted batch fed anaerobic digestion system already assembled with instrumentation for measurements, final testing was started by switching on the solar PV system for powering the measuring tools. Immediately, continuous data collection of the parameters explained above was commenced. Later on, data analysis, e.g. computation of average temperature, rate of change of temperature, and the results and discussion from the experiment followed, where some modifications and or minor redesigning or remedying of some components were done. The mean temperature values and their standard deviation were computed. The rate of change of temperature (°C/h) was determined by dividing the standard deviation temperature from the mean of a given factor by 24 hours of a day.



**Figure 3.5: Experimental set up of adapted batch anaerobic digestion system**

Final testing was done in a room with walls made of muddy materials (sandy clay soil) and lined with cement mortar. The whole inside surface, front and part of the outside left sides' surface of the room were lined. The walls' thickness was about 0.3 m. The room was slant roofed by corrugated iron sheets of gauge 30 with low and high heights of 2.5 m and 3.1 m, respectively. Its plan had a dimension of 3.7 m by 5.1 m. The room had a screening floor with an average thickness of 0.15 m. Furthermore, the room had a window made of wooden frames with dimensions of 0.6 m by 0.5 m, fitted with a 2 mm thick glass. The room door was made of timber and a corrugated iron sheet of gauge 30, with dimensions of 1.8 m by 0.8 m.

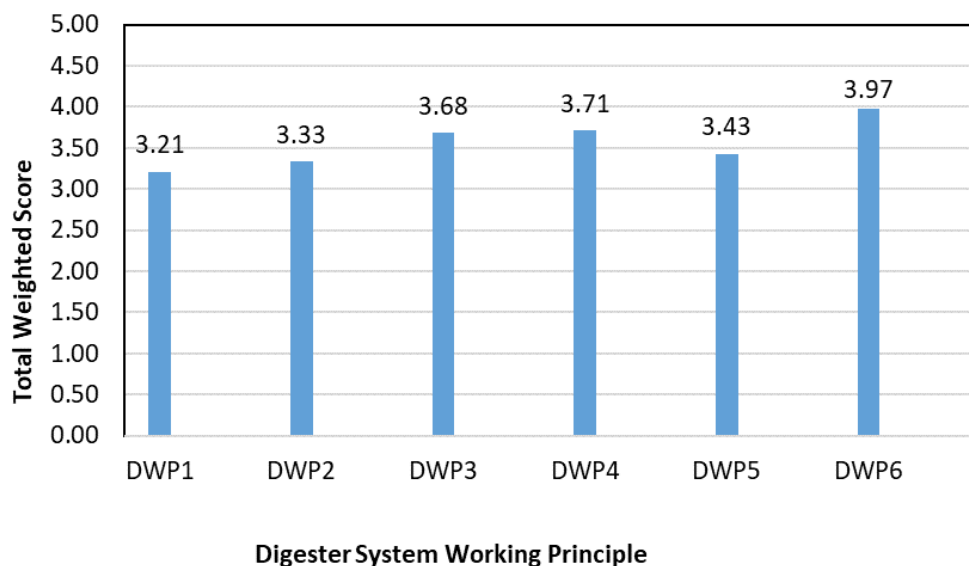
After all, the components and the whole anaerobic digestion system passed the processing phase satisfactorily; then, their finishing was done. This phase produced the intended design products, including the system's components and adapted batch fed anaerobic digestion (ABFAD) system.

### 3.2.5 Selection of working principles and fabrication of the ADS components

The adaptation of the conventional batch anaerobic digestion system (ADS) was conducted successfully. It produced the adapted batch fed anaerobic digestion system, which addressed some challenges encountered in the conventional ADS. Also, the adapted batch anaerobic digestion system may be integrated into renewable energies system appropriate for individual households in communities living in rural semi-arid areas. In the course of adapting the system and its components, findings were obtained. The findings related to the auxiliary components are discussed first, followed by those of the whole system.

#### i. Selection of working principle and fabrication of the digester

All components related to the intended anaerobic digestion system were selected based on decision matrix analysis (DMA), followed by conceptual designing. The first component to be worked on using DMA was the digester. The results obtained and shown in Figure 3.6 reveal that a working principle DWP6 secured the highest total weighted score of 3.97. Note that a frame of iron flat bars encases the plastic drum. With that score, it was selected as the best working principle compared to others.



**Figure 3.6: Decision matrix analysis results for digester working principles**

The score of 3.97 by DWP6 was based on the high likelihood of the following: the gasket

rubber to offer an airtight sealing and withstanding 16 kPa pressure, and the central core and its four wings to allow easy passage of biogas from the interior of the substrates. The ease of passage of biogas from the interior reduces the possibility of building up a biogas mass at the bottom of the digester, pushing the substrate mass up, leading to system clogging.

The central core offers a space for the leachate to be squeezed into the bottom centre of the digester because the central core was perforated and not be filled with cow dung during digester feeding. Also, the leachate may rise to wet the above substrates through the perforated wall of that central core and its wings as the digestion process continues. It was assumed that as the leachate mass finds space in the central core, the solid substrates drop down to occupy its space. In doing so, the solid substrates may be kneaded by the central core wings. It was proven at the end of the experiment by finding the leachate concentrated in the central core. The level of leachate was about 0.45 m levels from the bottom of the digester.

Moreover, the provision of the central core and its wings resulted in increased contact surface area for the growth of the biogas generating microbes in the central mass of the substrate. There was a likelihood of increased biogas microbes as they would be away from the possible rapid changes of temperature near the wall of the digester. The rapid temperature changes affect the performance of the microbes adversely.

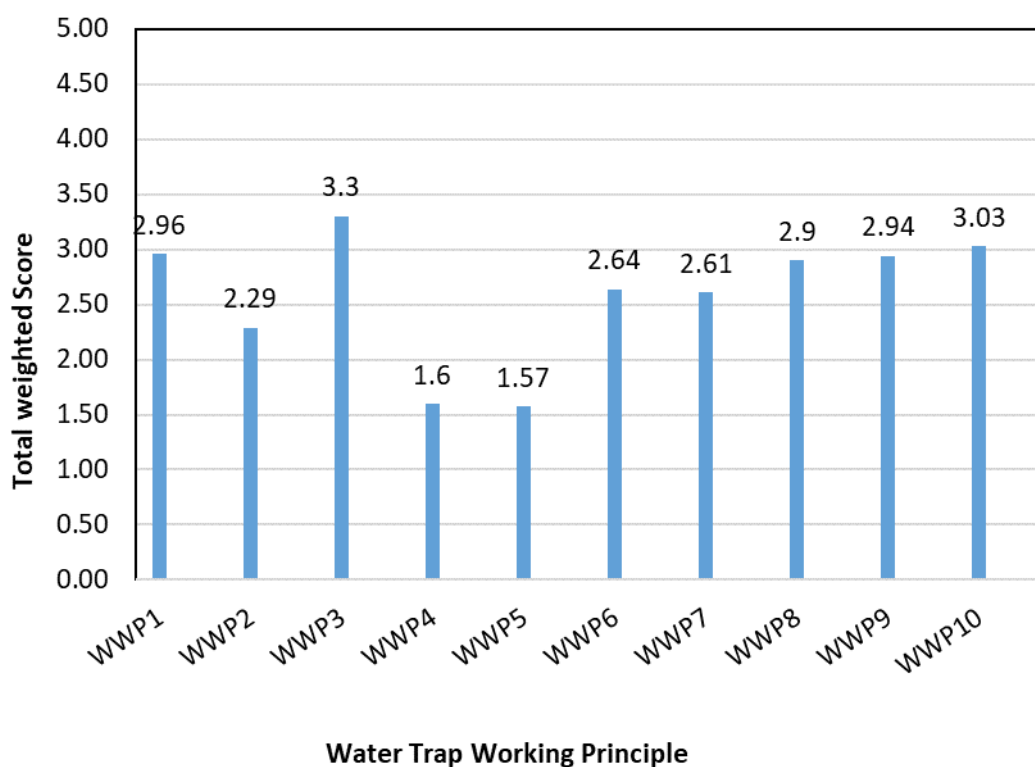
The iron bar frame offers support to the gasket for airtight sealing as it holds together the top lid and the plastic drum of the digester, even above 16 kPa pressure. According to Tubecon (2018), a flat bar may withstand more than 16 kPa under tension, a factor of safety exclusive. The fabricated batch anaerobic digester is shown in Plate 3.1.



**Plate 3.1: Fabricated digester ready for use**

**ii. Selection and fabrication of the water trap working principle**

The DMA results were not conclusive regarding the high weighted design criterion. Therefore, the three water trap working principles were used for fabrication, followed by testing for leakage. The concepts in question are WWP1, WWP3, and WWP10. All three concepts had equal-weighted scores for the high weighted design criterion of withstanding airtight sealing. After the leakage test, the WWP3, shown in Plate 3.2 (c), was selected as the best option for sealing the leakages by 100% plus the highest-scoring of the total weighted score as shown in Figure 3.7.



**Figure 3.7: Decision matrix analysis results for water trap working principles**

The freshwater volume of 140 ml was added to the water trap. This volume was determined by trial and error methods to ensure no water and air inflow to the digester and water outflow beyond the water trap in case of accidental opening of the system to air. Water enhances moisture and Carbon dioxide (CO<sub>2</sub>) trapping. Note that, by assuming the annual mean atmospheric pressure of 101.9 kPa at the study site (TDA, 2018) and pressure and temperature of both 6 kPa and 28°C, respectively in the water trap, the solubility of CO<sub>2</sub> in water was taken to be 15 ml of CO<sub>2</sub> per one gram of water (Diamond and Akinfiev, 2003). Therefore, about 2.1 litres of CO<sub>2</sub> can be removed from the 7 litres of biogas (assuming biogas containing 30% of CO<sub>2</sub>) passing through the water trap.



(a) WWP1

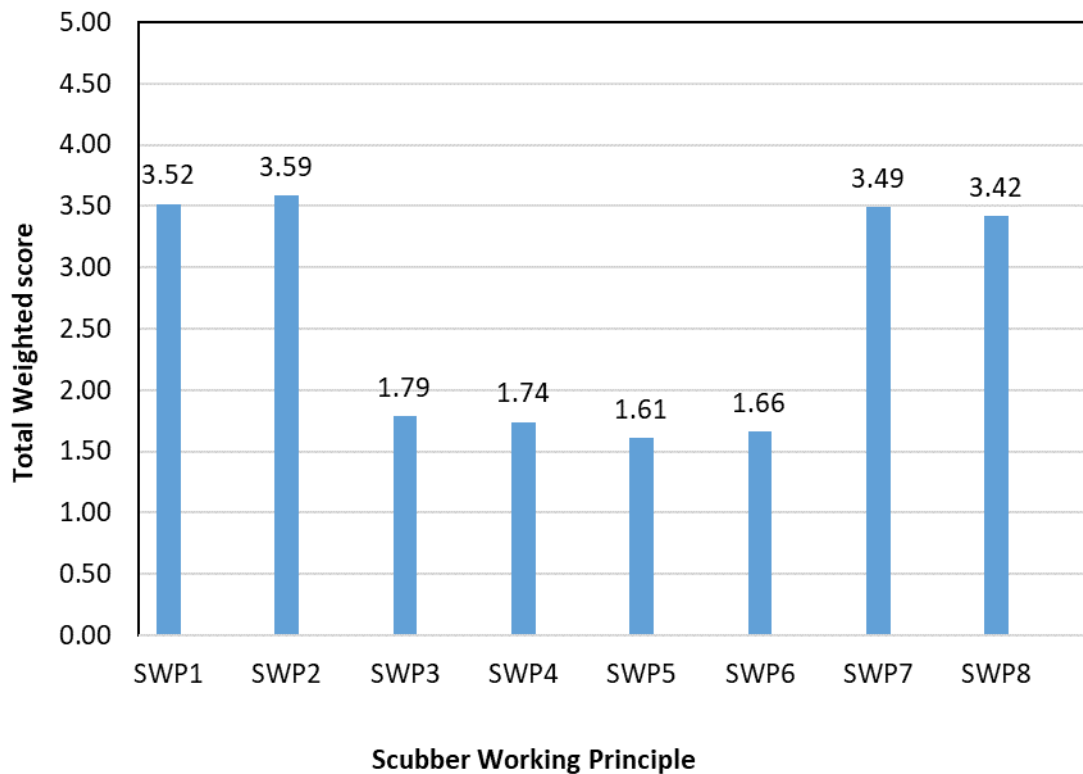
(b) WWP10

(c) WWP3

**Plate 3.2: The screened fabricated water trap concepts**

**iii. Selection of the working principle and fabrication of the scrubber**

The SWP1 and SWP2 shown in Plate 3.3 were subjected to the leakage test while parked with iron wools. Both concepts were fabricated, and they were not leaking at all under testing conditions. Therefore, the selection was made based on the total weighted score shown in Figure 3.8. Following these results, the SWP2 shown in Plate 3.3 (b), with a total score of 3.59, was selected as the best scrubber design to be incorporated in the anaerobic digestion system intended.



**Figure 3.8: Decision matrix analysis results for scrubber working principles**



(a) SWP1



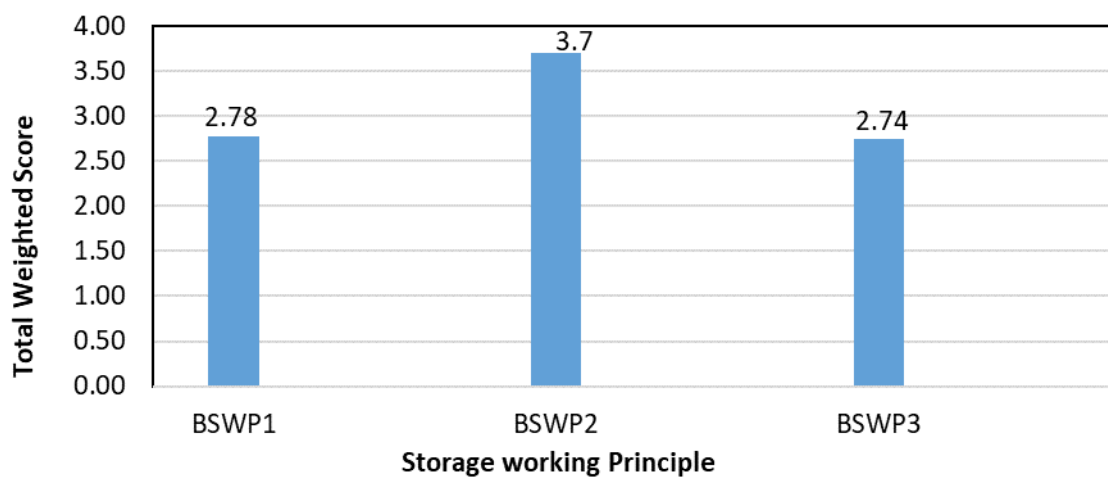
(b) SWP2

**Plate 3.3: The screened fabricated scrubber concepts**

#### iv. Selection of the working principle and fabrication of the biogas storage

Three concepts of biogas storage facility were subjected to DMA, and the results are, as shown in Figure 3.9. The two concepts, namely the inflatable plastic bag (BSWP1) and tyre inner tube (BSWP2), were further subjected to leakage test after their fabrication process. The BSWP1 performed poorly; therefore, the BSWP2 shown in Plate 3.4 (b) was

selected as biogas storage best option to be added to the list of components of the ADS. The tyre tube sizes used were 7.5-15 (TR174A), 8.25-16 (TR177A), 9-20 (TR177A) and 12-24 (TR177A.).



**Figure 3.9: Decision matrix analysis results for biogas storage concepts**



(a) BSWP1

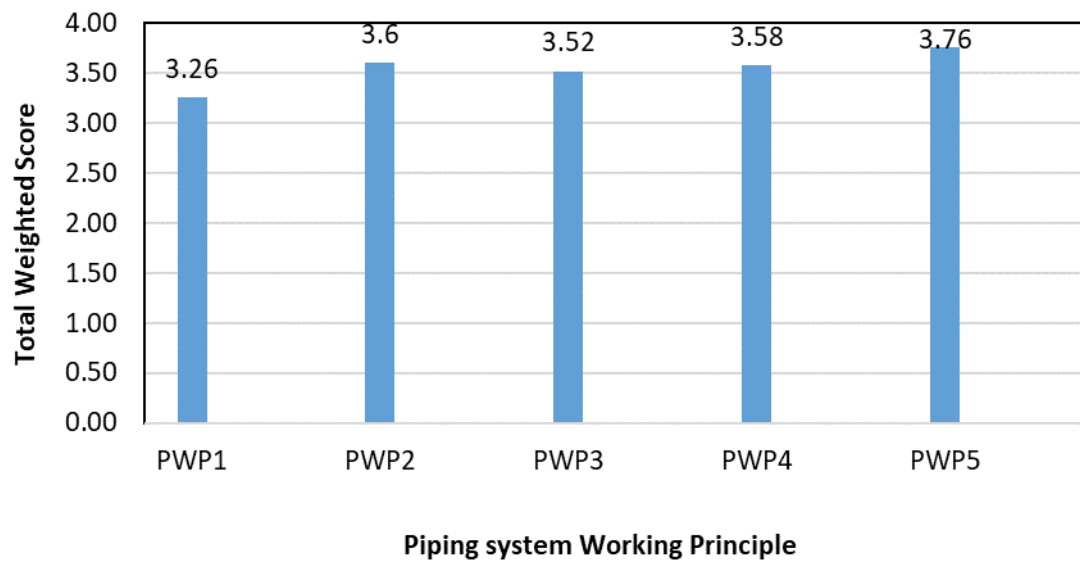


(b) BSWP2

**Plate 3.4: The screened fabricated biogas storage working principles**

**v. Selection of the working principle and fabrication of the piping system design**

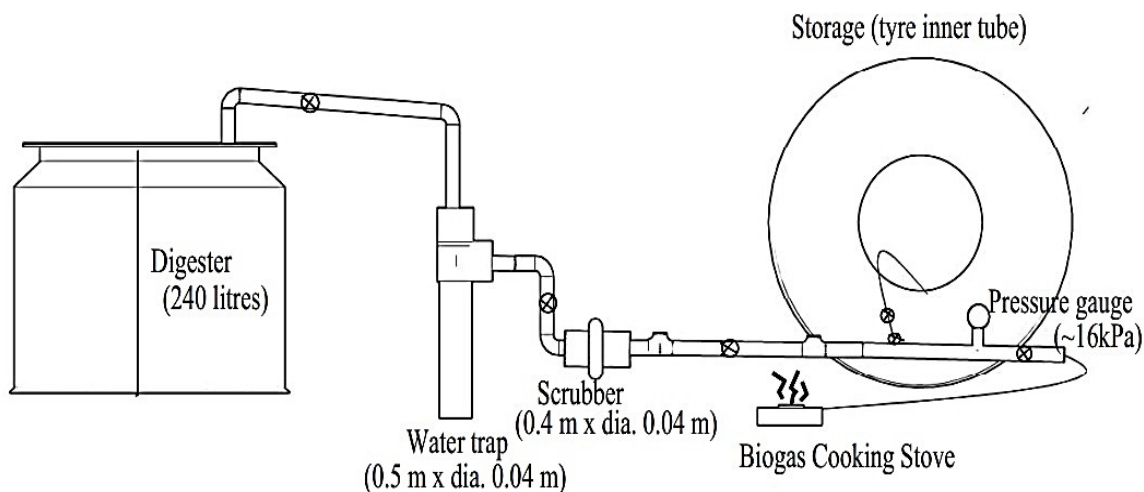
Selection of the piping system option was made based on the results from the DMA, as shown in Figure 3.10. The option PWP5 (IPS plastic pipe (70 %) + other flexibles (25 %) + horse pipe (5 %) + IPS fittings), was selected as its scoring was highest. This option secured the total weighted score of 3.76.



**Figure 3.10: Decision matrix analysis results for piping system concepts**

### 3.3 Results and Discussion

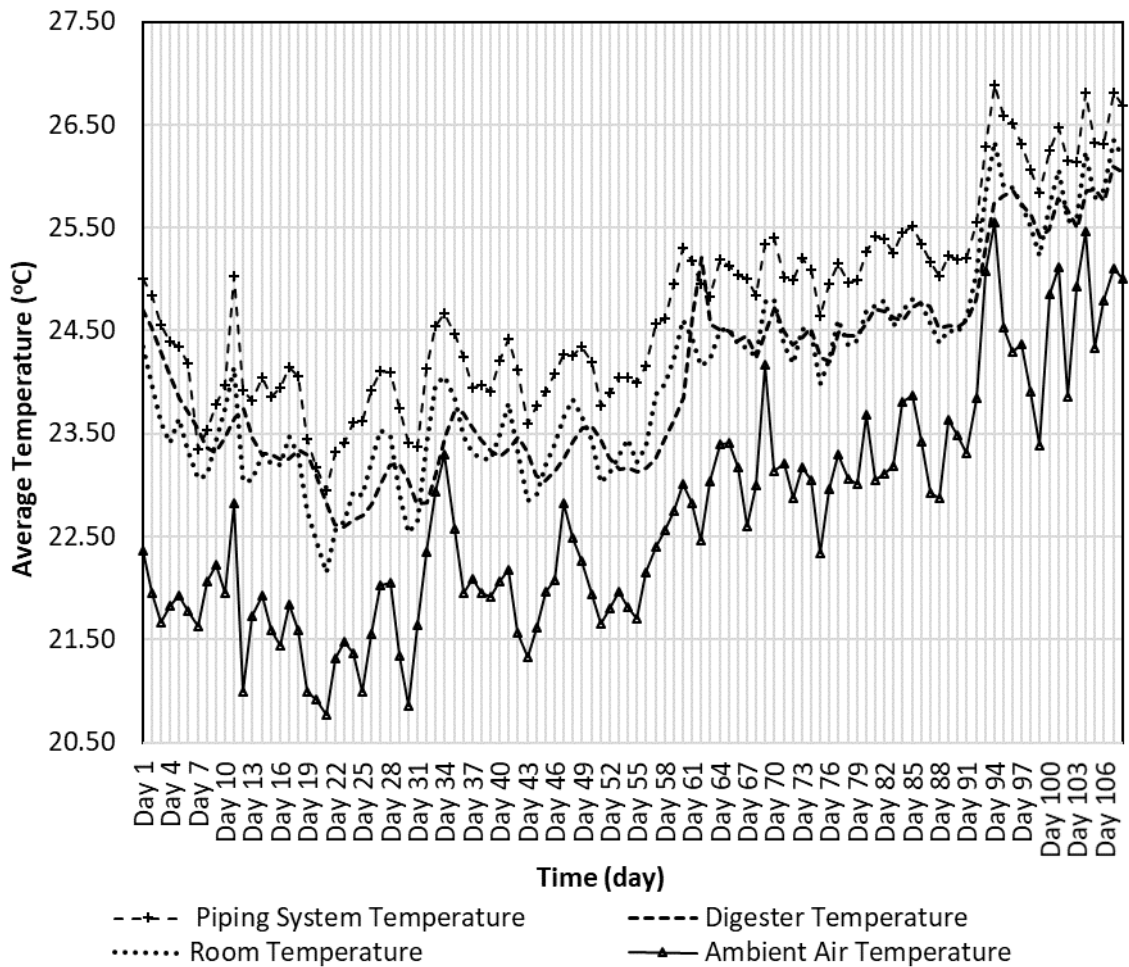
After selecting all components suitable for making the anaerobic digestion system, as discussed in Subsection 3.3.1, the assembling of these components followed. The assembling was done, as shown in Figure 3.11, illustrating the complete connected batch fed anaerobic digestion system that is ready to be used or incorporated in the integrated renewable energy system. The assembled ADS was experimentally tested as described in Sub-section 3.2.4 and the results obtained after analysis are discussed in this Sub-section. The results include the independent variables: ambient air temperature, temperature response variables of room, digester and piping system. Also, the results included the CH<sub>4</sub> content in the biogas, pH, DO inside the digester and pressure of the whole system. These parameters are essential for the technical evaluation and running of the system.



**Figure 3.11: Assembled adapted batch fed anaerobic digestion system sketch**

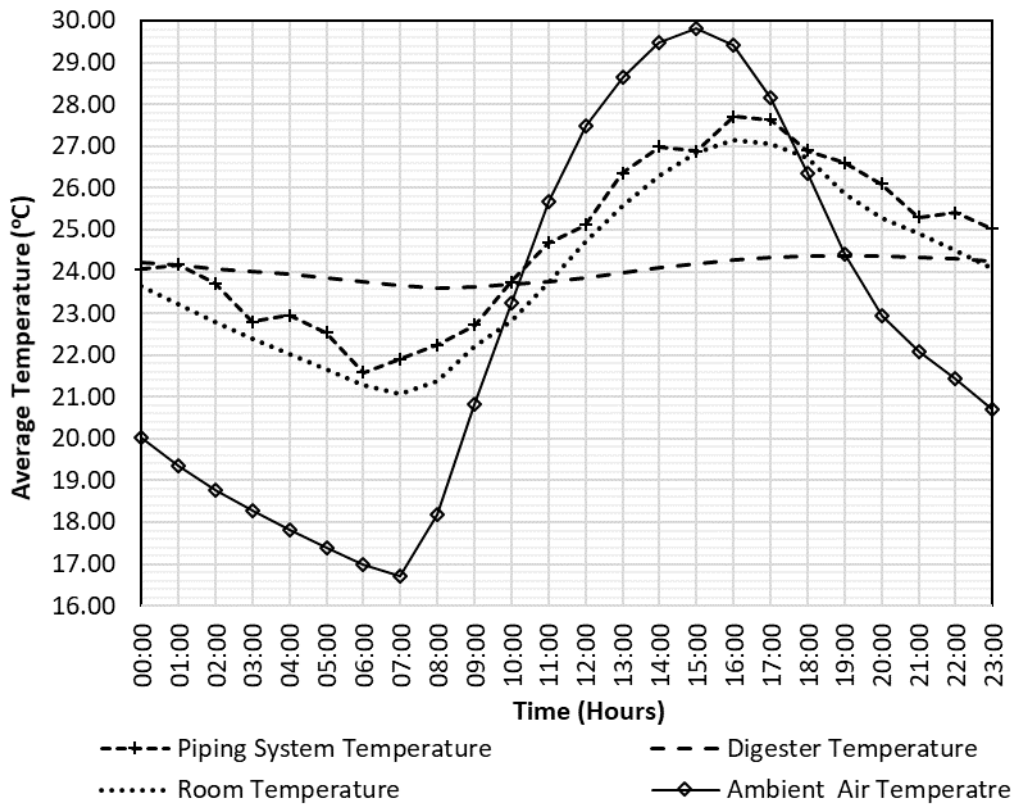
**i. Temperature and CH<sub>4</sub> content of the adapted batch fed ADS**

Ambient air temperature and room temperature varied proportionally with piping system temperature (Figure 3.12). The room accommodated the digestion system. However, the ambient air temperature, room temperature and piping system temperature varied proportionally with digester temperature in a leading manner. As illustrated in Figure 3.12, these phenomena indicate that the substrate inside the digester absorbs and emits heat slowly. From the same figure, it is shown that, on average, the ambient air temperature was lower than the temperature in the room and the digester. This phenomenon might have been caused by the room building materials, which enhanced absorbing more heat and emitting less absorbed heat.



**Figure 3.12: Daily average temperature variations of ABFADS (Jun 16 - Oct 1/ 2017)**

The similar trends of the proportional relationship among temperature of the piping system, room, the digester and ambient air shown in Figure 3.12 are also clearly seen in Figure 3.13. Figure 3.13 is based on the analysis of the temperature data on an hourly basis within a day. This figure shows that the piping system temperature curve is not smooth compared to the other curves. The piping system temperature curve indicates that temperature oscillates as it follows the trend of room temperature. The oscillation may have been caused by the intermittent flow of varying amounts of biogas at a low-temperature level through the piping system from the digester. Usually, the digester has a lower temperature compared to the piping system most of the time (Figure 3.12).



**Figure 3.13: Hourly average temperature variations in ABFADS (Jun 16 - Oct 1/ 2017)**

The other computed factor was the rate of change of temperature, which was based on standard deviation from the mean temperature of the piping system, room, the digester and ambient air. Values of factors obtained for each of the ABFADS’s parameters are shown in Table 3.5. Table 3.5 shows that the rate of change of temperature inside the digester was the lowest with the value of 0.01°C/h while that of ambient air was highest at 0.18°C/h. This revelation indicates that any ADS intended to be installed outside should be protected from ambient air temperature variation, which has been the case for all biogas plants installed outside. The high-temperature variation affects biogas microbes adversely.

**Table 3.5: Temperature rate of change and other factors of ABFADS's parameters**

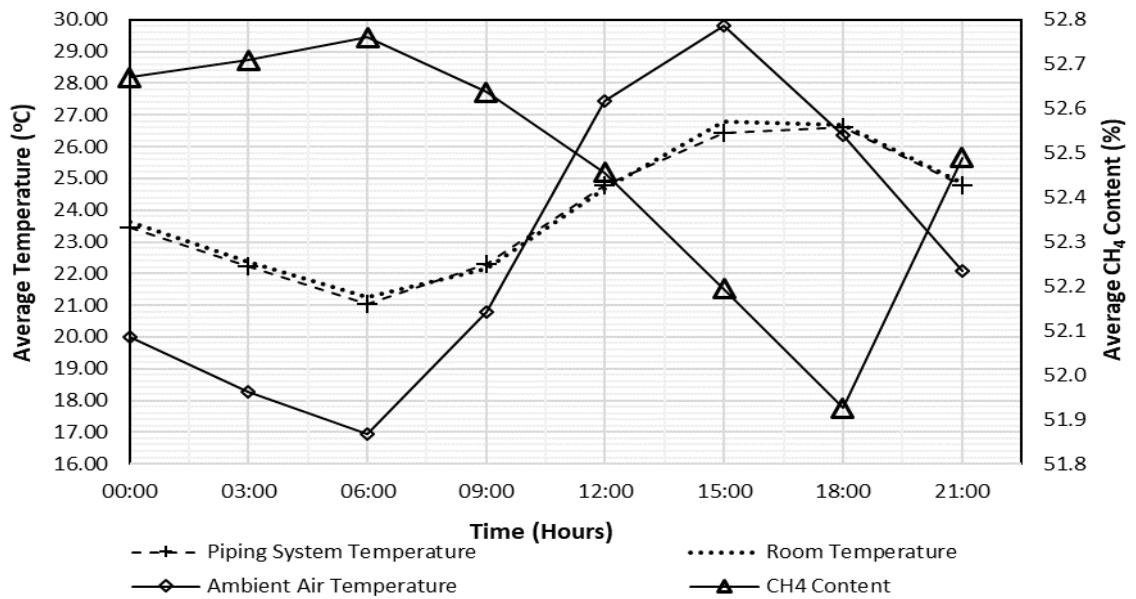
Factor (unit)	Parameter			
	Piping System	Digester Temperature	Room Temperature	Ambient Air Temperature
Mean Temperature (°C)	24.71	24.04	24.05	22.67
Standard deviation (°C)	1.86	0.26	1.95	4.38
Temperature rate of change (°C/h)	0.08	0.01	0.08	0.18

Additionally, the average digester temperature of 24.04°C shown in Table 3.5 indicates that the ABFADS was operating in the mesophilic phase of temperature, i.e. 20-39°C of anaerobic digestion. The optimum temperature for mesophilic microbes' performance is 35°C.

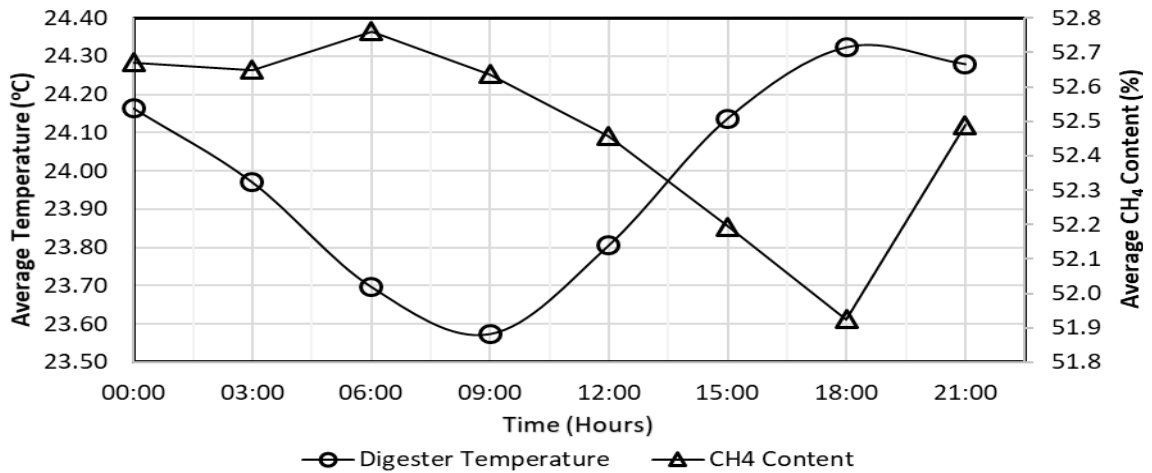
The digester's low rate of change of temperature indicates that the substrate mass exhibited insulation behaviour towards the centre of the digester. This situation is based on the fact that the temperature probe for measuring digester temperature was close to the central digester core. The temperature probe was placed at 0.19 m and 0.3 m from the circumferential periphery and bottom of the digester, respectively. Moreover, the room walls and air insulated the digester from an extreme variation of ambient air temperature regarding the experimental setup. The phenomenon is evident from the closeness of temperature trends of room and digester piping system as well as their rate of change (Figure 3.13 and Table 3.5).

Temperatures of ambient air, room, and piping system are inversely proportional to CH<sub>4</sub> content in the time ranges of 00:00 -15:00 hrs (Figure 3.14). Furthermore, the temperatures decrease at the different slope with CH<sub>4</sub> content between 15:00 and 18:00 hrs before the ambient temperature decreasing fast than a room, and piping system temperatures while CH<sub>4</sub> content increases fast to 52.65%. In a range of 18:00-00:00 hrs.

The digester temperature is directly proportional to CH<sub>4</sub> content in the time ranges of 00:00 - 3:00 hrs and 6:00 -9:00 hrs. Between 18:00 and 00:00 hrs, the digester temperature slowly descends to 24.15°C while CH<sub>4</sub> content quickly ascends to 52.65%. In the remaining time ranges in Figure 3.15, both digester temperature and CH<sub>4</sub> content are inversely proportional.



**Figure 3.14: CH<sub>4</sub> content and piping system, room and ambient air temperature (Jun 25- Oct 1/ 2017)**



**Figure 3.15: CH<sub>4</sub> content and digester temperature relationship (Jun 25- Oct 1/ 2017)**

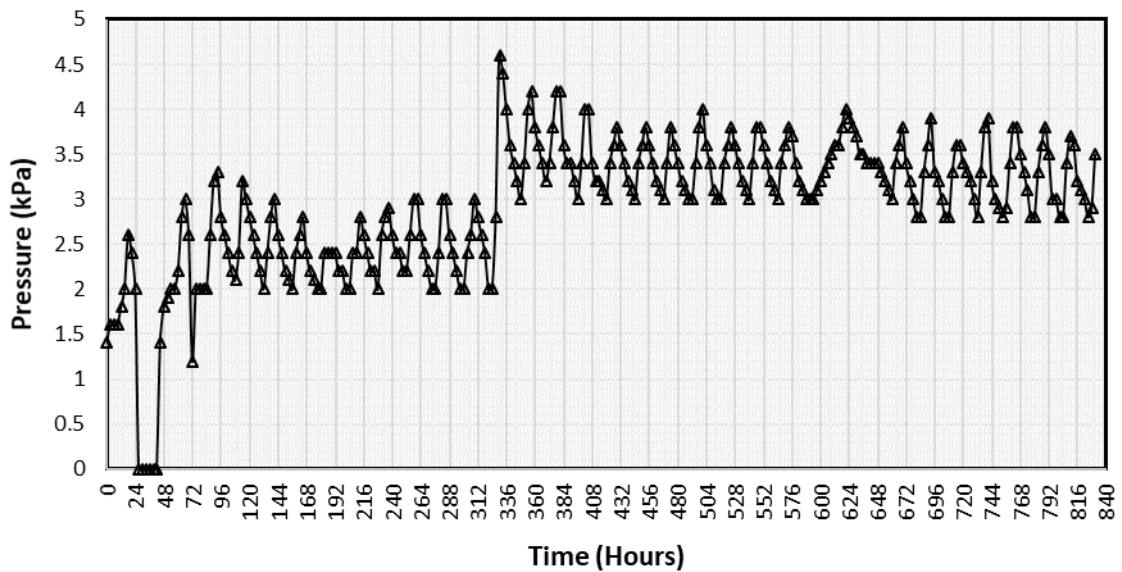
Average CH<sub>4</sub> content in biogas generated from 25/06/2017 to 01/10/2017 was 52.4%, with a standard deviation of 2.9%. From Figure 3.14, it is shown that the temperature of both the room and digester piping system increased as the average methane content decreased and vice versa.

CH<sub>4</sub> content was higher (averagely 52.8%, with a standard deviation of 0.3%) in the morning when the temperature was very low. Then CH<sub>4</sub> content decreased to 51.9% at 18:00 hours when the temperature inside the digester and in the digester piping system was in the high range. This phenomenon may have been caused by the high solubility of carbon dioxide (CO<sub>2</sub>), which is one of the principal constituents of biogas in the water at low temperature. The solubility is given as moles of solute, i.e. CO<sub>2</sub> per 100 grams of solvent, e.g. water. Wu *et al.* (2006) reported that CO<sub>2</sub> has half of the solubility at 60°C compared to the same quantity of CO<sub>2</sub> when the temperature was 35°C. Wu *et al.* (2006) found out this phenomenon after carrying out a laboratory-scale experiment. The aim was to assess the influence of temperature fluctuation on thermophilic anaerobic digestion of municipal organic solid waste. Therefore, the relationship between CH<sub>4</sub> content and temperature shown in this study is supported scientifically.

## **ii. Pressure, DO, and pH in the adapted batch fed anaerobic digestion system**

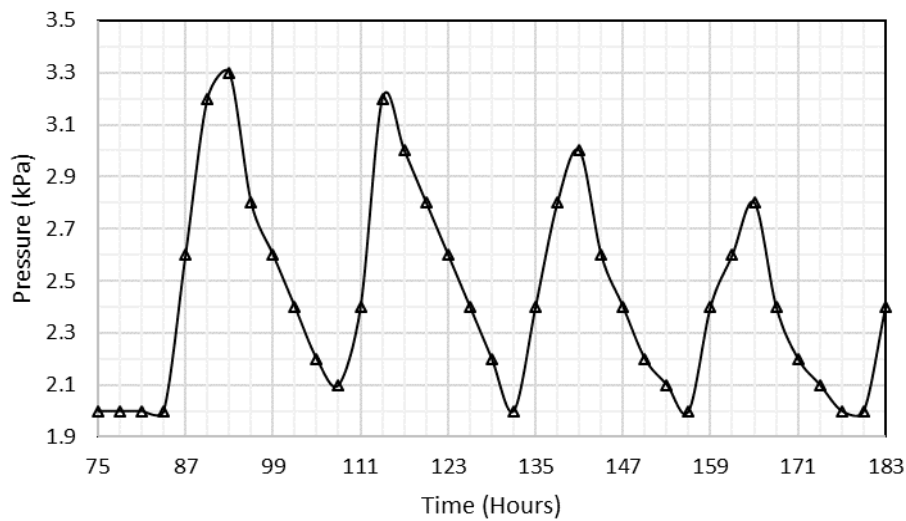
There are various indicators of the functionality of the anaerobic digestion system, including pressure inside the digester. Pressure can indicate whether the system is leaking or not, as it was described by Oloche *et al.* (2017) on testing the underground ADS. Also, pressure indicates the amount of biogas in the system. Figure 3.16 showed pressure-variations of the ABFADS when the system was leaking due to the failure of some pipe fittings. Pressure rose to maximum levels between 15:00 hours and 18:00 hours and then decreased afterwards before rising again from 9:00 hours. This phenomenon is indicated

by the peak and trough of the pressure curve in Figure 3.16. Besides, the phenomenon is shown clearly in the expanded view in Figure 3.17. The curves in both figures (Figure 3.16 and 3.17) indicate leakage of biogas from the ABFADS, calling for immediate remedial measures.



**Figure 3.16: Pressure variation of ABFADS (08/07/2017 (21:00 hours) - 10/08/2017)**

Furthermore, the rising of pressure in the daytime at high temperature is probably an indication of more generation of biogas than biogas leakage from the system. This condition may also imply that biogas generation microbes are very active, producing biogas at high temperature, as shown in Figure 3.17. As temperature decreases, the generation of biogas declines. It implies the reduced activity of microbes to generate biogas, while the rate of biogas leakage is higher than the rate of biogas generation; hence the pressure in the system drops. In the phenomenon of system leakage, the pressure was hardly above 4.5 kPa.

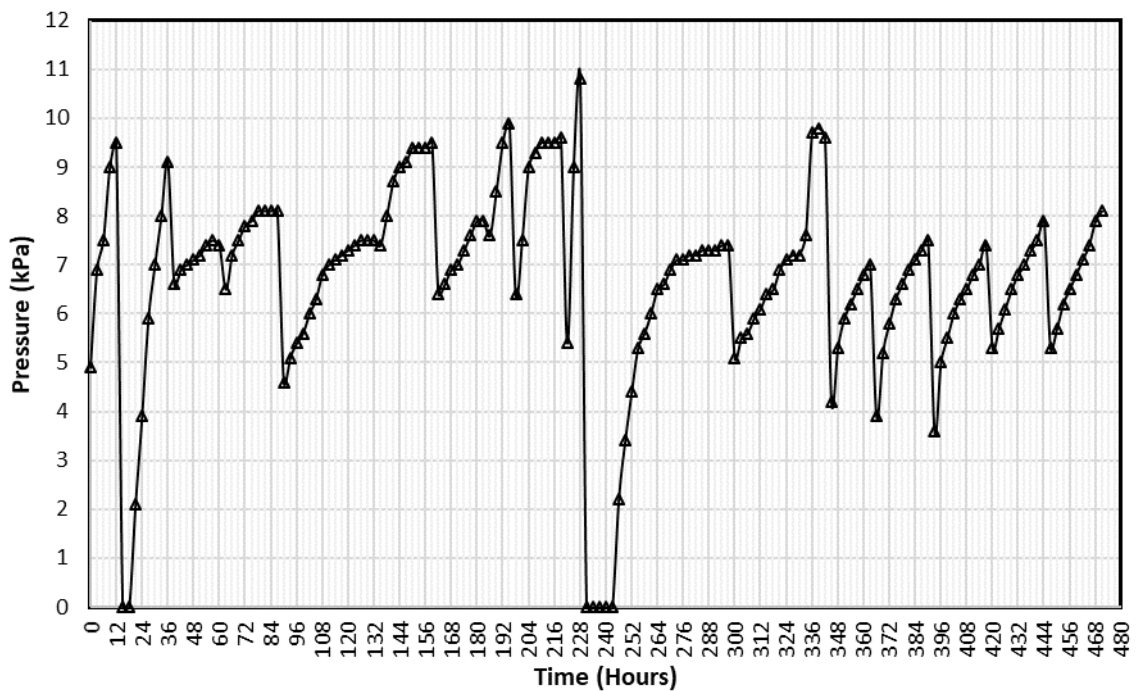


**Figure 3.17: Pressure variation of ABFADS (12/07/2017 (00:00 hours) - 16/07/2017)**

Window 24-48 hours, 75-81 hours, 321-327 hours, and 588-594 hours in Figure 3.16 indicate the time of remedying the fault pipe fittings identified after troubleshooting them. The rise of pressure after window 321-327 hours indicates the improvement of sealing the biogas leakage, although rising and falling pressure levels continued afterwards. At 831 hours, the pressure recording was stopped, and the piping system of ABFADS was disassembled and reassembled to replace all of its faulty pipe fittings. Generally, both pressure curves in Figures 3.16 and 3.17 have a shape similar to a sinusoidal curve presented by Kuhl *et al.* (2019).

Figures 3.18 and 3.19 illustrate the variation of pressure in the ADS after fixing the faults causing leakage. The leakage occurred on the top lid. The rubber gasket of 2 mm thickness was replaced with that of 4 mm thickness. In this case, pressure drop did not occur without releasing biogas for boiling test and replacing the biogas storage. The sudden drop in pressure seen in Figure 3.18 indicates the event of releasing generated biogas from the storage or replacing the biogas storage. In Figure 3.18, the pressure drops within windows 12-24 hours and 228-240 hours were due to the change of biogas storage with the empty

biogas storage, while the rest occurred due to boiling tests. However, as the pressure level increased in the ABFADS, the pressure rising rate decreased (Figures 3.19). The situation might have been caused by the biogas compressibility, digester's biogas generating rate, and or physical elasticity property of the biogas storage. The biogas storage, i.e. inner tyre tube, was proven to safely withstand a pressure of up to 10.8 kPa (Figure 3.18 at 228 hours). Generally, shape of increasing pressure curve before the pressure drop in the system is similar to that of the logarithmic curve (Figures 3.18 and 3.19). Grossman-Ponemon *et al.* (2019) have described the logarithmic curve.



