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An Improved Load Modelling Approach for Sustainable Rural Microgrid Electrification: Optimization and Sustainability Metrics

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Abstract: Robust metrics to measure sustainability of such projects are still lacking. In this thesis, research is carried out to examine the sustainability of rural microgrids and then develop metrics to enhance how sustainability can be measured for these types of projects. The research further seeks to formulate and design an optimum, robust, sustainable and economical solar PV based microgrid solution for electrification of a remote area focusing on green areas that currently have no access to electricity. The objective is to achieve a system that is cost effective, reliable and sustainable. The results show that gender considerations have a significant impact on load profiles and a higher consumption is obtained when gender is considered. Next, an efficient and robust sizing approach for off-grid PV microgrid systems has been developed and named the ComµGrid Sizing Approach. This approach utilizes "Mixed Integer Linear Programming (MILP)" to optimally size the PV microgrid and the "ComµGrid Based Spatial Clustering of Applications with Noise (DBSCAN)" algorithm to aggregate load and meteorological data. MATLAB software is used to execute the optimization algorithm.

Keywords: Load Modelling Approach, Optimization, Applications Spatial, Microgrid

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INTRODUCTION

Smart grid is the most promising topic around the world. Smart appliances are started manufacturing all around the world. Multiple researchers are working on this topic around the world. Various researchers use numerous technologies to resolve the issues that arise on the path of deployment of smart grids (Elgenedy et al., 2015). Along with deploying renewable resources at production and consumer levels, automation goes hand in hand. Automation is applied on the transmission and distribution side to enhance the credibility of the smart grid (Yoldas et al., 2017). The problem discussed in the smart grid is different for different countries. South Africa has increased its use of renewable generation, de-carboning electricity generation, and improved network reliability and availability. For Asian countries, smart grid efforts are related to generation expansion, transmission expansion, and reducing emissions.

The smart grid is expected to be implemented fully by around 2050 around the world (Ferro et al., 2020). Only a little work is done to implement it in the real world, so it is quite a new topic, although it is in discussion worldwide. The implementation is in progress, and optimization ideas are also under discussion. The work done in the smart grid under multiple performance indices are to create a grid with high reliability, security, and energy efficiency. The result is carried out using different technologies and modes. Some use other technologies implemented in other applications and try to implement them in smart grids to get better realistic results.

The current work studied the system's energy have used either efficiency single-generation sources or the cost is not considered if multiple sources are used. So, in this work, numerous renewable energy sources are considered along with cost. The energy-efficient system with the reliability of the microgrid is evaluated and optimized. The work done in the research work is subjected to the conditions like low power lossy networks are applied when lossy networks are considered. The existing algorithms can be used only in home area networks, wide area networks, or neighborhood area networks. There is no work done that can be implemented in all these networks. So, there should be a protocol that can be used in any area and at any distance. Data customization can be done to use the algorithm at various places. The protocol should be optimized for energy efficiency and, at least, the reliability of the smart grid. The different generation sources can be used to enhance the credibility of the smart grid, like solar, wind, biogas, biomass, PV panel, etc.

REVIEW OF LITERATURE

V. Kumar and Verma Ashu (2021) discussed that increased energy consumption and fossil fuel shortages had heightened worries over rudimentary energy security. The most popular method of ensuring power reliability is to use diesel generator (DG-set) backup systems. The cost of DG-set-based electricity generation has skyrocketed and has a negative environmental impact. Renewable energy-based power generation (solar/biomass) is viable, although it is inherently intermittent and changeable. One of the essential solutions in multi-generation systems is energy storage (MGS). Because it smooths out periodic generation changes and stabilizes net load fluctuations, energy storage is crucial in MGS.

Allouhi A. et al. (2021) emphasized the economic advantages of combining energy-saving technology with hybrid PV biomass decentralized systems to build isolated rural dwellings in Morocco. It uses optimum selection procedures to discover resources and renewable energy technologies that are widely available in the region, to lower housing unit costs and energy consumption. The integrated design results imply that an ideal house might save 25% of life cycle expenses and 47.13 percent of carbon emissions compared to current practices.

