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Smart metering and remote monitoring for biogas production and management: Small scale biogas plants as a case for the study.

J Ntaganda[1,2*], G Gasore[2], E Twahirwa[3], I I Mwaisekwa[3], H E Kapalamula[3] and T Kabera[4]

[1]Chalmers University of Technology, Department of Space, Earth and Environment, Division of Energy Technology, SE- 41296, Gothenburg, Sweden.
[2]University of Rwanda, African Centre of Excellence in Energy for Sustainable Development (ACE-ESD), P.O.BOX 3900, Kigali, Rwanda.
[3]University of Rwanda, African Centre of Excellence in Internet of Things (ACE-IoT), P.O.BOX 3900, Kigali, Rwanda.
[4]University of Rwanda, School of Engineering, Department of Civil, Environmental and Geomatics Engineering, P.O.BOX 3900, Kigali, Rwanda.

*E-mail: ntaganda@chalmers.se

Abstract. Biogas potential assessments indicate that low-income countries have biogas resource potential to substantially contribute to the clean cooking transitioning and also reduce carbon emissions linked to the use of solid biomass as cooking fuels. However, the estimated biogas potentials have not been harnessed, and its contribution to the clean cooking targets remains off-targets. Literature often focuses on barriers to the technology adoption and diffusion. There is lack of mechanisms to monitor the gas production and management, specifically at small scale use. This study combines smart biogas metering and remote monitoring of biodigester conditions to ascertain user-end dynamics for a family-sized biodigesters use. Daily biodigesters' health is remotely monitored using IoT device. Biogas production, usage, leakage, and venting are used to study the role of technology biogas production and management and its contribution to clean cooking pathways , as well as Green House Gas (GHG) emissions mitigations. Findings indicate that the success of the technology is not only hindered by barriers reported in literature. Rather, user practices affect the biogas production and management. Results emphasise the need for developing mechanisms to enhance energy demand side management, irrespective of the primary resource, resource-to-energy conversion technology, and scale of use.

1. Introduction

Household biogas production has gained a considerable attention as a viable and sustainable household energy solution in low-income countries [1]. Through anaerobic digestion of organic waste materials such as agricultural residues, animal manure, and kitchen waste , biogas—a mixture gases predominantly composed of methane (CH_4) and carbon dioxide (CO_2) is produced [2]. Small-scale biogas digesters suitable for individual households are used to convert these waste materials into a clean and renewable source of energy, which can be used at a household scale , mainly for cooking. Various types of biogas digesters have been developed and optimised for household use. According to Rao et al.[3], fixed-dome, floating-drum and polyethene-made digesters are the mostly used designs in low-income countries.

Studies have shown that biogas systems can significantly reduce household expenditure on traditional fuels such as wood and charcoal. I has been demonstrated that households using biogas save time and money by not having to purchase or collect firewood, which can be redirected towards other productive activities. Household biogas systems have profound social impacts, particularly on health and gender equity. The use of biogas for cooking significantly reduces indoor air pollution, which is linked to respiratory and cardiovascular diseases. Bonjour et al. [4] highlighted that switching to biogas can reduce the incidence of such health issues, thereby improving the quality of life for rural families. Additionally, biogas systems alleviate the burden on women and children, who are typically responsible for collecting firewood, thus allowing more time for education and other activities. Katuwal, H. and Bohara, A. K.[5] hights the environmental benefits of household biogas production are significant. Biogas systems help in reducing deforestation and mitigating greenhouse gas emissions by replacing traditional biomass fuels. Furthermore, the digestate produced as a byproduct of anaerobic digestion is a valuable organic fertiliser that enhances soil fertility and reduces the need for chemical fertilisers [3]. This integrated approach to energy and agricultural production promotes sustainable land use practices.

Despite the forementioned advantages of household hold biogas technology, several challenges hinder the widespread of its adoption and use in low-income countries, and there is an increase of cases where the technology had been adopted but now being abandoned, more specifically in the sub-Saharan Africa (SSA) [6]. Available literature mostly focus on challenges related to economic, social, policy aspects, and technical [7]. One of the primary technical challenges is the maintenance and durability of biogas digesters. Biodigester structures often suffer from construction flaws and material degradation over time. According to L. Ioannou-Ttofa et al. [8], technical failures such as gas leakages and digester cracks are common, leading to reduced efficiency and operational problems. Additionally, the variability in feedstock quality and quantity can significantly affect biogas production rates.