**Figure 3.18: Pressure variation of ABFADS (12/09/2017(03:00 hours) - 01/10/2017)**



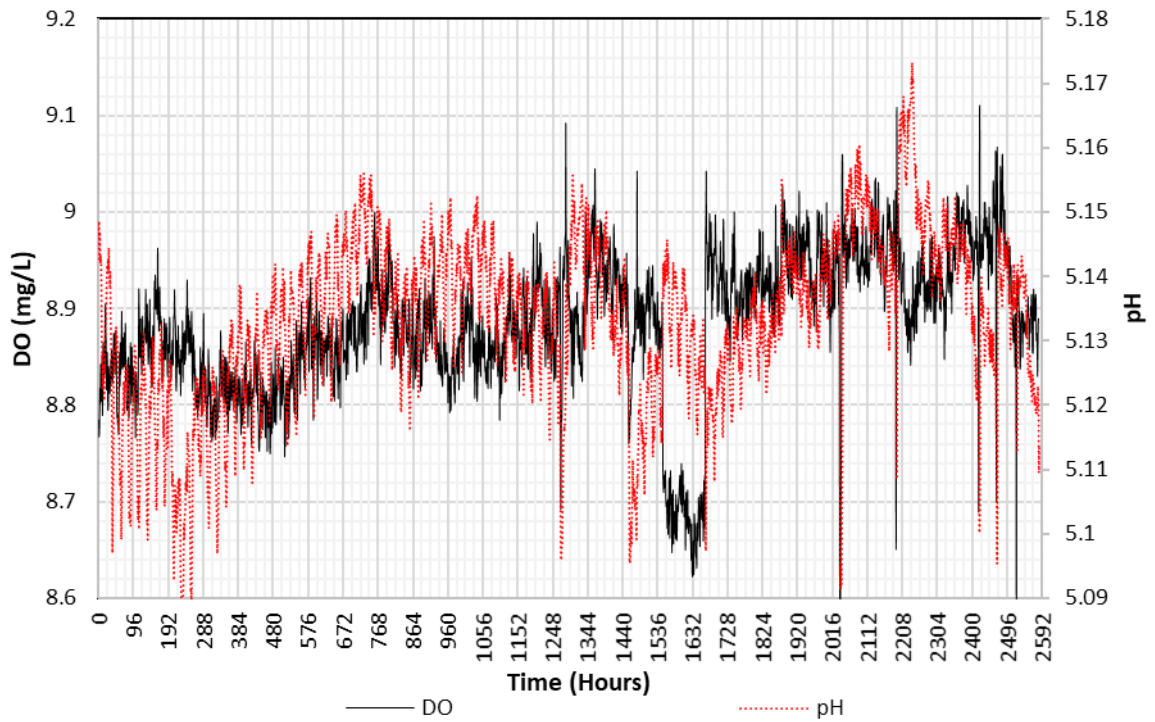


Figure 3.20: DO & pH versa time of ABFADS (16/06/2017 (00:00 hours) -01/10/2017)

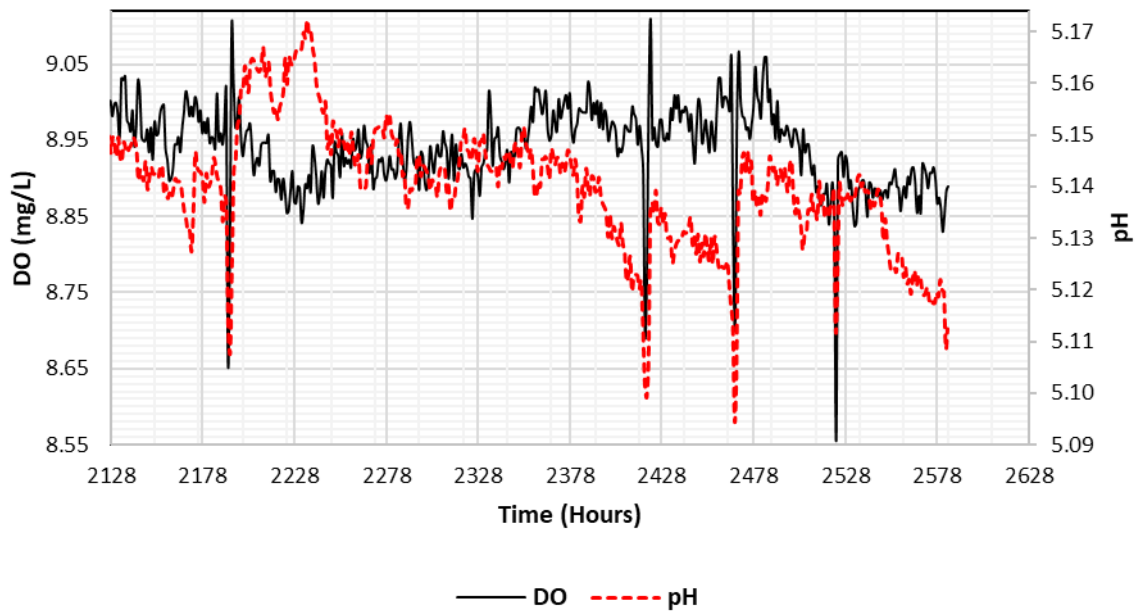
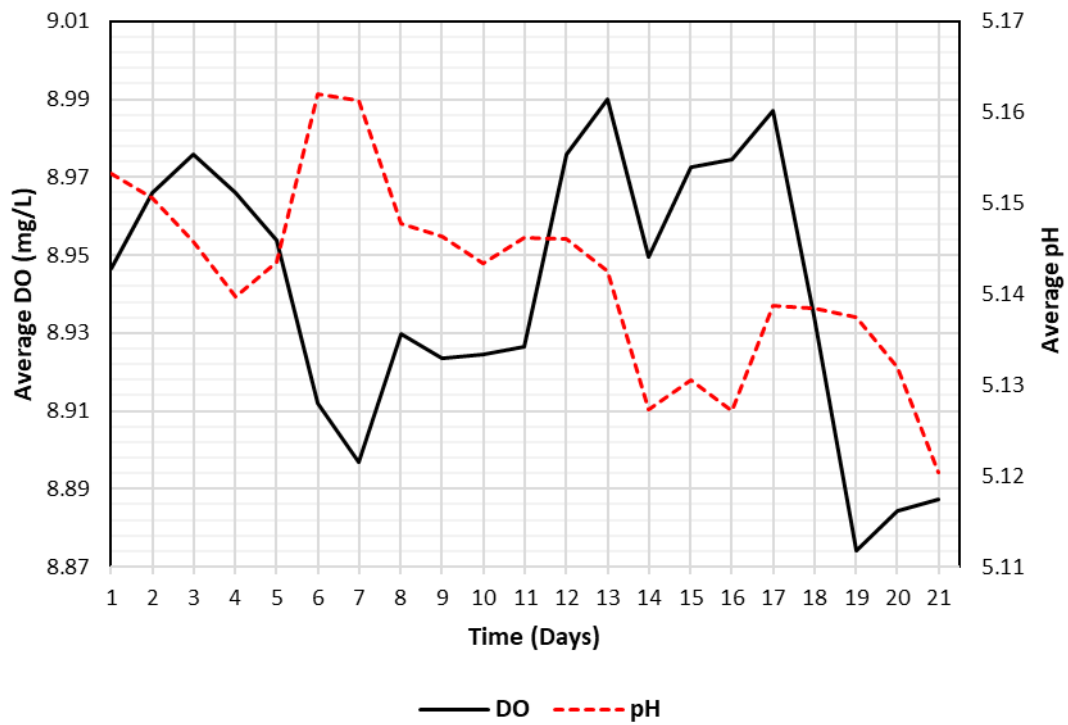
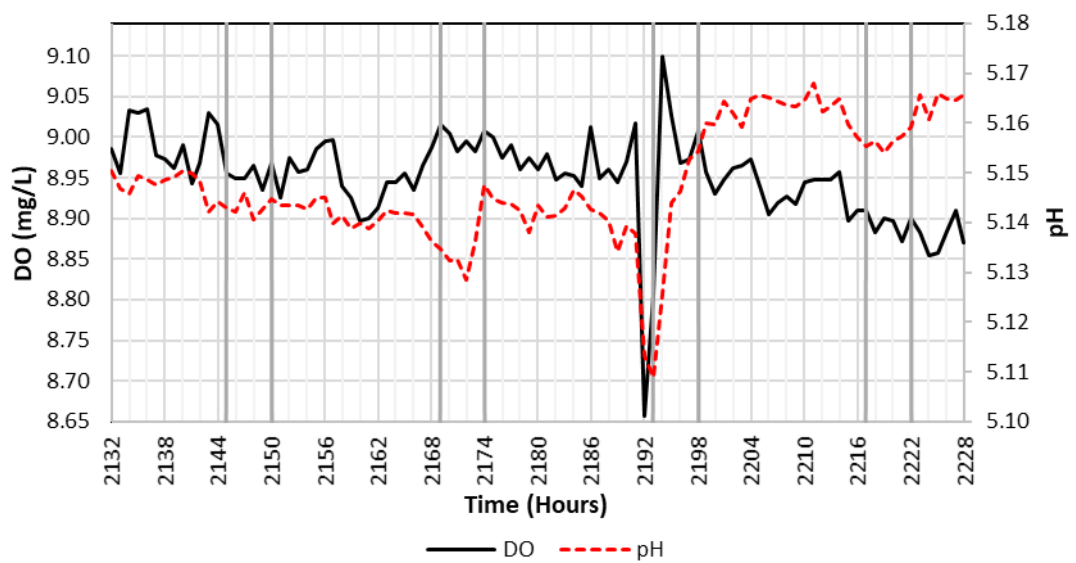


Figure 3.21: DO & pH versa time of ABFADS (12/09/2017 (00:00 hours) -01/10/2017)



**Figure 3.22: DO & pH versa time (days) of ABFADS (12/09/2017 (00:00 hours) - 01/10/2017**



**Figure 3.23: DO & pH versa time of ABFADS (13/09/2017 (00:00 hours) - 17/09/2017)**

Although not tested, the durability of the ABFADS was envisaged to be more than 15 years if kept away from ultraviolet radiation and physical damages. However, replacement of valve made of iron-based material, which is located between the water trap and digester of ABFADS, is expected to occur after at least seven years (Sun and Nestic, 2007). The replacement is needed because biogas contains a trace of Hydrogen sulphide ( $H_2S$ ) gas, which corrodes iron materials. The corrosion is caused by the reaction of iron with sulphur found in  $H_2S$ .

### **3.4 Conclusions and Recommendations**

#### **3.4.1 Conclusions**

The formulated approach of anaerobic digestion system adaption research, which involves a decision matrix analysis (DMA) tool, is crucial. The approach enabled the development of the small-sized (with digester of  $0.24\text{ m}^3$ ) ABFAD system, which addresses the design and operational constraints encountered in applying existing conventional biogas generation systems in rural semi-arid areas. The results of addressed constraints are as follows: no clogging of system biogas flow; easy handling of its auxiliary components like replacing of iron wool, and portable biogas storage; withstanding appreciable pressure (10.8 kPa), and self-squeezing capability for easy release of quality biogas with a methane content of 52% ready for use.

Other results are leachate recycling for the substrate near the bottom of the digester and creating a favourable environment (low-temperature variation of  $0.01^\circ\text{C/h}$ ) for the biogas generation microbes at the mass of the central substrate in the digester. The low-temperature variation observed indicated that the substrate mass exhibits insulation behaviour towards the centre of the digester. This phenomenon allows increased biogas generation, as microbes would have growth contact surface area increased on the central core and wings inside the digester.

Furthermore, the piping system temperature of the ABFAD system varies inversely proportional with methane content. This situation implies that temperature influences methane content due to the solubility of CO<sub>2</sub>, a biogas component, which increases as temperature declines. The ABFAD system's pressure curves, which are in the sinusoidal curve shape, indicate that the system is leaking, while the ones in the logarithmic curve form indicate that the system is not leaking. Furthermore, biogas microbes' activities in the ABFAD system's digester increase with temperature based on the pressure curves produced.

The experimental test data analysis results of both pH and DO relative to time were obtained. They showed that in the ABFAD system's digester, Dissolved Oxygen and pH ranged from 8.8-9.0 mg/l and 5.11-5.15, respectively. Also, pH values varied inversely proportional with DO values when considering the time of at least one day under anaerobic digestion. Additionally, pH varied more inversely proportional with temperature than DO did with the temperature inside the ABFAD system's digester. Therefore, pH is a more reliable indicator of the microbial activities in the system than DO. Finally, when the ABFAD system is in good working condition, it minimises biogas' loss to the atmosphere because it has only one controlled possible outlet of biogas.

### **3.4.2 Recommendations**

The methodological design approach, involving DMA and conceptual designing, which was used to develop the adapted ADS, is recommended for biogas system designers. Additionally, the ABFAD system is recommended to be used by individual households in areas where the variation of temperature around the digester will be within the  $\pm 3^{\circ}\text{C}$  temperature range. Furthermore, the establishment of digester temperature variation at a different height from the digester's bottom during the operation of the ABFAD system is a point of research interest.

The whole piping system and the biogas storage are recommended to be kept at a low temperature ( $\leq 21.04^{\circ}\text{C}$ ) level aiming to increase  $\text{CH}_4$  content in the generated biogas. The ABFAD system's pressure in the sinusoidal curve shape (leaking) and in the logarithmic curve form (not leaking) are recommended for identifying the system's operating status. The pH parameter is recommended to be used as a reliable indicator of the operating status of the ABFAD system.

Further research is needed for determining the optimum amount of steel wool filled in the scrubber and optimum time to replace for this developed ABFAD system, whether installed above or on the ground, while minimizing the digester temperature variation.

Finally, the adapted ABFAD system is recommended to be incorporated in any integrated renewable energy system intended for sustainable energy supply to cater for cooking and powering of electrical and electronic gadgets.

### **3.5 Acknowledgement**

Refer to Section 2.5 in Chapter Two of this thesis.

### 3.6 References

- Abatzoglou, N. and Boivin, S. (2009). A review of biogas purification processes. *Biofuels, Bioproducts and Biorefining* 3(1): 42 – 71.
- Abu-Taha, R. and Daim, T. (2011). Multi-criteria applications in renewable energy analysis: A literature review. In: *Technology Management in the Energy Smart World Proceedings of Portland International Centre for Management of Engineering and Technology (PICMET)'11: Technology Management in the Energy Smart World*. pp. 1-8.
- Achinas, S., Achinas, V. and Euverink, G. J. W. (2017). A technological overview of biogas production from biowaste. *Engineering* 3(3): 299 – 307.
- Adekunle, K. F. and Okolie, J. A. (2015). A review of biochemical process of anaerobic digestion. *Advances in Bioscience and Biotechnology* 6(3): 205 – 212.
- Awe, O. W., Zhao, Y., Nzihou, A., Minh, D. P. and Lyczko, N. (2017). A review of biogas utilisation, purification and upgrading technologies. *Waste and Biomass Valorisation* 8(2): 267 – 283.
- Bond, T. and Templeton, M. R. (2011). History and future of domestic biogas plants in the developing world. *Energy for Sustainable Development* 15(4): 347 – 354.
- Chae, K. J., Jang, A. M., Yim, S. K. and Kim, I. S. (2008). The effects of digestion temperature and temperature shock on the biogas yields from the mesophilic anaerobic digestion of swine manure. *Bioresource Technology* 99(1): 1 – 6.
- Diamond, L. W., & Akinfiev, N. N. (2003). Solubility of CO<sub>2</sub> in water from – 1.5 to 100 C and from 0.1 to 100 MPa: Evaluation of literature data and thermodynamic modelling. *Fluid Phase Equilibria* 208(1-2): 265-290.
- Divya, D., Gopinath, L. R. and Christy, P. M. (2015). A review on current aspects and diverse prospects for enhancing biogas production in sustainable means. *Renewable and Sustainable Energy Reviews* 42: 690-699.

- Garfí, M., Martí-Herrero, J., Garwood, A. and Ferrer, I. (2016). Household anaerobic digesters for biogas production in Latin America: A review. *Renewable and Sustainable Energy Reviews* 60: 599 – 614.
- Grossman-Ponemon, B. E., Heimisson, E., Lew, A. J. and Segall, P. (2019). Logarithmic growth of dikes from a depressurizing magma chamber. EarthArXiv & California Digital Library-Preprint Version, University of California, USA. [<https://doi.org/10.1029/2019GL086230>] site visited on 19/03/2018.
- Jørgensen, P. J. (2009). *Biogas-Green Energy. PlanEnergi and Researcher for a Day*. Faculty of Agricultural Sciences, Aarhus University. pp.34.
- Kaena, N. P. A (2012). Guideline for choosing the best alternative solution for engineering academic projects. *Proceeding of the 2<sup>nd</sup> International Conference on Mechanical and Industrial Engineering- Engineering Innovations for Sustainable Development*. February 16-17, 2012, Naura Springs Hotel, Arusha, Tanzania. pp. 218 – 227.
- Kapdi, S. S., Vijay, V. K., Rajesh, S. K. and Prasad, R. (2005). Biogas scrubbing, compression and storage: Perspective and prospectus in the Indian context. *Renewable Energy* 30(8): 1195 – 1202.
- Karellas, S., Boukis, I. and Kontopoulos, G. (2010). Development of an investment decision tool for biogas production from agricultural waste. *Renewable and Sustainable Energy Reviews* 14(4): 1273 – 1282.
- Kranert, M., Kusch, S., Huang, J. and Fischer, K. (2012). *Anaerobic Digestion of Waste. In Waste to Energy*. Springer, London. 135pp.
- Kuhi, H. D., Hossein-Zadeh, N. G., López, S., Falahi, S. And France, J. (2019). Sinusoidal function to describe the growth curve of dairy heifers. *Animal Production Science* 59(6): 1039-1047.

- Kulkarni, M. B. and Ghanegaonkar, P. M. (2019). Hydrogen sulfide removal from biogas using chemical absorption technique in packed column reactors. *Global Journal of Environmental Science Management* 5(1): 155 – 166.
- Kusekwa, M. A. (2011). A review on the renewable energy resources for rural application in Tanzania, Renewable energy - trends and applications. [<http://www.intechopen.com/books/renewable-energy-trends-and-applications/areview-on-the-renewable-energy-resources-for-rural-application-in-tanzania>] site visited on 20/2/2019.
- Li, Y., Park, S. Y. and Zhu, J. (2011). Solid-state anaerobic digestion for methane production from organic waste. *Renewable and Sustainable Energy Reviews* 15(1): 821 – 826.
- Mardani, A., Jusoh, A., Nor, K. M. D., Khalifah, Z., Zakwan, N. and Valipour, A. (2015). Multiple criteria decision-making techniques and their applications—A review of the literature from 2000 to 2014. *Economic Research-Ekonomska Istraživanja* 28(1): 516 – 571.
- Masse, D. I., Masse, L. and Croteau, F. (2003). The effect of temperature fluctuations on psychrophilic anaerobic sequencing batch reactors treating swine manure. *Bioresource Technology* 89(1): 57 – 62.
- Mélard, G. (2014). On the accuracy of statistical procedures in Microsoft Excel 2010. *Computational Statistics* 29(5): 1095-1128.
- Menya, E., Alokore, Y., and Ebangu, B. O. (2013). Biogas as an alternative to fuelwood for a household in Uleppi sub-county in Uganda. *Agricultural Engineering International: CIGR Journal* 15(1): 50-58.
- Mrema, G., Gumbe, L. O., Chepete, H. J. and Agullo, J. (2011). *Rural Energy. In: Rural Structures in the Tropics: Design and Development*. Technical Centre for Agricultural and Rural Cooperation, Wageningen. 455pp.

- Muñoz, R., Meier, L., Diaz, I. and Jeison, D. (2015). A review on the state-of-the-art of physical/chemical and biological technologies for biogas upgrading. *Reviews in Environmental Science and Bio/Technology* 14(4): 727 – 759.
- Nasir, I. M., Ghazi, T. I. M. and Omar, R. (2012). Anaerobic digestion technology in livestock manure treatment for biogas production: A review. *Engineering in Life Sciences* 12(3): 258 – 269.
- Olabanji, O. M. and Mpofu, K. (2014). Comparison of weighted decision matrix, and analytical hierarchy process for CAD design of reconfigurable assembly fixture. *Procedia Centre d'Insertion et de Réinsertion Professionnelle (CIRP)* 23: 264 – 269.
- Oloche, B., Ozigis, I., Adeyemi, K. and Ikpe, E. (2017). Construction and leakage detection of a dome-type biogas digester in a village at Abuja, Nigeria, Federal. *Journal of Engineering and Technology* 2(1): 27 – 31.
- Ordway, E. M., Asner, G. P. and Lambin, E. F. (2017). Deforestation risk due to commodity crop expansion in sub-Saharan Africa. *Environmental Research Letters* 12(4): 044015-044029.
- Pham, C. H., Vu, C. C., Sommer, S. G. and Bruun, S. (2014). Factors affecting process temperature and biogas production in small-scale rural biogas digesters in winter in Northern Vietnam. *Asian-Australasian Journal of Animal Sciences* 27(7): 1050–1056.
- Poulsen, T. G. and Adelard, L. (2016). Improving biogas quality and methane yield via co-digestion of agricultural and urban biomass wastes. *Waste Management* 54: 118 – 125.
- Rajendran, K., Aslanzadeh, S. and Taherzadeh, M. J. (2012). Household biogas digesters: A review. *Energies* 5(8): 2911 – 2942.

- Rebernik, M., Bradač, B., Rebernik, M. and Bradač, B. (2008). *Idea Evaluation Methods and Techniques*. Institute for Entrepreneurship and Small Business Management, University of Maribor, Slovenia. 69pp.
- Rowse, L. E. (2011). "Design of Small Scale Anaerobic Digesters for Application in Rural Developing Countries". *Graduate Theses and Dissertations*. Civil and Environmental Engineering, University of South Florida, USA. 125pp.
- Ryckebosch, E., Drouillon, M. and Vervaeren, H. (2011). Techniques for transformation of biogas to biomethane. *Biomass and Bioenergy* 35(5): 1633 – 1645.
- Salonen, M. and Perttula, M. (2005). Utilization of concept selection methods: A survey of Finnish industry. *Proceeding of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE) 2005 American Society of Mechanical Engineers (ASME)*. 24-28 September, 2005, California, USA. pp. 527 – 535.
- Schnurer, A. and Jarvis, A. (2010). *Microbiological Handbook for Biogas Plants*. Swedish Waste Management U2009:03, Swedish Gas Centre Report 207, Uppsala, Sweden, 138pp.
- Siefers, A., Wang, N., Sindt, A., Dunn, J., McElvogue, J., Evans, E. and Ellis, T. (2010). A novel and cost-effective hydrogen sulfide removal technology using tire derived rubber particles. *Proceedings of the Water Environment Federation* 12: 4597 – 4622.
- SimGas (2018). The SimGas biogas system is an integrated farm solution for rural households in Africa and Asia. [<https://simgas.org/biogas-system>] site visited on 27/07/2018.
- Su, H., Liu, L., Wang, S., Wang, Q., Jiang, Y., Hou, X., & Tan, T. (2015). Semi-continuous anaerobic digestion for biogas production: influence of ammonium acetate supplement and structure of the microbial community. *Biotechnology for Biofuels* 8(1): 1-11.

- Subedi, M., Matthews, R. B., Pogson, M., Abegaz, A., Balana, B. B., Oyesiku-Blakemore, J. and Smith, J. (2014). Can biogas digesters help to reduce deforestation in Africa? *Biomass and Bioenergy* 70: 87 – 98.
- Sun, W. and Nestic, S. (2007). A mechanistic model of H<sub>2</sub>S corrosion of mild steel. *Corrosion-March 19, 2007*, NACE International Conference and Expo, Paper No. 07655. [<http://www.icmt.ohio.edu/nestic/papers/FullText/conference-91.pdf>] site visited on June 09, 2021.
- Surendra, K. C., Takara, D., Hashimoto, A. G. and Khanal, S. K. (2014). Biogas as a sustainable energy source for developing countries: Opportunities and challenges. *Renewable and Sustainable Energy Reviews* 31: 846 – 859.
- TDA, Time and Date AS (2018). All year climate and weather averages in Dodoma, Annual weather averages in Dodoma based on weather reports collected during 1985–2015. [<https://www.timeanddate.com/weather/tanzania/dodoma/climate>] site visited on 31/05/2018.
- Theuerl, S., Kohrs, F., Benndorf, D., Maus, I., Wibberg, D., Schlüter, A., Kausmann, R., Heiermann, M., Rapp, E., Reichl, U., Pühler, A. and Klocke, M. (2015). Community Shifts in a Well-Operating Agricultural Biogas Plant: How Process Variations Are Handled by the Microbiome. *Applied Microbiology and Biotechnology* 99(18): 7791 – 7803.
- Tubecon (2018). Mechanical properties of steel for flat bars and sections. Steel Properties, Tubecon Africa (PTY) Ltd., Pretoria, South Africa. [<http://www.tubecon.co.za/en/technical-info/tubecon-wiki/properties-flat-steel-bars-and-sections.html>] site visited on 29/05/2018.
- Tumwesige, V., Fulford, D. and Davidson, G. C. (2014). Biogas Appliances in Sub-Saharan Africa. *Biomass and Bioenergy* 70: 40 – 50.

- Walekhwa, P. N., Mugisha, J. and Drake, L. (2009). Biogas energy from family-sized digesters in Uganda: Critical factors and policy implications. *Energy Policy* 37(7): 2754 – 2762.
- Wawa, A. I. (2012). The challenges of promoting and adopting biogas technology in semi-arid areas of Tanzania: The Case of Kongwa and Bahi Districts in Dodoma Region. Thesis for Award of PhD Degree at the Open University of Tanzania. 211pp.
- WB, World Bank (2015). Promoting Biogas as Sustainable Clean Cooking Fuel for Rural Households in Kenya Project. [<http://documents.worldbank.org/curated/en/350771468272038585/pdf/SFG1441-EA-P153493-ESMF-Box393229B-PUBLIC-Disclosed-10-20-2015.pdf>] site visited on 25/08/2018.
- Wu, M. C., Sun, K. W. and Zhang, Y. (2006). Influence of temperature fluctuation on thermophilic anaerobic digestion of municipal organic solid waste. *Journal of Zhejiang University Science* 7(3): 180–185.
- Yadvika, S., Sreekrishnan, T. R., Kohli, S. and Rana, V. (2004). Enhancement of biogas production from solid substrates using different techniques: A review. *Bioresource Technology* 95(1): 1–10.
- Yang, L., Xu, F., Ge, X. and Li, Y. (2015). Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. *Renewable and Sustainable Energy Reviews* 44: 824 – 834.
- Zalm, J. E. (2017). Performance of domestic biodigesters in Kenya towards the development of a comparative method for measuring the performance of different biodigester types in Sub-Saharan Africa. Dissertation for Award of MSc. Degree at Utrecht University, Utrecht, Netherlands. 132pp.

## CHAPTER FOUR

### 4.0 Designing of an Integrated Solar and Wind Energy with Anaerobic Digestion System for Energy in Rural Semi-Arid Areas

#### Abstract

Off-grid rural semi-arid communities in developing countries need reliable access to sufficient, affordable and clean energy for cooking and powering electrical and electronic gadgets. This chapter presents a study of developing an on-ground i-SWEAD system, circumventing underground biogas plants' constraints and simultaneously produce biogas and electricity. The study approach involved synthesising five integrated renewable energy options, selecting one best option using decision matrix technique, conceptual design, fabrication testing the best option, and extrapolating an annual electrical energy generation from best option test results. The test results of the i-SWEAD system show that the system had an average biogas yield of 0.077 m<sup>3</sup>/kg of fresh cow dung (0.343 m<sup>3</sup>/kg of cow dung dry matter), and higher biogas production performance by 34% based on the existing AD systems' biogas production rate (0.4 m<sup>3</sup>/m<sup>3</sup> of digester in a day) in semi-arid areas. Biogas consisted of average methane content of 48.57± 2.15%. The i-SWEAD system was able to keep its digester temperature variation within 1.28°C/day, which is tolerable to biogas microbes. The system could at least generate annual electrical energy of 5.69 kWh and 25.55 kWh using its solar PV unit and wind sub-systems, respectively. The results are promising for the i-SWEAD system application in rural semi-arid areas with a lack of sufficient energy when the up-scaled i-SWEAD system at higher than 92 days of hydraulic retention time would be considered.

**Keywords:** *Integrated energy system; temperature variation; biogas and electricity; solar and wind; semi-arid areas*

#### 4.1 Introduction

The growing population in most rural semi-arid areas in developing countries is in high need of affordable energy for cooking and powering electrical and electronic gadgets. This need is due to the ongoing deforestation and poor access to electricity in these areas. In Tanzania, most of the communities living in rural semi-arid areas are not connected to the national grid (Felix and Gheewala, 2011; NBS, 2014). The central Tanzania region may be cited as an example of the above-stated situation. However, initiatives were made to counter the challenges of poor access to energy in these areas. It involved introducing underground installed biogas plant technology under subsidised schemes for communities to access clean energy (Mshandete and Parawira, 2009; Ng'wandu *et al.*, 2009). However, the technology was tricky to troubleshoot faults like leakage, although it was able to keep temperature variation low if no seepage of water around the digester.

Furthermore, the technology needed much water as it was of liquid-state anaerobic digestion type. Most semi-arid areas lack sufficient water. These challenges and constraints led to low adoption of the technology in these areas (Wawa, 2012).

The introduction of affordable and above ground installed biogas plants, which need less water, is the envisaged ideal solution for the rural semi-arid areas based on the stated constraints. However, sustainable biogas generation by use of above-ground installed anaerobic digester in semi-arid areas is very challenging. The main challenge is the high-temperature variation occurring in these areas throughout the day. Temperature is very high during day time, low during the night and very low in the early morning. This phenomenon affects the anaerobic microbes responsible for biogas generation very much. These microbes offer best results when temperature variation is kept at  $\pm 0.5^{\circ}\text{C}$ ; but, they may tolerate variation of up to  $\pm 2\text{-}3^{\circ}\text{C}$  (Schnurer and Jarvis, 2010). The ambient air

temperature difference in semi-arid areas may go up by 10°C within a few hours. This phenomenon hinders biogas generation for the on-ground installed biogas plants without means of controlling temperature variation. Several means to control temperature variation for small biogas digesters installed on the ground have been put in place. They include using the greenhouse effect structures, covering the digesters with crop residues, covering the ground around the digesters with charcoal, and using solar ponds (Yadvika *et al.*, 2004). However, these control measures are weather (solar radiation, ambient temperature, and precipitation) dependent and do not cause long-lasting temperature stability.

Therefore, developing an affordable and sustainable integrated renewable energy system involving biogas digester was the main objective. This chapter presents an approach of designing the integrated solar and wind energy with anaerobic digestion (i-SWEAD) system, results of the design process, experimental testing and test results.

## **4.2 Material and Methods**

### **4.2.1 Study area**

The description and geographical location of the study site are given in Sub-section 2.2.1.

### **4.2.2 The system design approach**

The i-SWEAD system designing was accomplished by the use of an engineering design approach. The approach primarily involved systematic technique as well as intuitional technique. These techniques were derived from methods described by Tveit (2006), Pahl *et al.* (2007) and Tayal (2013). The researcher systematically identified the desired outputs of the system and constraints of developing the system. Also, other issues were assessment of inputs needed to develop the system, selection of the best system concept, conceptual design of the best system concept and testing of functionality of the developed system

experimentally. The decision technique used for the selection of the best system concept is explained in the subsequent sections.

On the other hand, the intuitional technique was used in the generation of the system concepts, where system topology illustrations were adopted in the fabrication of the i-SWEAD system. The approach adopted to design the i-SWEAD system is illustrated by the framework shown in Figure 4.1. The figure shows the i-SWEAD system having solar, wind and anaerobic digestion (AD) components.

The solar component is made of solar PV and solar thermal parts, as shown in Figure 4.1. The solar thermal part was conceived from experimental tests results of the locally available solar thermal heat collection and storage materials. These materials included water, salt, greenhouse structure and the combination of some or all of them. The collected and stored heat was intended to be used to stabilize the AD unit temperature. The solar PV was intended to generate electricity to stabilise the AD unit temperature and power electrical and electronic gadgets. Moreover, the wind component was included for contributing heat to equalise AD unit varying temperature towards ideal constant temperature condition.

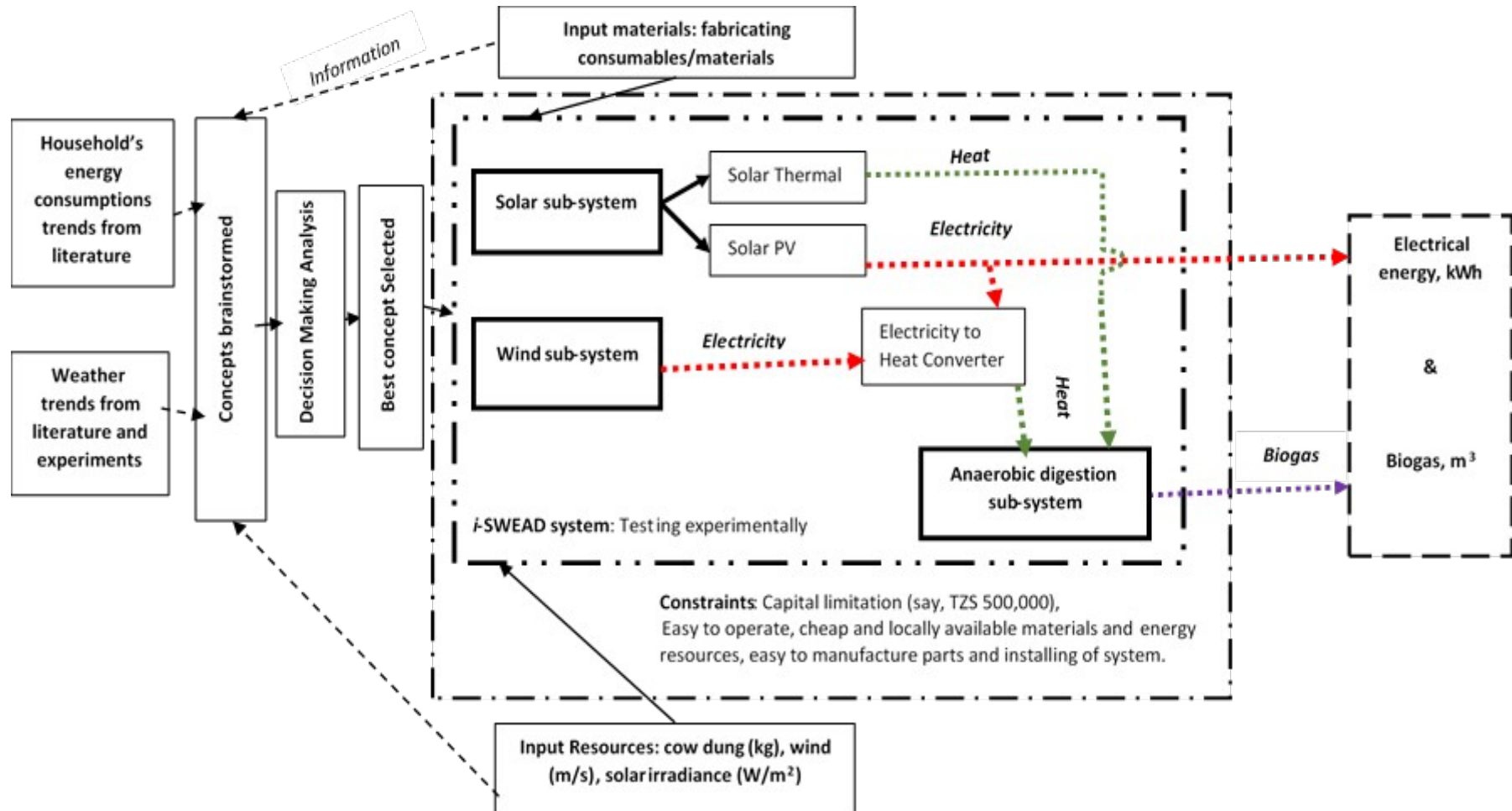


Figure 4.1: Framework used for the development of the i-SWEAD system

The anaerobic digestion component used for this i-SWEAD system is the ready-made adapted batch fed anaerobic digestion (ABFAD) system. It is the one that was described in the manuscript of Chapter Two of this thesis. This component is a batch anaerobic digestion system made of a 0.24 m<sup>3</sup> plastic barrel, equipped with a water trap, a scrubber and a separate biogas storage facility as its auxiliary accessories.

#### 4.2.3 The development of i-SWEAD system concepts

Concepts developed were based on energy consumption at the household level in rural semi-arid areas. The energy consumption was for cooking using biogas and powering electrical and electronic gadgets by use of electricity. Also, a part of the electricity generated was intended for AD component temperature stabilization. Moreover, the development of the concept considered information on the availability of cheap input materials and resources at the study site and local market in the Dodoma region. Therefore, with the above information, ultimately, five i-SWEADs concepts were synthesised. These system concepts are described and illustrated in Table 4.1 and Figure 4.2.

**Table 4.1: Synthesised concepts**

S/N	Concept	Components included
1	Concept 1	Solar PV, Vertical Wind Turbine (VAWT) and Anaerobic Digestion (AD) unit
2	Concept 2	Concentrating Solar Power (CSP) unit, VAWT and AD unit
3	Concept 3	Solar PV, Solar Heat Collection and Storage (SHCS) or Solar Thermal unit and AD unit
4	Concept 4	Horizontal Axis Wind Turbine (HAWT), Solar PV, SHCS unit and AD unit
5	Concept 5	HAWT, CSP unit and AD unit

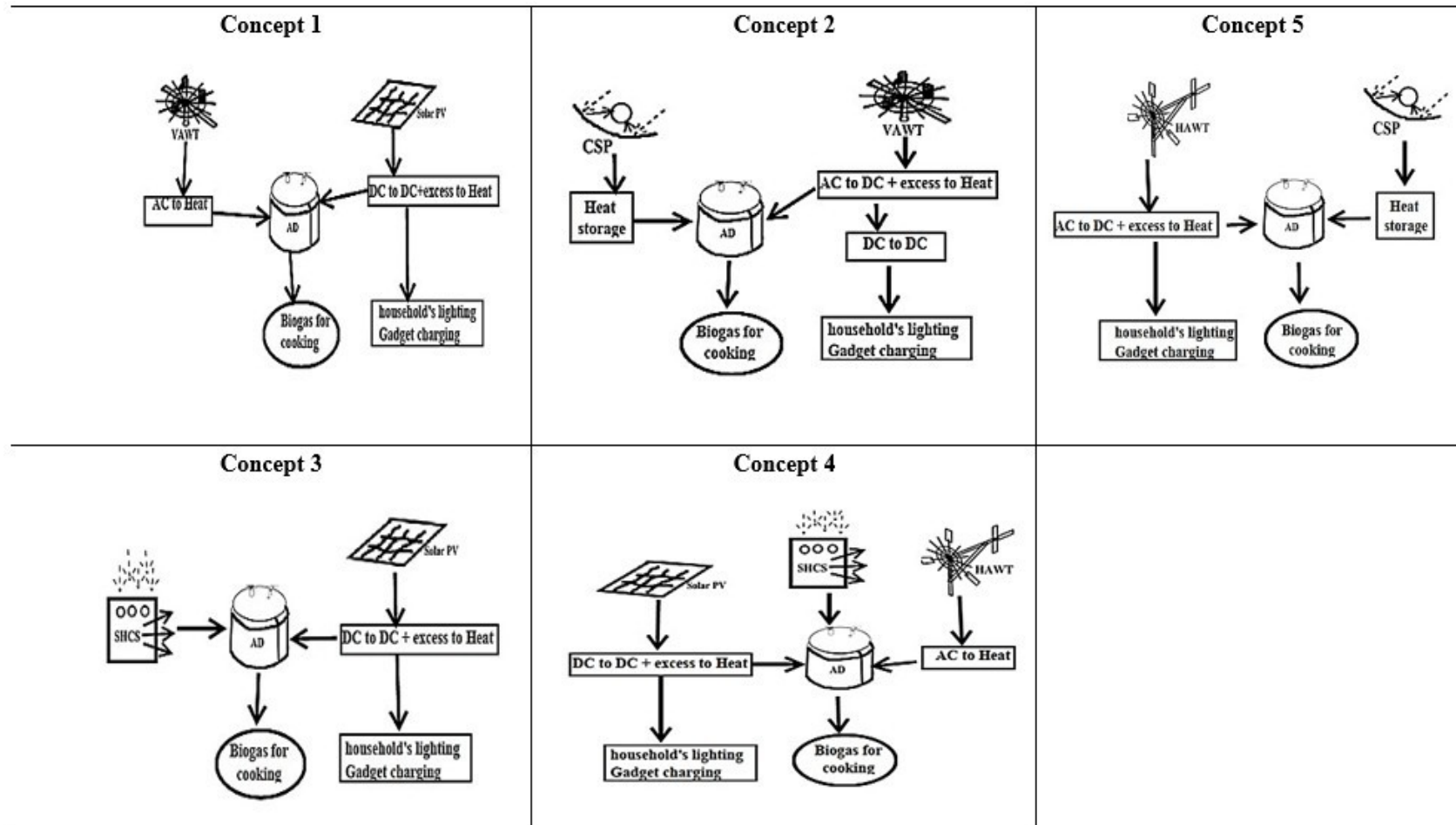


Figure 4.2: Sketches of System topologies of synthesised concepts

#### **4.2.4 Selection of the best system concept and its conceptual designing**

The choice of best concept/option selection techniques was based on the same approach described in the manuscript presented in Chapter Three, subsection 3.2.4 (b) (ii). With this information, the selection technique of the best-synthesised concept for this study was Decision Matrix Analysis (DMA).

##### **i. Decision matrix analysis adoption**

The decision matrix analysis (DMA) method was employed for this procedural task, as illustrated by Kaena (2012), Olabanji and Mpofu (2014) and Salonen and Perttula (2005). The task involved assigning weight to design criteria. Design criteria were based on constraints and requirements of supplying rural semi-arid households with electricity for powering electric and electronic gadgets and AD component temperature stabilization. Also, design criteria were formulated by considering the supply of the biogas generated at an ideal constant temperature for cooking in rural semi-arid households.

Design criteria formulated based on sustainable electricity supply and biogas production, with their assigned weight in brackets, were listed as follows: made of cheap locally available materials (0.30), ideally keep AD unit temperature constant, i.e. sustainable biogas generation (0.28), simple to produce electricity for lighting and gadget charging (0.12), safety to users and the system (0.10), easy fabrication and installation (0.11), and more durable (0.09). The assignment of weight values to the design criteria was based on experts' advice. Experts involved were selected intuitively by considering their experience in designing and operating renewable energy systems and or machines involving fluid systems. Thirty experts were contacted to participate in this exercise, but only eighteen experts were effectively ready. Therefore, based on readiness to participate effectively in this task, they were categorized as follows (with their total number in brackets): renewable

energy system developers (8); mechanical engineers (7); structural engineers (2) and an electrical engineer (1). Moreover, the Likert rating factor scale was set to indicate the possibility of each system concept in the selection process to meet each design criterion mentioned above. The rating factor scale was set as follows: not at all able, lowly able, moderately able, highly able and very highly able with assigned values of 1, 2, 3, 4 and 5, respectively.

Furthermore, a weighted score of the concept relative to each design criterion was determined as the product of the design criteria weight value and the rating factor scale value assigned. The total weighted scores for each concept was determined by summing up the weighted scores. Then plots of the total weighted score against concepts were produced. The system concept with the highest total weighted score was selected as the best and used for the conceptual design phase. Concept 4 was selected, as illustrated in Figure 4.2. The figure shows all of the interconnections of the parts forming the system for conceptual design and fabrication.

## **ii. Selection of solar heat collection and storage materials**

As Concept 4 included the solar heat collection and storage (SHCS) unit, selection of the heat collection and storage materials was done. The selection was based on the experimental testing results of eighteen experimental units assigned randomly to three replicas of six factors, control factor included. These factors are described in Table 4.2. All the factors were subjected to day and night conditions for 14 days at the study site.

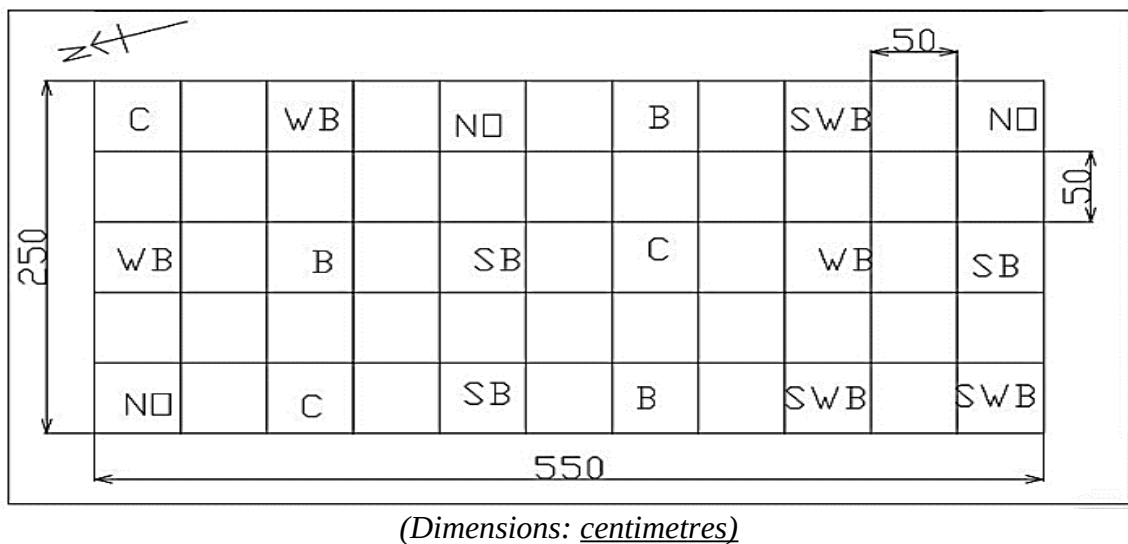
**Table 4.2: Factors for the heat collection and storage materials selection**

<b>S/ N</b>	<b>Factor</b>	<b>Code</b>
1	Control factor-bare sandy soil	<b>C</b>
2	Twelve 0.5 l transparent plastic bottles filled with water + black plastic sheet + greenhouse structure	<b>WB</b>
3	Greenhouse structure only	<b>NO</b>
4	Black plastic sheet + greenhouse structure	<b>B</b>
5	Six 0.5 l transparent plastic bottles filled with water + Six 0.5 l transparent plastic bottle filled with salt + black plastic sheet + greenhouse structure.	<b>SWB</b>
6	Six 0.5 l transparent plastic bottles filled with salt + black plastic sheet + greenhouse structure	<b>SB</b>

Responses of experimental testing were temperature values recorded in degrees Celsius. The recording was done in the one-hour interval for the first five days and later on two hours' intervals for nine days. The one-hour interval was skipped after five days based on the assumption that the responses in the experimental units' transient state would have stopped after five days. During the analysis, the one-hour interval temperature values for the last nine days were traced by interpolation.

Temperature values were recorded using Scan Temp 440, a non-contact infra-red (IR)-thermometer with serial number E1062016398. The thermometer has an inbuilt thermo-element (Type K) with a temperature range of -64°C to + 1400°C and an accuracy of 0.01°C. The layout of the experimental units is shown in Figure 4.3. The figure shows that each experimental unit, which is indicated by a factor code, occupied a 50 x 50 cm area on the ground. Also, all the units were spaced at 50 cm. The experimental testing set-up area had dimensions of 5.5 x 2.5 m. The experiment was done on 1-14 June 2017. The date for experimenting was chosen such that no interruption will occur due to precipitation, i.e. rainfall.

The plot of temperature variation for all the factors was produced. Based on temperature variation curves, option WB was selected. This option had the least temperature variation throughout the 24 hours among all options. The variation was quantified by the standard deviation of all the factors' responses.



**Figure 4.3: The layout of the experimental unit at the Idifu study site**

#### 4.2.5 Fabrication of the i-SWEAD system

The fabrication stage of the i-SWEAD system involved the utilization of materials and resources found at the study site and from local markets in the region. The fabrication of the i-SWEAD system components was done using materials, equipment, and tools prepared after the selection and conceptual designing of the best concept. Note that the AD component had already been fabricated. Therefore, only the solar and wind components or sub-systems were fabricated, and then the assembling of AD, solar and wind sub-systems was done to produce the entirely fabricated i-SWEAD system. The subsequent subsections explain how solar and wind sub-systems were fabricated.

**i. Solar energy sub-system**

The detailed specifications of items used to fabricate the solar energy sub-system are shown in Appendices 3 and 4 of this thesis. The connection of these items is described in this subsection. A 20 Wp solar module, mounted on a mild steel hollow section frame, was connected to the Pulse Width Modulation (PWM) charge controller. The controller was connected to a 12-5 V DC-DC conditioning unit on the load terminal and a string of parallel connections of two 12 V batteries at its charging terminal. Also, a shunt for powering five 1W DC bulbs was made at the controller load terminal. Out of the five bulbs, one bulb was used for AD component heating purposes. The connections were made of 2.5 mm electrical wire to form a complete solar PV unit powered by solar radiation, to enable household lighting, gadget charging, and heating the AD sub-system.