Cao Yan et al. (2021) explained that the integration of hybrid resources in the generation of green energy is an innovative strategy that solves each renewable resource's particular limits. This article builds, evaluates, and optimizes a revolutionary coupled power cycle powered by hybrid resources from the standpoints of exergy, economics, and the environment. Solar energy produces hydrogen, which is pumped into the gas turbine's post-firing combustion chamber.

Chen Heng et al. (2021) developed and tested a hybrid renewable energy system that could provide heat and power. To complete the integration, the heat gathered from the sun using parabolic trough collectors is channelled into the steam cycle of a biomass-fired cogeneration facility. The solar heat is utilized to power an absorption heat pump that warms or cools the boiler's feedwater, conserving steam in the cogeneration or power generation modes.

Tilahun Fitsum Bekele et al. (2021) discussed the advantages of cogeneration plants supplying power to an industry that must be realized. The design optimization approach must holistically integrate economic, technological, and environmental components. Maximizing solar fraction, decreasing vestment costs, minimizing thermal storage loss, and cutting down on biomass resource use are all goals that can be achieved by implementing performance criteria. In addition, issues impacting the plant's performance must be considered, with industrial demand playing a pivotal role. This optimization method is not static but adapts as factors change. However, many contemporary design optimization methodologies do not incorporate such a condition. An alternate optimization strategy is provided in this paper, which overcomes the concerns mentioned earlier. As such, a TRNSYS solar plant model is coupled with a MATLAB-developed molten salt biomass boiler. According to an example study, the optimum efficiency is 31 percent with 23 percent solar insolation, giving in a Levelized generation cost of roughly 0.094$/kWh.

RESEARCH METHODOLOGY

Proposed Improved Load Modelling Approach

A better stochastic strategy for simulating load characteristics that vary with environment and consumer behaviour is suggested in this research. Each appliance in the electrified village has its own rating and set of operating hours. The monthly invoices of each user are used to estimate their daily consumption. The usage per hour is calculated all year round. A daily load is allocated to each customer in the electrified village based on consumption of a comparable customer in the unelectrified village. This load is determined by classifying the customers in the unelectrified village according to their electric demands.

Each client in the electrified hamlet is handed a questionnaire as part of an energy survey. We take stock of all the appliances, noting their power ratings and how often they are used. This poll determines whether the clients can afford the first payment and continue making payments in the future. It also impacts how consumption changes over time. This electrified community is evaluated based on gender using the following indicators, which are derived from the residents of the unelectrified hamlet fill out a survey to learn more about the home appliances they would want to buy. Each category's appliances and their use periods are collected. A programme called MATLAB will used to create the algorithm.

Sustainability Of Rural Electrification Projects

According to the Brundtland Commission, “Sustainability” simply refers to “the ability to meet the needs of the present without compromising the ability of the future generation to meet their needs”. In general sustainability encompasses the social, economic, cultural and environment. When looking at rural electrification projects, a much better definition for sustainability in their context is given in where the authors define sustainability as “The systematic preparedness for a project to maintain an electricity service provision over its life span”. This is the definition that has been adopted in formulation of the sustainability metrics for PV based rural electrification projects in this research. It is essential that rural electrification projects and systems are designed, planned, implemented and managed appropriately for them to be fully sustainable. According to in which a review of off- grid rural electrification projects was carried out, the four categories of sustainability mentioned are institutional, economic, environmental and socio-cultural.

Much as these categories are important for project sustainability, other aspects like health and safety, legal framework, security, technological aspects, supplier and procurement aspects, documentation, ethical and gender aspects are equally important.

DATA ANALYSIS

Results obtained using the Improved Load Modelling Approach

The proposed improved load modelling approach discussed above was used to determine load profiles considering an area in eastern Uganda known as Tororo. The rural community in consideration constitutes of 100 households with a population of approximately 530 people. Based on the energy survey conducted by the Uganda Bureau of Statistics and Ministry of Energy and Mineral Development for 2012 as well as the Uganda National household survey for 2016, the household categories and appliance usage of this area were estimated. Using data based on surveys done by , and, the load categories and probabilities P_{th} , P_{td} and P_t for appliance usage during each hour, day of week and month respectively were defined. The probabilities were populated in an excel sheet. An example of the load data presentation. This data describes the time of use of the maize mill throughout the year. Since the rural communities depend on agriculture, the energy consumption of a maize mill is lowest when there is low produce of harvested crops and highest when there is high produce. Consequently, the load can be categorised into low season, mid-season and high season. In this example, P_{th} , P_{td} and P_t are defined. defines the probabilities that each category is activated. These probabilities vary by day of week and month of year.