In light of forementioned challenges, effective pre-treatment methods and regular monitoring are necessary to ensure consistent biogas yields, but these require technical expertise that is often lacking in rural areas. Despite the ever-increasing use internet of things (IoT), data sensor networks (DSNs), and smart metering for remote data acquisition and monitoring, there has been little attention to use such information technologies for the proper monitoring of the small scale biodigester health as well as the user-end dynamics to enhance timely interventions. This has led to contradictions between the technology policy implementation and the technology users stemming from lack of data to explain underlying technical issues. The aim of this study is to ascertain user-end dynamics for family-sized biodigesters by using smart metering for biogas production and use. IoT system is also used to for remote data monitoring of biodigester conditions.

2. Methodology

This study used heuristic approach which resulted into different data sets. First , after a review of challenges of household biogas technology, it was imperative to carryout national survey in a specific country. As such, a national survey was conducted in Rwanda as case study to understand the trends of household biogas use in SSA. The IoT and DSNs were used to gather data on biodigester heath and smart meter was used to monitor gas production and use.

2.1. National surveys in case study country

Rwanda was chosen from SSA as the case study due to its small size and its documented national domestic biogas programme. After reviewing policy papers, audit reports, scholarly work related to biogas production and use in Rwanda, it was established that the high failure rates and technology abonnement was alarming, thus calling further research. A total of 10,701 domestic deployed domestic biogas plants was obtained from national data hosted by Rwanda's Energy development cooperation limited (EDCL), a subsidiary of the Rwanda energy group, in charge of energy project development.

2.1.1. Determining the sample size.
Considering underlying differences in terms of temperatures and geographical location of acquired database, the stratified random sampling technique was applied to determine respondents (household/units) of deployed biogas plant to be surveyed countrywide and in each district. Because the total population is known, sample size determination of the biogas plants was computed using guidelines on research sample provided by Berman H.B [9], and 376 household were surveyed.

2.1.2. Deploying enumerators during data collection
While data collection is increasingly collected using android and other portable devices, the budget for printing was more affordable than handheld gadgets. Data was collected by nine (9) enumerators deployed in respective districts in December of 2021. Deployment sheet contained contacts and location of all randomly selected respondents. Collected data by use of structured questionnaire were gathered for data entry. Data types gathered are qualitative , quantitative and GIS waypoints indicating exact locations. GPS waypoints were consolidated for spatial visualisation of the households related to data collected. Spatial representation of site surveyed are presented in Figure 1.