The solar thermal unit consisted of fourteen 0.5 litre transparent plastic bottles filled with water for storing heat and 8 mm thick spent paper sheets for insulation purposes. The spent paper sheets were the ones, which are used to make packages of heavy-duty deep freezers and motorcycles. The solar thermal unit also included two galvanized corrugated iron sheets. The iron sheets were used to protect the insulation materials and the AD sub-system from rain. Furthermore, a transparent corrugated fibre sheet was placed on top at a slope of 1.2° as a rainwater draining cover and for creating the greenhouse effect. The outdoor encasing structural frame, which supported the insulation materials and iron sheets, was made of hardwood timber, while the top cover frame was made of softwood timber.

The cover frame was made of softwood to reduce its weight since softwood is less dense than hardwood. Spent mattresses, one padlock, one lock, 0.25 kg of roofing nails together with other nails of size 3 and 4 inches were used to assemble the Outside Encasing

Structure (OES). The OES enclosed the AD sub-system digester, water traps and scrubber, while the biogas storage unit was kept inside a separate room. The OES enclosed the digester, placed in the open dugout hole of 0.8 x 0.8 x 0.5 m without backfilling. Detailed specifications of layers of materials inside the hole are shown in Appendix 4 and Figures 4.4 and 4.5 of this thesis. From the bottom, they were piled as follows: lean concrete (M10), black polyethene plastic sheet, spent paper sheets and loose pearl millet chaff. It is a hole in which the digester and the water trap were vertically placed. Approximately 0.35 m thick loose pearl millet chaff was filled into the hole around the periphery of the digester and water trap. Specifications of items used to fabricate the OES was chosen based on the experimental results of choosing the best heat collection and storage, locally available materials and the functionality of the solar PV unit and the intended OES.

## **ii. Wind energy sub-system**

Fabrication of the wind energy sub-system involved the use of some items, which their detailed specifications are shown in Appendix 5 and Figures 4.4 and 4.5 of this thesis. The fabrication of this sub-system is described in this sub-section. The selection of the materials used and their fabrication was guided by the constraints illustrated in Figure 4.1. A pillow block bearing was used to support a post made of joined hardwood timber and a black steel pipe. The black steel pipe was fixed into the bearing, while the hardwood timber was used to carry the wind turbine's hub and blades. The bearing carrying the post was fitted on a three-leg hardwood mast making a hub height of 4.2 m.

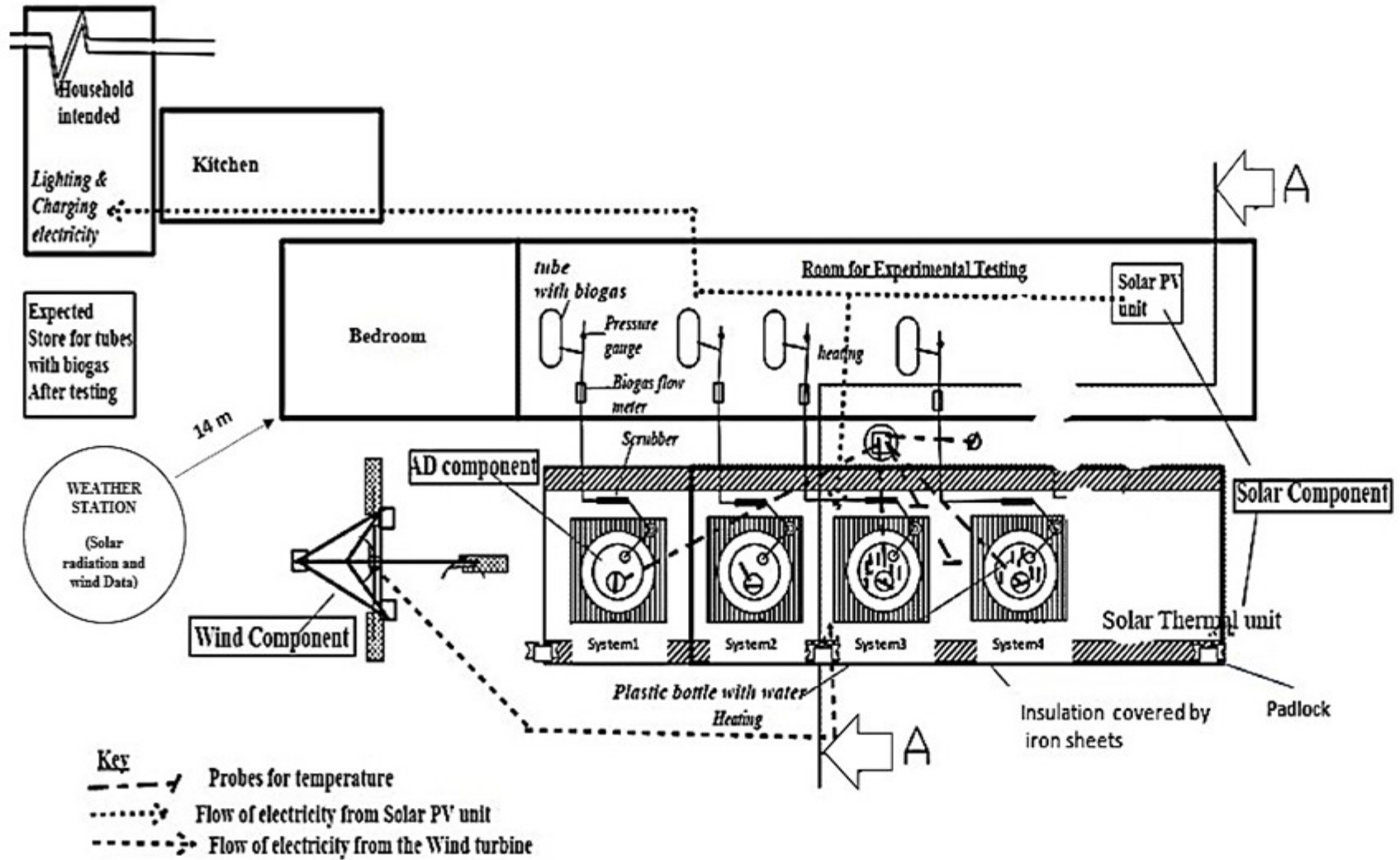


Figure 4.4: Experimental set up for testing the i-SWEAD system (plan view)

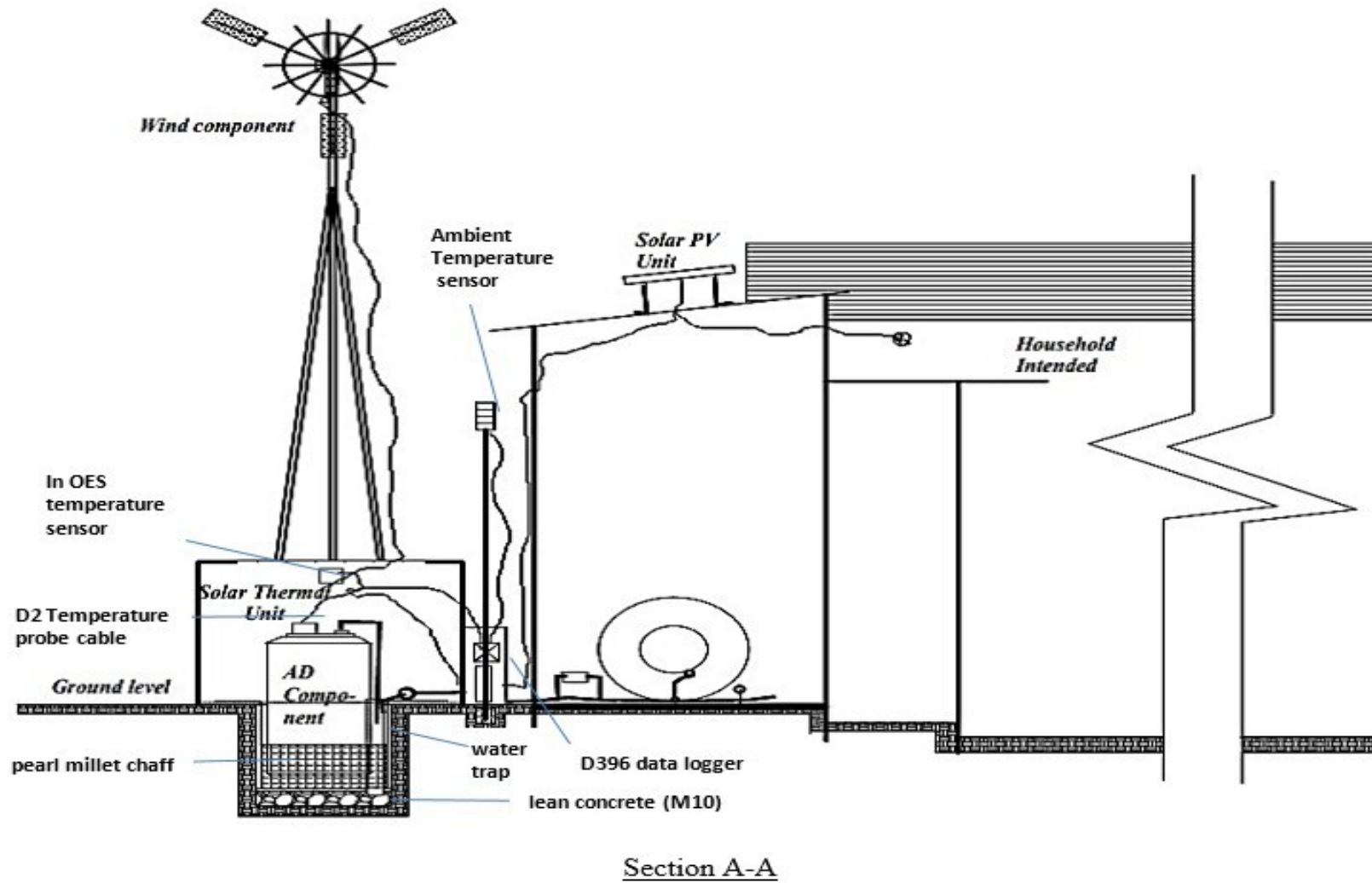


Figure 4.5: Experimental set up for testing the i-SWEAD system (section view)

The 190 mm long hub with a 9.5 mm diameter axle was fixed in a 660 mm diameter bicycle wheel rim by 3 mm diameter spokes, forty in total. A 5 mm thick rubber filled the periphery groove of the rim. Then twelve 780 x 25 x 25 mm soft wooden blade handles were tied on the rim by use of 3 mm diameter aluminium wire. Furthermore, three plastic blades with an approximate size of 150 x 350 mm, cut from a 20 l-plastic bucket, were screwed radially and equally spaced on the three-blade handles to form a three-blade turbine. Schubel (2010) reported that three blades of commercial 3-blades horizontal axis wind turbine rated at 1 MW costs utmost to 13% of 8 million Great British Pound (GBP) of the whole system. Averagely, 1 GBP traded at 1.55 US dollars by the year 2010 ([www.poundsterlinglive.com](http://www.poundsterlinglive.com)).

Neglecting the annuity and discount rates of value for money while considering the Schubel (2010) given data; therefore, by 2018, three blades of a wind turbine were priced at \$ 0.12/W. This price of three-blade is equivalent to TZS 275/W as of the year 2017 (USD 1 = TZS 2290). The wind energy sub-system was intended to be rated at 50 W. On a commercial basis, the three blades of the intended wind energy sub-system would have cost TZS 13 755.00. However, the cost of three blades made of plastic material was TZS 2550.00 (Appendix 9). Therefore, using these types of blades, money was envisaged to saved.

Additionally, the wind turbine had an effective rotor diameter of 1.62 m; the blades, blade handles, hubs and rim weighing 7 kg. A tail made of 1160 x 100 x 50 mm hardwood was provided at the rotor to track wind direction. Together with the three wind turbine blades mentioned above, this tail was connected to the turbine hub. Finally, the wind sub-system fabrication was completed by fixing a 6 W and 12 V bicycle alternator, with the rotating head covered by a rubber ring with 30 mm diameter and 10 mm thick wall, on the turbine

post while ensuring its rotating head was in contact with the rim rubber for the generation of electricity when the turbine was revolving.

#### **4.2.6 Procedure followed to test the i-SWEAD system**

Equipment and tools used for testing the system were obtained from the Department of Engineering Sciences and Technology, Sokoine University of Agriculture. Experimental testing of the i-SWEAD system functionality involved collecting solar irradiance, wind and ambient air temperature data for 92 days at the study site using the installed weather station and hand-held thermometer and anemometer. Also, other measuring devices were used as detailed in the subsequent subsections.

##### **i. Experimental setup design**

The experiment involved three different solar thermal-based energy systems integrated with the AD sub-system of the i-SWEAD system for comparison purposes. Therefore, digesters ( $0.24 \text{ m}^3$ ) that were used are the same for all four systems. Four systems, which were used for the experiment, included the i-SWEAD system. Also, one system among the four systems was taken as the control, and it had low heat storage features. The four systems and their digesters are described and coded, as shown in Table 4.3. Holes mentioned in this table had dimensions of  $0.8 \times 0.8 \times 0.5 \text{ m}$  and spaced at  $0.25 \text{ m}$ . The experimental setup illustrating systems arrangements is shown in both Figures 4.4 and 4.5.

**Table 4.3: Systems and their digesters description and codes**

S/N	System Description	System Code	Digester Code
1	The digester and water trap were placed vertically in a hole, which has a thin concrete slab (M10) at the bottom only. The hole and digester were put under the greenhouse effect by the use of OES. The OES was made of a galvanized corrugated iron sheets with 0.8 mm thickness and a top cover made of transparent corrugated fibre sheet with a 1.5 mm thick set at a slope of 1.2°. The system was taken as the control	System1	D1
2	The system included the digester and water trap treated the same way as those of System1. However, for this case, the OES described in System1, its inside three side walls were laminated with heat insulation materials of spent paper sheets (8 mm thick).	System2	D2
3	The i-SWEAD system with digester and water trap were placed in the hole the same way as those in System1. However, the hole, digester and OES explained in System1 had more features added. The hole, which held the digester and water trap was layered consecutively with lean concrete (M10) at the bottom only, black polyethene plastic sheet, spent paper sheets (8 mm thick) and loose pearl millet chaff of approximately 0.2 m thickness. The top of the digester was covered by the heat storage unit (fourteen 0.5 L transparent plastic bottles filled with water). On top of the heat storage unit, there were two electrical energies to light and heat energy bulbs with 6 W and 1 W connected to the wind sub-system and solar PV unit, respectively. The heat was used for stabilizing digester temperature. Two parallel OES's inside side walls were laminated with heat insulation materials of spent paper sheets (8 mm thickness).	System3	D3
4	The system had the same features as System3 except that it did not have heat supply from the wind sub-system and solar PV unit.	System4	D4

It should be noted that the digester and water traps items of each AD component were placed in the four holes shown in Figure 4.4. The bottom of the four holes was sealed by lean concrete (M10) with a cement sand aggregate ratio of 1:3:6 (0.1 m thick), as shown in Figure 4.5. The specifications of the materials, which were used in the holes of System3 and System4 were black polyethene plastic sheet covering the whole hole (0.3 mm thick), a 0.75 x 0.75 m spent paper sheet (8 mm thick), and lose pearl millet chaff (0.2 m thick) at the bottom.

The OES structural frame, which supported the insulation materials and iron sheets, was made of hardwood and softwood described in Appendix 4. The OES had dimensions of 5.25 x 1.2 x 0.8 m, and it was divided into two compartments. The first small compartment consisted of System1, while the second large compartment enclosed the second system up to the fourth system, as shown in Figure 4.4. The AD sub-system items, which are digester, water trap and the scrubber, were enclosed in the OES while the biogas storage and measuring instruments, i.e. the pressure gauge and biogas flow meters, were kept inside a different structure/house. Other items used to assemble OES are the same as those described in subsection 4.2.5 (i).

The four systems' digesters were fed with fresh cow dung as substrates. The cow dung was aged between nine hours and two days. Each system digester was filled with eight 20 L buckets full of fresh cow dung with no inoculum added. The ratio in the volume of the substrate to digester was 0.66, which was close to 0.60 that was used by Sadi (2010) when studying anaerobic digestion of organic matter using 100 L batch type digester. The cow dung full bucket weighed 19.3 kg after deducting the empty bucket weight. Therefore, 154.4 kg cow dung was filled into each of the system digesters. The cow dung sampling and properties analysis was done. Averagely, characteristics of cow dung fed in all the four systems' digesters were total DM of 224 g/kg of cow dung, VS of 691 g/kg of DM, pH of 6.87 and C/N ratio of 18.75 as reported in Chapter two of this thesis. Due to the microbe's activities, substrate parameters' values must have changed to lower levels at the end of the experiment. However, the initial values provide ideal maximum values of properties of the cow dung; therefore, it is justified to use these initial values. These parameters were used in deriving the biogas yield in terms of mass, DM, and VS of cow dung added into the systems' digesters.

**ii. Data collection approach**

The collection and analysis of data were based on the experimental set-up for testing an entirely fabricated i-SWEAD system, i.e. System3 together with other systems, as shown in Figures 4.4 and 4.5. Parameters considered as responses were ambient temperature ( $^{\circ}\text{C}$ ), OES inside temperature and digesters' temperature. Other parameters considered were the systems' pressure and  $\text{CH}_4$  content. Also, wind speed and time in which the wind turbine sub-system started to generate heat were considered in the data collection. Specifications of some of the measuring instruments mentioned in this sub-section are the same as those described in Chapter Two, Sub-Section 2.2.3 (iii) and Chapter Three, Sub-Section 3.2.4 (ii).

Regarding Figure 4.4, the temperature inside the OES's large part was collected at 15 minutes' intervals using VOLTcraft DL111K temperature data logger with Serial Number 15120153 and thermo-element type K, placed between the System3 and System4. The temperature inside the three digesters of System1, System3 and System4 were collected at the one-hour interval using UGT 386 temperature data logger with type K three thermocouples, placed 0.3 m from the bottom 0.2 m towards the periphery of systems' digesters. Also, the UGT 386 temperature data logger had a combined humidity-temperature sensor for ambient air temperature measurement. The System2 digester temperature was measured at 15 minutes using VOLTcraft DL111K temperature data logger with Serial Number 15090497 and thermo-element type K, placed inside the digester the same as those of fore mentioned systems. Pressure (kPa) data were collected using a Sim Gas product pressure gauge. The  $\text{CH}_4$  content (%) responses were collected using the Ultrasonic biogas flow meter Version BF-2000 with the  $\text{CH}_4$  content measurement tool. Both pressure and  $\text{CH}_4$  content measurements were carried out for all the four systems' digesters at three hours' intervals.

Other parameters were obtained by derivation using the parameters mentioned above; wind parameter values presented in Chapter Two, Sub-Section 2.3.2, Figures 2.4, 2.5 and 2.6 were for deriving turbine cut-in wind speed. The derived parameters include biogas volume, System3 electricity efficiency, cut-in wind speed, System3 biogas energy density, availability of System3 in hours per day for household cooking, and wind energy harnessed by the wind turbine.

The assumption of an energy density or heating value of the biogas produced by System3 was based on the cumulative total amount of biogas produced with its corresponding CH<sub>4</sub> content and biogas energy conversion techniques discussed by Cuéllar and Webber (2008) and Kurchania *et al.* (2010). After 16 trials of releasing biogas from the system at a pressure range of 2-9 kPa and an interval of 0.5 kPa, an optimum biogas flow rate was found to be 0.445 m<sup>3</sup>/h. This task was done during the simulation of cooking by boiling water. This flow rate is almost half of the flow rate proposed by Kurchania *et al.* (2010) of 1 m<sup>3</sup>/h for biogas cooking stove design for the community.

### **iii. Analysis of availability of the i-SWEAD and biogas energy generated**

Daily constant biogas production from System3 was assumed while considering the cumulative total amount of biogas produced by the system, the established biogas flow rate at the study site and hydraulic retention time. It was assumed to be a way to enable the computation of availability of the system in hours per day for the household cooking purpose using Equation 4.1. Concurrently, from the same assumptions and considerations, System3, i.e. the i-SWEAD system's biogas energy available per day, was calculated using Equation 4.2. Derivation of Equations 4.1 is shown in Appendix 6. Equation 4.2 derivation is the same as the one in Appendix 6 with the exception. The exception is that the unit of biogas energy density, MJ/m<sup>3</sup>, is converted into kWh/m<sup>3</sup> using a factor of 0.2778, which was similar to that of 0.277 reported by Cook *et al.* (2012).

$$H_{bio-cook} (h/day) = \frac{C_{bio}}{Q_{flow-bio} \times HRT} \left( \frac{m^3}{m^3} \times \frac{h}{1} \times \frac{1}{day} \right) \dots\dots\dots \text{Eq. (4.1)}$$

$$E_{av-cook} (kWh/day) = \frac{E_{HV-bio} \times C_{bio}}{HRT} \left( \frac{MJ}{m^3} \times \frac{m^3}{1} \times \frac{1}{day} \times \frac{0.2778 kWh}{MJ} \right) \dots\dots \text{Eq. (4.2)}$$

The terms in Equation 4.1 are illustrated as follows:  $Q_{flow-bio}$  is an optimum biogas flow rate of 0.4 m<sup>3</sup>/h in 12.5 mm diameter plastic pipe established at the study site, and it was recorded between biogas storage and biogas burner using Ultrasonic biogas flow meter version BF-2000;  $C_{bio}$  is the cumulative total amount of biogas in m<sup>3</sup> produced by the system; ( $HRT$ ) is a hydraulic retention time, i.e., 92 days, and the  $H_{bio-cook}$  is the availability of the system in hours per day for household cooking purpose. The terms in Equation 4.2 are described as follows:  $E_{HV-bio}$  is energy density, or heating value of biogas in MJ/m<sup>3</sup> produced by the system and ( $E_{av-cook}$ ) in kWh is biogas thermal energy available per day from the system.

#### iv. Analysis of Derivation of biogas volume from pressure measurements

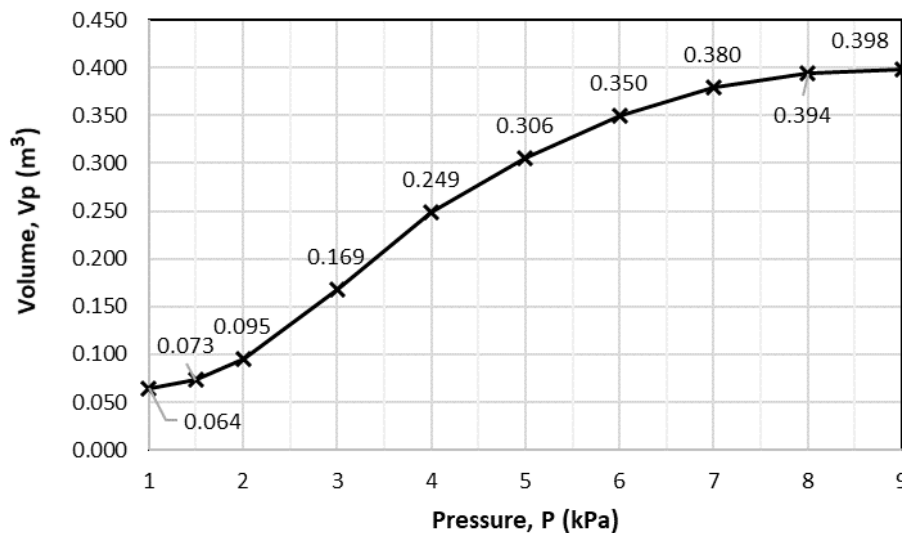
During the initial biogas collection measurement at the study site, it was observed that the Ultrasonic biogas flow meter Version BF-2000 was not able to detect the biogas volume collected at a flow rate less than 0.025m<sup>3</sup>/h, as the value was the minimum measurement capacity of the biogas flow meter. Therefore, the volume of biogas collected was derived from regression Equation 4.3, which includes the independent variable measured pressure, and the dependent derived variable biogas volume.

$$V_p = -5.889(10)^{-5} P^5 + 0.00178 P^4 - 0.02057 P^3 + 0.1055 P^2 - 0.1663 P + 0.144497 \dots\dots \text{Eq.}$$

(4.3)

$V_p$  is the volume of biogas in the torus butyl tube with size 8.25-15 TR174A at a measured pressure  $P$ , and  $P$  is the pressure recorded ranging between 1kPa and 9 kPa.

Equation 4.3 was obtained from the regression analysis of pressure and volume data plotted in Figure 4.6 using Microsoft Excel Version 2013. Data of volume and pressure collected during biogas storage pressure experimental testing was used to create Equation 4.3. The experiment aimed at establishing a relationship of the volume of biogas storage or the tube filled with biogas at various pressure levels and its ability to withstand pressure. The obtained relationship was used to quantify the biogas collected based on the pressure increments in the system. For instance, considering that at 6:00 hours' pressure  $P_1$  in the system was 2 kPa, and at noon pressure,  $P_2$  was 3.5 kPa, then using Equation 4.3, the volume of biogas at  $P_1$  ( $V_{P1}$ ) and  $P_2$  ( $V_{P2}$ ) can be obtained. Therefore, the volume difference between  $V_{P1}$  and  $V_{P2}$  at 6:00 hours and noon respectively was computed and taken as the amount of biogas collected within that stated period.



**Figure 4.6: Volume computed against pressure at a temperature of  $28 \pm 3^\circ\text{C}$**



Appendix 7 describes the experiment, which generated data for creating Figure 4.6 and the formulation of Equation 4.3. Therefore, during the experiment illustrated in Figures 4.4 and 4.5, pressure values in the system were recorded to derive biogas volume, among other reasons.

The i-SWEAD system biogas production rate was computed using Equation 4.3(a), and its performance based on the existing systems biogas production rate was determined using Equation 4.3(b).

$$Pr_v = \frac{V_{i-SWEAD}}{D_{i-SWEAD} \times HRT} \dots\dots\dots \text{Eq. 4.3(a)}$$

where  $Pr_v$  is the i-SWEAD system biogas production rate ( $\text{m}^3/\text{m}^3$  of digester in a day),  $V_{i-SWEAD}$  is the total volume of biogas collected within hydraulic retention time ( $\text{m}^3$ ),  $D_{i-SWEAD}$  is the volume ( $\text{m}^3$ ) of the i-SWEAD system's digester, which was  $0.24 \text{ (m}^3\text{)}$  and  $HRT$  is the hydraulic retention time (days), i.e. 92 days.

$$P_{i-SWEAD} = \frac{(Pr_v - Pr_{v_{existing}})}{Pr_{v_{existing}}} \times 100 \dots\dots\dots \text{Eq. 4.3(b)}$$

where  $P_{i-SWEAD}$  is the i-SWEAD system biogas production performance based on the existing systems biogas production rate (%),  $Pr_v$  is the i-SWEAD system biogas production rate ( $\text{m}^3/\text{m}^3$  of digester in a day) and  $Pr_{v_{existing}}$  is the AD systems' biogas production rate ( $\text{m}^3/\text{m}^3$  of digester in a day), which is taken to be  $0.4 \text{ m}^3/\text{m}^3$  of digester in a day. This figure is clearly explained in Sub-Section 1.3.1 of Chapter One of this thesis.

**v. Electrical and heat energies generated by solar PV unit and wind sub-system analysis**

System3, i.e. i-SWEAD system, was generating electrical energy for powering electrical and electronic gadgets. Two gadgets were used to convert electricity from the i-SWEAD system's solar and wind sub-systems into heat intended to supply heat energy to the AD sub-system's digester for temperature stabilization. The solar PV unit, a part of the solar subsystem, generated electricity. The quantification of the electrical energy generated per year from the solar PV unit was done based on the generator, i.e. solar PV module's power rating, efficiency and annual average insolation at the study site. Note that insolation (kWh/m<sup>2</sup>/day) is equivalent to peak sun hour (hour) at a ratio of one to one. The peak sun hour was used in this study. Although experimental data at the site has a high temporal resolution (hourly data collection), its annual average insolation was not used because it had small temporal coverage (one year). Therefore, the RetScreen Plus annual average insolation was used as it has broad temporal coverage (more than 25 years) though with low temporal resolution (daily) as described in Chapter Two, Sub-section 2.2.3 (i) of this thesis.

Equation 4.4 was used for the quantification of the annual electrical energy generated by the solar-sub system. This equation is based on the relationship of energy (Wh or J) being equal to power (W) multiplied with time (h).

$$E_{pv} = 365 \times \eta_{pv} \times I \times P_{pv} \dots \dots \dots \text{Eq. (4.4)}$$

where  $E_{pv}$  is annual electrical energy generated by solar PV unit (kWh);  $\eta_{pv}$  is the efficiency of polycrystalline solar PV module and it was taken as 13% (Mirzaei and

Mohiabadi, 2017);  $I$  is the annual average insolation (kWh/m<sup>2</sup>/day) or peak sun hours (h) at the study site, which was 5.88 kWh/m<sup>2</sup>/day or only six peak sun hours (refer Sub-section 2.3.2 of Chapter Two of this thesis),  $P_{pv}$  is the power rating of the solar PV module (W), and 365 is the number of days per year.

The wind sub-system of the i-SWEAD system also produced electrical energy, which was for stabilizing only the temperature of System3's digester. The electrical energy generated by this sub-system was computed based on the rated power of its electricity generator, i.e. bicycle alternator and frequency of a range of wind speed equal to or above annual average wind speed. An assumption was made that wind turbine, the component of the wind sub-system, was running at or above annual average wind speed. Also, it was assumed that the annual average wind speed was above the cut-in wind speed of the wind turbine that was used at the study site. Weibull cumulative distribution function (Equation 4.5) was used to determine the probability of events of the wind speed equal to or above the annual average wind speed at the study site. This equation was adapted from the equation, which was illustrated by Bidaoui *et al.* (2019). The probability value obtained  $F(v)$  was then multiplied with the 8760 hours, i.e. the total number of hours in a year. The product obtained gave the frequency of wind speed at that given wind speed range in a year. With the value of frequency of a given range of wind speed and rated power of electricity generator actuated by a wind turbine ( $P_{wg}$ ), the electrical energy generated by the wind sub-system ( $E_{we}$ ) was computed using Equation 4.6. This equation is based on the same relationship considered in Equation 4.4.

$$F(v) = P(v \geq v_m) = e^{-\frac{v}{k}} \dots \dots \dots \text{Eq. (4.5)}$$

where  $v$  is the wind speed, which is equal to or above the average wind speed at 4 m hub height at the study site  $v_m$ ,  $e$  is an exponential function,  $c$  is the characteristic wind speed or scale factor at the study site (m/s), and  $k$  is the shape parameter (dimensionless). Note: that  $v_m$  was extrapolated from the reference height of 2.5 m, where the anemometer in the weather station was positioned. The extrapolation was done using Equations 2.2 and 2.2a.

Parameters  $k$  and  $c$  were determined using Equations 4.5a and 4.5b, respectively (Kutty *et al.* (, 2019).

$$k = \left[ \frac{\sigma}{v_m} \right]^{-1.086} \dots\dots\dots \text{Eq. (4.5a)}$$

$$c = v_m \left( 0.568 + \frac{0.433}{k} \right)^{\frac{-1}{k}} \dots\dots\dots \text{Eq. (4.5b)}$$

where  $\sigma$  is the standard deviation of wind speed values from mean wind speed.

$$E_{we} = 8760 \times F(v) \times P_{wg} \dots\dots\dots \text{Eq. (4.6)}$$

The heat gained by System3’s digester from both solar PV unit and wind sub-system,  $H_d$ , was computed using Equation 4.7. The assumption is that no loss of heat occurred.

$$H_d = [(8760 \times \eta_{pv} \times C_{pv}) + (8760 \times F(v) \times \eta_w \times C_w)] \dots\dots\dots \text{Eq. (4.7)}$$

where  $\eta_{pv}$  and  $\eta_w$  are 60% and 92% efficiencies of converting electricity into heat energy by use of 1 W Light Emitting Diode (LED) bulb and 6 W Incandescent Light (IL) bulb

respectively (Li *et al.*, 2014a),  $C_{pv}$  and  $C_w$  are ratings of LED bulb of PV unit and IL bulb of wind sub-system in Watts respectively and  $H_d$  in kWh is heat energy gained by AD sub-system's digester.

#### **vi. The cut-in wind speed and power of wind sub-system turbine analysis**

Referring to Figure 4.1, which illustrates the framework used for designing the i-SWEAD system, the framework indicates that the designing was done while taking care of the constraints. Constraints included the limitation of capital, the necessity of using locally available materials and energy resources, and easy to manufacture the sub-system's parts and install the system. With these constraints, the fabrication of the wind sub-system was done before the establishment of wind turbine cut-in wind speed.

Cut-in wind speed is the wind speed at which the wind turbine starts to rotate and generate appreciable useful power. In this study, cut-in wind speed (m/s), time (minutes) and temperature ( $^{\circ}\text{C}$ ) were recorded. They were recorded so as to establish the wind speed and time at which wind turbine will produce appreciable heat to be used by the AD sub-system's digester for temperature stabilization. The choice of period of time during a day, which was used for taking records of fore mentioned parameters, was done arbitrarily. The recording activity was done between 16:00 hours and 22:00 hours.

Figure 4.7 shows the experimental setup for establishing the cut-in wind speed of the i-SWEAD system wind component. Wind speed was recorded by Observer 2 using an anemometer (TESTO416, SN.02238844 with an accuracy of 0.01 m/s) at the time the 6 W bulb started to glow brightly based on the signal given by Observer 1 as shown in Figure 4.7. Observer 1 recorded the respective initial time and temperature using a mobile phone

stopwatch and thermometer (Eco Scan Series Thermocouple thermometer, SN. 884436 with an accuracy of 0.1°C.) when the bulb started glowing brightly. Then Observer 1 finally recorded the time when the thermometer read 28°C. The temperature value of 28°C was chosen arbitrarily as suitable for the mesophilic biogas microbes, which thrive in temperature values ranging between 20°C and 40°C (Salam *et al.*, 2015).

If the bulb stopped glowing before the needed temperature was reached, all already observed data were discarded, and the process was repeated after one hour. The one-hour rest before repeating the exercise was chosen in the sense that all electrical appliances would have been cooled to the ambient temperature level. Three days each month were randomly picked for the experiment, where observations were done only twice per day. It was done in November and December 2017, and January 2018. Therefore, eighteen observations were obtained. Based on these observations, the average and standard deviation of cut-in wind speed were computed. Note that the bulb was used to convert electrical energy from the bicycle alternator actuated by the wind turbine into thermal energy for assisting the AD sub-system's digester in keeping the temperature constant.

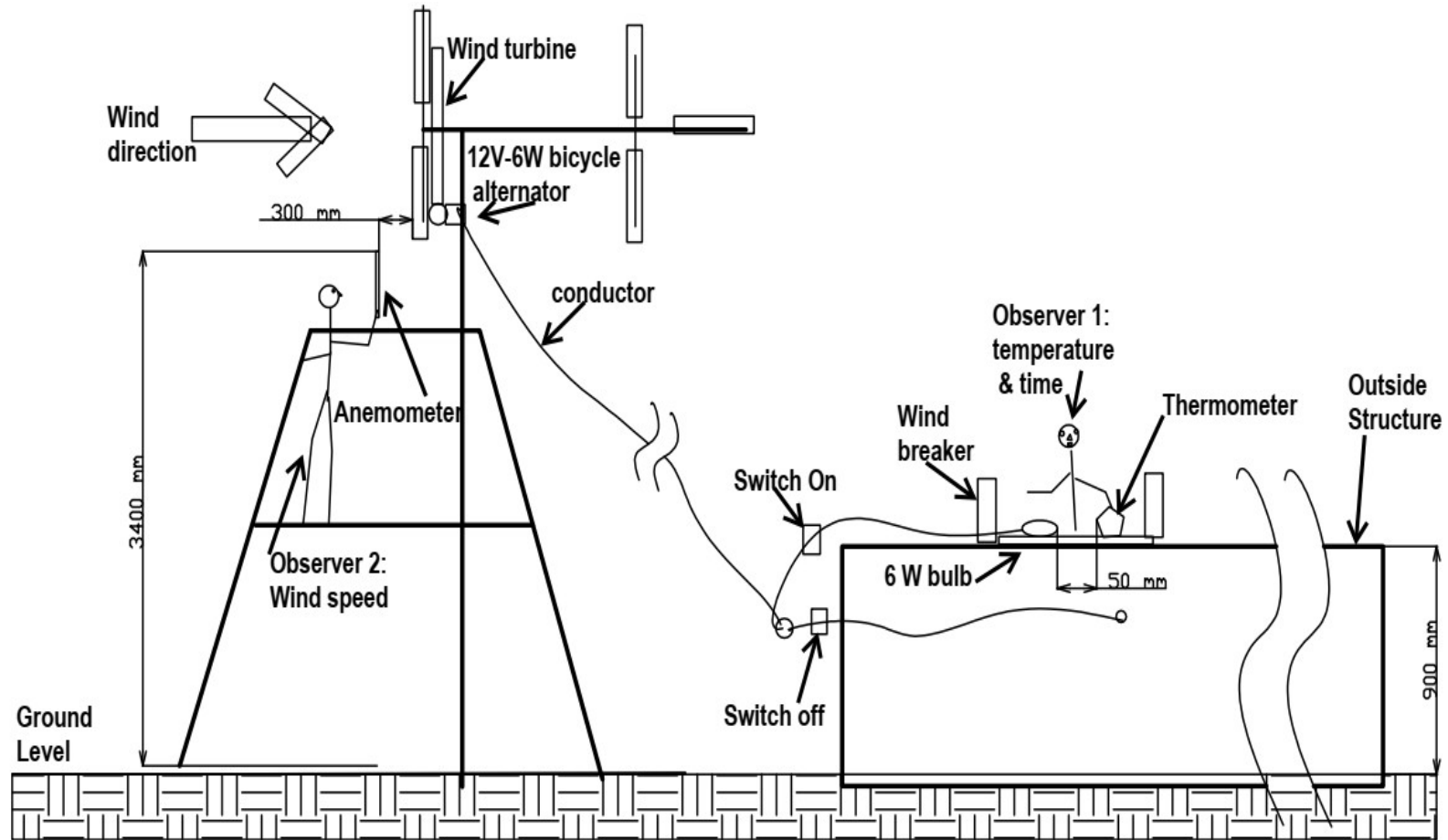


Figure 4.7: Experimental set up for cut-in wind speed, temperature and time measurements

The annual wind energy, which was harnessed by the wind turbine at 4 m hub height, was based on the frequency of wind speed range of just above cut-in wind speed for a small wind turbine. The average power harnessed by the wind turbine at that fore mentioned hub height was based on the annual average wind speed. The power harnessed by the wind turbine  $P_{wt}$  (W) is expressed by Equation 4.8 (Kusiak *et al.*, 2013; Chowdhury *et al.*, 2012).

$$P_{wt} = \left(\frac{1}{2}\right) \times C_p \times \rho_a \times A \times v^3 \dots\dots\dots \text{Eq. (4.8)}$$

where  $A = \pi R^2$  is the rotor swept area perpendicular to the direction of airflow (in m<sup>2</sup>),  $R$  is the rotor radius, i.e. a length from the hub to the tip of the blade (for this study, it was 0.81 m),  $v$  is annual average wind speed (in m/s) at height hub of 4 m,  $\rho_a$  is the density of air (assumed to be 1.26 kg/m<sup>3</sup>) and  $C_p$  is the power coefficient based on Betz limit (taken as 40%). It should be noted that the annual average wind speed was higher than the cut-in wind speed.

The power value obtained from Equation 4.8 was used in Equation 4.9 to compute the wind energy  $E_{wt}$  (kWh), which was harnessed by the wind turbine in a year. Also, solar energy flux received by D3 daily,  $E_{SE}$ , through transparent top cover of OES was determined using Equation 4.10.

$$E_{wt} = 8760 \times F(v) \times P_{wt} \dots\dots\dots \text{Eq. (4.9)}$$

where  $E_{wt}$  is the energy harnessed by the wind turbine,  $F(v)$  is the probability of finding the wind speed range equal to or above annual average wind speed,  $P_{wt}$  is the power

harnessed by the wind turbine, and 8760 is the number of hours in a year.

$$E_{ES} = \tau_{cov} \times A_{D3} \times I \dots \dots \dots \text{Eq. (4.10)}$$

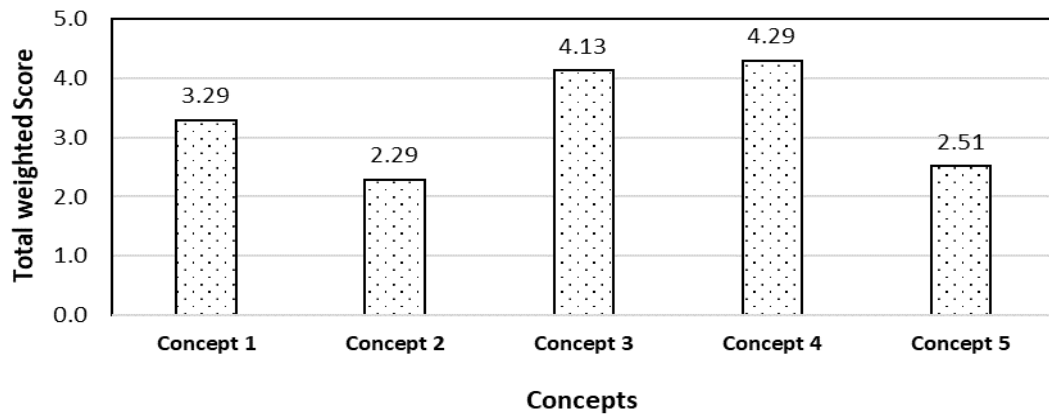
where  $E_{ES}$  is the solar energy flux received daily by D3,  $\tau_{cov}$  is the transmittance of fibre transparent top cover of OES, which was assumed to be 0.8 and  $A_{D3}$  is the rectangle top exposed area of the D3 with 0.6 m and 1 m dimensions.  $I$  is the insolation assumed to be 6 kWh/m<sup>2</sup>/day at the study site.

### 4.3 Results and Discussion

Subsequent subsections describe in detail the results of i-SWEAD system design and experimental testing.

#### 4.3.1 Selection of the best concept

The paramount step in the methodological design framework was to select the best-synthesised concept that will enable the development of the desired design product. For this study, this step was handled carefully using the already proven techniques of Decision Matrix Analysis (DMA), which were explained in Subsection 4.2.4 of this Chapter. Results obtained show that Concept 4 had a higher weighted score of 4.29 than the other concepts (Figure 4.8). Concept 3 had a slightly lower total weighted score than Concept 4 as it lacked the wind sub-system, which was useful for increasing the reliability of the energy system. Therefore, Concept 4 was selected for further development. This concept involved a combination of a horizontal axis wind turbine (HAWT), solar PV, solar heat collection and storage (SHCS) unit and AD sub-system.

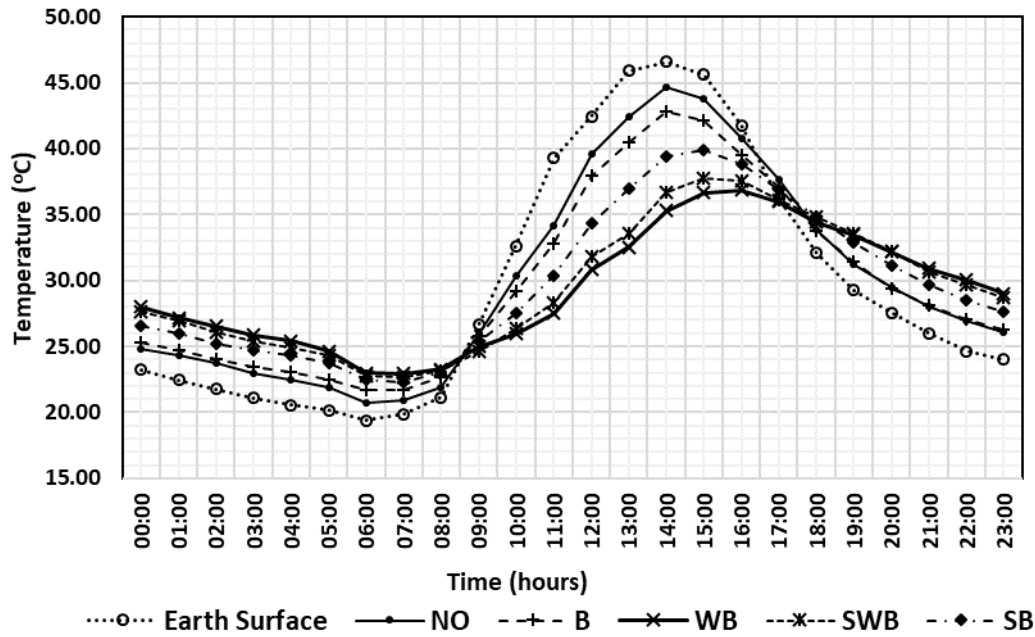


**Figure 4.8: Decision matrix analysis results for brainstormed system concepts**

#### **4.3.2 Selection of the storage medium for the SHCS unit**

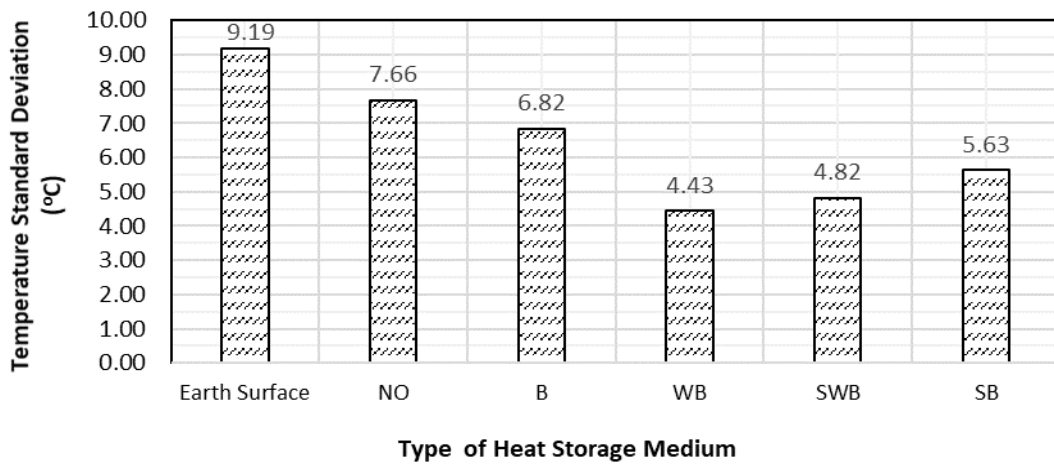
The selected concept included a unit for collecting and storing heat from solar radiation. Therefore, selecting the best heat collection and storage option from locally available materials was made based on systematic testing. The selection criterion was that the best option can keep its temperature variation at the lowest level of all options.

Results of the systematic testing are presented in Figures 4.9 and 4.10. Among all factors (Table 4.2), factor WB had the least variation of temperature, as shown in Figures 4.9 and 4.10. This factor consisted of twelve 0.5 l transparent plastic bottles filled with water, a black plastic sheet, and a greenhouse structure.



**Figure 4.9: Daily temperature variation of materials combinations for SHCS tested (1-14/06/2017)**

Figure 4.9 gives proof of the WB factor having the least temperature variation of all the factors. The WB had a temperature range of 23-38°C, which was minimum regarding other factors' temperature ranges. In Figure 4.10, it is shown that the temperature's standard deviation of 4.43°C due to the factor WB was the least of all other factors.