The following load profiles were generated which show load variation by month of the year. load variation for month of February, May and August. These months lie in low, mid and high agricultural produce season respectively so the load due to milling contributes to the different load profiles. The profiles showing the hourly consumption as a percentage of the daily load for different customer categories are households in the Low consumption category show a small morning peak and high evening peak. The appliances consist of mainly lights and phone charging.

The power consumption of these appliances is dependent on occupancy in the home and time of day in case of the lights. The Medium household profile shows that both the morning peak and evening peak have significant contribution to the overall daily consumption. This may be attributed to appliances such as radios and televisions that are used throughout the day. The High consumption households show that the morning peak and evening peak have an almost equal contribution to the overall daily load. This is attributed to appliances such as refrigerators that are in use throughout both day and night. the profile of the maize mill in the months February, May and August. These months correspond to the Low, Medium and High consumption seasons respectively. In August, the maize mill is continuously operational throughout the window from 8:00 am to 8:00 pm. All hours have an almost equal contribution to the daily load. In February, the operation of the mill is higher from 3:00 pm to 8:00 pm and in May, the operation is high starting from 12:00 pm.

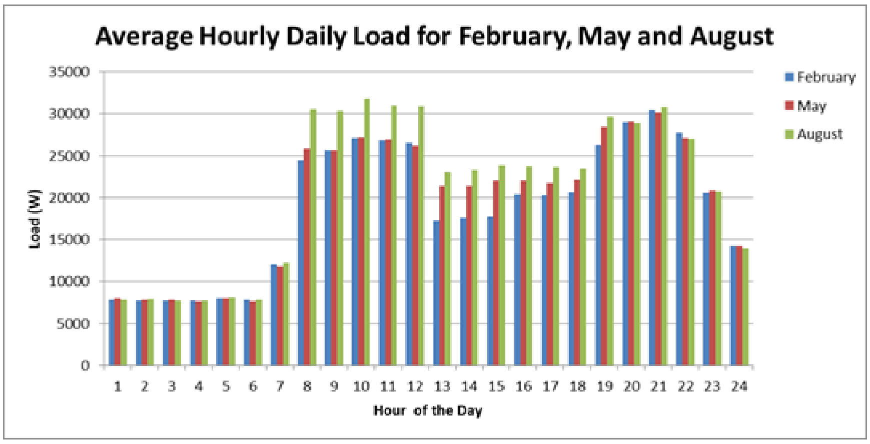

Figure 1: Average Hourly Daily Load Variation for February, May and August

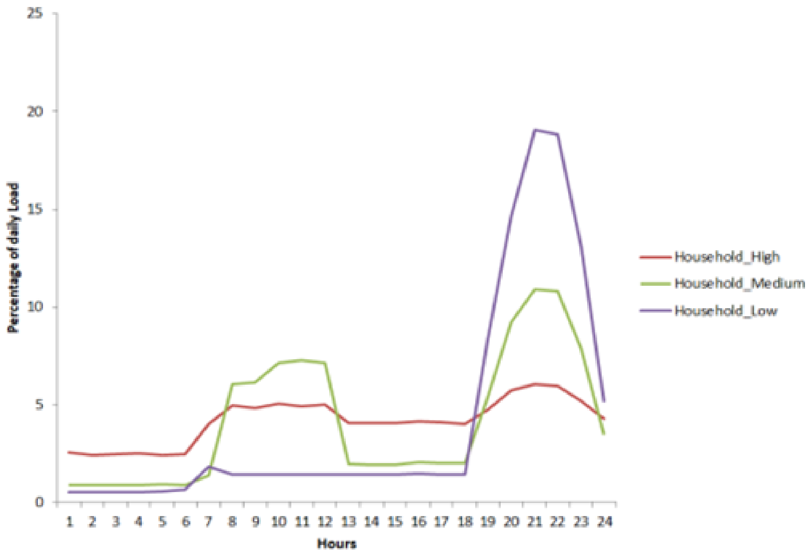

Figure 2: Load Profile for Household Category (High, Medium and Low Consumption)