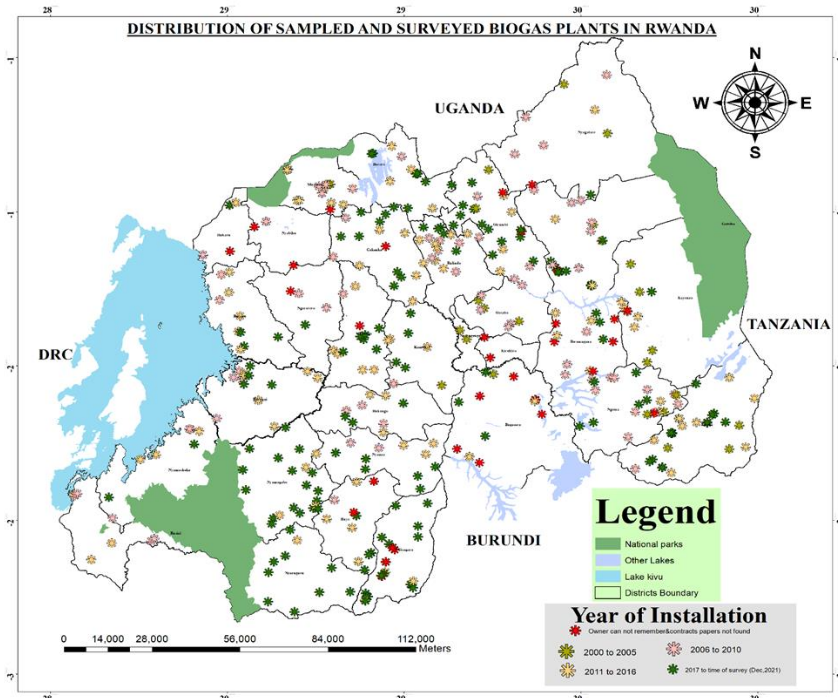

Figure 1. Surveyed sample of households which used biogas technology between 2000 and 2021 and their deployment trends.

2.2. Deployment of remote data acquisition systems
After analysing the national deployment of household biogas plants in the case study country (Rwanda) , it was observed that a deeper analysis was needed because there was no sufficient and objective data to explain why some biodigester were nonfunctional while others with similar volumetric sizes, technology and within close vicinities were still functional. This motived the

deployment of two subsystems to be integrated from 2022 to 2024. The two subsystems formed an integrated smart metering and remote monitoring systems to remotely monitor biodigester health and gas production and use on daily basis.

2.2.1. Deployment of IoT system

The Internet of Things (IoT) is the interconnection of embedded physical devices with sensors, software, and other technologies which enable them to collect and exchange data over the internet. Data sensor networks are critical components of IoT. They consist of spatially distributed sensors that gather and transmit data about environmental conditions, equipment status, and other variables to centralised systems for processing and analysis. This synergy between IoT and data sensor networks have enhanced operational efficiency, decision-making, and innovation in fields such as smart cities, healthcare, and agriculture[10],[11]. By leveraging the increased use of IoT and DSNs, four household biogas plants were constructed on four chosen sites, each site in four provinces of Rwanda. The four household biogas plants were constructed to incorporate the data acquisition systems in four spatially distributed provinces of Rwanda. Figure 2 (c) indicates the four locations in the northern, western, eastern, and southern provinces of Rwanda where the research sites are located. A prototype of the IoT system was developed at the University of Rwanda's IoT Lab for monitoring biodigester health. The first phase of the project, presented in this paper tracks pH, temperature, and humidity, with plans to add sensors for carbon and nitrogen levels to calculate the C/N ratio. The system alerts household biogas technology users, researchers, and technology monitoring personnel when parameters exceed normal ranges. The system includes a microcontroller, pH sensors, weatherproof temperature and humidity sensors, and a GSM (SIM800L GSM/GPRS) module for communication. It is powered by a rechargeable battery charged by a 50W solar panel. Figure 2 (a) shows the circuit design for IoT system while Figure 2 (b) depicts the IoT system designed and assembled for remote monitoring of biogas plants. The IoT system features a printed circuit board with an ESP32 microcontroller, SHT30 sensors for internal temperature and humidity, a pH meter, and a DHT22 sensor for external conditions, ensuring precise monitoring.

(a) Printed circuit design (b) IoT system assembly (c) system deployment sites

Figure 2. IoT development and deployment for remote biogas plant condition monitoring

The selection of programming languages, frameworks, and libraries was guided by the need for compatibility with hardware platforms and sensor interfaces. Key criteria included ensuring seamless integration, real-time data processing, and visualization to derive actionable insights. The software implementation involves developing firmware for the ESP32 microcontroller to manage data tasks efficiently. Sensor libraries and data logging algorithms are integrated to enhance data capture and processing precision. For reliable data transmission, GSM-based communication was chosen due to its extensive coverage in Rwanda, which is essential for remote areas with limited internet connectivity. The SIM800L GSM module was integrated to provide SMS-based data transmission, ensuring redundancy, and minimizing data loss. TCP/IP protocols were implemented to secure data transmission over cellular networks, ensuring data integrity and confidentiality. Configuration was done using Blynk, an IoT mobile application that facilitates prototyping, deployment, and remote management of IoT systems. Blynk enables real-time data visualisation of all monitored parameters, while the GSM module notifies users and monitoring officers via SMS.