**Figure 4.10: Temperature standard deviation of materials combinations for SHCS tested (1-14/06/2017)**

### 4.3.3 Fabricated i-SWEAD system

Fabrication of the i-SWEAD system was based on its selected working principle's conceptual design and heat collection and storage medium. Plate 4.1 shows an entirely fabricated and installed i-SWEAD system and its components during its experimental testing. The wind component is on a tripod stand, and the solar PV unit is on the roof of a house. Also shown is an outdoor encasing structure (OES) made of transparent cover on top (large area of its middle part) and corrugated iron sheets on all sides. The OES encompassed the AD sub-system items.



**Plate 4.1: The installed i-SWEAD system at the study site (Photo of 11/01/2018)**

### 4.3.4 Digesters' outdoor encasing structure and ambient air temperature values

The essence of this study was to come up with means of keeping digester temperature at a minimum level of variation for sustainable production of biogas and generating electricity in rural semi-arid areas. For that matter, the i-SWEAD system was designed, fabricated and tested experimentally to suit the phenomenon mentioned above. Three other biogas generation systems using the same type of AD sub-system like that of the i-SWEAD system were tested simultaneously. The testing, among others, involved a collection of temperature data by temperature probes inserted into the systems' biogas digesters,

temperature sensor inside the outdoor encasing structure (OES), and another temperature sensor set to measure ambient air temperature.

Figures 4.11 and 4.12 illustrate the behaviour of the systems' digesters, OES and ambient air during testing with regard to temperature data collected. The digester temperature for System1, System2, System3, i.e. i-SWEAD system and System4 are represented by TD1, TD2, TD3 and TD4 codes, respectively. T\_AAir and T\_OES codes, respectively, represent ambient air and OES temperature values. Both figures, as mentioned above, show that the interior of the OES's exhibited a maximum temperature value of 58.10°C for all the system digesters tested. The systems' Digesters D1 and D3 had the lowest maximum temperature values of 29.40°C and 34.42°C, respectively. Digester D1 had the lowest mean temperature of 26.6°C, followed by Digester D2 with 28.52°C (Figure 4.12). Both Digesters D3 and D4 had a mean temperature of approximately 30°C. The mean temperature of all systems' digesters falls in the mesophilic state range of temperature of anaerobic digestion, which is between 20°C and 40°C as reported by Salam *et al.* (2015) and Schnurer and Jarvis (2010).

In Figure 4.12, D4 exhibited the lowest variation of temperature of all the digesters, with a standard deviation of 0.96°C. However, Digester D3 had the highest mean and standard deviation temperature values of 34.42°C and 1.28°C, respectively. Generally, based on standard deviation, temperature variation in all systems' digesters were above the recommended variation of  $\pm 0.5^\circ\text{C}$  for best results of biogas generation microbes but within the tolerable temperature variation of  $\pm 2\text{-}3^\circ\text{C}$  (Schnurer and Jarvis, 2010). Also, Figure 4.12 shows that ambient air, OES and all digesters temperature values were low in the window demarcated by 15:12-20:16 hours. This window represents the period of the prevalence of rains during the rainy season, which began in late December 2017 to mid-January 2018.

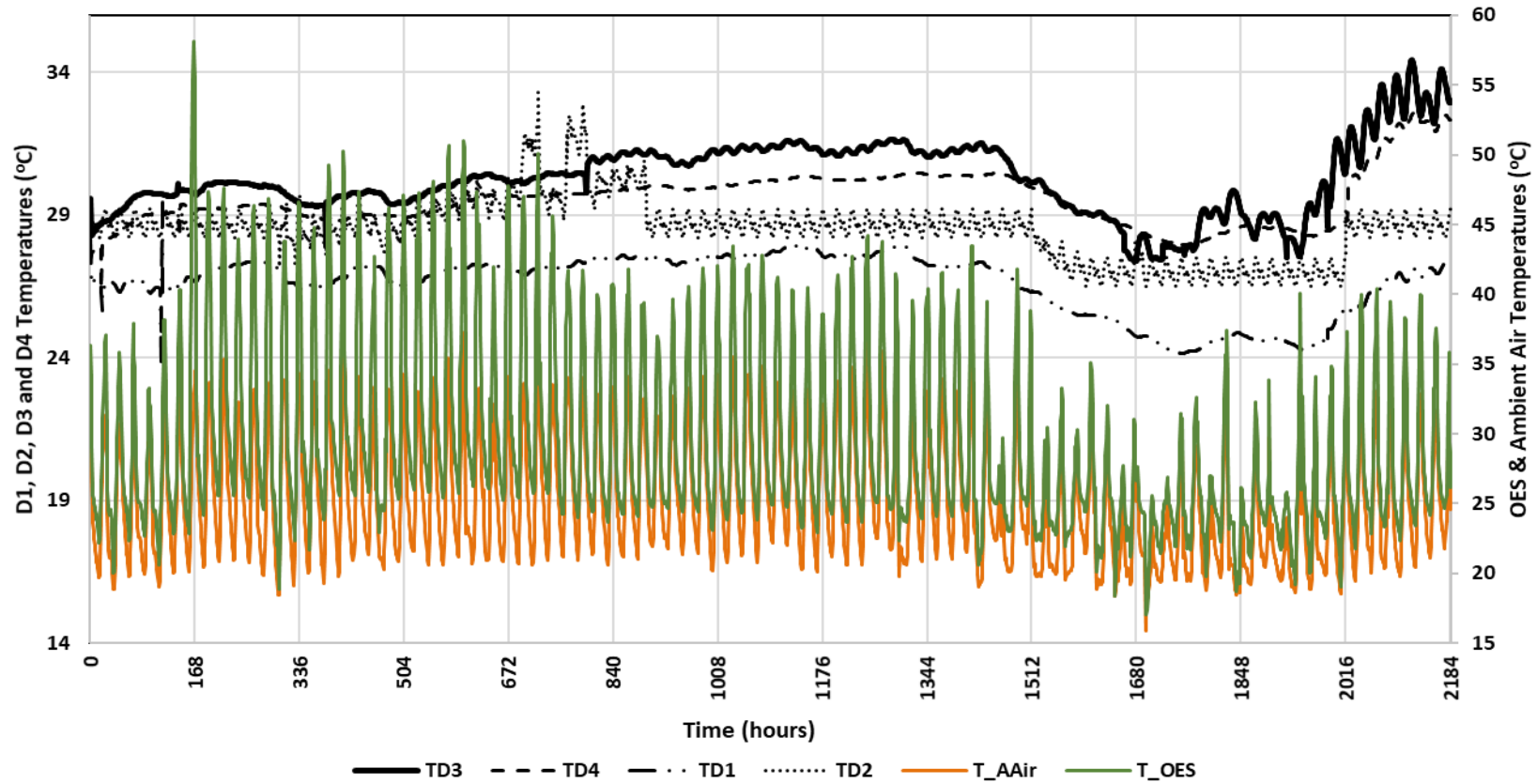


Figure 4.11: Ambient air, OES, D1, D2, D3 and D4 temperature values from 01/11/2017 to 31/01/2018

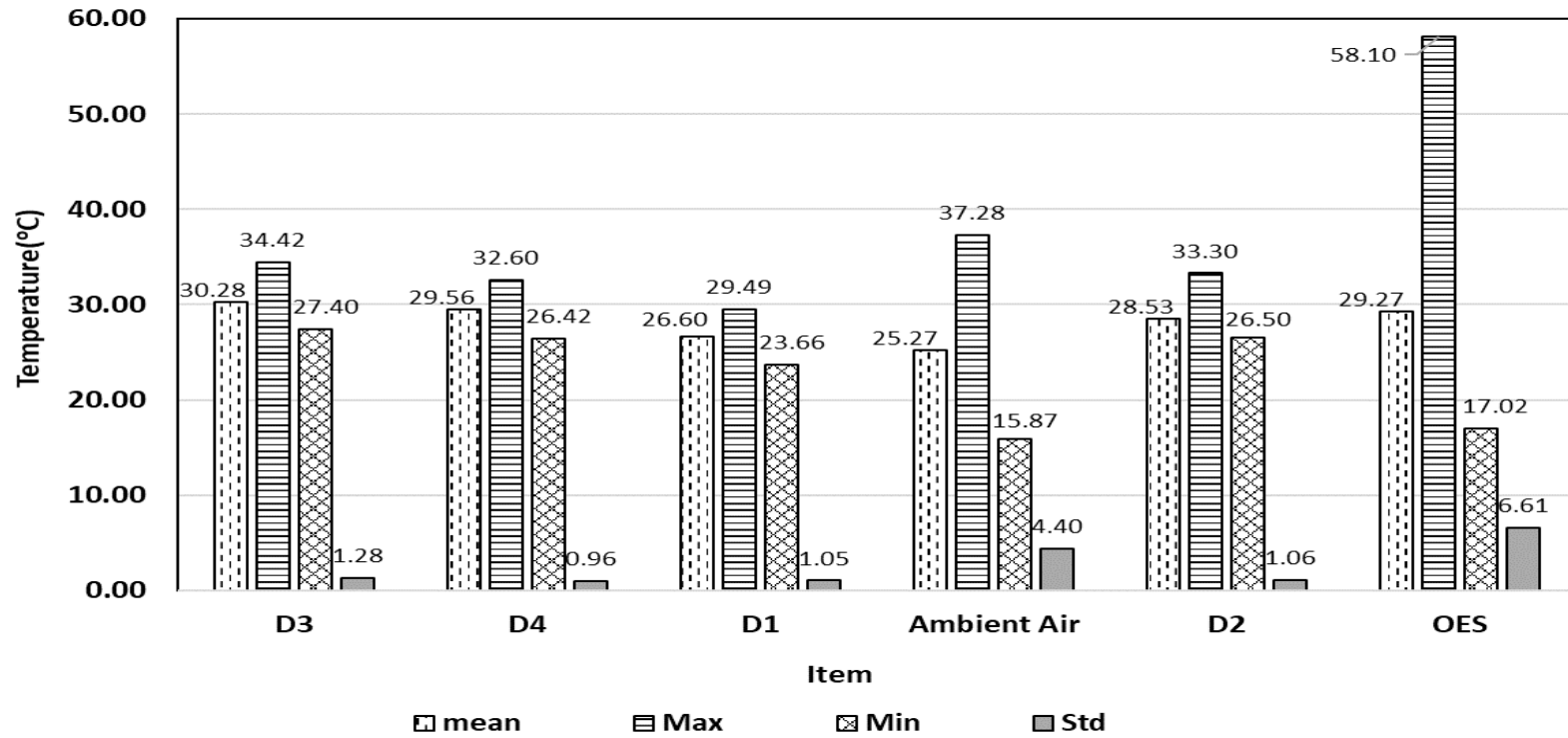


Figure 4.12: Mean, maximum, minimum, and standard deviation temperature values

The high-temperature variation mentioned above in the i-SWEAD system may be due to an uncontrolled supply of heat from both wind and solar sub-systems. It was assumed that the control of heat supply to the i-SWEAD system's digester is regulated by the solar heat collection and storage (SHCS) component of the system in this study. However, during the experiment, it was impossible to control the variation to the optimum range of  $\pm 0.5^{\circ}\text{C}/\text{day}$ , as shown in Figures 4.11 and 4.12. Options to control heat due to the greenhouse effect (from solar radiation) may include an automated blocking or allowing solar radiation into the OES through its top cover using the opaque material sheet. The wind and the solar PV sub-systems heat controls may include the automated switching on and off of the flow of electricity from both sub-systems. The automated control mechanism, coupled with electrical switching gears, can connect and disconnect the electricity flowing into the OES from both the wind sub-system's electrical generator and solar PV unit to ensure the stabilized digester's temperature.

#### **4.3.5 Volume of biogas collected and methane content**

The volume of biogas collected was derived from pressure measurements of each system, which were recorded at three-hour intervals using Equation 4.3. Figure 4.13 shows the relationship between the volume of biogas collected and the time in hours of all four systems. The collected volume of biogas for System1, System2, System3 and System4 is represented by code VolBiogasD1, VolBiogasD2, VolBiogasD3 and VolBiogasD4, respectively. Also, VolBiogasD1, VolBiogasD3 and VolBiogasD4 values are multiple of factor 0.5, 2 and 4 respectively. The factors were chosen to enhance the visibility of their curves in the figure. The maximum volume of biogas collected within three hours was  $0.067\text{ m}^3$  for Digester D3. Both D1 and D2 had a maximum event of biogas yield of  $0.065\text{ m}^3$  within three hours. However, D4 had the maximum event of biogas yield of  $0.066\text{ m}^3$  within three hours. These values of biogas yield in three hours from fresh cow dung ageing between nine hours and three days for digesters with a volume of  $0.240\text{ m}^3$  have not been reported in the literature reviewed so far.

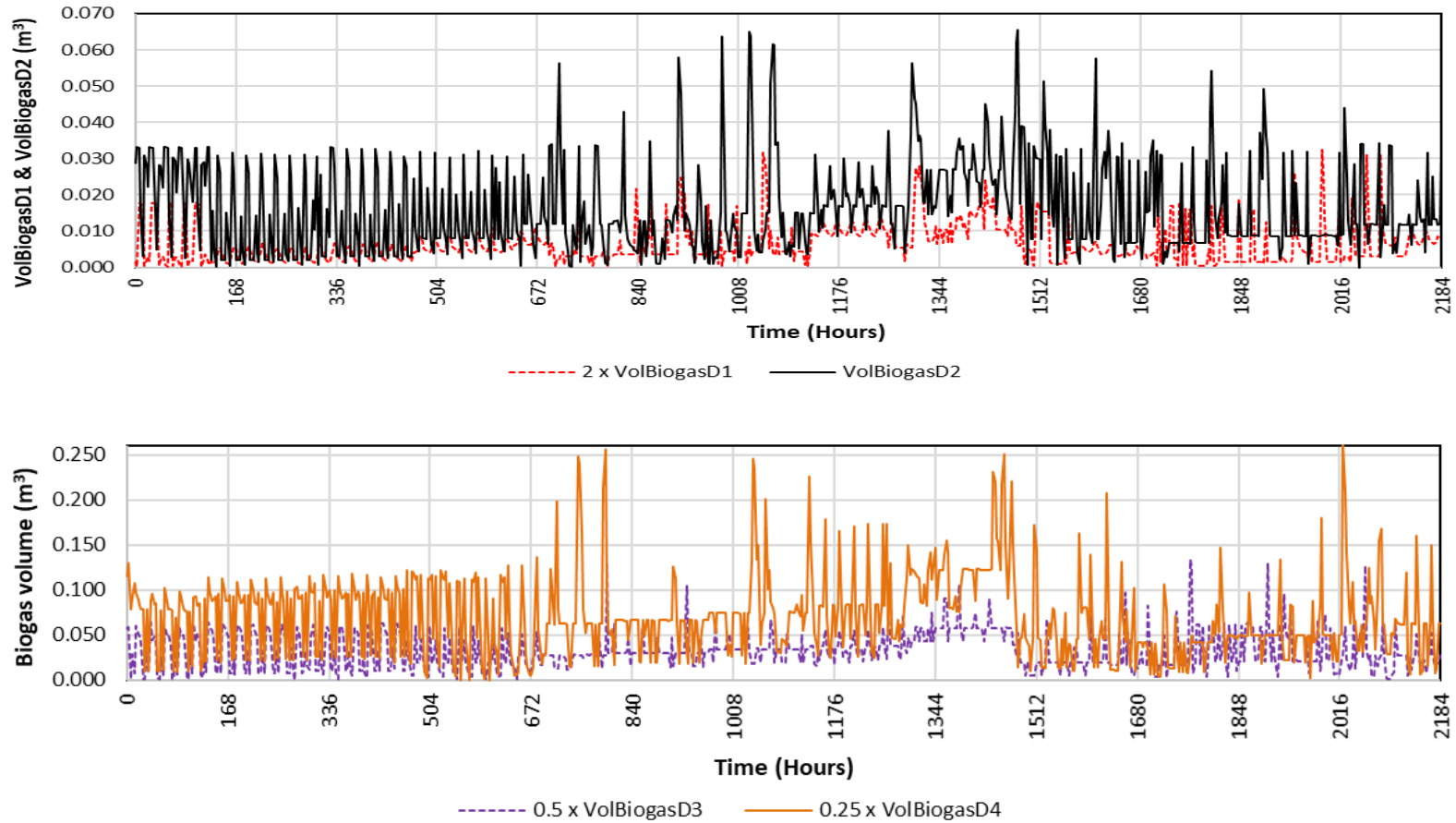


Figure 4.13: Biogas yield of system's Digester D1, D2, D3, D4 from 1/11/2017 to 31/1/2018

Figure 4.14 presents the cumulative biogas volume collected from the four systems' digesters in three-hour intervals for all 92 days. The figure shows that the cumulative biogas yield of D1, D2, D3, and D4 was 9.191 m<sup>3</sup>, 11.794 m<sup>3</sup>, 11.855 m<sup>3</sup> and 12.879 m<sup>3</sup>, respectively. Characteristics of the substrate (cow dung), described in Subsection 4.2.6 of this chapter and the above mentioned cumulative biogas volume values, were used to derive a number of biogas yield parameters for all the four systems' digesters. The parameters for D1 include biogas yield of 0.059 m<sup>3</sup>/kg of fresh cow dung (CD) with 0.244 m<sup>3</sup>/kg of dry matter (DM) and 0.353 m<sup>3</sup>/kg of volatile solids (VS) added into the digester. Also, biogas yield for D2, D3 and D4 with corresponding qualities of cow dung in brackets was 0.076 m<sup>3</sup>/kg of CD (0.341 m<sup>3</sup>/kg DM; 0.494 m<sup>3</sup>/kg VS), 0.077 m<sup>3</sup>/kg of CD (0.343 m<sup>3</sup>/kg DM; 0.496 m<sup>3</sup>/kg VS) and 0.083 m<sup>3</sup>/kg CD (0.372 m<sup>3</sup>/kg DM; 0.539 m<sup>3</sup>/kg VS), respectively. The values of biogas yield in terms of DM and VS were different because each digester produced different amounts of biogas, which was used in determining those values.

Digesters D4 and D1 produced the highest and lowest cumulative amount of biogas of all the four digesters, respectively. Biogas yields of all digesters in this study are higher than the ones reported in the literature reviewed. The literature review was based on investigating anaerobic digestion of fresh cow dung for biogas production within the mesophilic temperature range, which is the same temperature range applied in this study. The reviewed works of literature include the works of Li *et al.* (2014a), Li *et al.* (2011b), and Alfa *et al.* (2014), which reported biogas yield of 56.38 l/kg CD (0.056 m<sup>3</sup>/kg CD), 56.94 l/kg CD (0.057 m<sup>3</sup>/kg CD), and 0.032 m<sup>3</sup>/kg CD, respectively.

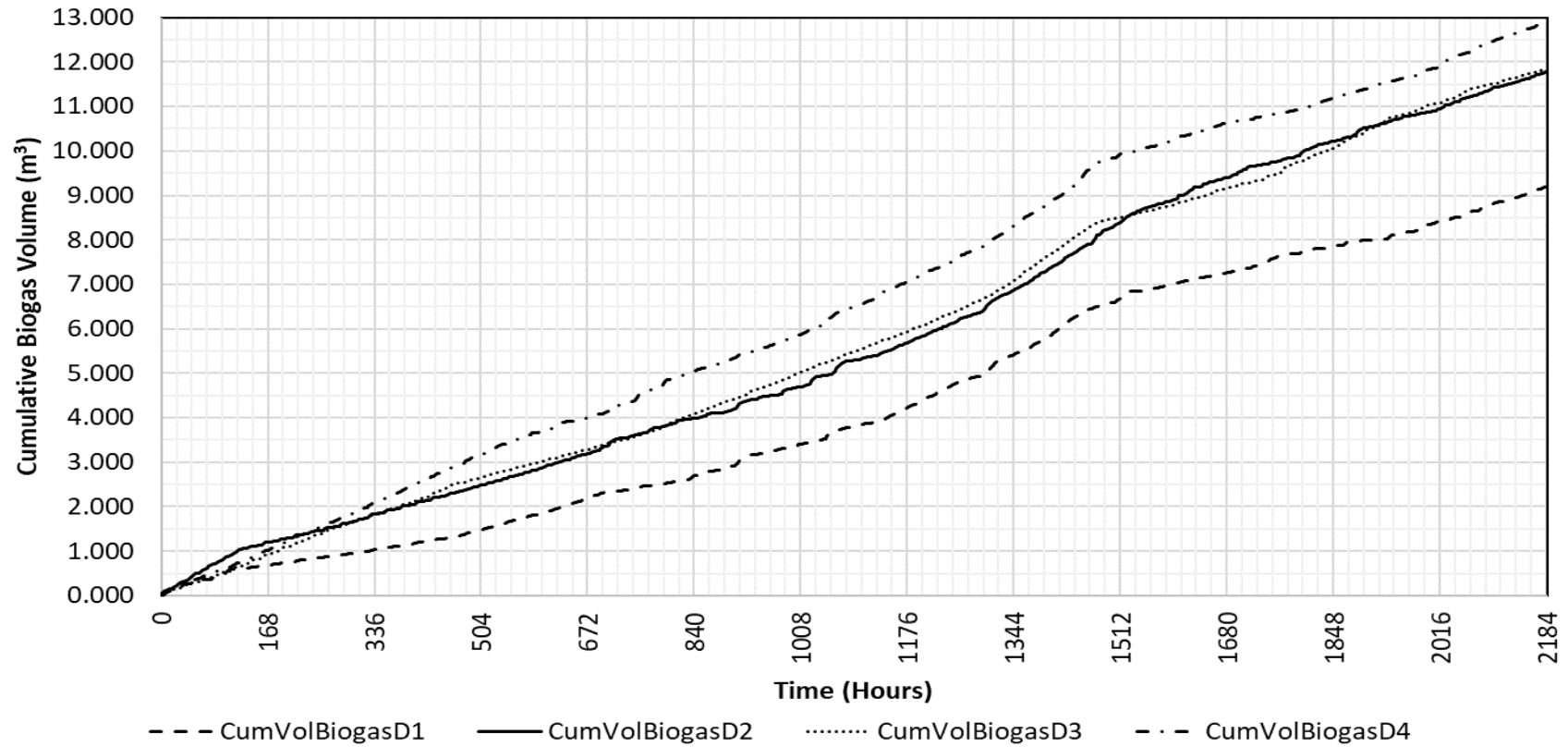


Figure 4.14: Cumulative biogas volumes (1/11/2017 '18:00 hours' - 31/1/2018 '18:00 hours')

The existing AD systems in the semi-arid areas have a biogas production rate of  $0.40 \text{ m}^3/\text{m}^3$  of digester in a day. This figure is referred to in Chapter One Sub-section 1.3.1. Equation 4.3(b) was used to find the i-SWEAD system biogas production rate. Results have shown that the system has a biogas production rate of  $0.54 \text{ m}^3/\text{m}^3$  of digester in a day. Also, Equation 4.3(b) was applied to find the i-SWEAD system's performance. The results have also shown that the i-SWEAD system has a higher biogas production performance by 34% based on the existing AD systems' biogas production rate in semi-arid areas.

A range of hydraulic retention time applied and reported in the reviewed literature mentioned above is 60 - 120 days. Among other factors, the choice of hydraulic retention time of batch type AD system depends on the temperature subjected to the digester. The lower the temperature, the higher the hydraulic retention time and vice versa, applicable in the mesophilic state (Kim *et al.*, 2006). This study applied the hydraulic retention time of 92 days, correlating to the average of the lower and upper limits of the temperature range of the reviewed literature as mentioned earlier. The temperature at the study site falls in the middle of the temperature range of the reviewed literature mentioned above.

Table 4.4 gives descriptive statistics summary of the  $\text{CH}_4$  content in biogas from each system digester. Generally,  $\text{CH}_4$  content for all the four systems' digesters ranged between 55% and 43%, and on average, D3 (the i-SWEAD system) produced biogas with the highest  $\text{CH}_4$  content of 48.57%, while production from D2 had the lowest  $\text{CH}_4$  content of 46.35% of all. Many researchers reported a range of  $\text{CH}_4$  content from cow dung in which the range mentioned above is included. For example, Borhan *et al.* (2012) reported a range of  $\text{CH}_4$  content of 40% to 65% in biogas collected from anaerobic digestion of cow dung. Also, Borhan *et al.* (2012) reported that  $\text{CH}_4$  content was averagely 49% over a period of 40 days of hydraulic retention time. The value is very close to that of the i-SWEAD

system (48.57%). The fact is that biogas with the highest CH<sub>4</sub> content has the highest energy density. However, this is true if other high energy density gas content in biogas, e.g., Hydrogen content, is assumed to be very low compared to CH<sub>4</sub> content. For that matter, D3 of the i-SWEAD system was favourable to be applied despite the highest biogas yield generated by D4.

**Table 4.4: Methane content descriptive statistic in all the four digesters**

Descriptive Statistics summary of CH <sub>4</sub> content	Digester			
	D1	D2	D3	D4
Average (%)	47.71	46.35	48.57	46.37
Standard deviation (%)	2.35	1.84	2.15	1.26
Maximum (%)	55	53	55	49
Minimum (%)	43	43	44	43
Number of observations (n)	736	736	736	736

#### 4.3.6 Availability of the i-SWEAD system and biogas energy generated

Biogas energy conversion into useful consumable energy was discussed by Cuéllar and Webber (2008) as well as Kurchania *et al.* (2010). With this background and data of the biogas amount generated by the i-SWEAD system with its respective methane content, then energy density (a heating value) of biogas generated by the system was estimated at 18 MJ/m<sup>3</sup>. Equation 4.1 was used to compute the availability of the system for household cooking purposes. The availability of the system was 0.32 h/day. Equation 4.2 was used to determine the biogas energy available from the system per day. The system biogas energy generated was 0.64 kWh/day. These values seem to be underestimated values because more biogas could have been collected beyond the hydraulic retention time of 92 days that was applied in this study. Figure 4.14 illustrates this phenomenon, as the curve of the cumulative volume of biogas collected from D3 was still rising at an angle of around 45°, which indicates the continuation of biogas generation at an appreciable high rate.

#### **4.3.7 Electrical and heat energies from solar PV unit and wind sub-system**

The annual electrical energy generated by the solar PV unit, which has a 20 Wp rating, was calculated using Equation 4.4. The value of annual electrical energy generated by the solar PV unit was 5.69 kWh. The solar PV unit was meant to power five 1 Wp-bulbs and charge the 5 V-1 A mobile phone. Four bulbs were allocated to the household, while one bulb was used to stabilise System3's digester temperature.

Electrical energy per year from the wind sub-system was computed using the power rating of the generator actuated by the wind turbine, which was 6 W. Also, the computation involved the annual wind speed extrapolated using Equations 2.2 and 2.2a at the hub height of 4 m with a reference height of 2.5 m. The annual wind speed extrapolated was 4.69 m/s. The probability of events of wind speed equal to or above annual average wind speed at the study site was computed using the extrapolated annual wind speed and values calculated using Equations 4.5, 4.5a and 4.5b. The probability was 0.486. This figure of probability indicates that wind speed equal to or above the 4.69 m/s at the site will be available for about 49% of the period of the whole year. Therefore, using this information and Equation 4.6, the electrical energy per year generated by the wind sub-system was computed and found to be 25.55 kWh. The annual heat energy generated by solar PV unit and wind sub-systems for stabilising System3's digester temperature was calculated using Equation 4.7. It was found to be 28.76 kWh.

#### **4.3.8 The cut-in wind speed and power of wind sub-system turbine**

Additionally, the wind turbine of the wind sub-system was tested for its functionality to supply heat to System3's digester. The supply of heat aimed at keeping the digesters' temperature constant. The testing also aimed at establishing the cut-in wind speed and

time needed to raise the temperature of the probe positioned 50 mm from the 6 W bulb, i.e. heat source, to at least 28°C from ambient air temperature, which was lower than the mentioned temperature level. Results obtained show that averagely, the wind turbine unit had a cut-in wind speed of 3.99 m/s ( $\sigma = 0.51$  m/s) and it was able to increase the temperature to 28°C from the average ambient temperature of 21.3°C ( $\sigma = 2.9^\circ\text{C}$ ) within 2.21 min ( $\sigma = 0.11$  min). The cut-in wind speed value obtained was lower than the annual wind speed of 4.69 m/s at the hub height of 4 m at the study site. Also, the cut-in wind speed obtained is within the cut-in wind speed range of 3.00 - 4.00 m/s for a small wind turbine reported by Arnett *et al.* (2013).

The computation of annual wind energy produced by System3's wind sub-system included using wind speed just above the cut-in wind speed at 4 m hub height. The value intuitively selected was 4.45 m/s, which was just above the cut-in wind speed of a standard small wind turbine. Also, the computation included the probability of finding the wind speed range above the cut-in wind speed. The probability found at a wind speed of 4.45 m/s was 0.48604. The average power of wind turbine due to harnessing wind energy, which was calculated using Equation 4.8, was 53.58 W. Therefore, using the average power of 53.58 W and Equation 4.9, then the wind energy generated by the wind turbine of System3 in a year was calculated. It was found to be 228.13 kWh per year. Determination of solar energy flux received by D3 daily involved solar insolation at the study site, top exposed area digester D3 and the transmittance of the transparent top cover of OES. With this information and using Equation 4.10, then solar energy flux received by D3 was found to be 2.88 kWh/day.

#### **4.4 Conclusion and Recommendations**

The i-SWEAD system designing and experimental testing results' discussion unleashes

insights on the system's functionality and performance. Firstly, the robust designing approach involving the decision matrix analysis tool is essential for conceptual designating of the energy system. Secondly, the i-SWEAD with its digester of 0.24 m<sup>3</sup> capacity system and at a hydraulic retention time of 92 days, has a higher biogas yield (0.077 m<sup>3</sup>/kg of fresh cow dung) compared to other similar biogas systems reviewed, which had the maximum biogas yield of 0.057 m<sup>3</sup>/kg of cow dung. Thirdly, the i-SWEAD system has the highest average CH<sub>4</sub> content (48.57%) of all other systems simultaneously tested together at the study site. Also, the i-SWEAD system has a biogas production rate of 0.54 m<sup>3</sup>/m<sup>3</sup> of the digester, which indicates that the system has higher biogas production performance by 34% based on existing anaerobic digestion systems' biogas production rate of 0.4 m<sup>3</sup>/m<sup>3</sup> of digester in a day in semi-arid areas.

Fourthly, the system can keep its digester temperature variation (1.28°C/day) within the biogas generation microbes' tolerable temperature variation range ( $\pm 3.0^\circ\text{C}/\text{day}$ ), which was reported by Schnurer and Jarvis (2010). Although tolerable by biogas microbes, the variation noticed among others is due to the uncontrolled heat supply of wind and solar sub-systems. Fifthly, the availability of the i-SWEAD system (0.32 h/day) and its biogas energy (0.64 kWh/day) values based on the hydraulic retention time of 92 days are underestimated, as there was a high possibility of generating more biogas beyond 92 days of hydraulic retention time. Sixthly, the system can generate minimum annual electrical energy from solar PV unit and wind sub-systems of 5.69 kWh and 25.55 kWh, respectively. Also, it can generate the total annual heat from both the wind sub-system and solar PV unit intended for stabilizing the i-SWEAD system's digester temperature of 226.13 kWh. Furthermore, the system's digester can receive the solar energy flux of 2.88 kWh/day based on Equation 4.10. Finally, the i-SWEAD system's sub-systems, which are wind, solar and anaerobic digestion sub-systems, can all be scaled up. However, the scaling up is determined by the limitations of space, investment costs and not been able to

predict up-scaled performance.

With this information, the robust designing approach involving the decision matrix analysis tool applied in this study is recommended to researchers and other renewable energy system designers. Also, the i-SWEAD system is recommended for application in the rural semi-arid areas since it generated clean electricity for powering electrical and electronic gadgets as well as efficiently producing biogas for cooking. Further research is recommended for developing the control mechanism responsible for regulating the heat supply of both wind and solar sub-systems. The establishment of optimum power coefficient, tip speed ratio parameters and performance curve of the i-SWEAD system's wind turbine is an essential research topic.

Since biogas is a fuel, which is very useful and needed for cooking purposes in rural semi-arid areas, it is prudent that modelling biogas production of this novel developed system, i.e., the i-SWEAD system for facilitating the adoption and upscaling, is an area of further research interest. Finally, the economic and technical evaluation of the i-SWEAD system is recommended to be conducted. It has been presented in Chapter Six of this thesis.

#### **4.5 Acknowledgement**

Refer to Section 2.5 in Chapter Two of this thesis.

#### **4.6 References**

Alfa, I. M., Dahunsi, S. O., Iorhemen, O. T., Okafor, C. C. and Ajayi, S. A. (2014).

Comparative evaluation of biogas production from poultry droppings, cow dung

and lemongrass. *Bioresource Technology* 157: 270 – 277.

Arnett, E. B., Johnson, G. D., Erickson, W. P. and Hein, C. D. (2013). *A Synthesis of Operational Mitigation Studies to Reduce Bat Fatalities at Wind Energy Facilities in North America*. Bat Conservation International. Austin, Texas, USA. pp.38.

Bidaoui, H., El Abbassi, I., El Bouardi, A. and Darcherif, A. (2019). Wind speed data analysis using Weibull and Rayleigh distribution functions, case study: five cities northern Morocco. *Procedia Manufacturing* 32: 786-793.

Borhan, S., Rahman, S. and Ahn, H. K. (2012). Dry anaerobic digestion of fresh feed-yard manure: A case study in a laboratory setting. *International Journal of Emerging Science* 2: 509 – 525.

Chowdhury, N. R., Reza, S. E., Nitol, T. A. and Mahabub, A. F. I. (2012). Present scenario of renewable energy in Bangladesh and a proposed hybrid system to minimize power crisis in remote areas. *International Journal of Renewable Energy Research* 2(2): 280 – 288.

Cook, S., Hall, M. and Gregory, A. (2012). Energy use in the provision and consumption of urban water in Australia: An update. *Desalination* 15: 1-20.

Cuéllar, A. D. and Webber, M. E. (2008). Cow power: The energy and emissions benefits of converting manure to biogas. *Environmental Research Letters* 3: 034002-034010.

Felix, M. and Gheewala, S. H. (2011). A review of biomass energy dependency in Tanzania. *Energy Procedia* 9(2): 338 – 343.

Kaena, N. P. A. (2012). Guideline for choosing the best alternative solution for engineering academic projects. *Proceeding of the 2<sup>nd</sup> International Conference on Mechanical and Industrial Engineering - Engineering*

- Innovations for Sustainable Development*. February 16-17, 2012, Naura Springs Hotel, Arusha, Tanzania. pp. 218 – 227.
- Kim, J. K., Oh, B. R., Chun, Y. N. and Kim, S. W. (2006). Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. *Journal of Bioscience and Bioengineering* 102(4): 328-332.
- Kurchania, A. K., Panwar, N. L. and Pagar, S. D. (2010). Design and performance evaluation of biogas stove for community cooking application. *International Journal of Sustainable Energy* 29(2): 116 – 123.
- Kusiak, A., Zhang, Z. and Verma, A. (2013). Prediction, operations and condition monitoring in wind energy. *Energy* 60: 1 – 12.
- Kutty, S. S., Khan, M. G. and Ahmed, M. R. (2019). Wind energy resource assessment for Suva, Fiji, with accurate Weibull parameters. *Energy Exploration and Exploitation* 37(3): 1009-1038.
- Li, J., Jha, A. K. and Bajracharya, T. R. (2014a). Dry anaerobic co-digestion of cow dung with pig manure for methane production. *Applied Biochemistry and Biotechnology* 173(6): 1537 – 1552.
- Li, J., Jha, A. K., He, J., Ban, Q., Chang, S. and Wang, P. (2011b). Assessment of the effects of dry anaerobic co-digestion of cow dung with wastewater sludge on biogas yield and biodegradability. *International Journal of Physical Sciences* 6(15): 3723 – 3732.
- Li, S., Chen, H., Tan, S. C., Hui, S. Y. R. and Waffenschmidt, E. (2014). Critical design issues of retrofit light-emitting diode (LED) light bulb. In: *2014 IEEE Applied Power Electronics Conference and Exposition-APEC 2014 IEEE*. pp. 531-536.
- Mirzaei, M., and Mohiabadi, M. Z. (2017). A comparative analysis of long-term field test of monocrystalline and polycrystalline PV power generation in semi-arid climate conditions. *Energy for Sustainable Development* 38: 93-101.

- Mshandete, A. M. and Parawira, W. (2009). Biogas technology research in selected Sub-Saharan African countries – A review. *Journal of Biotechnology* 8(2): 116–125.
- NBS (2014). *Tanzania Mainland Household Budget Survey Main Report-2011/12*. Ministry of Finance, Dar es Salaam, Tanzania. 201pp.
- Ng'wandu, E., Shila, L. C. and ter Heegde, F. E. W. (2009). Programme Implementation Document. Tanzania Domestic Biogas Programme, Arusha, Tanzania. 95pp.
- Olabanji, O. M. and Mpofu, K. (2014). Comparison of weighted decision matrix, and analytical hierarchy process for CAD design of reconfigurable assembly fixture. *Procedia Centre d'Insertion et de Réinsertion Professionnelle (CIRP)* 23: 264 – 269.
- Pahl, G., Beitz, W., Feldhusen, J. and Grote, K. H. (2007). *Engineering Design: A Systematic Approach*. (Third Edition), Springer-Verlag London, UK. 617pp.
- Sadi, M. A. (2010). *Design and building of biogas digester for organic materials gained from solid waste* (Doctoral dissertation). [<https://repository.najah.edu/handle/20.500.11888/6792>] site visited on 23/07/2020
- Salam, B., Biswas, S. and Rabbi, M. S. (2015). Biogas from mesophilic anaerobic digestion of cow dung using silica gel as catalyst. *Procedia Engineering* 105: 652 – 657.
- Salonen, M. and Perttula, M. (2005). Utilization of concept selection methods: A survey of Finnish industry. *Proceeding of International Design Engineering Technical Conferences and Computers and Information in Engineering Conference (IDETC/CIE) 2005 American Society of Mechanical Engineers (ASME)*. 24-28 September 2005, California, USA. pp. 527 – 535.
- Schnurer, A. and Jarvis, A. (2010). *Microbiological Handbook for Biogas Plants*. Swedish, Waste Management. Sweden. 74pp.
- Schubel, P. J. (2010). Technical cost modelling for a generic 45-m wind turbine blade

- produced by vacuum infusion (VI). *Renewable Energy* 35(1): 183-189.
- Tayal, S. P. (2013). Engineering design process. *International Journal of Computer Science and Communication Engineering (IJCSCE)*, IJCSCE Special issue on “National Conference on Recent Advances in Engineering and Technology (NCRAET)” - 2013. pp.1-5.
- Tveit, T. M. (2006). A systematic procedure for analysis and design of energy systems. Thesis for Award of PhD Degree at Helsinki University of Technology, Helsinki, Finland. 70pp.
- Wawa, A. I. (2012). The Challenges of Promoting and Adopting Biogas Technology in Semi-arid areas of Tanzania: The Case of Kongwa and Bahi Districts in Dodoma Region. Thesis for Award of PhD Degree, Open University of Tanzania. 211pp.
- Yadvika, S., Sreekrishnan, T. R., Kohli, S. and Rana, V. (2004). Enhancement of biogas production from solid substrates using different techniques - A Review. *Bioresource Technology* 95(1): 1–10.

## CHAPTER FIVE

### **5.0 Artificial Neural Network (ANN) Biogas Production Model for an Integrated Solar and Wind Energy with Anaerobic Digestion (i-SWEAD) System**

#### **Abstract**

An integrated solar and wind energy with anaerobic digestion (i-SWEAD) system has been developed and tested to generate biogas and electricity for individual households in rural semi-arid areas. The i-SWEAD system was a needs tool to enhance adoption through prior knowledge of the system's biogas generation performance. This chapter presents a novel Artificial Neural Network (ANN) model and assessment results of its capacity to predict the i-SWEAD system biogas production. Input variables of the developed ANN model were hydraulic retention time, solar radiation, wind speed, ambient air temperature and digester temperature due to heat collected. In contrast, the output variable was biogas volume. Six datasets of data of input and output variables were formed. Each of the six datasets was used to generate a model. Nevertheless, four datasets among the six datasets were based on the i-SWEAD system and the other three systems. The remaining two datasets were based on the two virtual renewable energy systems. The first and the second virtual systems' datasets were obtained by combining fore mentioned four systems' datasets in series and averaging those four system's datasets, respectively. All datasets were split into training data (75%) and testing data (25%). The best ANN model, Model4, was selected among the six ANN models built during the initial stage of model assessment. It secured a coefficient of determination value of 0.6 and the least residual mean sum of squares of 0.24. During the final stage of model assessment, the model predictive power was tested using the testing data. Model4 showed strong predictive power of the i-SWEAD system measured biogas volume values by getting Absolute Model Prediction Accuracy (AMPA) of 99%. Model4 also performed well when the

graphic technique was used, as predicted and measured biogas curves of the i-SWEAD system were close to each other. Model4 is recommended for application by energy stakeholders intending to apply the i-SWEAD system or other similar systems in the rural semi-arid areas or other similar conditions for informed decision making.

**Keywords:** *biogas generation; artificial neural network; i-SWEAD system; model assessment, semi-arid areas*

## 5.1 Introduction

Renewable energy is gaining appreciable attention worldwide regarding total energy consumption, investments, and research, as explained in REN21 (2018). Koçak and Şarkgüneşi (2017) reported a 39% predicted rise in electricity production from renewable sources by 2050. The prediction was based on an electricity production reference of 18% in 2002. Renewable energy research and technologies are at various levels based on renewable energy sources and resources exploited. Several renewable energy systems have been developed and tested, and some commercialised, while others are still undergoing laboratory tests. However, some developed systems are being studied for performance improvement purposes (Jha *et al.*, 2017). Due to the intermittent nature of renewable energy sources and resources, some integrated renewable energy systems have been developed to decrease the adverse intermittence effects on harnessing energy from the sources and resources (Jha *et al.*, 2017).

Anaerobic digestion based energy systems, which produce biogas, fall under the renewable energy systems category. Its process simulation and or energy and materials output prediction is challenging. The challenge is rooted in the anaerobic digestion process, which is chemically and biologically complex as its hydrolysis, acidogenesis, acetogenesis, and methanogenesis reactions occur simultaneously and consecutively in digesters. Numerous microorganisms trigger these reactions. Some of them include hydrogen gas-consuming, hydrogen gas-producing, acetogenic, carbon dioxide reducing and acetoclastic methanogenic bacteria (Yu *et al.*, 2013). Biogas production rate is affected by several factors, which include the type of biodigester design, physical and chemical characteristics of substrates, mode of operation of biogas plant and environmental characteristics prevailing in the field (Schirmer *et al.*, 2014; Yadvika *et al.*, 2004; Igoni *et al.*, 2008). These make the amount and quality of biogas produced estimate difficult to the extent of demanding the use of models.

With the above background information, models are required, which may give an in-depth understanding of process inputs for biogas or methane optimum yield and production rate (Sewsynker-Sukai *et al.*, 2017). Such models need to be robust to be used in various conditions. Some simple and complex models have been developed, attempting to simulate or predict the amount of biogas generated by anaerobic digestion systems (Rea, 2014). Input variables of most of them are based on feedstock characteristics, biogas plant operation issues and rarely environmental characteristics, while output variables may include methane content, the concentration of chemical oxygen demand and biogas volume (Qdais *et al.*, 2010; Yu *et al.*, 2013; Rea, 2014;). However, most of the models were built based on laboratory data of batch type systems and on results of testing continuous fed anaerobic digestion systems in the field. No model has been developed for predicting the volume of biogas collected from the integrated renewables energy systems, especially when those systems are installed in the field and include batch anaerobic digestion, solar and wind energy.

The integrated renewable energy system, which includes batch fed anaerobic digester installed on the ground biogas generated, is affected by environmental factors. Therefore, modelling this system's performance on generating biogas may need more variables based on environmental factors. The factors usually affect the system's microbes responsible for biogas generation. Temperature is one of the factors, which affect microbes. Microbes responsible for biogas generation in the mesophilic state survive in less or equal to  $\pm 3^{\circ}\text{C}$  temperature range. There is no appreciable biogas production inhibition within this temperature range (Schnurer and Jarvis, 2010). Modelling the anaerobic digestion based energy systems installed in the field should capitalise on factors, which influence temperature variation at the site. Qdais *et al.* (2010) argued that temperature is an essential factor to consider for sustainable biogas generation.

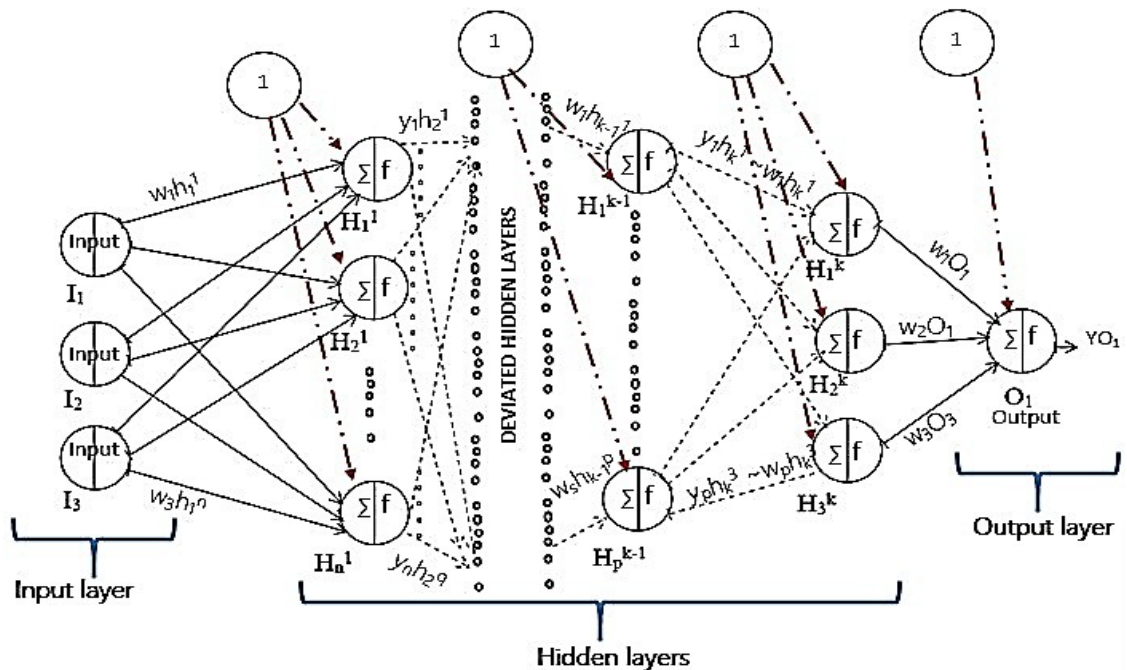
Modelling techniques have been devised for building more precise simulating or predicting models for biogas generation. These models include linear models, generalized additive models, classification and regression trees, multivariate adaptive regression splines, and artificial neural networks (ANNs). The linear models describe a continuous response/dependent variable as a function of one or more predictor/independent variables (Field, 2000). They can be used to understand and predict the behaviour of systems or analyse experimental and biological data. The generalized additive model is a generalized linear model in which the linear predictor depends linearly on unknown smooth functions of some predictor variables, and interest focuses on inference about the smooth functions (Yee and Mitchell, 1991). The smooth function attempts to capture important patterns in the data while leaving out noise or other fine-scale structures/rapid phenomena.

Another model that may be used for prediction purposes is the classification and regression trees obtained by recursively partitioning the data space and fitting a simple prediction model within each partition. As a result, the partitioning can be represented graphically as a decision tree (Loh, 2011). The multivariate adaptive regression splines model uses piecewise linear segments to describe non-linear relationships and interactions between variables (Friedman, 1991). ANNs models are biologically characterised computer programs models set to simulate how the human brain handles information. ANNs gather their knowledge by detecting the patterns and relationships in data and learn (or are trained) through experience. An ANN is formed from many single units, artificial neurons, which are simple processing units or processing elements (PE). The neurons are connected by synapses, which could have different levels of electrical conductivity, which is referred to as the coefficient or weight of the connection. The neurons and weights constitute the neural structure and are organised in layers (Agatonovic-Kustrin and Beresford, 2000; Sefeedpari *et al.*, 2013; Sewsynker-Sukai *et al.*, 2017).

Choice of a technique for modelling is based on data characteristics, underlying assumptions and conditions for applying the technique (Field, 2000). Literature reviewed shows that the ANNs have gained attention in different fields due to their capability to model complex, non-linear processes (Moisen and Frescino, 2002; Yu *et al.*, 2013; Sewsynker-Sukai *et al.*, 2017). The complex and non-linear processes include anaerobic digestion.

Various ANN algorithms are available, but the most applied for biofuel processes modelling is the feed-forward back-propagation neural network (BPNN) (Diamantopoulou *et al.*, 2011; Sewsynker-Sukai *et al.*, 2017). The BPNN is a multilayer network, including the input layer, hidden layer, and output layer. Each layer contains a number of artificial neurons. In the feed-forward ANNs architecture, output neurons do not have a connection back to the input neurons, and therefore, it does not keep a record of its previous output values (Agatonovic-Kustrin and Beresford, 2000).

A typical ANN model configuration is represented in Figure 5.1. The figure shows a typical topology of a multilayer artificial neural network model, which can be built by computer modelling software. The software which can build the model topology of this nature is R-Software. This software is explained in detail by RCoreTeam, 2018. Other modelling tools for building the ANN models are available. They include Neurosolution software (NeuroDimension, Inc., USA), Python (Version 3.7.0), and MATLAB (Sefeedpari *et al.*, 2013; Widyanto *et al.*, 2014; Hsieh *et al.*, 2018; Kana *et al.*, 2012). R-Software is the modelling tool that was used in this study.



**Figure 5.1: Illustrative multilayer artificial neural network model**

In Figure 5.1, the **I** is an input layer neuron, while **H** is for hidden layer neuron, and **O** is for output layer parameter neuron. The **w** implies the weight of the previous neuron into the next layer neuron. Nevertheless, the **h** and **y** denote a succeeding neuron in the hidden layers and output of the previous neuron, respectively. The **y** is obtained after the implementation of activation/transfer function **f**. The **f** is the transfer function, which is a mathematical function between the input feeding the current neuron and the output of that neuron going to the next layer. It has different types: a simple or unit step (threshold), sigmoid, piecewise linear, Gaussian, and Linear functions (Sefeedpari *et al.*, 2013). The threshold function introduces the non-linear properties into ANN by calculating the sum and adding the direction. This helps to decide whether to activate a particular neuron or not. The output is set at one of two levels, depending on whether the total input is greater than or less than some threshold value.

The sigmoid function has a non-linear property, and it consists of logistic and tangential functions. The logistic function values range from 0 to 1, and those of tangential function

range from -1 to +1. The piecewise linear function produce output, which is proportional to the total weighted output of previous neurons. Gaussian is the function, which produces a bell-shaped curve that is continuous. The neuron output, e.g. high or low, is interpreted in terms of class membership, e.g. 1 or 0, depending on how close the net input is to a chosen value of average. Another activation function is linear. It is like linear regression. Also, it transforms the weighted sum inputs of the neuron to an output using a linear function. The activation functions, which have non-linear properties, are primarily used in modern ANN modelling tools. Also, they reflect the non-linear properties of anaerobic digestion. These functions can be analogical as the activities happening in the digester of the i-SWEAD system.

Nevertheless, they allow backpropagation because they have a derivative function related to the inputs, and they allow multiple layers of neurons to create a deep neural network. Multiple hidden layers of neurons are needed to learn complex data sets with high levels of accuracy. The non-linear activation functions are suitable for modelling the complex and non-linear process of anaerobic digestion. The non-linear based ANN activation function, i.e. sigmoid, was applied in this study. This function represents the growth rates of biogas microbes, which are assumed to be affected by factors treated as input variables. Also, the growth rate of microbes is direct proportionally related to the volume of biogas generated.

In Figure 5.1, the shown  $\sum$  symbol represents a summation of incoming weights into that particular neuron. The weighted sum of input values from previous neurons is used to trigger the activation function (Sewsynker-Sukai *et al.*, 2017; Jha *et al.*, 2017). Furthermore, the '**n**', '**q**', '**s**' and '**p**' shown in Figure 5.1 are the last neuron numbers in some hidden layers, while **k** is the last hidden layer number. The **YO<sub>1</sub>** is a simulated or

predicted result produced by the ANN model under the effect of its input layer neurons' weight values. In this study, the  $YO_1$  was a predicted biogas volume. Arrows from neurons labelled '1' carry weight, representing a bias or an intercept coefficient input. Note that weight in the neural network model can be negative to indicate its hindrance effect (Sewsynker-Sukai *et al.*, 2017).

All input and output values of measured values are normalized and scaled. They are first normalised using Equation 5.1. Afterwards, they are scaled in ranges of either -1 to 1, -2 to 2 or 1, 0. The process suits the transfer function in the hidden and output layer. The  $YO_1$  result obtained is unscaled to actual values to make meaningful interpretations of results. The output of  $H_p$ , which is  $yp$  in hidden layer  $k-1$  obtained after enacting  $f$ , and based on  $w$  of neurons in the hidden layer  $k-2$  can be expressed by Equation 5.2.

$$\hat{X} = \frac{X - X_{min}}{X_{max} - X_{min}} \dots \dots \dots \text{Eq. (5.1)}$$

where  $\hat{X}$  is a normalised value, while  $X_{max}$  and  $X_{min}$  are maximum and minimum values of  $X$ , respectively.

$$y_p = f\left(\sum_1^s w_{ih_{k-1}^p}\right) \dots \dots \dots \text{Eq. (5.2)}$$

where  $i$  ( $i=1,2,3, \dots,s$ ) is the number of neurons in hidden layer  $k-2$ ,  $h_{k-1}^p$  is a label for neuron number  $p$  in the hidden layer number  $k-1$  and  $W$  is the weight.

Supervised learning aims to predict one or more target values from one or more input

variables. The feed-forward BPNN employs a supervised learning process. The supervised learning is a form of regression that relies on example pairs of data: inputs and outputs of the training set (Sewsynker-Sukai *et al.*, 2017; Agatonovic-Kustrin and Beresford, 2000). The literature reviewed so far indicates that none of the ANN models for the prediction of biogas production has been built based on the experimental data, which was collected from field batch fed anaerobic digestion testing results.

Assessment of the simulative or predictive power of built ANN models is essential for the reliability of those models' simulated or predicted results. There are numerous model assessment measures employed, which include Mean Square Errors (MSE), Coefficient of Determination ( $R^2$ ), Mean Absolute Percentage Error (MAPE) and the Root Mean Square Error (RMSE). The meaning and application of these measures are explained in detail by Cadenas and Rivera (2009), Alexander *et al.* (2015), and Nair *et al.* (2017). Other measures included are Percent Deviation (Dv\_D), Nash-Sutcliffe Efficiency or model efficiency (NSE), Residual Mean Sum of Squares (RMSS), and Pearson correlation coefficient. These measures are described intensively by Moriasi *et al.* (2007). Also, Absolute Model Prediction Accuracy (AMPA) and visual performance measures, which are based on graphics technique have been used for model assessment, and they have been illustrated in detail by Rajapaksha *et al.* (2015), Cadenas and Rivera (2009) and Donoso-Bravo *et al.* (2011). Some of the fore mentioned assessment measures had been used in this research. Their application descriptions are given in Sub-section 5.2.5 of this chapter.

The i-SWEAD system, which is the critical system in this study and discussed in Chapter Four, is intended for the production of biogas for cooking energy and electricity for powering electric, electronic gadgets as well as stabilizing the system digester temperature. The biogas for cooking energy is highly needed as it may reduce the time and

expenses incurred by the household to fetch firewood in rural semi-arid areas. Also, the biogas energy amount produced by the i-SWEAD system is large compared to the other forms of energy generated by the same system. Biogas energy for cooking is urgently and essentially needed in low-income households of rural semi-arid areas compared to the electricity for powering electric and electronic gadgets. Electricity is essentially needed but not urgently needed for a low-income household in rural areas. With this background, it was essential to develop and test the ANN model for biogas production prediction. This study aimed to build and assess a biogas generation prediction model for a newly developed i-SWEAD system and other similar systems.

## **5.2 Material and Methods**

### **5.2.1 Study area**

The description and geographical graphic of the study site are the same as that given in Sub-section 2.2.1 and Appendix 1 of this thesis, respectively. Therefore, these sub-sections will be referred to in this chapter.

### **5.2.2 Experimental setup and data collection**

Data needed for modelling purposes were collected from experimental testing of four integrated renewable energy systems, the i-SWEAD system inclusive. The experimental setup is shown in Figures 4.4 and 4.5 of Chapter Four of this thesis. The four systems consisted of an anaerobic digestion component and had different features. Also, the systems, together with their corresponding anaerobic digesters in brackets, were coded as follows: System1 (D1), System2 (D2), System3 (D3) and System4 (D4). System3 is the i-SWEAD system. These four systems are indicated in Figure 4.4 by their code names, and their detailed descriptions and the whole experimental set-up are presented in Table 4.3 and Sub-section 4.2.6 (i) of Chapter Four of this thesis.

The models developed were based on data, which included weather parameters collected using a weather station installed about 14 m away from the experimental space, as shown in Figure 4.4. The weather parameters were wind speed (m/s), solar irradiance ( $\text{W}/\text{m}^2$ ) and ambient air temperature ( $^{\circ}\text{C}$ ). Systems' anaerobic digesters temperature ( $^{\circ}\text{C}$ ) due to heat collected from solar and wind energy were measured using temperature probes. Hydraulic retention time (hours) at an increment of three hours' interval was recorded using a mobile phone with an inbuilt clock application.

The volume of biogas was derived from systems' pressure measurements using Equation 4.3 in Chapter Four, with a detailed description as provided in Sub-section 4.2.6 (iv). The adequate time to start the experiment was when the systems started to produce biogas with more than 45% methane. It happened eight days after feeding the systems with the substrate.

### 5.2.3 Data preparation for model development and testing

The data selected as input variables (predictors) for modelling purposes were the following: solar radiation (SolarRadiation), i.e. SR; wind speed (windSpeed), i.e. WS; ambient air temperature (AmbAirTemp), i.e. AAT; system digester temperature due to heat collected from solar and wind energy (Digester), i.e. DT and hydraulic retention time (DayD), i.e. T. Variable T was also in three hours' interval time, but its unit was converted into days' unit. The conversion of the unit was done using Equation 5.3.

$$T_d = \frac{T_h}{24 \text{ hours}} \times 1 \text{ day} \dots\dots\dots \text{Eq. (5.3)}$$

where  $T_d$  is the variable T in days while  $T_h$  is variable T in hours.

Output variable for modelling was biogas volume (BiogasVol3hr), i.e. BV3hr collected at three hours' time interval. All collected data from collection tools were transformed averagely using Microsoft Excel Spreadsheet to meet a three-hour interval setting. The three-hour interval was chosen as it was used during the collection of system pressure data used to derive the biogas volume responses data throughout the experimental testing of all systems.

With the transformation mentioned above, six datasets, including both input and output variables, were obtained. Four datasets among the six datasets were based on the i-SWEAD system and the other three systems. The datasets were coded as S1, S2, S3, i.e. i-SWEAD system's dataset and S4 for System1, System2, System3 and System4, respectively. The remaining two datasets among the six datasets were based on the two virtual renewable energy systems. The virtual systems were, namely, SystemG and SystemY. The first virtual system's dataset coded SG was obtained by combining fore mentioned four systems' datasets in series, while the second dataset coded SY was formed by averaging the same four systems datasets. This aimed at increasing the option datasets useful for building and testing. All datasets were imported from Microsoft Excel Spreadsheet into R-software for data analysis detailed in the subsequent sub-sections.

Data in dataset S1 was explored by scatter plot in the R-software. Dataset S1 was assumed to be representative of other datasets. The exploration of data aimed at finding out the properties of data to be used in modelling. The scatter plot provided the information of the linear relationship among the input variables data, the correlation between input variables data and output variable data (Field, 2000). The linear relationship among input variables data causes the bias of the model to be built. A large number of input and output variable

data, which are least correlated, is best modelled using the ANN model.

Furthermore, descriptive statistics of all datasets and the sampled test output variables data were found using R-software. This information is useful for future assessment of this study results by other researchers. Also, the information gives an insight into the variability of data, which can be assessed using statistics. The statistics determined in this study were minimum, first quartile (Q1), median, mean, third quartile (Q3) and maximum. If the Q1, median, mean and Q3 are dispersed, it indicates the high variability of data. Lee *et al.*, 2016 found out that data with high variability and nonlinear properties is well-modelled using ANN techniques. The models were built using the ANN modelling technique grounded on the feed-forward BPNN algorithm.

#### **5.2.4 The systems ANN modelling**

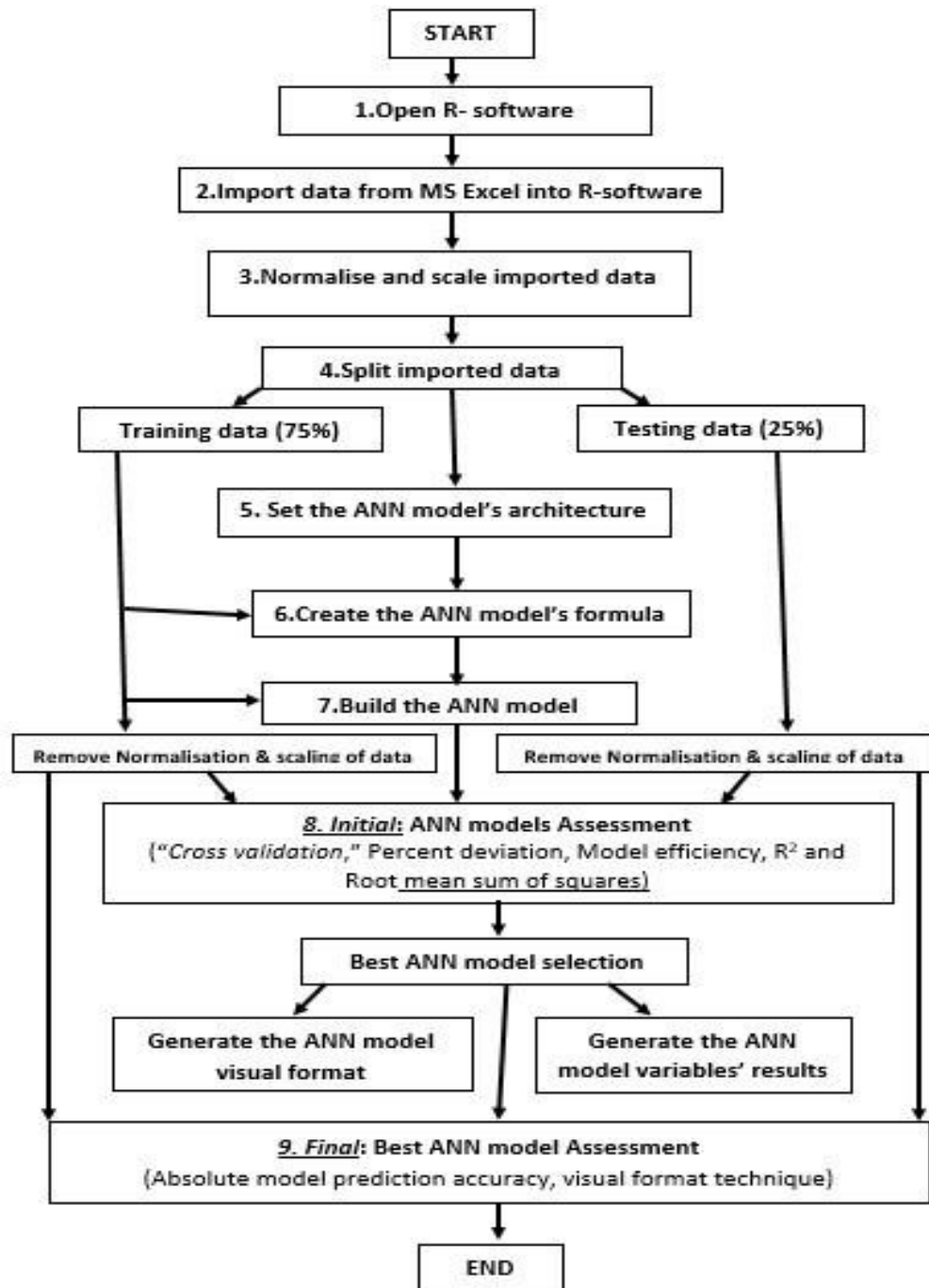
The ANN models for predicting biogas production from the i-SWEAD system and other similar systems were developed using the *neuralnet* package in R-software (R-Core-Team, 2018; Gunther and Fritsch, 2010). The *neuralnet* package is the computer program, which trains the ANN using backpropagation. Also, it trains resilient backpropagation with or without weight backtracking or the modified globally convergent version. It allows flexible settings through custom-choice of error and activation function (Fritsch and Gunther, 2016).

The models were developed/ built based on the datasets S1, S2, S3, S4, SG and SY. These datasets are described in Sub-section 5.2.3 of this chapter. Models built based on S1, S2, S3, S4, SG and SY were Model1, Model2, Model3, Model4, ModelG and ModelY, respectively. Multi-layered feed-forward architecture, illustrated in Figure 5.1, was adopted to design the artificial neural network models (Sewsynker-Sukai *et al.*, 2017).

The architecture can also be conveniently notated as  $A/H_i/\zeta B$ . The terms in this notation

described as  $A$  and  $B$  are integers representing a number of artificial neurons in input and output layers, respectively. The  $H_i$  is an integer representing a number of artificial neurons in the  $i$ -th hidden layer. The hidden layer is also separated by forwarding slash, i.e.  $/$ . Figure 5.2 illustrates and summarises the procedure, which was applied to develop and assess the models. The example showing the procedure is shown in Appendix 9 of this thesis. Appendix 9 shows the detailed steps followed during the implementation of building and initially assessing Model4 based on dataset S4 in R-software. Dataset S4 was chosen arbitrarily; although, it happens to be one, which produced the best model.

Figure 5.2 shows that the procedure started by opening the R-software. The dataset, for instance, S1, which was in a spreadsheet format file, was loaded into the software by importing it from MS. Excel Version 2013. The data in the S1 was normalised and scaled in a range of -2 and 2 using Equation 5.1. The normalisation was implemented in the R-software using 'apply' and 'scale' functions. Splitting the normalised and scaled data was done after loading the function 'set.seed(123)'. This function prepares the data for splitting and reproducing the results. The data of S1 was split into two groups: trainset (training data) and testset (testing data), with 75% and 25% of all data in S1, respectively. The explained fore mentioned and the following steps in relation to Figure 5.2 were repeated for all datasets S2-S4, SG and SY.



**Figure 5.2: Building and assessing of ANN model procedure flow chart**

The ANN model's architecture was set intuitively, where numbers of hidden layers and their neurons were chosen. The intuition of setting the ANN model's architecture was based on the recommendations of Panchal *et al.* (2011). The authors recommended that two hidden layers are required for modelling data with discontinuities, such as a saw tooth wave pattern. Also, they recommended that the number of hidden neurons should be less than twice the size of the input layer. The data collected in this study has a form similar to

the saw-tooth wave pattern. Therefore, it was justified to use two hidden layers. The number of variables to be included as neurons in the input layer was five. Therefore, the total number of neurons in the hidden layers was set as seven. It is justified as the number of neurons in hidden layers was less than twice the number of neurons in the input layers. The output layer has one neuron. The ANN model architecture that was used in this study is 5/4/3/1.

Figure 5.2 shows that the ANN model's formula was created after setting the architecture of the model. The formula was created using the trainset data as shown by step five in Appendix 9 of this thesis. Building the ANN model is the step followed after creating the model formula. The *neuralnet* package was loaded before building the model. The trainset data and *neuralnet* function were used when the model was being built. The hidden layers and their respective neurons were set as 4:3. At this stage, integer 4 represents neurons in the first hidden layer connected to the input layer, while integer 3 represents the neurons in the second hidden layer, which is between the first hidden layer and the output layer. Also, the activation function of the output layer was set as linear, and the default threshold limit of 0.01 set by R-software was kept. This limit value specifies the threshold for the partial derivatives of the error function as stopping criteria (Appendix 9). The enter key on the keyboard was clicked to mark the creation of the model. Steps one to seven shown in Figure 5.2 were applied to all six datasets. Therefore, all models were built and their performance assessed using R-software and Microsoft Excel Spreadsheet as explained in Sub-section 5.2.5 of this chapter.

### **5.2.5 Performance evaluation of models and selection of the best model**

Assessment of models performance was done in two stages, as shown in Figure 5.2. The stages in the figure are indicated as 'Initial ANN models assessment' and 'Final best ANN model assessment'. The initial ANN models assessment was done using parameters, which

include cross-validation (mean-cv.error), per cent deviation (Dv\_D), i.e. PD, Nash-Sutcliffe Efficiency (NSE) or Model Efficiency (MEF), coefficient of determination ( $R^2$ ), and Residual Mean Sum of Squares (RMSS). The final best ANN model assessment was done using the parameter Absolute Model Prediction Accuracy (AMPA) and the technique of visual format.

During the initial ANN model assessment, the mean-cv.error, PD and MEF of each model were determined based on the datasets (S1, S2, S3, S4, SG and SY) of each six systems. The mean-cv.error was determined using both normalised and scaled training data and testing data of each system dataset. However, the PD and MEF were determined using testing data only. The testing data, at this point, had no normalising and scaling properties (Figure 5.2). This procedure is shown in Appendix 9. The  $R^2$  and RMSS were found based on the testing data only. Each model built was used to predict the biogas volume collected from all six systems. The predicted and measured values of all testing data from six datasets were used to compute  $R^2$  and RMSS indices using MS Excel Version 2013. The predicted sum and measured sum of biogas volume collected were used. The predicted sum of biogas volume collected was obtained using R-software. Both  $R^2$  and RMSS indices were used to select the best model to predict biogas volumes collected from all six systems, including the i-SWEAD system. The best ANN model physical form (visual format) and its results of input variable that influence the output variable can be produced by R-software (Appendix 9). However, both the visual format and variable influence's information was beyond the scope of this study.

The final best ANN model assessment involved using the AMPA, where the accuracy of the selected model to predict the biogas volume collected from all systems was assessed. The best model was compared with another model having an RMSS value close to that of

the best model. Besides, the comparison was based on the AMPA values and their corresponding standard deviations values. The standard deviation values were derived based on the mean of AMPA values of all systems while excluding System1. Also, the visual format technique was used to assess the trends of predicted and measured biogas volume values based on the sampled data from the dataset. The sampled data was the testing data. The plots of predicted and measured biogas volume values against their corresponding observation number were produced using MS Excel Version 2013.

Criteria for assessing models prediction capacity were as follows. The first criterion was the mean cross-validation error (mean-cv.error), which indicates an error in squared units of the constituent of interest, where the value of 0 indicates a perfect fit of a model. Therefore, for this case, the accepted model was required to have mean-cv.error below 0.00002. This value was intuitively selected to include models, which are not perfectly fitting the measured data.

The second one was PD, which measures the average tendency of the simulated or predicted data to be larger or smaller than measured data. An optimal value for PD is 0.0. Positive values indicate model underestimation bias, and negative values indicate model overestimation bias. The lower the value of PD, the better the model and vice versa. At  $PD \leq 10\%$ ,  $10\% < PD = 20\%$  and  $20\% < PD = 30\%$ , the under or over prediction was termed as low (slight), moderate and severe, respectively (Ludovic, 2012). An acceptable model had to fall in the category of  $PD \leq 10\%$ .

The third criterion was NSE, which indicates how well the plot of measured data versus simulated or predicted data fits the 1:1 line. The 1:1 line is the one that occurs when the abscissa and ordinate are on the same scale. The NSE ranges between  $-\infty$  and 1.0

(1 inclusive). Its optimal value is 1, while values between 0.0 and 1.0 are generally viewed as acceptable levels of performance. Values less than zero indicate that the average of measured data is a better predictor than the simulated value, which indicate unacceptable performance. In this study, only models with an NSE value above zero were accepted.

The fourth criterion was  $R^2$ . The data used to obtain the  $R^2$  was the sum of measured biogas volume collected data and the sum of predicted biogas volume collected data of each of all six testing data. The predicated sum of biogas volume collected data was obtained using R-software. Each model was used to produce the sum of predicted biogas volume collected from all six systems' testing data. The 1:1 plots of all models based on all six models' values of predicted biogas volume against the measured biogas volume collected were produced. Also, the  $R^2$  values for each model were generated using the data analysis function of Microsoft Excel Version 2013. The models with  $R^2$  between 0.5 and 0.65 were selected as acceptable models. The model with the  $R^2$  between the fore mentioned range is assumed to be an excellent model, as it does not perfectly fit the measured data, a phenomenon leading to the biased model (Alexander *et al.*, 2015).

The fifth criterion used to assess models was RMSS. The model's RMSS was based on mean absolute error. This parameter was used to select the best model. The best model was supposed to have the least RMSS value of all models.

The sixth criterion was AMPA. It was adopted to measure the capacity of the best-selected model to accurately predict the measured biogas volume, which was collected from the i-SWEAD system and other similar systems. The data that was used is the system's testing data. In this research, the AMPA values of equal or greater than 75% were chosen to imply that the model was acceptable for prediction purposes of the respective energy system.

The seventh and last criterion was a visual format assessment of the best-selected model performance. This criterion was presented by plotting measured biogas volume data, and the model predicted biogas volume results against the number of sampled observations. Also, the data that was used is the testing data. The closeness of the curves of both plotted measured data and model-predicted data results would indicate the high accuracy of the model to simulate or predict the measured data. All seven criteria were used in this study.

### **5.3 Results and Discussion**

#### **5.3.1 Data exploration**

The scatter plot of dataset S1, which represents S2, S3, S4 and SY, was produced using R-software; the plot is shown in Figure 5.3. The figure has a diagonal boxes line, which starts from the top left corner to the bottom right corner. The boxes are labelled with input variables and output variable codes. The last box at the bottom right corner represents the output variable, which is collected biogas volume. The boxes with black circles, which are below and above the diagonal boxes line, depict the relationship among the input variables and the relationship between the input variable and output variables. Note that the boxes above the diagonal boxes line are a replica of the boxes below that diagonal boxes line. The number of the boxes is 15 for the top side, the same as the bottom side. In this study, we refer to the boxes below the diagonal boxes line.

In the same figures, the numbers on the periphery of the table represent the values of variables of the dataset. However, the scale of the column and rows are different. The values indicated in the columns from left to right are hydraulic retention time in days, solar irradiance ( $\text{W}/\text{m}^2$ ), wind speed (m/s), ambient air temperature ( $^{\circ}\text{C}$ ), digester temperature ( $^{\circ}\text{C}$ ), and collected biogas volume ( $\text{m}^3$ ) for dataset S1. The rows values from top to bottom represent the values and units of dataset S1 in the same sequence as described above.

The relationship among the input variables is determined by considering the box with black circles. This box should be the column and row intersection starting from different boxes with variable's code names. An example of the intersection box in Figure 5.3 shows the relationship between wind speed/windspeed1 and hydraulic retention time/DayD1. The box is found at the intersection of the column with DayD1 and the row with windspeed1. The relationship between the output variable and input variables is located in the bottom boxes in the row of BogasVol3hrD1.

Figure 5.3 shows no linear relationship among the input variables, as the black circles in the boxes were not concentrating linearly in the diagonals of those boxes. This indicates the variables data met the condition of eligibility to be used in generating model as it was discussed by Field (2000). Also, boxes, which are representing the relationship between input variables and output variables, show that there was a significant positive correlation for some input variables against the output variable.

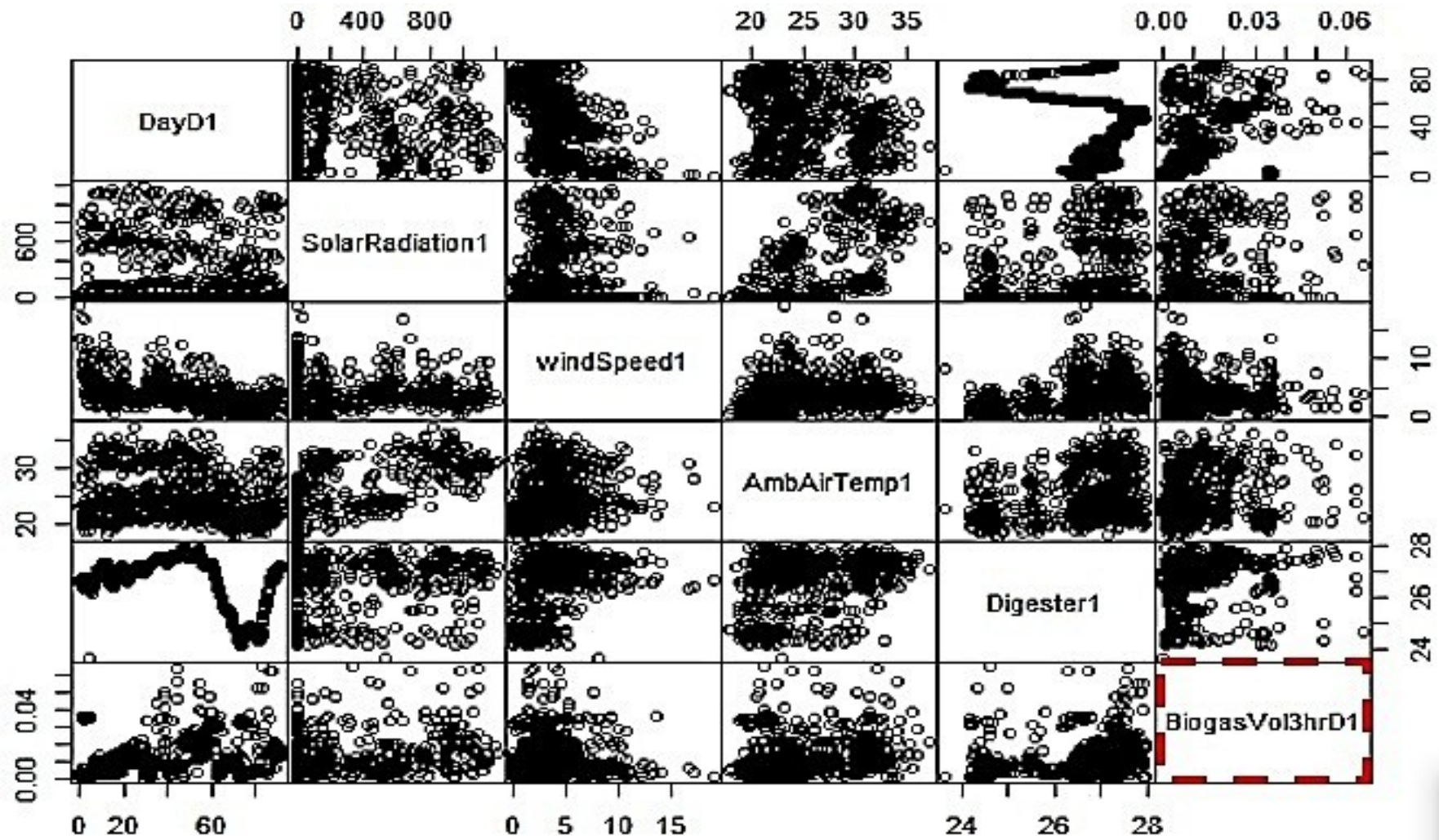


Figure 5.3: Input and output variables' relationship based on digester one (S1) data

The phenomenon is shown in the bottom boxes of the row, which include BiogasVol3hrD1 in Figure 5.3. The intersection boxes of DayD1, windspeed1 and AmbAirTemp1 against BiogasVol3hrD1 indicated a positive correlation. It was noted through the black circles concentrating from the origin towards the upper right corner of the box. The black circles in the intersection boxes of SolarRadiation1 and Digester1 against BiogasVol3hrD1 were randomly dispersed without showing any significant trend of relationship, e.g. the correlation between the variables considered. The above-explained results indicated that this study data qualified to be used for modelling purposes.

Statistics, which show the variability of the data used in this study, were determined using R-software. The statistics included the first quartile (Q1), median, mean, and third quartile (Q3). The results of these statistics are shown in Tables 5.1 and 5.2. Table 5.1 shows the results of statistics of all variables data used in the modelling process. Also, Table 5.2 gives the statistics summary of output variable data of all test datasets used for generating the models. The statistics summaries shown in both tables indicate that the data used in modelling has high variability. It was indicated by the dispersion of statistics from each other.

**Table 5.1: Summary statistics of all variables data used in the modelling process**

Serial Number	Variables	Descriptive Statistics of Variables of All data Used in Modelling Process							Remarks
		Minimum	1st Quantile	Median	Mean	3rd Quantile	Maximum	Number of observations (N)	
1	DayD1	0.1250	22.8750	45.6250	45.6250	68.3750	91.1250	729	These Variables data were used for S1-4.
	SolarRadiation1	0.0000	0.0000	2.2100	264.4200	528.6600	1205.9200	729	
	windSpeed1	0.0000	2.2200	3.5200	3.9880	5.1680	19.1480	729	
	AmbAirTemp1	17.8500	21.6100	24.1000	25.2900	29.2500	37.2800	729	
2	Digester1	23.6600	26.2700	27.0100	26.6000	27.3400	27.9700	729	Variables data for S1 only.
	BiogasVol3hrD1	0.0000	0.0054	0.0089	0.0126	0.0170	0.0650	729	
3	Digester2	25.3000	28.5400	28.6300	28.8800	29.1000	33.3000	729	Variables data for S2 only.
	BiogasVol3hrD2	0.0000	0.0067	0.0121	0.0162	0.0267	0.0655	729	
4	Digester3	26.8800	29.4400	30.1800	30.2700	31.2200	34.3900	729	Variables data for S3 only
	BiogasVol3hrD3	0.0001	0.0091	0.0145	0.0163	0.0243	0.0668	729	
5	Digester4	27.6500	28.9100	29.6000	29.5600	30.2100	32.6000	729	Variables data for S4 only.
	BiogasVol3hrD4	0.0000	0.0103	0.0165	0.0177	0.0237	0.0661	729	
6	DayDG	0.1250	22.8750	45.6250	45.6250	68.3750	91.1250	2916	Data of these Variables for SG are results of the series combination of variables data of S1-4.
	SolarRadiationG	0.0000	0.0000	2.2100	264.4200	528.6600	1205.9200	2916	
	windSpeedG	0.0000	2.2200	3.5200	3.9880	5.1680	19.1480	2916	
	AmbAirTempG	17.8500	21.6100	24.1000	25.2900	29.2500	37.2800	2916	
	DigesterG	23.6600	27.7400	28.8900	28.8300	29.9600	34.3900	2916	
	BiogasVol3hrDG	0.0000	0.0069	0.0129	0.0157	0.0225	0.0668	2916	
7	DayDy	0.1250	22.8750	45.6250	45.6250	68.3750	91.1250	729	Data of these Variables for SY are results of average values of the combination of variables data of S1-4.
	SolarRadiationy	0.0000	0.0000	2.2100	264.4200	528.6600	1205.9200	729	
	windSpeedy	0.0000	2.2200	3.5200	3.9880	5.1680	19.1480	729	
	AmbAirTempy	17.8500	21.6100	24.1000	25.2900	29.2500	37.2800	729	
	DigesterY	26.8900	28.3200	28.9500	28.8300	29.4300	30.6300	729	
	BiogasVol3hrDy	0.0036	0.0100	0.0145	0.0157	0.0203	0.0383	729	

**Table 5.2: Summary statistics of output variables data used for models testing**

Serial Number	Source of Data	Descriptive Statistics of Output Variable (BV3hr) of Sampled Test Data						(N)
		Min.	1st Qu.	Median	Mean	3rd Qu.	Max.	
1	System1 (S1)	0.000217	0.0049	0.0089	0.0117	0.0134	0.0650	182
2	System2 (S2)	0.000002	0.0067	0.0125	0.0163	0.0263	0.0638	182
3	System3 (S3)	0.000517	0.0086	0.0138	0.0164	0.0248	0.0646	182
4	System4 (S4)	0.000069	0.0105	0.0168	0.0181	0.0230	0.0619	182
5	SystemG (SG)	0.000015	0.0073	0.0128	0.0161	0.0236	0.0668	729
6	SystemY (SY)	0.003707	0.0103	0.0146	0.0158	0.0204	0.0383	182

An example of the dispersion of statistics from each other is indicated in serial number one of Table 5.1. The range of data values was extensive in this serial number by considering minimum with maximum, Q1 with Q3, and media with mean. It is similarly shown in serial number three in Table 5.2. Statistics were not close to each other. Therefore, it was justifiable to use ANN modelling approach, which handles complex and non-linear data from complex processes like anaerobic digestion to generate models (Sewsynker-Sukai *et al.*, 2017).

### 5.3.2 ANN models performance evaluation

As explained in subsection 5.2.4, all six ANN models were built from the datasets of S1 to S4, SG and SY. Also, they were assessed statistically and using other means explained in Sub-section 5.2.5 of this chapter. The assessment involved two stages, which were the initial and final stage assessments. Table 5.3 shows the initial stage assessment results. The parameters mean cross-validation error (mean-cv.error), per cent deviation (PD), and Nash-Sutcliffe Efficiency (NSE) were considered in the first part of the assessment. The model performance assessment criteria described in Subsection 5.2.5 of this chapter were considered. All ANN models were accepted except Model3, which failed on the criterion test of parameter NSE. Model3 scored a -0.09 value of the NSE, which is not acceptable as per the criterion set.

**Table 5.3: Results of model indices of the models' assessment**

<b>Model</b>	<b>Mean_cv.error</b>	<b>DP (%)</b>	<b>NSE</b>	<b>R<sup>2</sup></b>	<b>RMSS</b>
Model1	0.00016	-0.74	0.01	0.77	0.44
Model2	0.00013	3.76	0.09	0.38	0.43
Model3	0.00011	-1.20	-0.09	0.54	0.28
Model4	0.00012	4.47	0.03	0.60	0.24
ModelG	0.00011	3.92	0.13	0.36	0.40
ModelY	0.00003	2.73	0.18	0.35	0.96

However, Model3 was included in the list of models for the second part of the initial model assessment stage for comparison purposes. The second part of the initial model assessment stage results is discussed in Sub-section 5.3.3 of this chapter.

### **5.3.3 Selection and performance assessment of the best ANN model**

The results of the second part of the initial model assessment stage are shown in Table 5.3. They include the results of parameters R<sup>2</sup> and RMSS. The R<sup>2</sup> results were obtained from the linear relationship of predicted biogas volume collected and the measured biogas volume collected. Each model was used to predict biogas volume collected of each testing data of all six systems. The data from this process produced the unit plot of ANN models' predicted biogas volume collected against measured biogas volume collected. The data used was from the test sets of six systems' datasets. The unit plot is represented in Figure 5.4. The linear relationships of each model predicated data against measured data were drawn from this unit plot using MS Excel Version 2013 data analysis function.

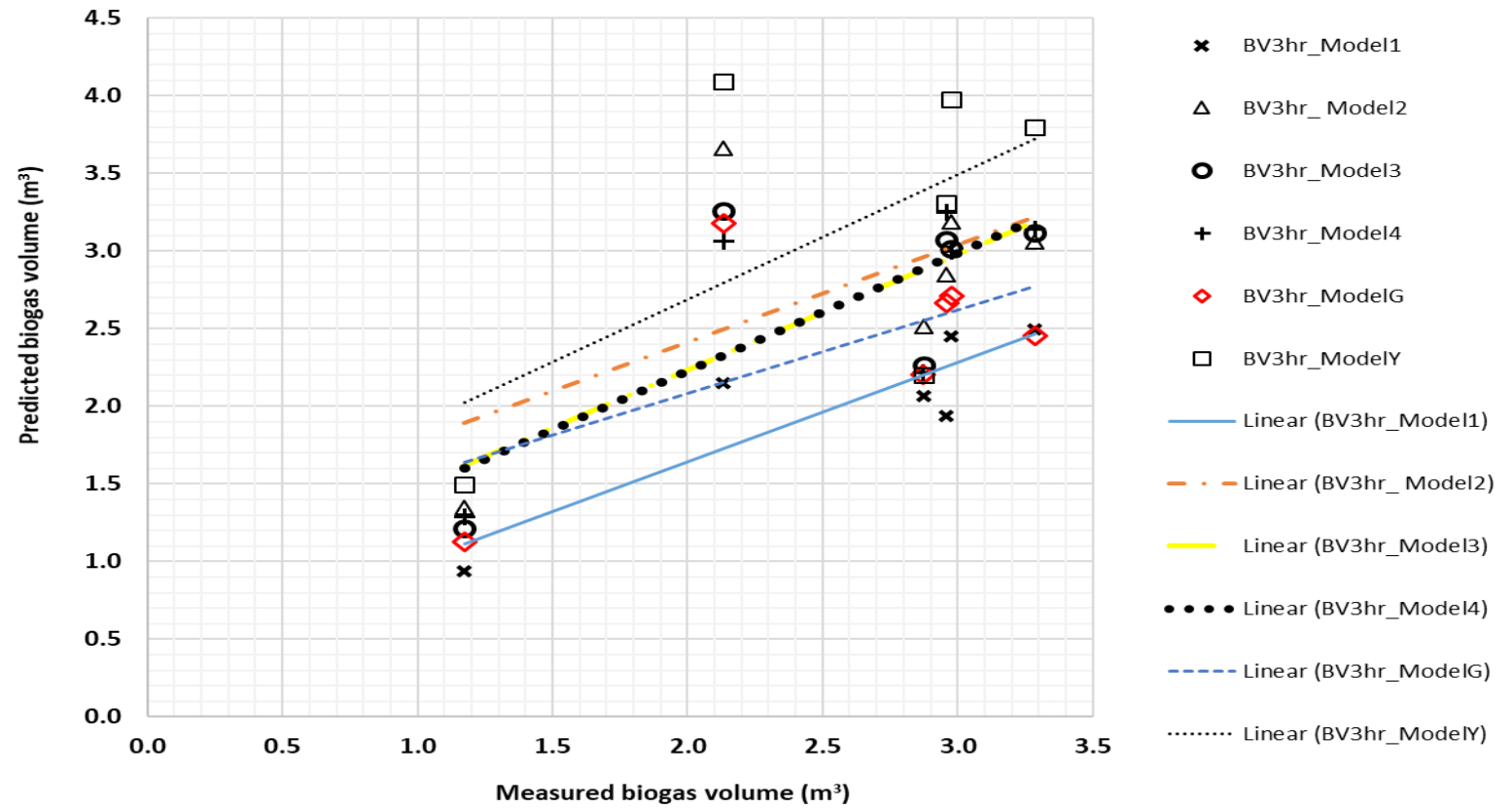


Figure 5.4: ANN models' predicted and measured biogas volumes' unit plots of six systems

Figure 5.4 indicates that collected biogas volume results predicted by Model3 and Model4 were not perfectly fitting the measured biogas volume. It was seen through linear trend lines of Model3 and Model4 and  $R^2$  values in Table 5.3. The  $R^2$  values were 0.54 and 0.60 for Model3 and Model4, respectively. This phenomenon indicates appreciable model prediction behaviour (Alexander *et al.*, 2015; Kaingo *et al.*, 2018), explaining criterion four found in Sub-section 5.2.5 of this chapter. However, this did not give a conclusive result of the best model to be selected. Therefore, the RMSS parameter was used to select the best ANN model.

The best ANN model was selected by finding out the model with the least RMSS value of all. By referring to Table 5.3, Model4 was selected as the best model for predicting biogas production as it had an RMSS of 0.24, which was the least of all ANN models involved.

The final stage assessment of the best model was done using parameter AMPA and visual format technique. The AMPA values and standard deviations of the selected best ANN model, i.e. Model4 prediction accuracy of each of the testing data of six systems, were found. This process was repeated to Model3, which has a close value of RMSS to that of Model4 for comparison purposes. Two values of standard deviations were computed based on AMPA values.

The first and second standard deviation values were based on AMPA values involving testing data of all systems and testing data of all systems excluding System1, respectively. System1 has no appreciable heat insulation compared to System2, System3, and System4. The remaining two systems were virtual. The heat insulation features of all systems are described in Table 4.3 in Chapter Four, while the description of virtual systems is given in Sub-Section 5.2.3 of this chapter.

Model4 prediction capability was high for System3, i.e. the i-SWEAD system and System4. It is indicated in Table 5.4, where AMPA values of System3 and System4 were 99% and 96%, respectively. These AMPA values were high compared to the values of the other systems. Comparison of models prediction capacity revealed that Model3 has low AMPA values (95%) for System4 while Model4 has a high AMPA value (96%) for the same system. However, both models have the same AMPA value for System3. Also, both models failed to obtain an acceptable value of equal to or greater than 75% of AMPA value for System1. This AMPA value was acceptable based on criterion six, which was explained in Sub-section 5.2.5 of this chapter. Table 5.4 shows that Model4 had a low standard deviation of 14% compared to 18% of Model3 when considering the AMPA values of all six systems. However, both models have the same standard deviation of 7% when considering the AMPA values of all systems while excluding System1.