2.2.2. Deployment of smart metering system

While the biodigester heath was monitored using the designed IoT device and connected DSNs, in order to build a robust and more reliable system , a smart meter was procured and configured between the biodigester output the biogas stove (biogas burner) at the kitchen end. For the purpose of counter verification, an analogue meter was configured aside of the smart and digital meter. This was to ensure and verify the accuracy of collected from smart meter.

(a)Analogue pressure meter (b) Smart meter. (c) biogas burner (stove) at kitchen end

Figure 3. Analogue and smart meters configured side by side at the kitchen end. Analogue meter was used for instant verification during site visits while smart meter was used for remote monitoring.

3. Results analysis and discussion

Results from the study indicated three main findings. First, the main findings from the national household survey are presented, followed by the findings from IoT and DSNs, and then the household production and use are also analysed and discussed.

3.1. Results from the survey

Results for the household national survey indicated that the national deployment was dominated by the fixed dome type of technology, followed by flex bag also known as canvas. Fiber glass was found to be rare in Rwanda. Semi structured interview from experts in the field of small scale biodigester technologies indicated that fixed dome biodigesters are durable, requires low-maintenance, and are suitable for long-term use, particularly in stable temperature environments. They have higher initial construction costs but offer consistent performance and low operational costs over time. Fiberglass biodigesters, on the other hand, are easier and quicker to install, lightweight, and flexible in terms of location. However, they can be fragile, require careful handling, and have higher repair and maintenance costs. As such, fixed dome was preferred over Fiber glass. The flex bags made of polyethene bag became popular in 2014. The technology diffusion trend and respective biodigester types are depicted in Figure 4.

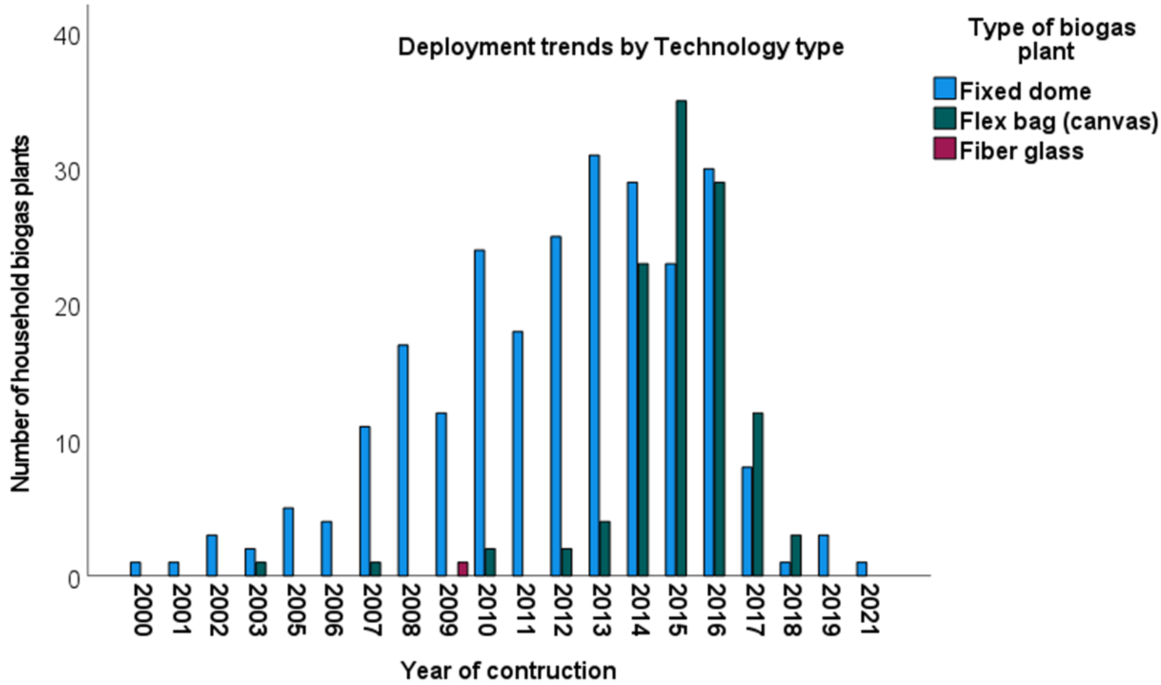

Figure 4. Survey results indicating technology deployment trends and deployed biodigester technologies.