**Table 5.4: Comparison of Model4 and Model3**

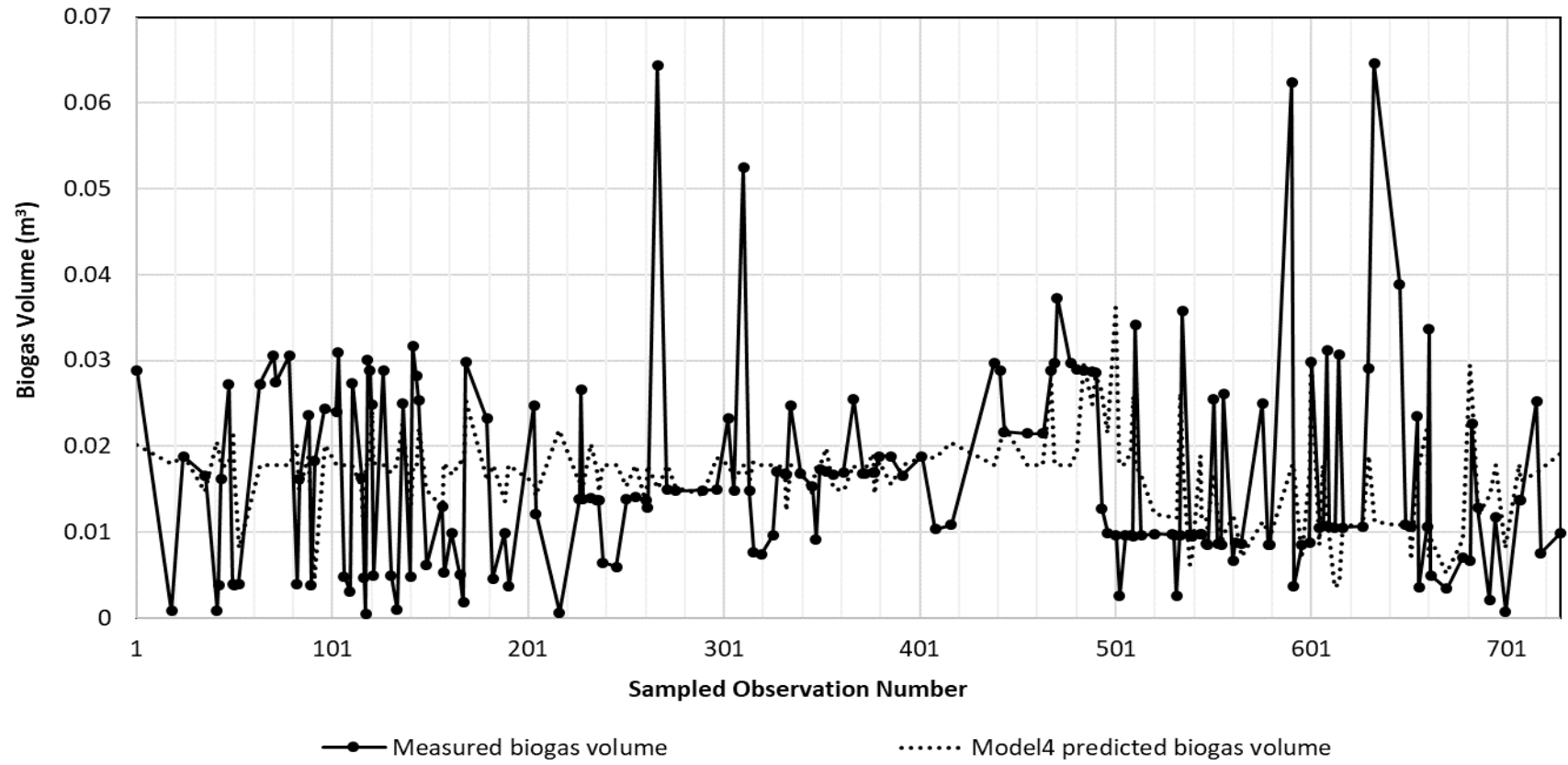
Model	AMPA (%)						Standard deviation (%)	
	System1	System2	System3	System4	SystemG	SystemY	All system	System1 excluded
<b>Model3</b>	47	96	99	95	97	79	18	7
<b>Model4</b>	57	90	99	96	90	77	14	7

Generally, based on AMPA and standard deviation values, Model4 is the best model prediction of collected biogas volume for systems with greenhouse effects and heat insulation materials to their batch fed anaerobic digesters. The model was not suitable for predicting the collected biogas volume of System1 at its AMPA value of 57% (Table 5.4). The graphical visual format technique as part of the final stage model assessment was done. It was done only for Model4, which is the best model compared to other models. It

has been proven using RMSS, AMPA, and AMPA based standard deviation values. The visual format assessment results of prediction capacity Model4 for the i-SWEAD system and other systems are described in the subsequent subsections.

**i. Visual prediction performance assessment of Model4 on i-SWEAD system data**

The visualization of the relationship of the predicted biogas volume values of the best ANN model, i.e. Model4 and System3, i.e. the i-SWEAD system's measured biogas volume values, were made using the graphical presentation. It gave more insight into the prediction behaviour of that best ANN model selected. In this regard, the assessment was based on the results presented in Figure 5.5. From this figure, both measured and predicted biogas volume values based on the i-SWEAD system's testing data were appreciably close for an almost whole range of sampled testing observation numbers. Furthermore, the model did not perfectly fit the measured biogas volume value outliers. The outliers are indicated in Figure 5.5 by the four spikes of measured biogas volume.



The actual values of these outliers and their corresponding predicted biogas volumes are located at observation number 267 (0.064<sub>measured</sub>, 0.015<sub>predicted</sub>); 311 (0.052, 0.017); 591 (0.062, 0.018), and 633 (0.065, 0.011). The outliers are due to the irregular random sampling of observation numbers. Therefore, the outliers are still important data of this study. The trend of predicted biogas volume values followed that of measured biogas volume values across the sampled testing observations for the i-SWEAD system.

The closeness of predicted and measured biogas values designated the accuracy of the best model, as explained by Huang and Chen (2001). Also, the lack of overfitting of predicted to the measured outlier's values and other values indicate the model's excellent performance, as explained by Subramanian and Simon (2013). Both characteristics indicated the best performance of Model4 in predicting the measured biogas volume values of the i-SWEAD system.

**ii. Visual prediction performance assessment of the best ANN model on other physical systems data**

The graphical technique was used to assess the prediction performance of Model4 for data based on System1 testing data. The assessment was referred to in Figure 5.6. The figure shows that the predicted and measured biogas volume values for System1 were not close, i.e. significant noise for almost half of all sampled observation numbers. It is evident in the range of 1-297 sampled observation number of Figure 5.6. Also, Model4 values were overestimating measured biogas values of System1 in that range of sampled observation numbers.

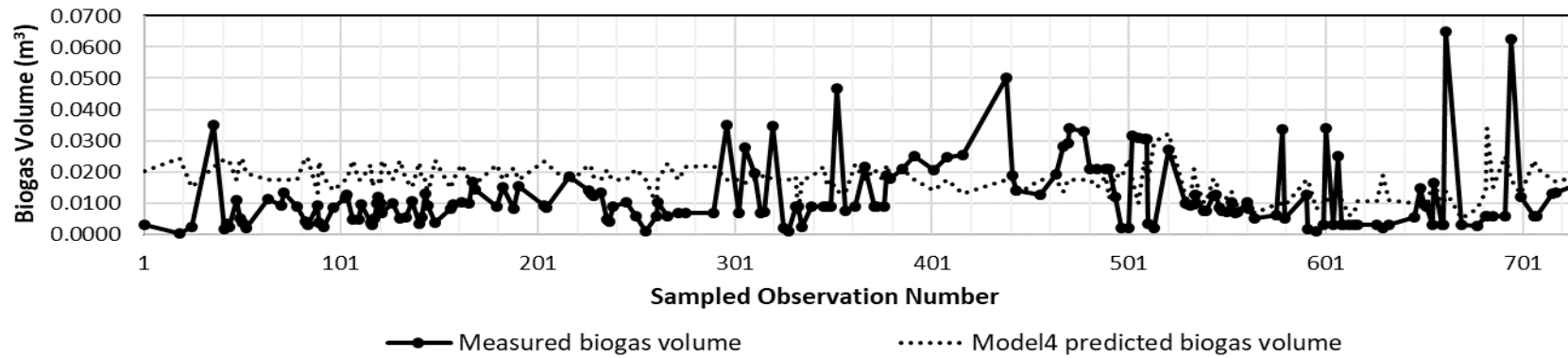


Figure 5.6: Relationship of predicted and measured biogas volumes for System1

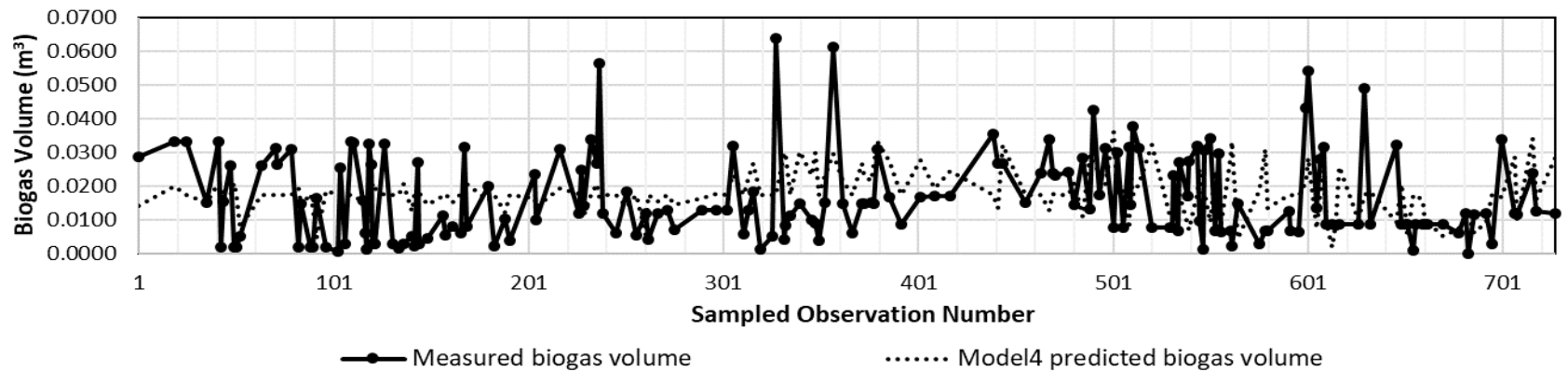


Figure 5.7: Relationship of predicted and measured biogas volumes for System2

Generally, regarding Figure 5.6, for a window of sampled observation numbers 392 to 491, Model4 underestimated measured biogas volume values of System1, while for the remaining observation numbers, the predicted and actual values were close enough. On the other hand, no significant perfectly fitting of predicted values to the measured biogas volume values was noted. However, in the exact figure, the predicted and measured biogas volumes referred from observation numbers 1 to 36 do not correlate. With the characteristics revealed from Figure 5.6, Model4 was neither suitable nor acceptable for predicting the measured biogas volume of System1, which has no heat insulation features.

Another Model4 prediction performance assessment using the visual technique was done to predict measured biogas volume values of System2. The assessment was based on data presented in Figure 5.7. This figure indicated that predicted and measured biogas volume values for System2 were not very close.

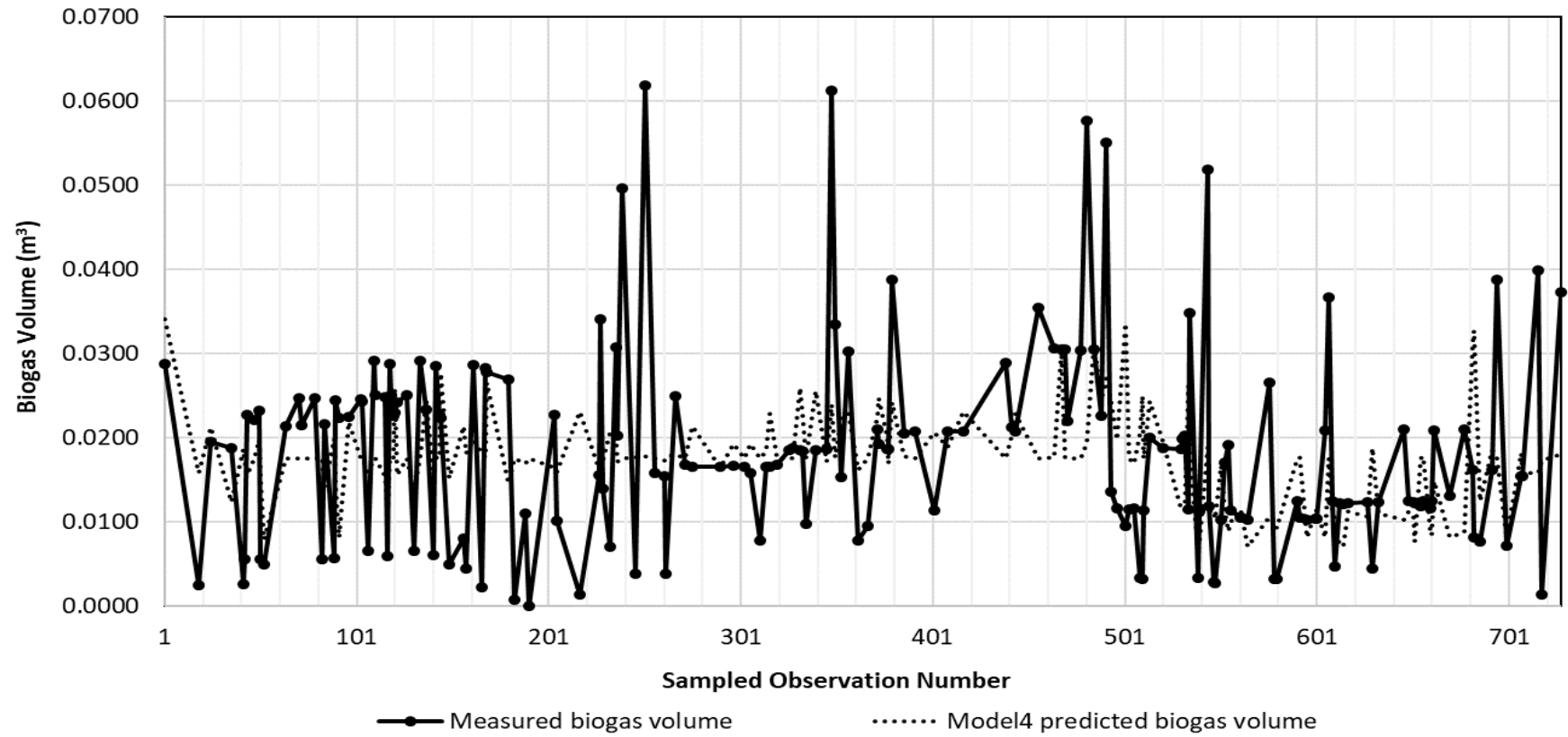
The closeness of the predicted and measured biogas values was not noted in the window of sampled observation number 1-490. However, from the sampled observation number 490 to 728, the closeness of the value in question was noted. Model4 results for System2 were not overfitting the measured biogas volume values. Nevertheless, from the sampled observations number 1 to 36, Model4 biogas volume values underestimated measured biogas volumes of System2.

Assessment based on the graphical technique of the Model4 in predicting biogas volume values of System4 was done. System4 had similar features as that of the i-SWEAD system, except that it did not have the heat supply from the wind sub-system and solar PV unit. The graphical technique assessment is presented in Figure 5.8. The figure shows that both measured and predicted biogas volume values of System4 and Model4, respectively,

are appreciably close. However, the closeness is not the same as that shown for data of the i-SWEAD system across the range of sampled observation numbers.

The model predicted that biogas volume values were not perfectly fitting the measured biogas volume of System4. This phenomenon indicates the excellent performance of the model, as explained in the previous subsection. However, based on Figure 5.8 for the first thirty-six sampled observation numbers, Model4 predicted biogas volumes overestimated measured biogas volume values of System4.

The spikes or outliers of measured biogas volume values noted in Figures 5.6, 5.7 and 5.8 have the same meaning explained in Sub-section 5.3.3 (i) of this chapter. They are also carrying the same meaning for the figures in Sub-section 5.3.3 (ii) of this chapter.



**Figure 5.8: Relationship of predicted and measured biogas volumes for System4**

### **iii. Visual prediction performance assessment of the best ANN model on virtual systems data**

The Model4 prediction performance was also assessed based on the datasets of both virtual systems that is SystemG and SystemY. The assessment of Model4 for SystemG and SystemY was based on the data presented in Figure 5.9 and Figure 5.10, respectively. These figures show that appreciable noise was noted for both systems. For instance, in Figure 5.9, the noise for predicted and measured biogas volume values was high in the first 160 sampled observation numbers. It was in this range where the Model4 overestimated the measured biogas volume values.

The results of Model4 were seen to be averaging the measured biogas volume of SystemG for the window of sampled observation numbers 160-430. Figure 5.9 also showed that predicted biogas volume was seen to be averaging the measured biogas volume for a sampled observation number range of 430-470, while for the remaining sampled observation numbers, Model4 results were close to the measured biogas volume values.

Also, Model4 results were not overfitting the measured biogas volume values. With this discussion, the inference from these results obtained by Model4 should be used cautiously. Therefore, the model prediction performance for SystemG was acceptable because results produced by this model based on data similar to that of SystemG should be used as indicative of the amount of biogas to be collected.

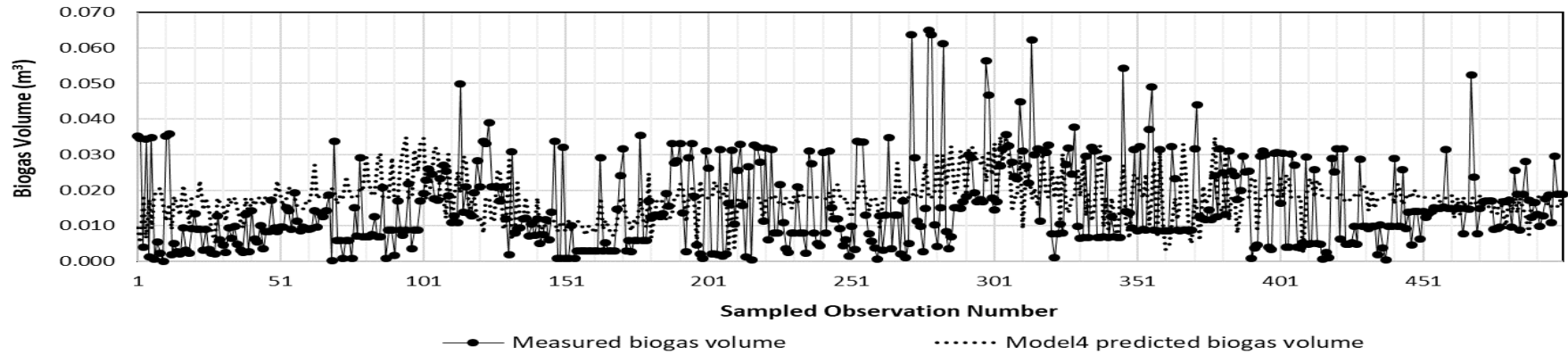


Figure 5.9: Relationship of predicted and measured biogas volumes for SystemG

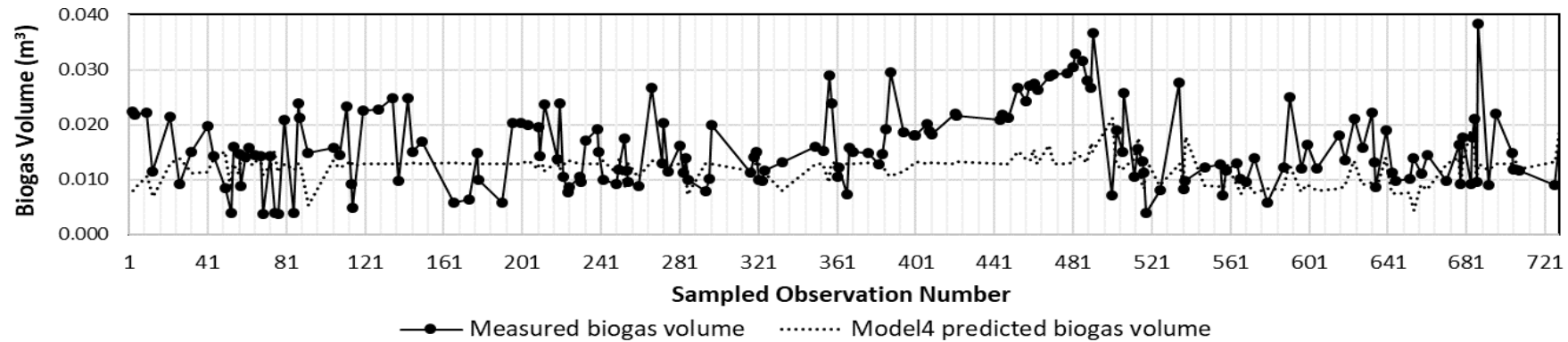


Figure 5.10: Relationship of predicted and measured biogas volumes for SystemY

On the other hand, a significant noise of predicted and measured biogas volume values was noted for SystemY testing data, as shown in Figure 5.10. For example, seven windows based on sampled observation numbers of noise were spotted from this figure.

The windows were of sampled observation number 3-27, 33-44, 85-115, 333-357, 366-501, 580-635, and 643-678. The predicted and measured biogas volume values were close for the other windows in the same figure. However, no overfitting was noted for this case. With this information, Model4 was not acceptable for the reliable prediction of biogas volume values of SystemY.

#### **5.4 Conclusions and Recommendations**

The best ANN model with appreciable predictive power was developed to predict the biogas generated from the i-SWEAD system using a robust ANN modelling technique. The ANN modelling technique enables building six ANN models based on four physical and two virtual systems datasets. All models passed the first part of the initial model assessment stage except Model3, which failed to meet the model efficiency (NSE) test criterion. However, for comparison purposes, Model3 was added to the second part of the initial model assessment stage of best model selection, where it emerged the second behind Model4, which secured the RMSS value of 0.24 and  $R^2$  value of 0.60. This situation raises the suspicion of NSE as a measure for assessments of ANN models.

Model4 adequately predicts the collected biogas volume from the i-SWEAD system as it secured AMPA = 99% (Table 5.4). Also, the model can predict the measured biogas volume values of other similar systems accurately with both greenhouse effect and suitable insulation materials features as those of the i-SWEAD system (Table 5.4). However, Model4 is not performing well on predicting measured biogas volume generated by System1 and virtual systems based on graphic technique results.

System4 generated the dataset that was used to build Model4 (Figure 4.12). Model4 failed to predict the measured biogas volume of System1 accurately because the system digester was subjected to a different environment (low operating temperature) from that System4 (high operating temperature). Also, Model4 failed to accurately predict the measured biogas volume of virtual systems because the testing data of virtual systems was mixed with testing data of System1. Furthermore, Model4 is not able to predict accurately measured biogas volume for all the systems for the first five days of hydraulic retention time (equivalent to the 36 sampled observation number shown in the figures of visual technique model assessment). The model adequately predicted measured biogas volume with high accuracy for more than five days.

With these concluding remarks, firstly, the robust ANN modelling technique and the approach applied to build the Model4 are recommended to modellers of biogas energy generation related systems. Secondly, Model4 is recommended to the decision-makers, policymakers, biogas production investors, and other clean energy practitioners in integrated renewable energy systems. It is recommended because Model4 is the best ANN model for predicting biogas generated by the i-SWEAD system and other similar systems with both greenhouse effect and suitable insulation material features as those of the i-SWEAD system. Also, it is recommended to apply Model4 while taking into account the specifications of the system, e.g. 0.24 m<sup>3</sup> of digester volume and properties of feedstock used to generate the biogas [approximately equal to total dry matter (DM) of 224 g/kg of cow dung, volatile solid (VS) of 691 g/kg of DM, pH of 6.87 and C/N ratio of 18.75], which produced the dataset for building this novel model. Besides, the application of Model4 for predicting measured biogas volume from the system with specifications other than that of fore mention invites further research interest.

Thirdly, Model4 is not recommended to predict measured biogas volume collected within equal or below five-day hydraulic retention time. Fourthly, NSE is not recommended to be used alone when assessing the biogas generation prediction ANN models. Finally, since the ANN model built was for biogas production prediction only in this study, developing another model to predict simultaneously biogas and electricity from the i-SWEAD system and other similar systems is an exciting research topic.

### **5.5 Acknowledgement**

Refer to Section 2.5 in Chapter Two of this thesis.

## 5.6 References

- Agatonovic-Kustrin, S. and Beresford, R. (2000). Basic concepts of artificial neural network (ANN) modelling and its application in pharmaceutical research. *Journal of Pharmaceutical and Biomedical Analysis* 22(5): 717–727. DOI: 10.1016/s0731-7085(99)00272-1
- Alexander, D. L. J., Tropsha, A. and Winkler, D. A. (2015). Beware of R 2: Simple, unambiguous assessment of the prediction accuracy of QSAR and QSPR models. *Journal of Chemical Information and Modelling* 55(7): 1316 – 1322.
- Cadenas, E. and Rivera, W. (2009). Short term wind speed forecasting in La Venta, Oaxaca, Mexico, using artificial neural networks. *Renewable Energy* 34: 274–278.
- Diamantopoulou, M. J, Georgiou, P. E. and Papamichail, D. M. (2011). Performance evaluation of artificial neural networks in estimating reference evapotranspiration with minimal meteorological data. *Global Network of Environmental Science and Technology (NEST) Journal* 13(1): 18 – 27.
- Donoso-Bravo, A., Mailier, J., Martin, C., Rodríguez, J., Aceves-Lara, C. A. and Wouwer, A. V. (2011). Model selection, identification and validation in anaerobic digestion: A review. *Water Research* 45(17): 5347 – 5364.
- Field, A. P. (2000). *Discovering statistics using SPSS for Windows: Advanced techniques for the beginner*. Sage Publication, London. 493pp.
- Friedman, J. H. (1991). Multivariate adaptive regression splines. *The Annals of Statistics* 1991: 1-67.
- Fritsch, S. and Guenther, F. (2016). Package ‘neuralnet’. *The Comprehensive R Archive Network*.
- Gunther, F. and Fritsch, S. (2010). Neuralnet: Training of neural networks. *The R Journal* 2(1): 30 – 38.

- Hsieh, M. H., Sun, L. M., Lin, C. L., Hsieh, M. J., Hsu, C. Y. and Kao, C. H. (2018). Development of a prediction model for pancreatic cancer in patients with type 2 diabetes using logistic regression and artificial neural network models. *Cancer Management and Research* 10: 6317–6324.
- Huang, L. and Chen, J. C. (2001). A multiple regression model to predict in-process surface roughness in turning operation via accelerometer. *Journal of Industrial Technology* 17(2): 1 – 8.
- Igoni, A. H., Ayotamuno, M. J., Eze, C. L., Ogaji, S. O. T. and Probert, S. D. (2008). Designs of anaerobic digesters for producing biogas from municipal solid waste. *Applied Energy* 85(6): 430 – 438.
- Jha, S. K., Bilalovic, J., Jha, A., Patel, N. and Zhang, H. (2017). Renewable energy: Present research and future scope of artificial intelligence. *Renewable and Sustainable Energy Reviews* 77: 297 – 317.
- Kaingo, J., Tumbo, S. D., Kihupi, N. I. and Mbilinyi, B. P. (2018). Prediction of soil moisture-holding capacity with support vector machines in dry sub-humid tropics. *Applied and Environmental Soil Science* 2018: 1 – 10.
- Kana, E. G., Oloke, J. K., Lateef, A. and Adesiyun, M. O. (2012). Modelling and optimization of biogas production on sawdust and other co-substrates using artificial neural network and genetic algorithm. *Renewable Energy* 46: 276-281.
- Koçak, E. and Şarkgüneşi, A. (2017). The renewable energy and economic growth nexus in the Black Sea and Balkan countries. *Energy Policy* 100: 51 – 57.
- Lee, K. Y., Chung, N. and Hwang, S. (2016). Application of an artificial neural network (ANN) model for predicting mosquito abundances in urban areas. *Ecological Informatics* 36: 172-180.
- Loh, W. Y. (2011). Classification and regression trees. *Wiley Interdisciplinary Reviews: Data Mining and Knowledge Discovery* 1(1): 14-23.

- Ludovic, R. A. (2012). Modelling the effects of land-use changes on water discharge catchment in the Uluguru Mountains. Thesis for Award of PhD Degree at the Sokoine University of Agriculture, Morogoro, Tanzania. 198 pp.
- Moisen, G. G. and Frescino, T. S. (2002). Comparing five modelling techniques for predicting forest characteristics. *Ecological Modelling* 157(3): 209 – 225.
- Moriasi, D. N., Arnold, J. G., Van Liew, M. W., Bingner, R. L., Harmel, R. D. and Veithand Veith, T. L. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the American Society of Agricultural and Biological Engineers (ASABE)* 50(3): 885 – 900.
- Nair, K. R., Vanitha, V. and Jisma, M. (2017). Forecasting of wind speed using ANN, ARIMA and Hybrid models. In: *Intelligent Computing, Instrumentation and Control Technologies, International Conference*. pp. 170 – 175.
- Panchal, G., Ganatra, A., Kosta, Y. P. and Panchal, D. (2011). Behaviour analysis of multilayer perceptrons with multiple hidden neurons and hidden layers. *International Journal of Computer Theory and Engineering* 3(2): 332-337.
- Qdais, H. A., Hani, K. B. and Shatnawi, N. (2010). Modelling and optimization of biogas production from a waste digester using artificial neural network and genetic algorithm. *Resources, Conservation and Recycling* 54(6): 359 – 363.
- Rajapaksha, A. U., Vithanage, M., Ahmad, M., Seo, D. C., Cho, J. S., Lee, S. E., Lee, S. S. and Ok, Y. S. (2015). Enhanced sulfamethazine removal by steam-activated invasive plant-derived biochar. *Journal of Hazardous Materials* 290: 43 – 50.
- R-Core-Team (2018). R: A language and environment for statistical computing. Package *utils* Version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria. [<https://www.R-project.org>] site visited on 20/2/2019.

- Rea, J. (2014). Kinetic Modeling and Experimentation of Anaerobic Digestion. Dissertation for Award of MSc Degree at Massachusetts Institute of Technology, Massachusetts, USA. 58pp.
- REN21 (2018). *Renewables Global Status Report*, Paris: REN21 Secretariat, Paris, France. 324pp.
- Schirmer, W. N., Jucá, J. F. T., Schuler, A. R. P., Holanda, S. and Jesus, L. L. (2014). Methane Production in Anaerobic (Brazil) Landfill: Evaluation in Refuse of Different Ages. *Brazilian Journal of Chemical Engineering* 31(02): 373–384.
- Schnurer, A. and Jarvis, A. (2010). *Microbiological Handbook for Biogas Plants*. Swedish Waste Management, Sweden. 74pp.
- Sefeedpari, P., Rafiee, S. and Akram, A. (2013). ‘Application of artificial neural network to model the energy output of dairy farms in Iran’, *Int. J. Energy Technology and Policy* 9(1): 82–91.
- Sewsynker-Sukai, Y., Faloye, F. and Kana, E. B. G. (2017). Artificial neural networks: An efficient tool for modelling and optimization of biofuel production (A mini-review). *Biotechnology and Biotechnological Equipment* 31(2): 221 – 235.
- Subramanian, J. and Simon, R. (2013). Overfitting in prediction models – Is it a problem only in high dimensions? *Contemporary Clinical Trials* 36(2): 636 – 641.
- Widyanto, S. A., Widodo, A., Hidayatno, A. and Suwoko, A. (2014). The use of ON-OFF and ANN controllers for automated irrigation system model based on Penman-Monteith Evapotranspiration. *Telkomnika* 12(3): 741 – 750.
- Yadvika, S., Sreekrishnan, T. R., Kohli, S. and Rana, V. (2004). Enhancement of biogas production from solid substrates using different techniques--A Review. *Bioresource Technology* 95(1):1–10.
- Yee, T. W. and Mitchell, N. D. (1991). Generalized additive models in plant ecology. *Journal of Vegetation Science* 2(5): 587-602.

Yu, L., Wensel, P. C., Ma, J. and Chen, S. (2013). Mathematical modelling in anaerobic digestion. *Journal of Bioremed Biodeg* 4(2): 1 – 12.

## CHAPTER SIX

### **6.0 Techno-Economic Appraisal of the Integrated Solar and Wind Energy with Anaerobic Digestion (i-SWEAD) System**

#### **Abstract**

The novel integrated solar, wind energy and anaerobic digestion (i-SWEAD) system was technically and economically assessed. The same was done to the integrated Adapted Batch Fed Anaerobic Digestion (ABFAD) and solar system. Both systems were meant for a sustainable supply of electricity and biogas energy for the individual households of rural semi-arid areas. This chapter presents the techno-economic assessment approach applied to appraise all components used to fabricate fore mentioned systems. The assessment was done in the systems' independence and mutual exclusiveness bases. The assessment results were used for comparing and contrasting both systems technically and economically. The i-SWEAD system was feasible based on the system's independence and mutual exclusive technical assessment, as it produced more energy (266.68 kWh/year) than the ABFAD-solar system (239.00 kWh/year). Also, the i-SWEAD system required an initial expense of TZS 1,136,141.11 (€<sub>2017</sub> 493.97), which is affordable to some households in rural semi-arid areas. The system's Levelized Cost of Energy (LCoE) was TZS 1464.63/kWh (€<sub>2017</sub> 0.64/kWh) at a discount rate of 9% and 25 years' systems lifetime. Also, at the same rate and lifetime, the i-SWEAD has NPV, IRR and DPP values of TZS 759 515.7 (€<sub>2017</sub> 330.22), 16.6% and eight years plus ten months, respectively. The ABFAD-solar system's values of LCoE, NPV, IRR and DPP at the same fore mentioned discount rates and system's lifetime was 1312.71/kWh (€<sub>2017</sub> 0.57/kWh), TZS 988 710.1 (€<sub>2017</sub> 429.87), 10.4% and six years plus eight months respectively. Therefore, in systems' independent economic assessment, the i-SWEAD system is a viable project, while in the mutual exclusive economic assessment, the ABFAD-solar system is a viable project. The

i-SWEAD system is an attractive project; therefore, it is recommended for application in rural semi-arid areas.

**Keywords:** *Techno-economic analysis; integrated systems; Semi-Arid Areas; solar and wind energy, anaerobic digestion system*

## **6.1 Introduction**

### **6.1.1 Background information**

Rural semi-arid areas are among the vulnerable areas regarding the accessibility to sustainable energy, especially in developing countries and in most of the Sub-Saharan region, Tanzania inclusive. Traditionally, communities in these areas depend chiefly on biomass energy resources (e.g., fuelwood and charcoal) for meeting their household energy consumption (Wiskerke *et al.*, 2010; Ding *et al.*, 2012). As a result, the high energy consumptions in households in these communities are for cooking, while energy consumptions for powering electrical and electronic gadgets are low. However, due to community shift from the use of fossil fuels (e.g. kerosene) to environmentally friendly sources of energy for lighting (NBS, 2014) and increase in the use of mobile phones for social and business communications in Tanzania (NBS, 2014); then, reliable and sustainable energy for those purposes is of paramount importance.

Initiatives to curb the problem of access to sustainable energy in rural semi-arid areas have been in place. The initiatives include expansion of electricity grid connection and introduction of biogas technologies to these rural areas. The central area of Tanzania, including the Dodoma region, was involved. It has appreciable resources of wind and solar energy, as well as biomass, mainly cow dung. The initiatives put in place are under various programmes implemented by Dodoma Biogas Project (MIGESADO) and the Rural Energy Agency /Rural Energy Fund (REA/REF) (Moner-Girona *et al.*, 2016; Wawa and Mwakalila, 2017). The renewable energy business sector is growing in the region, including the marketing of solar PV modules useful to meet part of energy consumption for powering electrical and electronic gadgets in these areas. However, the adoption rate of some of these technologies, mostly biogas generation plants, is not convincing due to several reasons, including the low financial capabilities of most families in the area and

difficulties associated with acquiring and operating the technologies (Wawa and Mwakalila, 2017). The biogas technology introduced in the areas was a fixed dome digester design, requiring daily feeding of substrate mixed with water at a ratio of 1:1.

A small sized newly introduced i-SWEAD) the system was designed, tested and modelled on its generation of biogas and production of electricity. The system is explained in detail in Chapter Four of this thesis. The i-SWEAD system was intended to contribute to energy supply to meet household energy consumption while at the same time addressing challenges that are facing some of the energy technologies introduced in the rural semi-arid areas of the central region of Tanzania. The i-SWEAD system is one of the mitigating measures towards curbing the vulnerability of access to sustainable energy in these areas. Therefore, assessing the i-SWEAD system and other renewable energy systems on their technical feasibility and economic viability is essential. This assessment was achieved through techno-economic analysis, as presented in this chapter.

### **6.1.2 Feasibility assessment of renewable energy systems**

Small and large renewable energy systems have been developed around the world. Also, they have been assessed in technical and economic terms. Some of the technical and economic assessments of these systems were reported by Sinha and Chandel (2014), Chandel *et al.* (2014), Bahramara *et al.* (2016) and REN21 (2018). The assessment of the systems is explained in indexes that may simply be summarised as technical and economic efficiencies. The technical efficiency is based on the maximum output produced with a given set of inputs. It gives insight into the functionality of the system to meet its designated objective (Marchetti *et al.*, 2008). The economic efficiency is expressed in terms of formed maximum output at a given maximum (opportunity) cost, or it is expressed in terms of achieving minimum (opportunity) at a given level of output (Ribeiro and Pereira da Silva, 2012). Both concepts were considered in this study.

Technical assessment of systems, which are intended to produce biogas and electricity have to include gathering information of biogas generation capacity, biogas energy content based on its methane content, the electricity generation capacity, the unmet load, operating condition factors, e.g. temperature and system envisaged life span (Masebinu *et al.*, 2017; Askari and Ameri, 2012; Marchetti *et al.*, 2008). The unmet load is an electrical load that the power system is unable to serve. It occurs when the electrical demand exceeds the supply. A system with a lower unmet load is technically feasible. Any system's economic performance assessment varies and depends very much on the assumptions used in that assessment. Economic considerations may include information on total investment cost, annual variable operating and maintenance cost, the annual cost of generating energy in the plant and annual capital-related cost (Masebinu *et al.* 2017).

Several tools and techniques are used to technically and economically analyse renewable energy systems. Some of the applied tools are RetScreen, Hybrid Optimization Model for Electric Renewables (HOMER), and HYBRID 2 (Sinha and Chandel, 2014; Kalinci *et al.*, 2015; Bahramara *et al.*, 2016). In most cases, the inputs to these tools involved load demand, resources, power system, component details and financial data. Also, some of the investments evaluation techniques in long-term assets are applied. They include payback period, discounted payback period (DPP), net present value (NPV), profitability index and internal rate of return (IRR) (Peterson and Fabozzi, 2002).

Cost analysis of renewable energy systems and their products' reliability was reported by Chandel *et al.* (2014) and other researchers. They applied some of the parameters during the assessment. The parameters were Levelized Cost of Energy (LCoE), design engineering and management (DEM) cost, installation labour cost, operation and maintenance (O&M) cost and capacity factor (Chandel *et al.*, 2014; Kalinci *et al.*, 2015;

Quinn and Davis, 2015). The benefit-cost ratio (BCR) is an index used in the assessment of renewable energy projects. The BCR and NPV are profit-based indexes that lead to the same conclusion (Rafique and Bahaidarah, 2019). Therefore, NPV was intuitively selected to be used in this study. Most of the assessment techniques were selected and applied to this study.

### **6.1.3 Techno-economic analyses of renewable energy systems in Tanzania**

A few research publications are available, which show technical and economic analyses of renewable energy systems in Tanzania. One of them is Aly *et al.* (2018), which explains the feasibility study of the concentrated solar power system. However, no research work has been found detailing the techno-economic analysis of an integrated energy system, which involves wind, solar and anaerobic digestion components in Tanzania and the world.

Doing a techno-economic analysis for the i-SWEAD system is useful for building up a case for the renewable energy stakeholders for furthering its promotion. In this Chapter, the technical and economic appraising results of the i-SWEAD system and the integrated adapted batch fed anaerobic digestion (ABFAD) with solar (ABFAD-Solar) system are presented.

## **6.2 Materials and Methods**

### **6.2.1 The study site**

The study site description is the same as that given in Sub-section 3.2.1 of Chapter Three of this thesis.

### **6.2.2 Research approach applied**

The study's main goal was to assess the technical feasibility and economic viability of the i-SWEAD system. The applied approach involves assessing the system mentioned above and another integrated system for comparison purposes. The system, which was compared with the i-SWEAD system in this study, was the integrated Adapted Batch Fed Anaerobic Digester (ABFAD) with a solar energy system. Hence, it is simply known as the ABFAD-solar system. However, during the assessment, both systems were treated independently; although, for comparison, they were treated in a mutually exclusive manner. Some results related to these systems have been discussed in Chapters Two, Three and Four of this thesis for adoption. Therefore, they were referred to for clarification.

Technical feasibilities of the i-SWEAD and ABFAD-solar systems included the use of some factors, which were explained in Sub-section 6.1.1 of this chapter. The factors included for this study were biogas generation capacity in a year, biogas methane content, biogas energy density based on its methane content, total biogas energy produced in a year, the electricity generation capacity, operating condition factors, especially temperature and system envisaged life span.

The economic viability assessment of fore mentioned systems also involved applying some of the factors described in Sub-section 6.1.1. The factors considered include the Levelized cost of energy (LCoE), discounted payback period (DPP), net present value (NPV), and internal rate of return (IRR). The cost analysis of both systems, which produced the data that was useful for economic assessment, consisted of the following cost types: design engineering and management (DEM) cost, installation labour cost, system fabrication cost and operation and maintenance (O&M) cost. In addition, some assumptions were made to simplify the techno-economic analyses of both systems. These assumptions are explained in the following respective sub-sections.

### **6.2.3 Description of the i-SWEAD and ABFAD-solar systems**

The i-SWEAD system is well described in Chapter Four. The ABFAD-solar system includes a solar PV unit, solar thermal unit and anaerobic digestion sub-system. These parts of the system are the same as those used to fabricate the i-SWEAD system. However, the anaerobic digestion system is the same as that of System4. System4 and the i-SWEAD system are described clearly in Table 4.3, Sub-section 4.2.6 (i) of Chapter Four of this thesis.

The significant difference between these systems is that the ABFAD-solar system has not wind sub-system like the i-SWEAD system. The land area needed for the installation of the i-SWEAD system was 6.45 m<sup>2</sup>. According to the system's components, the allocation of the land area was 1.2 m<sup>2</sup>, 2.25 m<sup>2</sup> and 3 m<sup>2</sup> reserved for wind and anaerobic digestion sub-systems as well as biogas storage, respectively. Solar PV module was installed on top of the roof of the house of a household. Therefore, its land requirement was not considered. On the other hand, the land area for the installation of the ABFAD-solar system was 5.25 m<sup>2</sup>. This is equal to the land required by the i-SWEAD system minus the wind sub-system allocated land area.

### **6.2.4 Data analysis for technical assessment**

The parameters' values used for the technical assessment of the i-SWEAD and ABFAD-solar systems were determined. The values of the amount of biogas in volume (m<sup>3</sup>) generated within ninety-two days of hydraulic retention time by the i-SWEAD and ABFAD-solar systems were deduced from Figure 4.13 Sub-section 4.3.5 of Chapter Four of this thesis. The total biogas volume in a year collected by each system was taken as four times the biogas volume collected within 92 days by both systems. It is a value, which was considered during the technical assessment of systems in this study. The value of biogas

amount generated by the i-SWEAD and ABFAD-solar systems was taken as that which was produced by digesters D3 and D4, respectively (Figure 4.13). Curve CumVolBiogasD3 and CumVolBiogasD4 represented the cumulative biogas generation of the i-SWEAD and ABFAD-solar systems, respectively, in Figure 4.13. However, biogas produced by D4 was intuitively assumed to be decreased by 5% in this study. The ABFAD-solar system digester is envisaged to receive the heat from the solar PV unit, which might have decreased the volume of biogas but increased the methane content. This phenomenon can be reflected in the results shown in Figure 4.12 and Table 4.4 of Chapter Four in this thesis.

Biogas methane content ( $\text{CH}_4$ ) in percentage (%) of each of both fore mentioned systems were derived from Table 4.4 Sub-section 4.3.5, Chapter Four of this thesis. The  $\text{CH}_4$  content average values from this table were considered for this study. The  $\text{CH}_4$  content average value of D3 and D4 in Table 4.4 was taken as  $\text{CH}_4$  content of biogas produced by the i-SWEAD and ABFAD-solar systems, respectively. However, the  $\text{CH}_4$  of the ABFAD-solar system was intuitively assumed to be increased by 0.7% in this study. The assumption is based on the same reason mentioned in determining the total volume of both systems.

The energy density ( $\text{MJ/m}^3$ ) of biogas produced by each of both fore mentioned systems was determined using the average methane content values and the relationship of biogas energy density with methane content. The average methane content values considered are those based on the biogas generated by both the i-SWEAD and ABFAD-solar systems. The relationship of biogas energy density with methane content was deduced from Figure 3 in Section 2 of the published work of Cuéllar and Webber (2008). Figure 3 showed that the relationship of biogas energy density ( $\text{MJ/m}^3$ ) with methane content (Mole-fraction)

was linear at standard conditions. This information was used to formulate the conversion factor between biogas energy density and methane content based on the data presented in Figure 3 (Cuéllar and Webber, 2008). The conversion factor,  $F_{\%CH_4}$ , in (MJ/m<sup>3</sup>/ %CH<sub>4</sub>) was formulated using Equation (6.1). The  $F_{\%CH_4}$  was found to be 36.8 MJ/m<sup>3</sup>/ %CH<sub>4</sub>. Therefore, it is the conversion factor, which was used in this study.

$$F_{\%CH_4} = \frac{Bd_f - Bd_i}{\%CH_4_f - \%CH_4_i} \dots\dots\dots \text{Eq. (6.1)}$$

where  $Bd_f$  and  $Bd_i$  is final and initial biogas energy density (MJ/m<sup>3</sup>) respectively while  $\%CH_4_f$  and  $\%CH_4_i$  is final and initial methane content (100 x Mole-fraction) traced from Figure 3 of Cuéllar and Webber (2008).

The total biogas energy produced in a year (MJ/year) by each of the i-SWEAD and ABFAD-solar systems was computed using Equation 6.1(a). This equation is based on the biogas energy density values and total biogas volume collected in a year. The total biogas energy values in MJ/year unit obtained were converted into kWh/year units for further economic analysis. The conversion unit was 0.27777778 kWh/MJ (Yoo *et al.*, 1998).

$$E_{biogas} = \rho_{e_{biogas}} \times V_{biogas} \dots\dots\dots \text{Eq. (6.1(a))}$$

where  $E_{biogas}$  is total biogas energy produced in a year,  $\rho_{e_{biogas}}$  is biogas energy density (MJ/m<sup>3</sup>) and  $V_{biogas}$  is total biogas volume collected in a year (m<sup>3</sup>/year).

The electricity generation capacities of the i-SWEAD and ABFAD-solar systems were obtained from Sub-section 4.3.7 of Chapter Four of this thesis. This capacity was

expressed in Electrical energy (kWh) per year. Since the ABFAD-solar system had only a Solar PV unit to generate electricity, then its electricity capacity was based on that unit. The operating condition of both fore mentioned systems was expressed in terms of temperature factor. The temperature values (°C) considered in this study were the average temperature of digesters of systems System3 (D3) and System4 (D4). System3 and System4 represented the i-SWEAD and ABFAD-solar systems, respectively. These systems are described in Chapter Four of this thesis. The average temperature of digesters was deduced from Figure 4.11 Sub-section 4.3.4 of Chapter Four of this thesis. The average temperature of ABFAD-solar systems was assumed to increase by 0.5% for the same reasons mentioned in computing the total biogas volume in this sub-section.

The i-SWEAD and ABFAD-solar systems were fabricated using components with a varying life span ranging from three years, e.g. electrical battery, to more than thirty years, e.g. mild steel flat bar. In order to simplify the assessment of both systems technically and later economically, it was intuitively assumed that the envisaged life span (years) of the systems was the same. However, during the techno-economic analysis, each item's life span was taken into account by factoring them in the determination of economic parameters' values. Therefore, for simplicity, the envisaged life span of both was assumed to be 25 years.

### **6.2.5 Data analysis for economic assessment**

The cost of the i-SWEAD and ABFAD-solar systems were analysed. The results obtained were useful for deriving the values of the financial parameters, which were also valuable for energy systems economic assessment. The following factors were considered in the systems' cost analysis: design engineering and management (DEM) cost, installation labour cost, system fabrication cost and operation and maintenance (O&M) cost.