The overall technology diffusion sharply fell to nearly zero by the year of the survey (December 2021). This was mainly due to a big number of nonfunctional biogas technologies but the cause for their failure were mostly subjective. Users claimed that the technology was not customised to their cooking practices while technology monitoring officers claimed the users lacked a sense of ownership. Because of the subjectivity, and insufficient data, it was imperative to use objective data from IoT and smart metering.

3.2. Results from biodigester health monitoring

Results from IoT and DSNs indicated that pH range in the biodigester was in the optimal pH range (6.5 to 8.0) as indicated in Figure 5. The temperature inside the biodigester (dome) fell in the mesophilic range 20°C to 45°C (68°F to 113°F) as depicted in Figure 6. The mesophilic is the most common temperature range used in anaerobic digestion. Mesophilic digestion is relatively stable compared to thermophilic digestion.

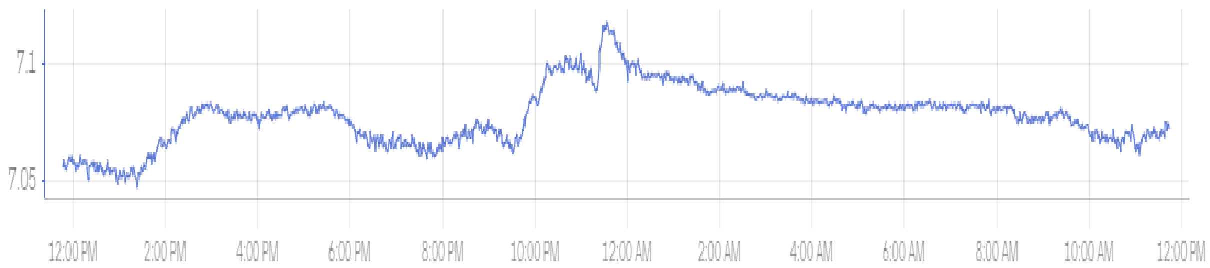

Figure 5. Biodigester pH data remotely captured by pH sensors and sent to remote monitoring offices.

The process within mesophilic range is slower than thermophilic digestion but provides a good balance between biogas yield, stability, and energy input. To ensure that the pH does not fall below 6.5 or rise above 8.0 to maintain microbial activity and biogas production efficiency, the

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SMS alerts were sent to researchers and technology monitoring officers for interventions as shown in Figure 6.

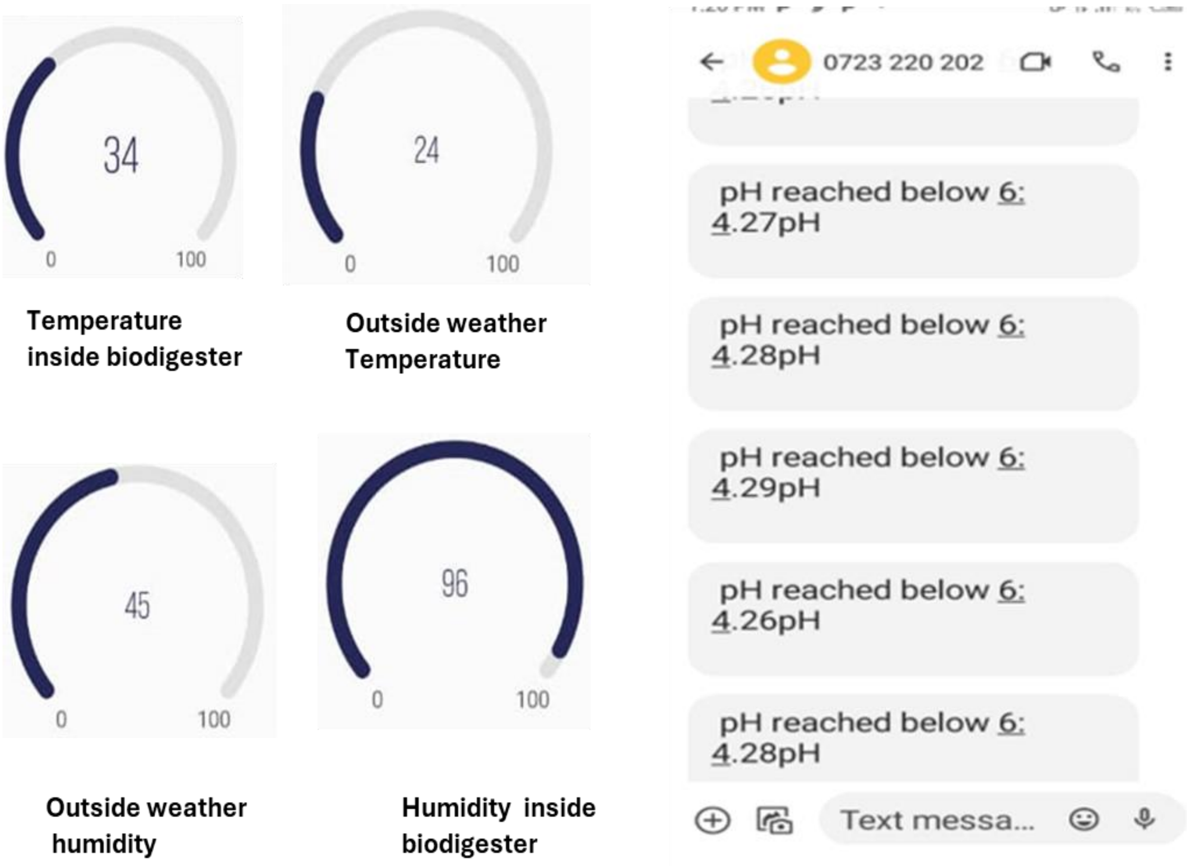

Figure 6. Dashboard reading from the DSNs indicating dome humidity, temperature, and pH. Alerting SMS are sent when parameters values fall out of normal operation range.

3.3. Results from biogas production and use.

Despite similar designs and volumetric sizes of the biodigesters, remotely acquired data from smart meter indicated different patterns of biogas production and use at household level. Ideally, a good pattern of biogas production and use should indicate peaks of biogas pressure when there is no consumption and at a zero-flow rate of biogas from the biodigester to the stove (biogas burner). It should also indicate the lowest biogas pressure immediately after highest level of biogas use (consumption). Such patterns are well observed by the user household depicted in Figure 7.

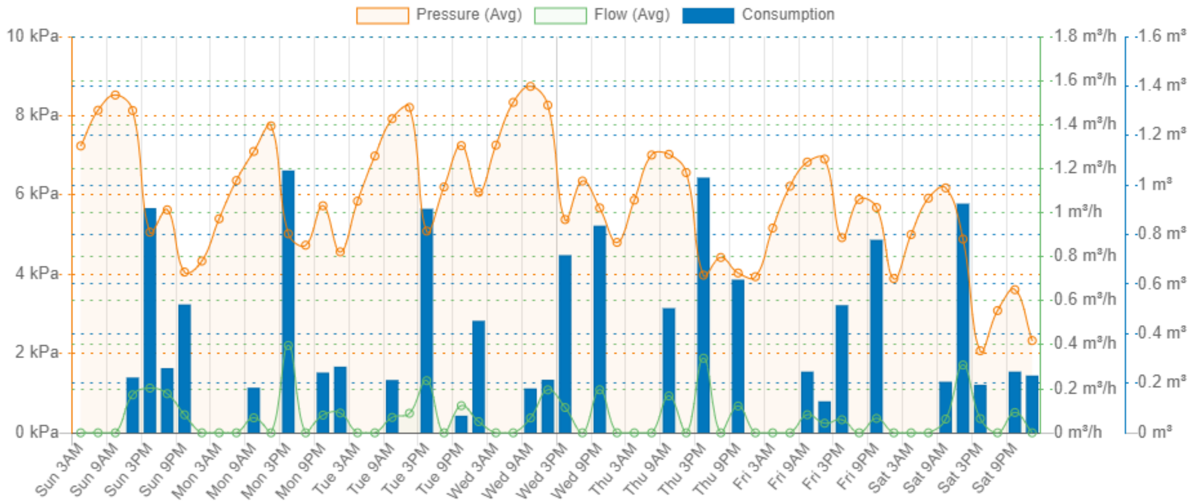

Figure 7. The household with best performing and well operated household biodigester.