The DEM cost (TZS) is the product of labour cost for design and management for a given man-hour and the number of hours for a given peak wattage of the system designed and managed. It is expressed by Equation 6.2.

$$DEM_c = Ld_{DEM} \times T_{DEM_{kwp}} \dots \dots \dots \text{Eq.6.2}$$

where  $DEM_c$  is DEM cost of the system,  $Ld_{DEM}$  is a labour cost for design, engineering and project management (TZS/man-hour) and  $T_{DEM_{kwp}}$  is design, engineering and project management number of hours per kWp (man-hour/kWp).

The peak wattage of the system was computed using Equation 6.2(a), which is shown below.

$$P_{syt} = \frac{E_{syst}}{A_{yr}} \dots \dots \dots \text{Eq. 6.2(a)}$$

where  $P_{syt}$  is peak wattage of the system (kW),  $E_{syst}$  is the energy generated by the system (kWh) and  $A_{yr}$  is the time (h) taken by the system to generate  $E_{syst}$ .

According to URT (2013), the  $Ld_{DEM}$  is TZS 10 000.00 /man-hour for the small company being involved. Although it was not stated of the calibre of the person involved in DEM regarding this rate, it was assumed to be the rate for a junior engineer. In this regard, the DEM was assumed to be done by a senior engineer for this study. Therefore, taking into account the calibre of the person involved in the DEM; the labour charge of the one senior engineer's assistant, the systems in question being designed, fabricated and tested in 2017;

considering the time value of money, inflation rate and value-added tax, then in this study, the  $Ld_{DEM}$  is assumed to be TZS 200 000.00/man-hour.

Chandel *et al.* (2014) reported that  $T_{DEM_{kWp}}$  it was 2 h/kWp. This figure was adapted to 8 h/kWp to care for contingent time for designing the system due to interruptions. The total biogas energy and electrical energy produced by the system were treated equally. Therefore, they were summed up together to get the total energy produced by the system. It was done so to simplify the analysis while bearing in mind that electrical energy was of higher quality than biogas energy in terms of handling. Also, it was intuitively assumed that both systems could operate for 45% of total hours in a year.

Installation labour cost (TZS) was also a factor considered in the cost analysis of both systems. It is computed the same way as the DEM cost. Therefore, Equation 6.2 is applied in this case. However, based on URT (2013), while considering Class VII Contractor being involved in the installation of the system, then labour charge for installation is TZS 1500.00/man-hour. Similar reasons mentioned during the description of DEM cost were applied to this study to set the labour charge for installation to this figure (TZS 150 000.00/man-hour) with an exception. The exception was that; five labourers were involved in installing the systems. Chandel *et al.* (2014) reported that the installation man-hour required per kWp was 12 h/kWp. This figure was adapted to 15 h/kWp to take care of the lack of sophisticated equipment for systems installation at the study site.

Another important factor for cost analysis was system fabrication cost (TZS). This cost included the materials and machining costs incurred for fabricating the systems. Transportation costs of materials were factored in the materials costs presented in this chapter. The machining costs included the machine operator labour charges. They are

presented in a lump sum. The material costs were grouped into the sub-systems of both ABFAD-solar and i-SWEAD systems.

The final factor considered for cost analysis was the operation and maintenance (O&M) cost (TZS). The O&M cost involves both fixed and variable O&M costs. The Fixed O&M costs are incurred irrespective of the energy generated by a process and may include the cost of office rental, staff wages, depreciation, property tax, insurance, and regular and irregular maintenance work. Variable O&M costs are based on per unit of energy produced. They may involve, for instance, cost of fuel, replacements of spares, periodic inspection, replacement, repairs of system components, consumables and disposal of residual and auxiliary materials (Schröder *et al.*, 2013).

In this study, the fixed O&M cost considered was the system's attendant wage, which included the regular simple maintenance work. It was considered on an annual basis. However, the system attendant wage for the ABFAD-solar system was intuitively assumed to be less by 25% of that of the i-SWEAD system attendant wage, which was set at TZS 180 000.00/year. The variable O&M cost included collecting and loading cow dung into the system's digester and unloading the substrate from the same digester. The loading and unloading were assumed to occur twice per year, and it was charged at TZS 2400.00/loading and unloading tasks.

Other variable cost items were the cost of replacing the bulb and the batteries after five years, replacing the flexible pipes and gate valves after seven years, and replacing the scrubber's iron wools and rubber for the cap of the wind turbine generator four times per year. The cost of replacing scrubber's iron wools and rubber for the cap of wind turbine generator for ABFAD-solar system was intuitively assumed to be less by 67% of the i-

SWEAD system. The reason for this was that the ABFAD-solar system had no wind energy sub-system. All variable costs were expressed on an annual basis to ease the O&M cost computation.

Levelized cost of energy (LCoE) is defined as the cost that, if assigned to every unit of energy produced (or saved) by the system over the analysis period, will equal the total life-cycle cost (TLCC) when discounted back to the base year. It is a financial parameter based on the above-described factors useful for cost analysis. The LCoE's unit is TZS/kWh or TZS/MWh, or the unit can be expressed in other nations' currencies for a given energy unit of measure. The TZS/kWh unit was adopted in this chapter. The LCoE in this study did not consider inflation and was called real LCoE. In contrast, LCoE that incorporates inflation is called nominal LCoE (Wang *et al.*, 2011, p. 4249; Chandel *et al.*, 2013).

The LCoE values are used in selecting the economically viable energy system among the group of energy generating systems, which are subjected to the same energy selling marketplace. The system with the least LCoE value is chosen to yield more profit, as the lowest cost will be incurred for the generation of the same unit of energy. LCoE of the solar energy-based hybrid system is computed using Equation 6.2(b) (Mundada *et al.*, 2016). Note that the hybrid system is similar to the systems considered in this study.

$$LCOE = \frac{I_c + \sum_{n=1}^N \frac{(I_c \times i_c + O_n + F_{nk} - ITC_n - PTC_n)}{(1+d)^n}}{\sum_{n=1}^N i_c}$$

$$LCoE = \frac{I_c + \sum_{n=1}^N \frac{(I_c \times i + O_n + F_{nk} - ITC_n - PTC_n)}{(1+d)^n}}{\sum_{n=1}^N \frac{E_k}{(1+d)^n}} \dots\dots\dots \text{Eq. 6.2(b)}$$

where  $I_c$  is the capital cost committed before the start of energy generation;  $O_n$  is O&M costs in year  $n$ ;  $F_{nk}$  is fuel costs of hybrid’s energy sub-system  $k$  other than wind or solar in year  $n$ ,  $ITC_n$  is investment tax credits in year  $n$ ,  $PTC_n$  is production tax credits in year  $n$ ,  $E_s$  is energy generated by hybrid solar energy sub-system in year  $n$ ,  $E_k$  is energy generated by hybrid’s energy sub-system  $k$  other than wind or solar in year  $n$ ,  $d$  is a discount rate as per financial regulation body of a country,  $d_s$  is the degradation rate of the hybrid’s solar energy sub-system per year (%),  $d_k$  is the degradation rate of hybrid’s energy sub-system  $k$  per year (%),  $k = 1,2,3,\dots$ ;  $N$  is the analysis period or lifetime of the project (years),  $i$  is the interest rate on the capital cost committed, i.e.  $I_c$  to the hybrid system for 100% debt (%).

Mundada *et al.*, 2016 reported that the  $d_s$  for amorphous silicon PV is 0.5–1.0%/year, for crystalline silicon is 0.1–0.5%, for polycrystalline silicon, PV is 0.1–1.0%, and for cadmium telluride 0.1–0.5%/ year. However, Nguyen *et al.* (2014) reported that most energy generating systems have a range of annual degeneration rate of 0.5–1.2%. Therefore, in the case of this study, the annual degeneration rate of all systems is intuitively assumed to be 0.6%. It means that both  $d_s$  and  $d_k$  were considered to be equal to 0.6%.

Assumptions were made to simplify the computation of LCoE of both ABFAD-solar and i-SWEAD systems. They include the following: systems did not yield tax credits, the investment was all made before the start of energy generation, and there was no debt interest rate for the investment. Therefore, Equation 6.2 was modified based on

assumptions made and then resulted in Equation 6.3. Equation 6.3 was applied to determine the LCoE of the systems in this study. The  $d$  was used for checking the sensitivity of both systems based on LCoE values. The range of  $d$  was intuitively selected, and it was 6-16%. The definition of the terms in Equation 6.3 remains the same as those of Equation 6.2(b).

$$LCOE = \frac{I_c + \sum_{n=1}^N \frac{O_n}{(1+d)^n}}{\sum_{n=1}^N \frac{1}{(1+d)^n}} \quad LCoE = \frac{I_c + \sum_{n=1}^N \frac{O_n}{(1+d)^n}}{\sum_{n=1}^N \frac{1}{(1+d)^n}} \dots\dots\dots \text{Eq. 6.3}$$

Equation 6.3 was transformed into Equation 6.4 using the theory of geometric progression summation and description of determining the LCOE value given by Blumsack (2020). Equation 6.4 was used to obtain the LCOE values of both systems in this study. The terms in this equation are the same as defined in Equation 6.2. Note that the  $O_i$ .e. O&M cost was expressed on an annual basis and  $O$  is the same as  $O_n$ .

$$LCOE = \frac{1}{E_s \times (1-ds)} \times \left[ \frac{d I_c}{1 - \frac{1}{(1+d)^N}} + O \right] \quad LCoE = \frac{1}{E_s \times (1-ds)} \times \left[ \frac{d I_c}{1 - \frac{1}{(1+d)^N}} + O \right]$$

..... Eq. 6.4

Discounted payback period (DPP) in years is the time needed to pay back the original investment in terms of discounted future cash flows or the duration that investment requires to recover its cost considering the time value of money. It is a financial parameter, which is determined, as shown in Equation 6.5 (<https://accounting-simplified.com>). DPP considers the change of cash flow for the whole year, and in some cases, the result obtained is rounded up. However, in this study, rounding up of results was not done.

$$DPP = (A-1) + \frac{I_c - CumPVCF_{(A-1)}}{PVCF_{(A)}} \dots\dots\dots \text{Eq. 6.5}$$

where  $A$  is the year, in which the cumulative present value of cash flows from investment exceeding the initial cost;  $PVCF_{(A)}$  is the present value of net cash flow in a year  $A$ ;  $CumPVCF_{(A-1)}$  is the cumulative present value of the cash flows from investment at the end of the year  $A-1$ , and  $I_c$  is the initial cost of investment.

The DPP was applied in this study, and its guiding decision rule depends on how fast the investment outlay is recovered. Therefore, the running of a project or system, which returns capital investment within a few years, i.e. DPP lowest value of other systems below the lifetime of that project or system, is accepted or otherwise rejected.

NPV in Tanzanian shillings (TZS) or other currency is the present value of all expected cash flows. NPV represented in summation notation was calculated using Equation 6.6 (Peterson and Fabozzi, 2002).

$$NPV = \sum_{t=0}^N \frac{CF'_t}{(1+d)^t} \dots\dots\dots \text{Eq.6.6}$$

Where  $t$  indicates any particular period,  $CF'_t$  represents the cash flow at the end of period  $t$ ,  $d$  is a discount rate as per the financial regulatory body of a country and  $N$  the number of periods making up the economic life of the investment.

IRR in % is the discount rate that makes the present value of all expected future cash flows equal to zero. It was computed based on the expression shown in Equation 6.7. The discount rate, which makes NPV value zero in Equation 6.6, is taken as *IRR* (Peterson and

Fabozzi, 2002).

$$0 = \sum_{t=1}^N \frac{CF'_t}{(1+IRR)^t} \dots\dots\dots \text{Eq. 6.7}$$

where the symbols have the same meaning as defined in Equation 6.5.

Decision rules for IRR and NPV techniques are shown in Table 6.1. NPV is preferable for mutually exclusive assessment of projects, while IRR is preferable for independent projects assessment (Arshad, 2012). Both financial parameters were adopted in this study for assessing the economic viability of both i-SWEAD and ABFAD-solar systems.

**Table 6.1: Decision rules for IRR and NPV techniques**

S/N	Condition of the Technique	Description	Rule
1	IRR is greater than the cost of capital	The investment is expected to return more than required.	Should accept the project.
2	IRR is less than cost of capital	The investment is expected to return less than required.	Should reject the project.
3	IRR is equal to cost of capital	The investment is expected to return what is required.	Makes indifferent between accepting or rejecting the project
4	NPV greater than zero	The investment is expected to increase shareholder wealth.	Should accept the project
5	NPV less than zero	The investment is expected to decrease shareholder wealth.	Should reject the project
6	NPV equal to zero	The investment is expected not to change shareholder wealth.	Makes indifferent between accepting or rejecting the project

Source: Peterson and Fabozzi, 2002

The energy tariff for customer category D1, i.e. the Low Usage Tariff for Domestic customers, e.g. rural area households who on average consume less than 75 kWh per month, is TZS 100.00/kWh and for every kWh exceeding the limit of 75 kWh per month is charged at TZS 350.00/kWh (TANESCO, 2016). Furthermore, EWURA (2019)

reported the approval of a standardized small power purchase tariff of TZS 203.11.00 /kWh for the main grid connection under the 1<sup>st</sup> Generation Small Power Producer (SPP) Framework (using avoided cost tariff).

Therefore, the criterion was set that if the system's LCOE value obtained was lower than the tariff reported by EWURA (2019), the EWURA (2019) tariff would have to be used in the computation of DPP, NPV and IRR. Otherwise, the system's LCOE value at 9% and end of life span, i.e. 25 years, which is the highest of the two systems, would have to be intuitively increased by 6% of its value and then be treated as the price of energy during the determination of DPP, NPV and IRR values. The 9% discount rate is the one, which is currently set in Tanzania by the Bank of Tanzania as of 2018 (BOT, 2018). The criterion aimed to give meaningful results that would be useful for comparing both systems.

Note that the costs discussed in this chapter were based on the local market prices as of the year 2017 in Tanzania and Dodoma region in particular. The costs are expressed in both Tanzanian shillings (TZS) and European Union currency, Euro, as of the year 2017. The conversion rate of Euro into TZS was taken as TZS 2300.00/Euro as of the same above mentioned year. Nevertheless, the conversion of TZS into United States dollar (USD) was considered for the year 2017 at an average rate of TZS 2290/USD.

### **6.3 Results and Discussion**

The i-SWEAD system was developed to generate clean energy in rural semi-arid areas. The techno-economic analysis of this system was done while comparing it with the ABFAD-solar system. Both systems were of the integrated type. Both analyses are presented and discussed in this section in the order of technical, cost and financial analyses results.

The results of technical analyses of each of the systems are presented in Table 6.2. The analyses were based on the description given in sub-section 6.2.4 of this chapter. Twelve technical factors' results are presented in Table 6.2. However, five factors from a list of twelve factors were mainly used to assess the feasibility of the systems. The five factors are biogas volume in years, biogas CH<sub>4</sub> content, total biogas energy generated, electrical energy generated, and total energy generated. These factors are related directly to the functionality of the systems in addressing household energy needs.

**Table 6.2: Results of the i-SWEAD and ABFAD-solar systems technical analysis**

Serial Number	Technical Factor	System	
		i-SWEAD	ABFAD-Solar
1	Biogas volume in 92 days (m <sup>3</sup> )	11.86	12.24
2	Biogas volume in year (m <sup>3</sup> )	<b>47.42</b>	<b>48.94</b>
3	Biogas CH <sub>4</sub> content (%)	<b>48.57</b>	<b>46.69</b>
4	Biogas energy density (MJ/m <sup>3</sup> )	17.87	17.18
5	Total biogas energy generated (MJ/year)	847.57	840.97
6	Total biogas energy generated (kWh/year)	<b>235.44</b>	<b>233.60</b>
7	The electrical energy generated (kWh/year)	<b>31.24</b>	<b>5.69</b>
8	Total energy generated (kWh/year)	<b>266.68</b>	<b>239.29</b>
9	Operating temperature (°C)	30.28	29.71
10	System's digester volume (m <sup>3</sup> )	0.24	0.24
11	Land area required (m <sup>2</sup> )	6.45	5.25
12	Systems life span (year)	25	25

Table 6.2 shows that the i-SWEAD system produced biogas with higher biogas CH<sub>4</sub> content (48.57%), total biogas energy (235.44 kWh/year), total electrical energy (31.24 kWh/year) and total energy (266.68 kWh/year) than the ABFAD-solar system. The ABFAD-solar system produced biogas with biogas CH<sub>4</sub> content, total biogas energy, electrical energy and total energy of 46.69%, 233.60 kWh/year, 5.69 kWh/year and 239.29 kWh/year, respectively. However, the ABFAD-solar system produced more biogas (48.94

m<sup>3</sup>/year) than the i-SWEAD system (47.42 m<sup>3</sup>/year). The i-SWEAD system produced more energy than the ABFAD system, although the biogas volume produced by i-SWEAD is less than that of the ABFAD system.

The descriptions in the first seven paragraphs of Sub-Section 6.2.5 of this chapter and Appendix 10 were the bases of the cost analysis results of the i-SWEAD and ABFAD-solar systems in Table 6.3. Appendix 11 gives the details of the costs used to derive the costs shown in Table 6.3. The critical parameters, which their results are shown in Table 6.3, include total investment and total Operation and Management (O&M) costs. The results of these parameters were used for financial analysis.

**Table 6.3: Results of the i-SWEAD and ABFAD-solar systems cost analyses**

Serial Number	Cost Factor	System	
		The i-SWEAD	The ABFAD-Solar
1	DEM cost (TZS)	108 241.50	97 124.30
2	Installation cost (TZS)	152 214.61	136 581.05
3	Total system fabricating cost (TZS)	875 685.00	737 535.00
5	<b>Total investment, I, (TZS)</b>	<b>1 136 141.11</b>	<b>971 240.35</b>
4	<b>Total O&amp;M cost (TZS/year)</b>	<b>220 364.29</b>	<b>171 364.29</b>

Table 6.3 shows that the i-SWEAD system has higher investment cost (TZS 1 136 141.11 or €<sub>2017</sub> 493.97) and total O&M cost (TZS 220 364.29/year or €<sub>2017</sub> 095.81/year) than those of the ABFAD-solar system. This investment cost of the i-SWEAD system can be afforded by some dwellers of rural semi-arid areas, as it has been reported that the average monthly income per rural area individual household in Tanzania is about TZS 292 500.00 (€<sub>2017</sub> 127.17). Also, in rural areas, 23.6% and 46.5% of households create their business start-up capital from their savings and proceeds from agricultural production (NBS, 2014) respectively. The ABFAD-solar system has investment cost (TZS 971 240.35 or €<sub>2017</sub>

422.28) and total O&M cost (TZS 171 364.29/year or €<sub>2017</sub> 74.51/year). The cost values are high for the i-SWEAD system, and this can be justified by comparing the number of components of both systems. The i-SWEAD system consists of more components, i.e. three sub-systems compared to the ABFAD system components, i.e. two sub-systems.

The total investment and total O&M costs results were used in deriving the Levelized Cost of Energy (LCoE) values of both systems. The procedure of obtaining the LCoE values is described in paragraphs eight to twelve of Sub-section 6.2.5 of this chapter. Equation 6.4 is the specific equation used to generate LCoE values of the i-SWEAD and ABFAD-solar systems. The results of both systems' LCoE values are shown in Figure 6.1.

The trend curves of LCoE values in the entire life span of both systems at various discount rates are shown in Figure 6.1. With some exceptions, curves indicate the LCoE of both systems is high at the beginning of the project's life span; then, it drops to the lowest level in either year 15 or year 20 before starting to rise towards the end of the life span of both systems. These fluctuations imply that there is an optimal number of years less than the envisaged systems' life span in which these systems can make the return of investment at the lowest LCoE values. The LCoE lowest values and the LCoE value at the end of the life span of both systems are shown in Figure 6.1 as a data label.

At the discount rate of 9% and 12%, the lowest values of LCoE for both systems were found in the year 20. At the discount rate of 9%, the lowest LCoE of ABFAD-solar and the i-SWEAD systems was TZS 1309.24/kWh (€<sub>2017</sub> 0.56/kWh) and TZS 1458.41/kWh (€<sub>2017</sub> 0.63/kWh), respectively; while at the end of the life span of both systems, as per consecutively fore mentioned discount rates, the LCoE was TZS 1312.71/kWh (€<sub>2017</sub> 0.57/kWh) and TZS 1464.63/kWh (€<sub>2017</sub> 0.64/kWh) respectively. At a discount rate of 6%, the lowest values of LCoE for ABFAD-solar and the i-SWEAD systems were obtained at year

25 with values of TZS 1201.47/kWh and TZS 1347.87/KWh, respectively. However, at a discount rate of 16%, the lowest values of LCoE for ABFAD-solar and the i-SWEAD systems were obtained at year 20 with values of TZS 1579.89/kWh and year 15 TZS 1740.70/KWh, respectively. These phenomena imply that both systems' investments will be repaid quickly at the lowest LCoE value of a higher discount rate.

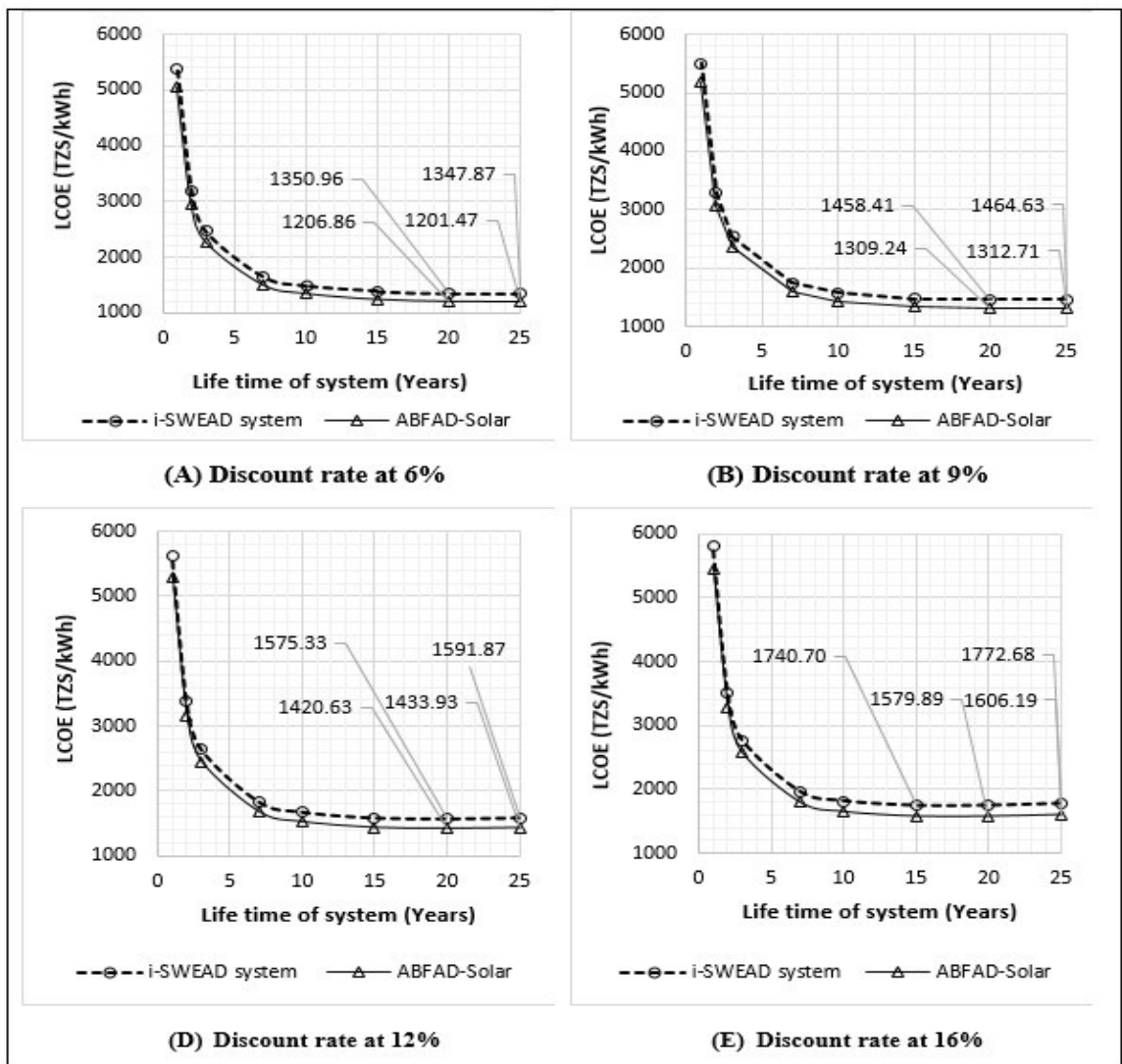


Figure 6.1: LCoE analysis results of the i-SWEAD and ABFAD-solar systems

The LCoE for both systems is higher than those set energy unit prices by the energy utility regulator in Tanzania, as explained in Sub-section 6.2.5 of this chapter. Also, it is higher

than those energy unit prices recorded in the global market. For example, at the current global market, solar PV energy price was TZS 299.00/kWh or USD<sub>2017</sub> 0.10/kWh based on Dundley (2018) report and the price of the electricity indicated in the FAO (2014) bioenergy and food security rapid appraisal user manual estimated at TZS 598.00/kWh or USD<sub>2017</sub> 0.20/kWh. Also, REN21 (2018) reported that LCoE<sub>2017</sub> for biomass, solar and onshore wind systems in Africa and elsewhere was USD0.1/kWh (maximum USD 0.175/kWh), USD 0.28/kWh (maximum USD 0.32/kWh) and USD 0.058/kWh (maximum USD 0.1/kWh), respectively. Therefore, considering these values of LCoE alone at all four selected discount rates, both systems will face a challenge to penetrate the market in Tanzania, Africa and at the global level.

In summary, the lowest LCoE of the i-SWEAD system were obtained at year 20 for all four selected discount rates except a discount rate of 16%, at which the lowest value was obtained in year 15. On the other hand, the lowest LCoE values of the ABFAD-solar system at all four selected discount rates were also obtained in year 20 except the discount rate of 6%, when the lowest value was obtained in year 25. Thus, the LCoE values of the i-SWEAD system were higher than that of the ABFAD-solar system at all discount rates and the entire life span of both systems. Therefore, by considering the mutually exclusive selection of the best system to invest in, the viable system based on the lowest LCoE values should only be the ABFAD-solar system. It implies that for the given duration of the life cycle of the projects, money invested in the ABFAD-solar system will be recovered by selling energy at a lower price per unit of energy than that of the i-SWEAD system. In other words, the ABFAD-solar system will produce energy at low capital investment.

Results of other financial factors, i.e. DPP, NPV and IRR, regarding the financial analyses

of the i-SWEAD and ABFAD-solar systems were obtained and presented in Table 6.4. The results were obtained using the procedure described in Sub-section 6.2.5 of this chapter. The values of DPP, NPV and IRR were specifically obtained using Equations 6.5, 6.6 and 6.7, respectively. The decision rules provided in Table 6.1 were used to assess both systems in financial terms independently and mutual exclusively as described in the first paragraph of Sub-section 6.2.2 of this chapter. In table 6.4, the results shown are based on a discount rate of 9% and 12%. The 9% discount rate is the one, which is currently set in Tanzania by the Bank of Tanzania as of 2018 (BOT, 2018). Therefore, results based on this discount rate were the ones considered for the final assessment decision.

**Table 6.4: Financial analyses results of the i-SWEAD and ABFAD-solar systems**

Serial Number	Financial Analysis	System	
		i-SWEAD	ABFAD-Solar
1	NPV at 9% (TZS)	<b>759 515.7</b>	<b>988 710.1</b>
2	NPV at 12% (TZS)	377 504.0	593 742.1
3	IRR at 9% (%)	<b>16.6</b>	<b>10.4</b>
	IRR at 12% (%)	7.0	7.4
4	Discounted payback period at 9% (years)	<b>8.8</b>	<b>6.7</b>
5	Discounted payback period at 12% (years)	10.8	7.8

At a 9% discount rate, the i-SWEAD system has higher values of IRR (16.6%) and DPP (8.8 years or eight years and ten months) and lower NPV value (TZS 759 515.7 or €<sub>2017</sub> 330.22) compared to the ABFAD-solar system. On the other hand, at the same discount rate, the ABFAD-solar system has NPV, IRR and DPP of TZS 988 710.1 or €<sub>2017</sub> 429.87, 10.4% or and 6.7 years or six years and eight months respectively. Therefore, both systems are economically viable as they will increase the worthiness, i.e. profit to the owner regarding the decision rules in Table 6.1.

It will be valid when assessing the system independently; as the NPV is positive, IRR is greater than the discount rate, and the DPP is less than the life span for both systems. However, if both systems were to be assessed in mutual exclusive means to choose the most economically viable system, then the ABFAD-solar system will be selected. This condition is vital because the ABFAD-solar system has a high value of NPV and a low value of DPP compared to the i-SWEAD system. Also, the condition is in line with Arshad (2012) recommendation of applying NPV and IRR value to assess the economic viability of projects. That author stated that when assessing the independent systems, the IRR should be given more weight in decision making; while considering assessing the system mutually exclusive, the NPV should be given more weight in decision making.

Both systems are outright rejected at the discount rate of 12%, as they are not economically feasible when considering them independently. The reason is that their IRR values were less than the discount rate (9%), which is set by the Bank of Tanzania (financial institution), and that rate was applied to assess the net cash flow of systems. However, for mutual exclusive economic assessment, the ABFAD-solar system is better (NPV is TZS 593 742.1 or €<sub>2017</sub> 258.15) than the i-SWEAD system (NPV is TZS 377 504.0 or €<sub>2017</sub> 164.13), where the recommendations of Arshad (2012) are taken into account.

#### **6.4 Conclusions and Recommendations**

A study has been carried out to assess the technical feasibility and economic viability of the i-SWEAD system to produce energy for individual rural households. In addition, another related renewable energy system, i.e. ABFAD-solar system, was assessed for comparison purposes. The assessment was based on the independence and mutual exclusiveness of both systems. However, the independence of systems carries more weight

in this study. It is because the goal of the study was to assess the novel developed i-SWEAD system. The results of analyses of both systems have been discussed in Section 6.3 of this chapter. Conclusions and recommendations based on the discussed results are presented in this section.

The i-SWEAD system is feasible technically as it produces more energy (266.68 kWh/year) than the ABFAD-solar system (239.29 kWh/year) at its digester operating temperature of 30°C and an average life span of 25 years. Also, the i-SWEAD system is affordable to some of the semi-arid households since its investment cost was TZS 1 136 141.11 or €<sub>2017</sub> 493.97 (NBS, 2014).

Determination of LCoE at the individual year in the entire life span of the i-SWEAD system and other similar systems should be carried out for coming up with fair decision making on feasible and viable systems or projects; since LCoE values of this kind of energy systems tend to be lowest between the start and end of the systems' life span. At a discount rate of 9% and for 25 years' systems lifetime, LCoE value of the i-SWEAD [TZS 1464.63/kWh (€<sub>2017</sub> 0.64/kWh)] and ABFAD-solar [TZS 1312.71/kWh (€<sub>2017</sub> 0.57/kWh)] systems are higher than those LCoE (REN21, 2018) of biomass, solar and onshore wind systems reported in Africa and elsewhere. The LCoE of the i-SWEAD system can be lowered even below other commercialised renewable energy systems by improving the systems' efficiency and ensuring all substrates released all biogas as much as possible.

Three investments evaluation techniques or financial performance indicators in long-term assets, i.e. the i-SWEAD and ABFAD-solar systems, namely NPV, IRR and DPP, were analysed, where annual constant cash flow was subjected to 9% discount rate and 25 years' lifetime of the systems. Both the i-SWEAD and ABFAD-solar systems are viable projects at the stated discount rate and life span when assessed independently. However, the i-SWEAD system is a more viable project than the ABFAD-solar system since it has a

higher IRR value (16.6%) than the ABFAD-solar system (10.4%). Also, the i-SWEAD system DPP value (eight years and ten months) is lower than its life span, and the NPV is positive (TZS 759 515.7 or €<sub>2017</sub> 330.22), i.e. the system can generate profit for the owner within its lifetime.

In summary, the i-SWEAD system produces high energy for rural semi-arid individual households. It has an investment cost, which is affordable in rural areas. Also, financial analysis results show that the system is viable in economic terms. Therefore, the i-SWEAD system is recommended for application in rural semi-arid areas.

## **6.5 Acknowledgement**

Refer to Section 2.5 in Chapter Two of this thesis.

## 6.6 References

- Aly, A., Bernardos, A., Fernandez-Peruchena, C. M., Jensen, S. S. and Pedersen, A. B. (2018). Is concentrated solar power a feasible option for Sub-Saharan Africa? Investigating the techno-economic feasibility of in Tanzania. [<https://www.sciencedirect.com/science/article/pii/S0960148118311285>] site visited on 19/2/2019.
- Arshad, A. (2012). Net present value is better than the internal rate of return. *Interdisciplinary Journal of Contemporary Research in Business* 4(8): 211-219.
- Askari, I. B. and Ameri, M. (2012). Techno-economic feasibility analysis of stand-alone renewable energy systems (PV/bat, Wind/bat and Hybrid PV/wind/bat) in Kerman, Iran. *Energy Sources, Part B: Economics, Planning, and Policy* 7(1): 45-60.
- Bahramara, S., Moghaddam, M. P. and Haghifam, M. R. (2016). Optimal planning of hybrid renewable energy systems using HOMER: A review. *Renewable and Sustainable Energy Reviews* 62: 609 – 620.
- Blumsack, S. (2020). Project Decision Metrics: Levelized Cost of Energy (LCoE): Energy Markets, Policy, and Regulation (EME 801), *Department of Energy and Mineral Engineering*, College of Earth and Mineral Sciences, The Pennsylvania State University, Pennsylvania, USA, [<https://www.e-education.psu.edu/eme801/node/560>] site visited on 12/09/2020.
- BOT (2018). Bank of Tanzania (BOT)- Annual Report 2017/18, *BOT*, Dar es Salaam, United Republic of Tanzania, ISSN 0067-3757, 102pp. [<http://www.bot.go.tz>] site visited on 14/09/2020.
- Chandel, M., Agrawal, G. D., Mathur, S. and Mathur, A. (2014). Techno-economic analysis of solar photovoltaic power plant for garment zone of Jaipur city. *Case*

*Studies in Thermal Engineering 2: 1 – 7.*

- Cuéllar, A. D. and Webber, M. E. (2008). Cow power: The energy and emissions benefits of converting manure to biogas. *Environmental Research Letters 3*: 034002-034010.
- Ding, W., Niu, H., Chen, J., Du, J. and Wu, Y. (2012). Influence of household biogas digester use on household energy consumption in a semi-arid rural region of northwest China. *Applied Energy 97*: 16 – 23.
- Dundley, D. (2018). Renewable energy will be consistently cheaper than fossil fuels. [<https://www.forbes.com/sites/dominicdudley/2018/01/13/renewable-energy-cost-effective-fossil-fuels-2020/#6bf2c40e4ff2>] site visited on 06/11/2018.
- EWURA (2019). Energy and Water Utilities Regulatory Authority (EWURA) - Annual report for the year ended 30<sup>th</sup> June 2019, EWURA, Dodoma, United Republic of Tanzania. 54pp.
- FAO (2014). *Bioenergy and Food Security Rapid Appraisal User Manual*. Biogas Community, Rome, Italy. 35pp.
- Kalinci, Y., Hepbasli, A. and Dincer, I. (2015). Techno-economic analysis of a stand-alone hybrid renewable energy system with hydrogen production and storage options. *International Journal of Hydrogen Energy 40*(24): 7652 – 7664.
- Marchetti, J. M., Miguel, V. U., and Errazu, A. F. (2008). Techno-economic study of different alternatives for biodiesel production. *Fuel Processing Technology 89*(8): 740-748.
- Masebinu, S. O., Akinlabi, E., Muzenda, E., Mbohwa, C. and Aboyade, A. O. (2017). Techno-Econometric Analysis of Membrane Technology for Biogas Upgrading. In: Ao, S. I., Kim, H. and Amouzegar, M. (eds) *Transactions on Engineering Technologies. WCECS 2015. Springer, Singapore*. [[https://doi.org/10.1007/978-981-10-2717-8\\_34](https://doi.org/10.1007/978-981-10-2717-8_34)] site visited on 19/03/2018.

- Moner-Girona, M., Ghanadan, R., Solano-Peralta, M., Kougiyas, I., Bódis, K., Huld, T. and Szabó, S. (2016). Adaptation of feed-in tariff for remote mini-grids: Tanzania as an illustrative case. *Renewable and Sustainable Energy Reviews* 53: 306 – 318.
- Mundada, A. S., Shah, K. K. and Pearce, J. M. (2016). Levelized cost of electricity for solar photovoltaic, battery and cogeneration hybrid systems. *Renewable and Sustainable Energy Reviews* 57: 692-703.
- NBS (2014). *Tanzania Household Budget Survey 2011/12*. National Bureau of Statistics, Dar es Salaam, Tanzania. 201pp.
- Nguyen. T., Spendelow, J. and Margolis, R. (2014), Levelized costs of electricity from CHP and PV. *Department of Energy*. Program Record (Office of Solar Energy Technologies & Fuel cell Technologies). February 27, 2014. Record#:14003.
- Peterson, P. P. and Fabozzi, F. J. (2002). *Capital Budgeting: Theory and Practice*. John Wiley and Sons, New York. 234pp.
- Quinn, J. C. and Davis, R. (2015). The potentials and challenges of algae-based biofuels: a review of the techno-economic, life cycle, and resource assessment modelling. *Bio-resource Technology* 184: 444 – 452.
- Rafique, M. M. and Bahaidarah, H. M. (2019). Thermo-economic and environmental feasibility of a solar power plant as a renewable and green source of electrification. *International Journal of Green Energy* 16(15): 1577-1590.
- REN21 (2018). *Renewables, 2018 Global status report*. Secretariat, Paris. 237pp.
- Ribeiro, L. A. and Pereira da Silva, P. (2012). Techno-economic Assessment on Innovative Biofuel Technologies: The Case of Microalgae, *International Scholarly Research Notices*, vol. 2012, Article ID 173753, 8 pp. <https://doi.org/10.5402/2012/173753>.
- Schröder, A., Kunz, F., Meiss, J., Mendelevitch, R. and Von Hirschhausen, C. (2013). Current and prospective costs of electricity generation until 2050. (No. 68).

- Data Documentation, DIW Berlin, Germany. 104pp.
- Sinha, S. and Chandel, S. S. (2014). Review of software tools for hybrid renewable energy systems. *Renewable and Sustainable Energy Reviews* 32: 192 – 205.
- TANESCO (2016). Tanzania Electric Supply Company Limited ("TANESCO") Tariff Adjustment Order – 2016, ORDER No. 2016-010, United Republic of Tanzania.
- URT (2013). Labour institutions wage order, Labour institutions act (CAP.300), *Government Notice No.196* of 28/06/2013.
- Wang, X., Kurdgelashvili, L., Byrne, J. and Barnett, A. (2011). The value of module efficiency in lowering the Levelized Cost of Energy of photovoltaic systems. *Renewable and Sustainable Energy Reviews* 15(9): 4248 – 4254.
- Wawa, A. and Mwakalila, S. (2017). Factors affecting the adoption and non-adoption of biogas technology in semi-arid areas of Tanzania. *Journal of the Geographical Association of Tanzania* 37(1): 123 – 132.
- Wiskerke, W. T., Dornburg, V., Rubanza, C. D. K., Malimbwi, R. E. and Faaij, A. P. C. (2010). Cost/benefit analysis of biomass energy supply options for rural smallholders in the semi-arid eastern part of Shinyanga Region in Tanzania. *Renewable and Sustainable Energy Reviews* 14(1): 148 – 165.
- Yoo, S. H., Lee, E. T. and Lee, J. K. (1998). Building-integrated photovoltaics: A Korean case study. *Solar energy* 64(4-6): 151-161.

## CHAPTER SEVEN

### 7.0 Conclusions, Recommendations and Essence of the Thesis

#### 7.1 General Conclusions

Conclusively, inadequate access to energy is still a challenge in most Sub-Saharan Africa (SSA) countries. The phenomenon is evident in rural areas of SSA, where abundant renewable energy resources and sources are available. SSA countries devised several mitigating measures to address the challenge. Progress has been made to counter the insufficient access to energy, for instance, in Tanzania. However, the progress made is slow, and it will not address the challenge by 100% in the soonest time. Some renewable energy-related technologies introduced to increase access to energy in the rural semi-arid areas of central Tanzania, where solar, wind and biomass resources are available, were not efficient and affordable; therefore, their adoption was low. The technology was expensive (introduced in the area under a subsidy scheme), and it had both design and operational problems leading to its low adoption.

This study has produced a novel renewable energy system. The system comprises integrated anaerobic digestion, solar and wind energy, which contributes to addressing the insufficient accessibility to energy in the rural semi-arid areas. In the course of achieving the study's primary goal, several observations, findings, and insights were drawn, and they are summarily presented in this section.

The comprehensive characterization of renewable energy-related resources and sources research approach was formulated and adopted. Adoption of the approach resulted in the identification of several issues. First, it was found out that the study site has quality biomass, i.e. cow dung suitable for biogas generation. The cow dung had a C/N ratio of

19.3, within the recommended C/N ratio of 15-30. Also, the study areas have abundant solar insolation of above 4.5 kW/m<sup>2</sup>/day on average for seven months of the year, which any existing solar energy-based technologies can harness.

Moreover, the annual average wind speed of nearly 4.69 m/s at 4 m hub height is adequate for converting useful and applicable energy. Predominantly wind blows from North East (NE) direction, which must be considered during the installation of renewable energy conversion systems or other engineering structures to ensure their stability and or proper orientation. The study site has a high ambient air temperature variation ( $\pm 4.04^{\circ}\text{C}$  within a day), affecting an uninsulated biogas generation system installed on or above ground.

The formulated and adopted robust adaptation of the anaerobic digestion system research approach has proven its relevancy and usefulness. The decision matrix analysis (DMA) tool is a crucial component of this proven engineering design adaption approach as it enhances unbiased best concept selection. The approach has produced a novel Adapted Batch Fed Anaerobic Digestion (ABFAD) system that addresses operational challenges of existing anaerobic digestion systems' like providing easy recycling of leachate and low-temperature variation for sustainable biogas generation. Furthermore, the system's piping temperature is inversely proportional to CH<sub>4</sub> content regarding the ABFAD system experimental test results. Besides, the pressure sinusoidal form of the curve of the ABFAD system indicates that the system is leaking, while the form of the pressure logistic growth curve indicates that the same system is not leaking.

Additionally, pH is inversely proportional to DO inside the anaerobic digester filled with substrate. Also, the pH is inversely proportional to temperature, while DO is directly proportional to the temperature inside the digester of the ABFAD system. Furthermore,

pH is more sensitive to temperature variation than DO; therefore, pH is a reliable indicator of microbial activities in the ABFAD system. Also, the system is not affected by clogging problems. The results obtained qualify the ABFAD system to be integrated with other renewable energy systems, including solar and wind energy systems.

The integration of the ABFAD system with solar and wind energy systems resulted in developing if integrated solar and wind energy with anaerobic digestion (i-SWEAD) system. The developed i-SWEAD system generates electricity and biogas while maintaining its biogas digester temperature variation at a low level (1.28°C per day). This level of variation is tolerable for microbes responsible for sustainable biogas generation. On the other hand, the i-SWEAD system has a higher biogas yield (0.077m<sup>3</sup>/kg of fresh cow dung) at the hydraulic retention time (HRT) of 92 days compared to other similar biogas systems reviewed with a maximum biogas yield of 0.057 m<sup>3</sup>/kg of fresh cow dung at HRT ranging from 60 days to 120 days. Also, the i-SWEAD system has a biogas production rate of 0.54 m<sup>3</sup>/m<sup>3</sup> of the digester, which indicates that the system has a higher biogas production performance by 34% based on existing AD systems' biogas production rate in semi-arid areas. Furthermore, the i-SWEAD system's components, including a wind turbine, solar PV unit and anaerobic digestion sub-systems, can all be scaled up while considering the limitations on space, cost and complexity of predicting up-scaled system performance.

The ANN modelling technique is useful for building the i-SWEAD system biogas prediction ANN models. It is reliable for handling complex and non-linear data than other modelling techniques like generalized additive modelling, classification and regression trees and multivariate adaptive regression splines for prediction model building. However, these other modelling techniques have application challenges, making them inappropriate to build a model for the i-SWEAD system biogas generation prediction.

The best ANN model (Model4), built by ANN modelling technique, accurately predicts the measured biogas generated by the i-SWEAD system. Reasons are due to its Absolute Mean Percentage Accuracy (AMPA) value of 99%, and the set adequate model prediction capacity criterion of AMPA value being  $\geq 75\%$  for this study. However, Model4 cannot accurately predict measured biogas from the system with the greenhouse effect but without insulation material features since the model was created using the dataset of a system with both greenhouse effect and insulation materials features. Finally, Model4 cannot predict the measured biogas accurately at a low number of observations (36 sampled observations corresponding to almost the first five days of hydraulic retention time).

The techno-economic assessment of the i-SWEAD system was done; it can be concluded that the system has an average life span of 25 years while considering the life span of individual components, which were used to fabricate this system ranging from four years to more than thirty years. The i-SWEAD system has a 0.24 m<sup>3</sup> digester producing appreciable biogas energy of 235.00 kWh/year and both the 20 Wp solar PV module and wind turbine with an average power of 54.00 Wp producing appreciable electrical energy of 31.00 kWh/year.

Furthermore, the investment cost of the i-SWEAD system (TZS 1 136 140.00 or Euro<sub>2017</sub> 493.97) is affordable to communities in the rural semi-arid areas based on the NBS (2014) reporting that the average monthly income per individual household in Tanzania being about TZS 292 500.00 (€<sub>2017</sub> 127.17) and respectively 23.6% and 46.5% of households in rural areas create their investment capital for business start-up from their savings and proceeds from agricultural production. This individual household ability to create its investment makes the same household raise funds for two i-SWEAD systems per year.

The i-SWEAD system's LCoE (TZS 1465.00/kWh or €<sub>2017</sub> 0.64/kWh) is higher than LCoE (maximum TZS 732.80/kWh or Euro<sub>2017</sub> 0.318/kWh) of biomass, solar and onshore wind systems that have been reported in Africa and elsewhere. Therefore, it is a challenge that can be addressed by improving the system performance to lower the LCoE. However, the i-SWEAD system is a technically and economically feasible project based on the system's independent techno-economic assessment results since it has positive NPV (TZS 759 515.7 or Euro<sub>2017</sub> 330.22), higher values of IRR (16%) than 9% of the discount rate of Bank of Tanzania, DPP (eight years and ten months) less than 25 years of an estimated lifetime of the system.

## **7.2 Recommendations**

The findings of this study are the basis of recommendations highlighted in this subsection, as shown hereunder.

The formulated and adopted comprehensive characterization of renewable energy-related resources and sources research approach is recommended to researchers and project developers engaged in assessing and developing renewable energy systems. The systems can be ones adopted for household use in rural semi-arid areas or other similar conditions, where the characterization of local renewable energy resources and weather parameters has not been done and/or the available secondary data are not conclusive for situation analysis. However, the use of this approach should consider any assumption made during its formulation. Any renewable energy system involving a biogas generation unit, which is to be installed above or on the ground in rural semi-arid areas, should be provided with heat insulation facilities because of the high fluctuation of temperature in these areas.