Contrary, Figure 8 shows unusual patterns. It shows a continuous biogas consumption from Sunday at 3AM to Monday 9PM, with maximum flow rate and nearly zero levels of biogas pressure during this specific time. This indicates that the user might have left the valve open for almost two days, thus emptying the biogas and this reflects that the users behaviour affects the biogas production and use. Similarly, unusual patterns are also observed from Monday 9PM to Saturday 9PM. The gas pressure flatulates without recorded consumption. The leakage may have occurred at some point because there is no recorded consumption and flow rates, yet the biogas pressure continue to fluctuate. Such results indicate that IoT and smart metering can help to understand the household biogas technology, user-end dynamics , and management of the household biogas production and use.

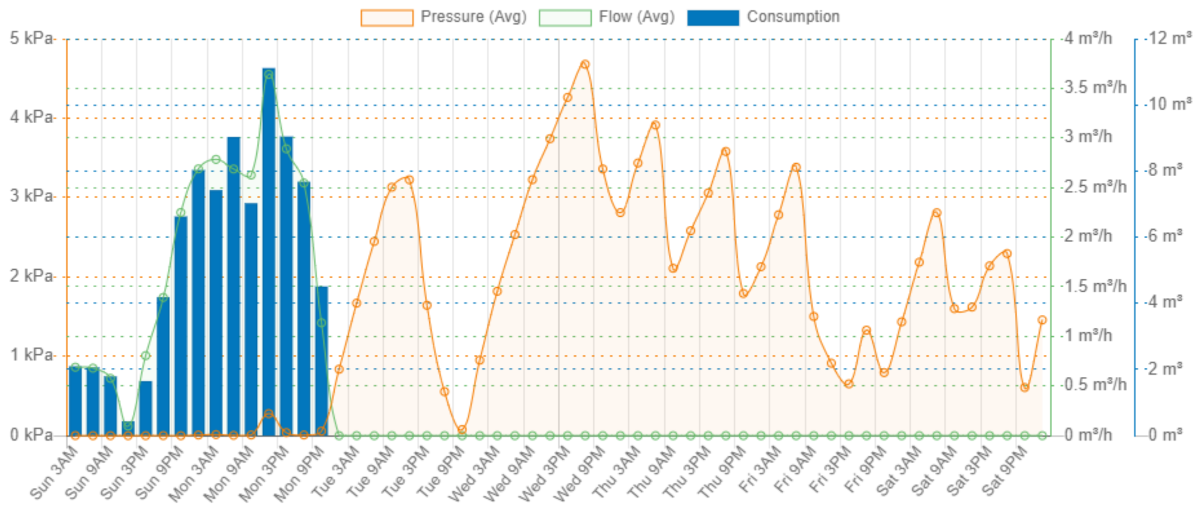

Figure 8. The household with poor performance and poorly operated household biodigester.

4. Conclusion

As household biogas technology becomes a relevance and potential technology to support clean cooking transitioning, it continues to face challenges, one of which is the lack of timely data portraying the performance of deployed household biogas plants, as well as household biogas user-end dynamics. The aim of this study was to study user-end dynamics for a family-sized biodigesters use smart metering for biogas production and remote data monitoring of biodigester conditions.

Results indicated that despite the conducive environment for household biogas production and use, and government support to the technology, its production and use at different user household differed. The implication from the finding indicated that despite biogas technology being a mature and basic technology, the user household behaviour and livelihood is crucial for the success and substantiality of the technology. This calls for a through research on livelihood of a particular household before installation of the technology for specified use.

Results also indicated that the use of IoT, smart metering and remote acquisition of data can enhance the technology monitoring mechanisms , thus leading to timely interventions. Analysis of the remotely and timely acquired data can help new policy formulation and technology designs for optimal utilisation of the technology.

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