The formulated and adopted robust adaptation of the anaerobic digestion system research approach, which includes the DMA tool, is recommended to researchers and developers of

renewable energy system's projects since it has been proven beneficial and enhances unbiased best concept selection. The piping system for the ABFAD system and the biogas storage is recommended to be kept at a low temperature ( $\leq 21.04^{\circ}\text{C}$ ) to maintain the  $\text{CH}_4$  content at a high level for increased biogas energy density. The ABFAD system's pressure sinusoidal and pressure logistic growth form curves are recommended for checking whether the system is leaking or not, respectively. The ABFAD system pH curve is recommended to be used as the indicator of the operating status of the system's digester. Additionally, the ABFAD system is recommended for generating biogas energy for cooking in individual households, where low-temperature variation  $\pm 3.0^{\circ}\text{C}$  around its digester is ensured. The ABFAD system is recommended to be incorporated in any integrated renewable energy system for sustainable energy supply for cooking, lighting and powering of electric and electronic gadgets.

The new novel i-SWEAD system is recommended for adoption in rural semi-arid areas as it has met its design function of producing energy efficiently. Furthermore, the scaling up of the i-SWEAD system's sub-systems or the whole system is recommended while considering space limitations.

The approach used for building and selecting the best ANN model is recommended to other modellers dealing with renewable energy systems involving biogas production. Also, the developed ANN model, Model4, for predicting biogas generated by the i-SWEAD system is recommended for making informed decisions. Users of this model include policymakers, biogas production investors and other clean energy practitioners who intend to utilise the novel developed i-SWEAD system in rural semi-arid areas or other similar conditions. Model4 is not recommended for predicting biogas collected from the system with the greenhouse effect but without insulation material features or the system with the

low number of data (36 sampled observations corresponding to almost the first five days of hydraulic retention time). However, it is recommended that Model4 be adopted while considering that the model was built based on a dataset of the system with a digester capacity of 0.24 m<sup>3</sup>. Its digester was fed with fresh cow dung aged up to three days, and the cow dung characteristics have approximate total dry matter (DM) of 224 g/kg of cow dung, volatile solid of 691 g/kg of DM, pH of 6.87 and C/N ratio of 18.75.

The i-SWEAD system is recommended for the application of generating clean energy (electricity and biogas) in rural semi-arid areas, where it has been proven to work for enhancing access to energy, and it is technically feasible (efficient) and economically viable (affordable).

It is recommended that most low energy consuming households in rural semi-arid areas of SSA be powered by affordable and efficient renewable energy systems like the i-SWEAD systems. In contrast, the national grid connection should be prioritised for use in industrial zones and institutions with high energy demand.

### **7.3 List of Issues Emanating From the Study for Further Researches**

Here below is a list of research items, which make a point of research interest.

- i. Establishing the relationship between cow dung availability and rainfall, as rainfall affects the grazing of cattle, which produces cow dung in rural semi-arid areas.
- ii. Investigating of digester temperature variation at a different height from digester's bottom during operation of ABFAD system.
- iii. Establishing ABFAD system's optimum amount of steel wool and time to replace it in the system's scrubber, as well as simple means of scrubbing CO<sub>2</sub> from the biogas using cheap locally available materials.

- iv. Developing the improved control mechanism responsible for regulating the heat supply of both wind and solar sub-systems of the i-SWEAD system.
- v. Establishing optimum power coefficient, tip speed ratio parameters and performance curve of the i-SWEAD system's wind turbine.
- vi. Developing another model to predict both biogas and electricity from the i-SWEAD system and other similar systems.

#### **7.4 Summary of the Work and the Essence of the Thesis**

The main results of this PhD thesis are the development of the novel i-SWEAD system, which generates clean energy (electricity and biogas). The system was developed as part of the specific objectives set to address the main challenge of energy accessibility. The work started with specific objective one, which involved the characterisation of the biomass (cow dung) and weather factors related to renewable energy resources. From this objective, it was concluded that the resources available in semi-arid areas are adequate in quantity and quality. These findings were important for highlighting the available opportunities but underutilised in terms of renewable energy resources. The main challenge remained at identifying suitable technologies that can harness the energy resources adequately.

Therefore, the study identified several existing technologies that can harness the resources for energy generation as part of the second objective. Despite the existence of multiple technologies, it was discovered that most of them had limitations in either operation or inadequate coverage of the available resources for energy generation. For the primary three resources of wind, solar and biomass which are abundant in rural semi-arid areas, there was no evidence of the availability of a system that integrated the three resources. Consequently, there was a need of designing the system that integrates the three resources,

and that was the specific objective two. The novel i-SWEAD system was designed, fabricated, and tested for its functionality. It was evident that the system efficiently integrated and utilized the three resources and that it can address the problems of energy accessibility in rural semi-arid areas.

Despite the adequate performance of the i-SWEAD system, further analysis was necessary for adoption and upscaling. In that sense, modelling biogas production of the i-SWEAD system was essential for predicting the i-SWEAD system's biogas performance for new locations, which was the specific objective three. Furthermore, using the ANN modelling technique, the system modelling availed that it could help upscale the i-SWEAD system based on available input information for solar irradiance, wind speed, temperature, and biogas output.

The decision of low-income households to adopt the technology depends on the technology's techno-economic realities. Therefore, objective four was on the appraisal of the i-SWEAD system to check the system's efficiency and affordability. As the novel i-SWEAD system was a new technology, the techno-economic appraisal was necessary for its feasibility and viability as a solution to energy access for rural semi-arid areas.

Thus, the achievements of this study are the formulation and use of a comprehensive characterisation research approach for biomass and weather factors related to renewable energy resources and sources. Other achievements are the formulation and use of a robust adaptation research approach for an anaerobic digestion system for sustainable biogas generation and developing the novel ABFAD system. Moreover, the combination of the design approaches of the i-SWEAD system followed by modelling using the ANN technique to inform decision making for adoption is a novel method and a significant

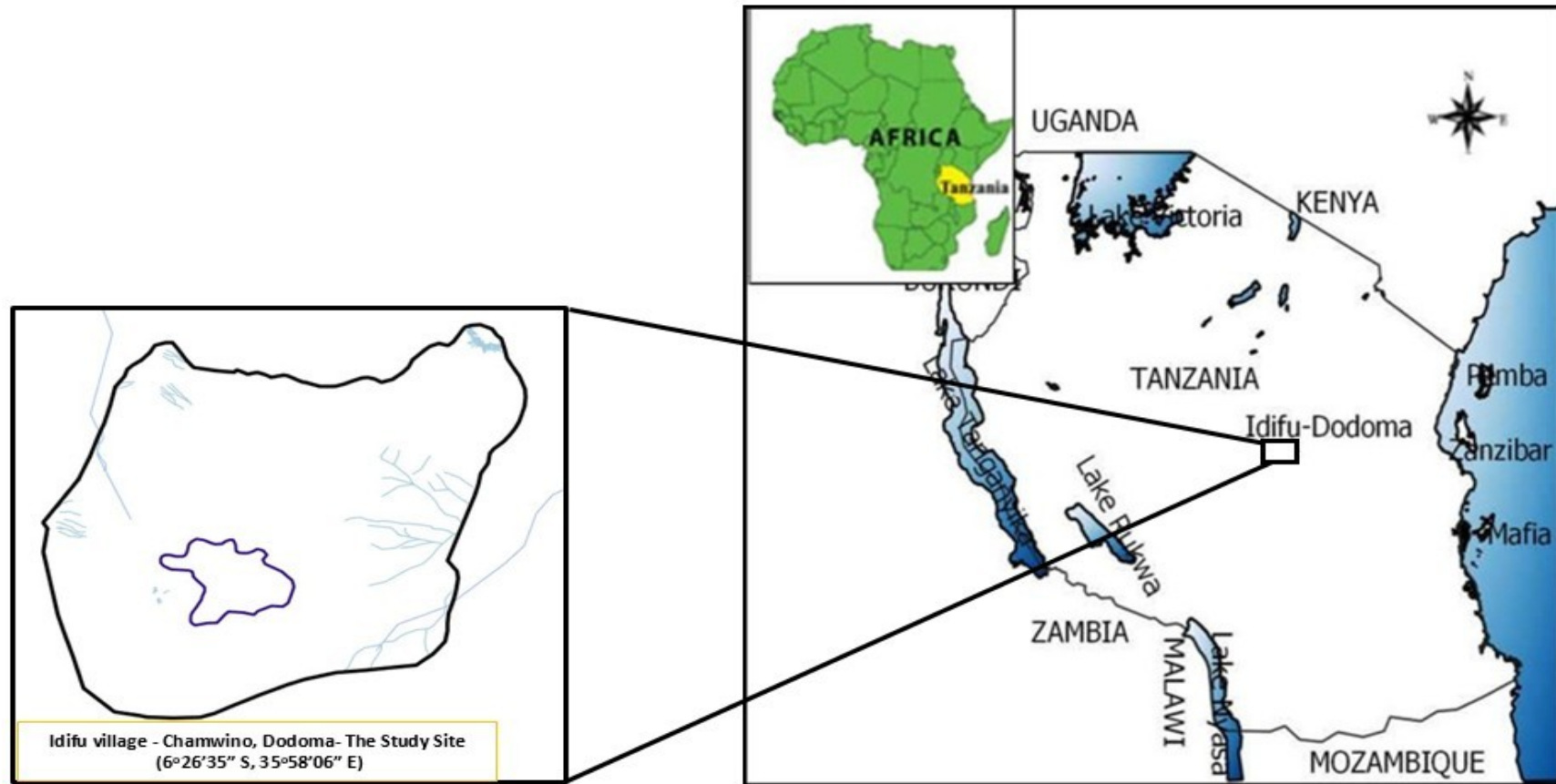
contribution to science. Furthermore, the detailed techno-economic assessment of the i-SWEAD system, which justifies technically and economically applying the system as a feasible and viable project, adds to the achievements of this thesis.

The thesis achievements have provided the basis for making scientific and developmental recommendations. The significant contribution to science includes the formulated approaches for comprehensive characterisation of renewable energy resources, robust anaerobic digestion designs' adaptation and designing of the novel i-SWEAD system, the ANN modelling technique for building the i-SWEAD system's biogas generation prediction model, the techno-economic appraisal of the developed i-SWEAD system, the development of the novel i-SWEAD system and its biogas generation prediction model.

Therefore, the approaches, the system and the model are recommended for application to researchers and project developers of renewable energy-related systems. In developmental terms, the developed i-SWEAD system is recommended to the development stakeholders as one of the energy systems for addressing the insufficient energy accessibility in rural semi-arid areas. Also, the built i-SWEAD system's biogas predictive model is recommended to the policy decision-makers to make an informed decision on the applicability of the i-SWEAD system in the intended areas. Finally, governments are advised to adopt the i-SWEAD systems in rural semi-arid areas due to the low energy demand of most households and currently or soon extending the national grid to such areas is not feasible.

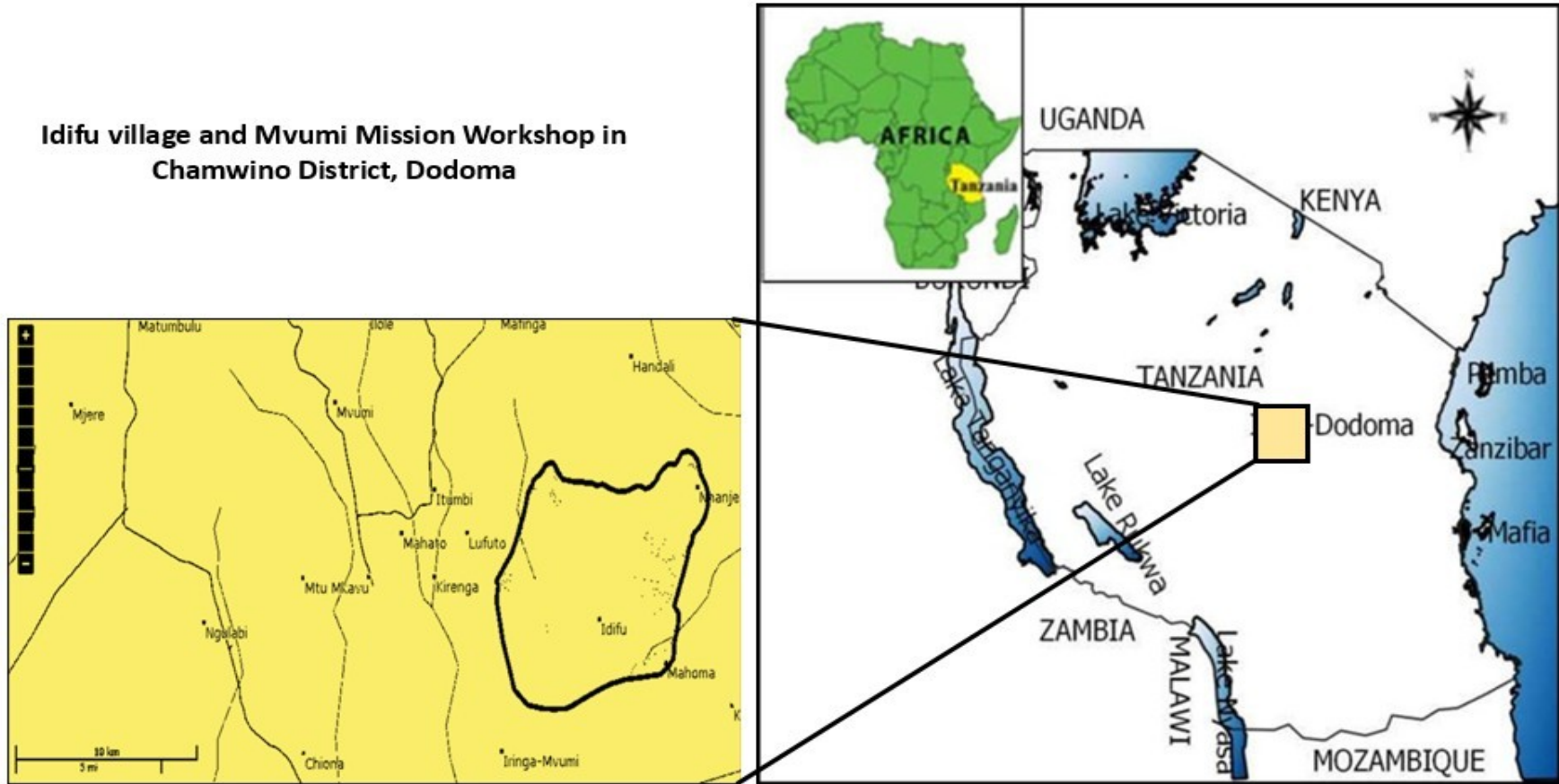
APPENDICES

Appendix 1: The Study site in Idifu Village, Chamwino-Dodoma, Tanzania



**Appendix 2: Idifu Village and Mvumi workshop, Chamwino-Dodoma, Tanzania**

**Idifu village and Mvumi Mission Workshop in Chamwino District, Dodoma**



### Appendix 3: Details of solar PV unit items for i-SWEAD system

Serial Number	Item	Quantity	Description	Specifications
1.	Solar PV module	1	Supplied DC voltage electricity	Power (P): 20 W; Voltage at maximum P: 17.3 V; Current at maximum P: 1.16 A; Open circuit voltage: 21.7 V; Short circuit current: 1.23 A; Production tolerance: +/- 3%, and Manufacturer: OCEANIC.
2.	Charge controller	1	Controlled the charging and discharging of batteries	Voltage: 12/24 V Current: 10 A Power conditioning: pulse width modulation (PMW)
3.	DC-DC converter	1	Reduced system voltage for phone charging	Conversion: 12DC voltage into 5DC voltage
4.	DC bulbs	5	For lighting, one bulb used for the heating purpose of the digester.	Power: 1W
5.	Solar PV module mounting frame	1	Supporting the solar PV module 0.2 m minimally away from the rooftop. It was a slanted frame with four legs.	The material used: Mild steel of 25x25 mm hollow section. Module support Dimension: 0.3x0.4 m Two Short legs length: 0.2 m Two long legs length: 0.3 m
6.	Batteries	2	For storing electrical charges.	Voltage: 12 V Charge: 7 Ampere hour.
7.	Wiring	1	Included switches, connectors and bulb holders.	Conductor: 2.5 mm Switch and Connector: 13 A

#### Appendix 4: Details of solar thermal unit items for the i-SWEAD system

Serial Number	Item	Quantity	Description	Specifications
1.	Greenhouse effect structure (GHES)	1	For solar heat collection, supportive protection of insulation materials, and draining rainwater. It included nails	Outdoor encasing structure (OES) frame side support material: hardwood 75x50 mm OES frame top support material: 200x25 mm softwood OES frame side cover: two galvanized corrugated iron sheets of 3 m and gauge 32 (0.8 mm thick) OES frame top cover: 1.5x0.8 m transparent corrugated fibre sheet with 1.5 mm thick was placed on top at a slope of 2%. OES frame dimension: 1.4x1.4x0.8 m. Nails: ½ kg of 6" size; 1 kg roof nails.
2.	Heat storage part	1	For solar heat storage. It consisted of 14 transparent plastic bottles.	Plastic bottles: each with 0.5 l volume and 0.6 mm thick wall filled by 75% of water Water used: soft water.
3.	Good insulation features	1	For minimizing solar heat loss from the GHES. Two types of insulation features were used.	First insulation feature: 8 mm thick waste boxes wall loose holes were sealed by spent waste mattress Second insulation feature supported by a concrete base and enclosed in the black polyethylene plastic sheet (0.3 mm thick): Approximate 0.20 m thick of loose pearl millet- chaffs were filled into the hole around the periphery of the digester and water trap while 0.1 m compacted pearl millet chaffs being placed at the bottom of the digester.

### Appendix 5: Details of fabricated wind energy sub-system items

S/N	Item	Quantity	Description	Specifications
1.	Wind turbine	1	For harnessing wind energy into mechanical energy. It was made of the hub, blades, rings, blade supports, wind turbine support post, bearing, and tail. Also, it had an effective rotor diameter of 1.62 m while blades, blade handles, hubs and rim amounted to 7 kg.	Hub: 190 mm length hub and its 9.5 mm diameter axle Blades: 3 plastic blades with an approximate size of 150 x 350 mm, cut from a 20 l plastic bucket fixed on three-blade supports Ring: a 660 mm diameter bicycle wheel rim fixed to the hub by forty, 3 mm diameter spokes. Blade supports: twelve 780 x 25 x 25 mm soft wooden blade handles fixed to the rim by 3 mm diameter aluminium wire
2.	Bicycle alternator	1	For the conversion of mechanical energy from the turbine into electrical energy	Power: 6 W; Voltage: 12AC V Rotating head covered by rubber ring with 30 mm diameter and 10 mm thick
3.	Mast	1	For supporting the wind turbine. It consisted of legs fixed into ground bases. Also, it raised the hub height to 4.2 m after fixing a wind turbine support post on it.	Three legs: made of 100 x 50 mm hardwood and had a length range of 2.87 - 3.0 m Three bases: made of concrete with a mix of cement (Simba 32.5R), coarse sand and aggregate (3/4") ratio of 1:2:4. Water cement ratio was approximately 0.7. Each base had 0.4x0.3 m top and deep into the ground by 0.3 m
4	Bulb	1	Conversion of electrical energy from bicycle alternator into heat	Power: 6 W; Voltage: 12 V
5	Tail	1	For tracking wind direction	Material used: 1160 x 100 x 50 hardwood Three wind turbine blades the same as those in serial number 1.
6	Wind turbine support post	1	For carrying the wind turbine, bicycle alternator and tail. It consisted of block bearing and the bearing to allow wind turbine tracking done by the tail	The material used: 1.38x0.10x0.05 m hardwood and 0.50 m length black steel pipe with a diameter of 25 mm Block bearing: 1.6 kg Pillow block bearing (UCFL207). It has a hollow section diameter of 35 mm, bolt size M14, and its housing material was cast iron. Bearing: made chrome steel material and it has 25 mm diameter.

**Appendix 6: Formulae derivation of the system availability**

- i) Consider hydraulic retention time of substrates in the digester, **RT**(day) and cumulative volume of biogas collected in **RT** from the digester, **C**(m<sup>3</sup>).
- ii) Assuming that **RT** is directly proportional to **C**, i.e. **RT**  $\propto$  **C**, then

$$RT = kC \dots\dots\dots \text{Eq. (A1)}$$

where **k** is a constant of proportionality of **RT** and **C**.

From Eq (A1), make **k** the subject of the formulae

$$k = \frac{RT}{C} \dots\dots\dots \text{Eq. (A2)}$$

- iii) Consider the time in hours, **t** (h), of collecting biogas volume, **V** (m<sup>3</sup>); then, using the relationship explained in ii) above and Eq (A2), then **k** can be expressed as follows.

$$k = \frac{t}{V} \dots\dots\dots \text{Eq. (A3)}$$

- iv) Multiply the unity ratio  $\frac{t}{t}$  with the left side of Eq (A1); then combine Equations A1 that has been modified by unity ratio with A3 by eliminating **k** to get the following equation.

$$\frac{t}{t} RT = \frac{t}{V} C \dots\dots\dots \text{Eq. (A4)}$$

- v) By considering several hours of collecting biogas in a day, the unity ratio in Eq (A4) changes into the  $\frac{t}{RT}$  expression.

- vi) By inserting the expression obtained in v) into Eq (A4) and re-arranging the same equation, we get the following formulae.

$$\frac{t}{RT} = \frac{Ct}{V RT} \dots\dots\dots \text{Eq. (A5)}$$

- vii) Illustrating Eq (A5) in terms of the variable units, we get the following expression.

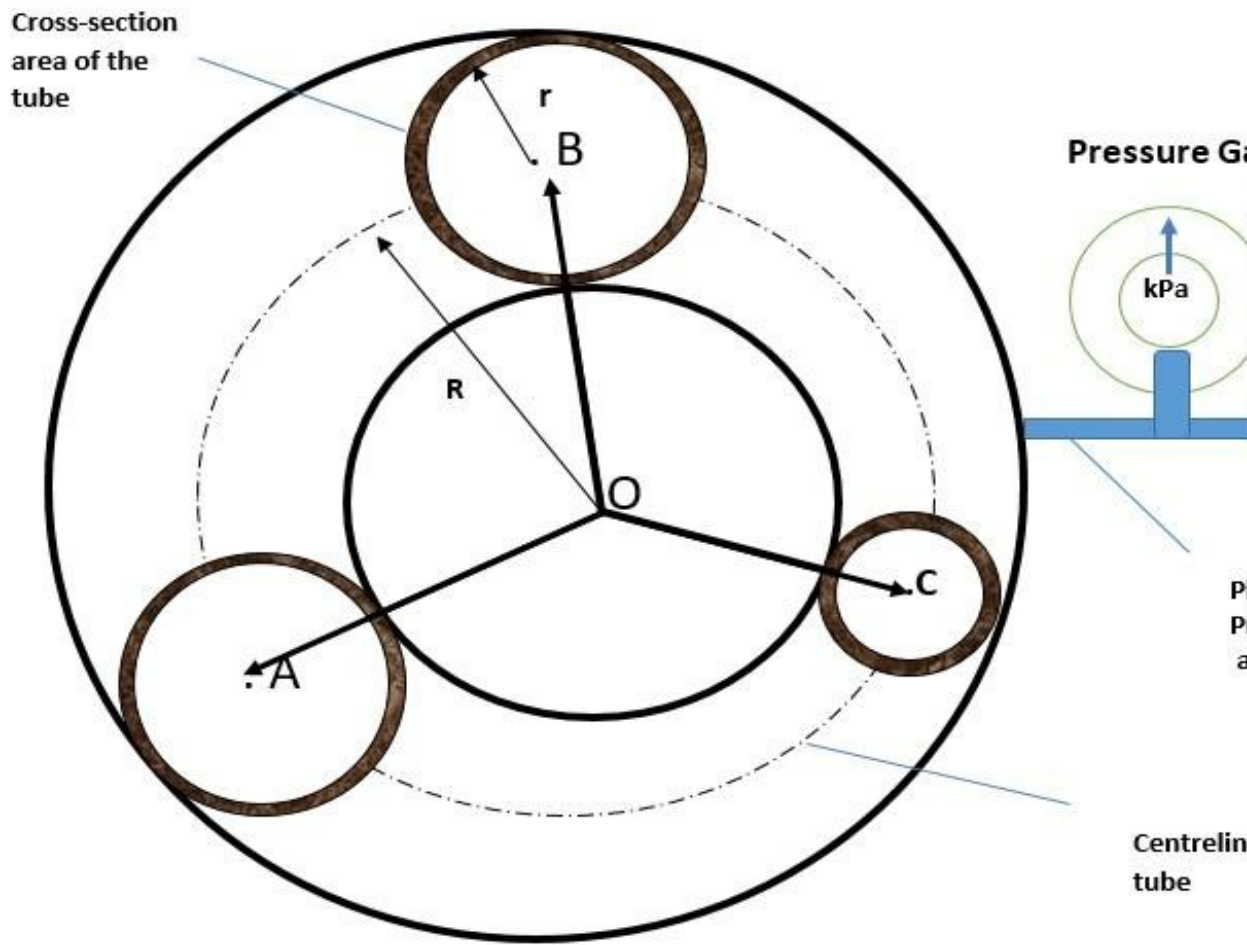
$$\left(\frac{h}{day}\right) = \left(\frac{m^3 \times h}{m^3 \times day}\right)$$

**Appendix 7: Relationship of the volume of biogas collected and measured pressure**

The biogas volume was derived from the relationship of biogas storage volume and pressure measurements during biogas storage's pressure test experiment. The biogas storage used in the experiment was a butyl tube with the size 8.25-15 TR174A. Note that the volume of biogas derived did not include the biogas in the headspace of the digesters and piping system as it was assumed to be constant. Regarding Appendix 8, filling air into the torus tube was done through the pipe connecting the tube and pressure gauge. The tube was air-filled using an Automobile tyre compressor with Model number FS-008B powered by a 12V rechargeable battery at an interval of thirty minutes in increments of 1 kPa after 2 kPa. This time period interval allowed appreciable stretching of the tube and bringing the pressure gauge reading steady. On reaching 9.5 kPa, the filling was stopped, and the tube was left to stretch for the same thirty minutes, whereby in doing so, the pressure dropped to 9 kPa.

At 9 kPa point of pressure, the measurements of room temperature, the torus radius (**R**) and circumferential length around at three cross-section areas ( $C_r$ ) of the tube were done immediately. The circumferential length around three cross-section areas are indicated by points A, B, and C in Appendix 8. The process was repeated to other low-pressure levels, which were reached by dropping pressure at 1 kPa except when 2 kPa was reached and the pressure drop used was 0.5 kPa. The exception was due to the appreciable change of volume of the tube toward 1 kPa level. Finally, six repetitive experiments on three biogas storages of the same type and size were conducted at the study site to get the average values.

**Appendix 8: Sketch of tube torus showing points where measurements were Taken**



Referring to Appendix 8 and using Equation 2.4, the volume of tube torus at pressure  $P$  ( $V_p$ ) was computed based on the average values of  $R$  and the radius,  $r$ , at all three cross-section area points. It was done under the assumptions that both air and biogas are ideal gases without compressibility properties and the atmospheric pressure was the same throughout the six repetitive experiments and during the testing of the i-SWEAD system.

$$V_p = 2\pi R^2 r \dots \dots \dots \text{Eq. (2.4)}$$

$V_p$  is the tube's volume,  $R$  is the torus radius,  $r$  is a radius at the cross-section, and  $\pi$  is 3.1415926.

Furthermore, the measured temperature during the experiment, for all the six repetitive experiments, was found to be an averagely of  $28 \pm 3^\circ\text{C}$ . The plot of the computed volume,

$V_p$ , and measured pressure,  $P$ , is shown in Figure 4.6. Using Microsoft Excel Version (2013), the plot in Figure 4.6 was used to generate a polynomial model equation, which depicts the relation of measured pressure and expected amount of biogas volume in the biogas storage at that same pressure. This relationship helped to get the amount of biogas collected from all systems at a given time in this study.

### Appendix 9: Codes for building and initially assessing Model4 using R-Software

```
> #R Software Codes Used to create and initially assess
  the best Model for the i-SWEAD system and other similar systems biogas production prediction

> #=====

> #DIGESTER FOUR
> #-----
> #ANNmodeling
> #-----

> #Step1: normalizing and scaling data
> maxs4<-apply(ANNFinalModelPhD4,2,max)
> mins4<-apply(ANNFinalModelPhD4,2,min)
> ScaledD4<-as.data.frame(scale(ANNFinalModelPhD4, center=mins4,scale=maxs4-mins4))

> #Step2: Splitting data into training and testing
> #a)prepare data for splitting for results reproducibility
> set.seed(123)
> #b)splitting data
> splitD4 <- sample(seq_len(nrow(ScaledD4)), size = floor(0.75 *nrow(ScaledD4)))
> #TRAINING AND TEST DATA
> D4trainset <- ScaledD4[splitD4,]
> D4testset <- ScaledD4[-splitD4,]
> #-----
```

```

> #c) check the splitting
> #head(D4trainset)
> #-----
> #head(D4trainset)

> #Step3: Choose a number of hidden layers:2

> #Step4: Choose a number of neurons per each hidden layers (4:3 after numerous trials)

> #Step5: Creating a formula to be used in the ANN model generation
> #a) call the names of training data
> nD4 <- names(D4trainset)
> #b) the formula creation
> dfD4 <- as.formula(paste("BiogasVol3hrD4 ~", paste(nD4[!nD4 %in% "BiogasVol3hrD4"], collapse = " +
"")))
> #step6: Creating a model needed
> library(neuralnet)
> d4nnD4 <- neuralnet(dfD4,data=D4trainset,hidden=c(4,3),linear.output=T,threshold=0.01)

> #Step7: Create a model results matrix
> d4nnD4$result.matrix

> #Step8: Generate a visual format of the model (gives an insight of
Model intended)
> plot(d4nnD4)
> #-----

> ####Step9: Cross validation (cv)
> #For neural network model we will use 'for loop'
> #=====
> # For the ANN model, cross-validation, we follow these processes.
> #1. splitting the data in this way: 75% train set and 25% test set in a random way for ten times
> #Calculate the prediction error, Repeat the process ten times
> #Then by calculating the average error we can get a grasp of how the model is doing
> #2. initializing a progress bar using the 'plyr' library for keeping an eye on the status of the process since
the fitting of the neural network may take a while.
>> ScaledD4_<-as.data.frame(scale(ANNFinalModelPhD4, center=mins4,scale=maxs4-mins4))
> library(neuralnet)
> set.seed(450)
> cv4.error <- NULL
> k <- 10
> library(plyr)
> pbar <- create_progress_bar('text')
> pbar$init(k)
  > for(i in 1:k){
+ SplitD4_4 <- sample(1:nrow(ANNFinalModelPhD4),round(0.75*nrow(ANNFinalModelPhD4)))
+ train.cvD4 <- ScaledD4_[SplitD4_4,]
+ test.cvD4 <- ScaledD4_-[SplitD4_4,]
+ d4nnD4 <- neuralnet(dfD4,data=train.cvD4,hidden=c(4,3),linear.output=T,threshold=0.01)
+ pr.d4nnD4_4 <- compute(d4nnD4,test.cvD4[,1:5])
+ pr.d4nncvD4 <- pr.d4nnD4_4$net.result*(max(ANNFinalModelPhD4$BiogasVol3hrD4)-
min(ANNFinalModelPhD4$BiogasVol3hrD4))+min(ANNFinalModelPhD4$BiogasVol3hrD4)
+ test.cvD4.r <- (test.cvD4$BiogasVol3hrD4)*(max(ANNFinalModelPhD4$BiogasVol3hrD4)-
min(ANNFinalModelPhD4$BiogasVol3hrD4))+min(ANNFinalModelPhD4$BiogasVol3hrD4)
+ cv4.error[i] <- sum((test.cvD4.r - pr.d4nncvD4)^2)/nrow(test.cvD4)
+ pbar$step()
+ }
###calculating the average MSE while ensuring convergence state is reached
> mean(cv4.error)

> #Step10: Find (Dv). The model prediction performance and its acceptance limit are explained by under

```

```

and over prediction limit from the value obtained by Percent Deviation (Dv),
> # (((Totalmeasured-Total predicted)/Total measured) X100) =Dv
> #Acceptable limit for the model should have +- 20% of Dv.
> #The lower the value of Dv, the better the model. At <=10%, 10-20% and 20-30% the under or over-
prediction were termed as low (slight), moderate, and severe respectively. (Ludovic Thesis,2015)
> #-----
> #Use test.cvd4.r and pr.d4nncvD4 to find Dv
> Dv_D4<-((sum(test.cvd4.r) - sum(pr.d4nncvD4))/(sum(test.cvd4.r))*100)
> #Result for Dv
> Dv_D4
> data.frame(test.cvd4.r, pr.d4nncvD4)
> #=====

> #Step11: Model efficiency (MEF), measure a fitness of the predicted value to the observed value; MEF
varies from negative infinity for total absence of fit to one for exact fitting (i.e. perfect match of model and
original values)
> #Zero value of MEF indicate that the model predictions are as good as that of 'no knowledge' model
continuously simulating the mean of the observed values.
> #negative value indicate that the model is performing worse than the no
knowledge model (Beven,2001)
> #MEF=(1-((sum(i_obseverd - i_predicted)^2)/(sum(i_observed - (mean(i-observed mean)))))) where i-
number of observations
> MEF4<- (1-(sum((test.cvd4.r-pr.d4nncvD4)^2))/(sum((test.cvd4.r-(mean(test.cvd4.r))^2)))
> MEF4

```

### Appendix 10: Expenses of the i-SWEAD system parts

A SOLAR COMPONENT-Solar PV (cost as of the year 2017)								
Serial Number	Item	Quantity	Description	Specifications	Unit price	Quantity	Cost (TZS)	Euro
1	Solar PV module	1	Supplied DC voltage electricity	Power (P): 20 W ;  The voltage at maximum P: 17.3 V ;  Current at maximum P: 1.16 A ; Open circuit voltage: 21.7 V ; Short circuit current: 1.23 A ; Production tolerance: +/- 3%, and Manufacturer: OCEANIC® .	55 000.00	1	55 000.00	23.91
2	Charge controller	1	Controlled the charging and discharging of batteries	Voltage: 12/24 V  Current: 10 A  Power conditioning: pulse width modulation (PWM)	14 500.00	1	14 500.00	6.30
3	DC-DC converter	1	Reduced system voltage for phone charging	Conversion: 12DC voltage into 5DC voltage	6 000.00	1	6 000.00	2.61
4	DC bulbs	5	For lighting one bulb used for heating purpose of the digester	Bulb Power: 1W	2 850.00	5	14 250.00	6.20
5	Solar PV module mounting frame	1	It was supporting the solar PV module 0.2 m minimally away from the rooftop. It was a slanted frame with four legs.	The material used: Mild steel of 25x25 mm hollow section. Module support Dimension: 0.3x0.4 m  Two Short legs length: 0.2 m Two long legs length: 0.3 m	45 000.00	1	45 000.00	19.57
6	Batteries	2	For storing electrical charges	Voltage: 12 V  Charge: 7 Ampere hour (Batteries).	17 500.00	2	35 000.00	15.22
7	Wiring	1	Included switches and	Conductor: 2.5 mm				

connectors	Switch and Connector : 13 A	30 000.00	1	30 000.00	13.04
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**TOTAL**

**199**  
**750.00** 86.85

**B SOLAR SUB-SYSTEM-Solar thermal unit (cost as of the year 2017)**

Serial Number	Item	Quantity	Description	Specifications	Unit price	Quantity	Cost(TZS)	Euro
1	Greenhouse effect structure(GHES)	1	For solar heat collection, supportive protection of insulation materials; and draining rainwater. It included nails.	Outdoor Encasing Structural (OES) frame side support material: hardwood 75x50 mm	6000.00	3	18 000.00	7.83
				OES frame top support material: 200x25 mm softwood	12 500.00	2	25 000.00	10.87
				OES frame side cover: two galvanized corrugated iron sheets of 3 m and gauge 32 (0.8 mm thick)	15 000.00	2	30 000.00	13.04
				OES frame top cover: 1.5x0.8 m transparent corrugated fibre sheet with 1.5 mm thick was placed on top at a slope of 2%. (Unit price per metre)	16 700.00	1.5	25 050.00	10.89
				OES frame dimension: 1.4x1.4x0.8 m. Nails: ½ kg of 6" size; 1 kg roof nails.	3500.00	1.5	5250.00	2.28
2	Heat storage part	1	For solar heat storage. It consisted of 14 transparent plastic bottles.	Plastic bottles: each with 0.5 l volume and 0.6 mm thick wall filled by 75% of water	-	14	-	-
				Water used: soft water (7 litres).	-	7	-	-
3	Good insulation features	1	For minimizing solar heat loss from the GHES. Two types of insulation features were used.	First insulation feature: 8 mm thick waste boxes wall loose holes were sealed by spent waste mattress (unit price per square metre)	1500.00	5.09	7635.00	3.32

Second insulation feature supported by the concrete base and enclosed in the black polyethylene plastic sheet (0.3 mm thick) of pearl millet chaffs amounting seven buckets of 20 l each making a compacted thickness of 0.1 m. Also, a loose pear millet chaffs amounting three buckets of 20 l each of approximate 0.20 m thick were filled into the hole around the periphery of the digester and water trap. All were obtained freely.

- 10 - -

**TOTAL****110 935.00 48.23****C WIND ENERGY SUB-SYSTEM (cost as of the year 2017)**

S/N	Item	Quantity	Description	Specifications	Unit price	Quantity	Cost(TZS)	Euro
1	Wind turbine	1	For harnessing wind energy into mechanical energy	Hub: 190 mm length hub and its 9.5 mm diameter axle	6000.00	1	6000.00	2.61
			It was made of the hub, blades, rings, blade supports, wind turbine support post, bearing, and tail.	Blades: 3 plastic blades with an approximate size of 150 x 350 mm, cut from a 20 l plastic bucket fixed on three-blade supports.	850.00	3	2550.00	1.11
			Also, it had an effective rotor diameter of 1.62 m while blades, blade handles, hubs and rim amounted to 7 kg.	Ring: a 660 mm diameter bicycle wheel rim fixed to the hub by forty, 3 mm diameter spokes (spokes and rim).	24 000.00	1	24 000.00	10.43
				Blade supports: twelve 780 x 25 x 25 mm soft wooden blade handles fixed to the rim by 3 mm diameter aluminium wire	1300.00	12	15 600.00	6.78
2	Bicycle alternator	1	For conversion of mechanical energy from turbine into electrical energy	Power: 6 W; Voltage: 12AC V	7000.00	1	7000.00	3.04

				Rotating head covered by rubber ring with 30 mm diameter and 10 mm thick	1000.00	1	1000.00	0.43
3	Mast	1	For supporting the wind turbine	Three legs: made of 100 x 50 mm hardwood and had length range of 2.87 - 3.0 m	6000.00	4	24 000.00	10.43
			It consisted of legs fixed into ground bases.	Three bases: made of concrete with a mix of cement (Simba 32.5R), coarse sand and aggregate (3/4") ratio of 1:2:4. Water cement ratio was approximately 0.7. Each base had 0.4x0.3 m top and deep into the ground by 0.3 m	30 000.00	1	30 000.00	13.04
			Also, it raised the hub height to 4.2 m after fixing a wind turbine support post on it.					-
4	Bulb	1	Conversion of electrical energy from bicycle alternator into heat	Power: 6 W; Voltage: 12 V	-	1	-	-
5	Tail	1	For tracking wind direction	Material used: 1160 x 100 x 50 hardwood				-
				Three wind turbine blades the same as those in serial number 1.	9 000.00	1	9000.00	3.91
6	Wind turbine support post	1	For carrying the wind turbine, bicycle alternator and tail. It consisted block bearing and the bearing to allow wind turbine tracking done by the tail	The material used: 1.38x0.10x0.05 m hardwood and 0.50 m length black steel pipe with a diameter of 25 mm	10 000.00	1	10 000.00	4.35
				Used Block bearing: 1.6 kg Pillow block bearing (UCFL207). It has a hollow section diameter of 35 mm, bolt size M14, and its housing material was cast iron. Bearing: made chrome steel material and it has 25 mm diameter.	9000.00	1	9000.00	3.91

<b>TOTAL</b>								<b>138 150.00</b>	<b>60.07</b>
<b>D ANAEROBIC DIGESTION SUB-SYSTEM (cost as of the year 2017)</b>									
S/N	Item	Quantity	Description	Specifications	Unit price	Quantity	Cost(TZS)	Euro	
1	Digester,	1	For handling anaerobic digestion. It consisted of a central plastic perforated core pipe with four wings, the high-density polyethylene plastic barrel, top, lid, iron bar frame for holding together the top lid and the plastic barrel.	Central perforated core pipe: with length, wall thickness, and diameter, of 0.85, 0.0015, and 0.1 m, respectively while its perforated holes were spaced at 0.05 m, c/c had 0.01 m diameter.	6000.00	1	6000.00	2.61	
				Wing: with length, wall thickness, and diameter of 0.275, 0.001, and 0.03 m, respectively while its perforated holes were spaced at 0.05 m c/c had 0.01 m.	2000.00	1	2000.00	0.87	
				HDEP plastic barrel: with volume, height, middle diameter and a wall thickness of 0.24 m <sup>3</sup> , 1.0 m, 0.58 m and 0.0022 m, respectively while taped on top to 0.48 m diameter. Also consists top lid made of plastic with 0.48 m diameter and 0.00m thick.	75 000.00	1	75 000.00	32.61	
				Iron bar frame: made of mild steel flat with a width of 25 mm and thickness of 2 mm (see Plate 3.1) and fixed by two types of Galvanised Class 4.6 bolt M8x150 and M8x25 while nuts were of M8 size.	15 000.00	2	30 000.00	13.04	
2	Water trap,	1	For screening Carbon dioxide and water vapour from biogas. It was filled	Fittings and their sizes: 2 nipples of ½"; 2 reducer bush of 1 - ½", three reducer bush of 1 ½ - 1", one	26 200.00	1	26 200.00	11.39	

			with 140 ml soft water and consisted of IPS plastic pipe, flexible pipes and fittings. All fittings were of IPS type.	socket of 1 ½", one plug of 1" and one tee-joint of 1 ½",					
				IPS pipe: 0.5 m length and diameter of 38.1 mm.	8500.00	1		8500.00	3.70
				Flexible pipe: 0.6 m length and 2 mm diameter	2100.00	1		2100.00	0.91
3	Scrubber,	1	For trapping hydrogen sulphide from biogas. It was filled with steel wools. It consisted of a number of fittings.	Fittings and their sizes: 2 nipples of ½"; 2 reducer bush of 1 - ½", two reducer bush of 1 ½ - 1" and two sockets of 1 ½" and union 1 1/2".	27 000.00	1		27 000.00	11.74
				2 IPS pipes: 0.2 m length and 38.1 mm in diameter	1700.00	1		1700.00	0.74
				Steel wool: 2 small packages	500.00	1		500.00	0.22
4	Biogas Storage,	1	It is storing biogas ready for use. Two of them are needed where one is kept for reserves if the production of biogas is higher than its utilization.	Butyl inner tyre tube: torus tube with the size of 8.25-15 and truck valve model number TR174A	30 000.00	1		30 000.00	13.04
5	Pressure Gauge	1	Indicating instantaneous pressure and amount of biogas available in the system.	One Pressure gauge: Sim Gas product Pressure gauge with accuracy of 0.5 kPa (www.simgas.com)	10 000.00	1		10 000.00	4.35
6	Cooking Stove.	1	For converting biogas into heat energy	1 CAMARTEC biogas cooking stove. It can support up to 30 kg of weight.	50 000.00	1		50 000.00	21.74
7	Piping System	1	Transporting biogas from the digester to the storage then to the cooking stove through water trap and scrubber.	Fittings: 1 tank connector of ¾", one reducer of ¾ - ½", 12 nipples of ½", two elbow ½", five gate valves of ½", four unions of ½", two tee-joints of ½", one socket of ½", and two clamps of rang ½-1".	93 000.00	1		93 000.00	40.43
			It consists, IPS pipes,	Flexible pipe: 4 pieces of plastic	15 000.00	3		45 000.00	19.57

			flexible pipes, and fittings.	base pipe of ½” with 0.6 m and one piece of hose synthesised pipe of ½” with 1.0 m length				
8	Supporting Base	1	For carrying i-SWEAD system digester and water trap. It was placed in a hole with dimensions of 0.8 x 0.8 x 0.5 m	Piled layers: the lean concrete (M10) with cement sand aggregate ratio of 1:3:6 (0.1 m thick); 0.3 mm thick polyethylene plastic sheet covering the whole hole; 0.8 mm thick waste box of 0.75 x 0.75 m and loose pearl millet chaffs (0.1 m thick).	19 850.00	1	19 850.00	8.63
<b>TOTAL</b>							<b>426 850.00</b>	<b>185.59</b>

### Appendix 11: Cost Analyses results of the i-SWEAD and ABFAD Systems

Serial Number	Cost Factor	System	
		The i-SWEAD	The ABFAD-Solar
1	Total energy (kWh)	266.68	239.29
2	Labour charge DEM (TZS/man-hour)	200 000.00	200 000.00
3	Time DEM(h/kWp)	8.00	8.00
4	Operation time in year (45%)	3942.00	3942.00
5	Rated Power(kWp)	0.07	0.06
<b>6</b>	<b>(a) DEM cost (TZS)</b>	<b>108 241.50</b>	<b>97 124.30</b>
7	Labour charge Installation (TZS/man-hour)	150 000.00	150 000.00
8	Time Installation (h/kWp)	15.00	15.00
<b>9</b>	<b>(b)Installation cost (TZS)</b>	<b>152 214.61</b>	<b>136 581.05</b>
10	Fabricating Solar PV unit cost (TZS) - refer Appendix 9	199 750.00	199 750.00
11	Fabricating Solar thermal unit cost (TZS) - refer Appendix 9	110 935.00	110 935.00
12	Fabricating Anaerobic Digestion sub-system cost (TZS) - refer Appendix 9	426 850.00	426 850.00
13	Fabricating Wind energy sub-system cost (TZS) - refer Appendix 9	138 150.00	0.00
<b>14</b>	<b>(c)Total system fabricating cost (TZS)</b>	<b>875 685.00</b>	<b>737 535.00</b>
	<b>TOTAL INVESTMENT, I, (TZS)</b>	<b>1 136 141.11</b>	<b>971 240.35</b>
15	Fixed cost-system's attendant wage (TZS/year)- TZS 15 000.00/month	180 000.00	135 000.00
16	Collecting and loading system's digester cost (TZS/year)-TZS 2400.00/loading and unloading task	4800.00	4800.00
17	Replacing the bulb and the batteries after five years cost (TZS/year)-refer to Appendix 9	9850.00	9850.00
18	Replacing the systems' pipes and gate valves after seven years cost (TZS/year)-refer to Appendix 9	19 714.29	19 714.29
19	Replacing of scrubber's iron wools and wind turbine's cap generator rubber four times per year cost (TZS/year)-refer to Appendix 9	6 000.00	2000.00
	<b>Total O&amp;M cost, O, (TZS/year)</b>	<b>220 364.29</b>	<b>171 364.29</b>