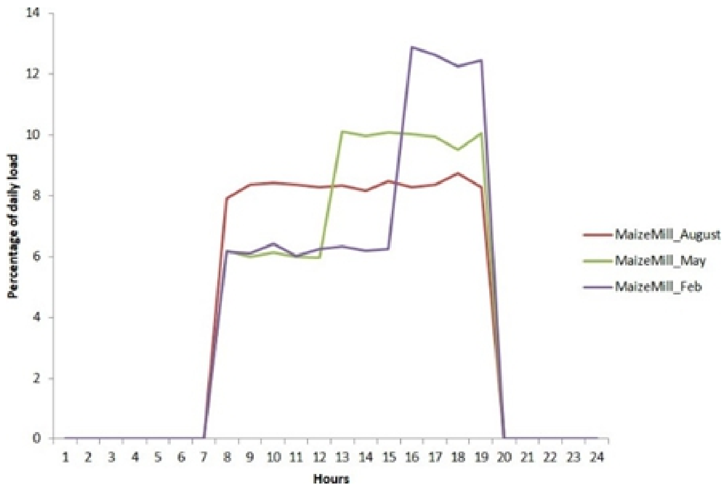

Figure 3: Load Profile for the Maize Mill in February, May and August

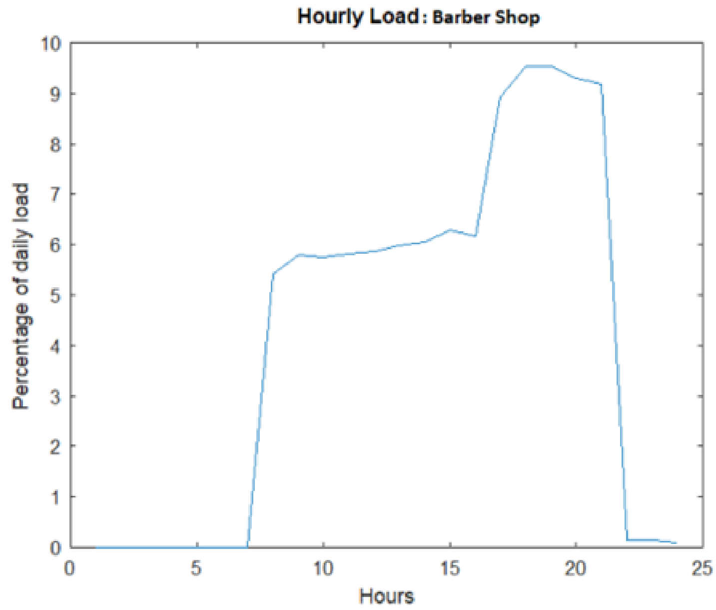

Figure 4: Load Profile for the Barbershop

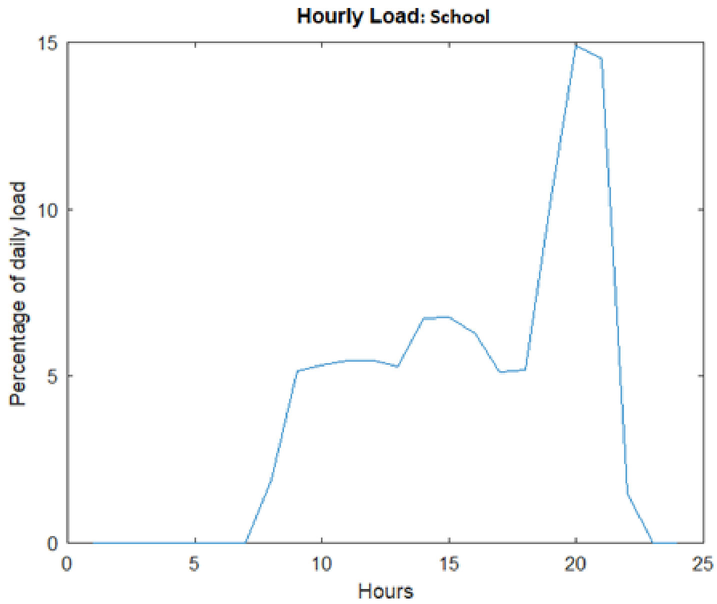

Figure 5: Load Prfile for the School

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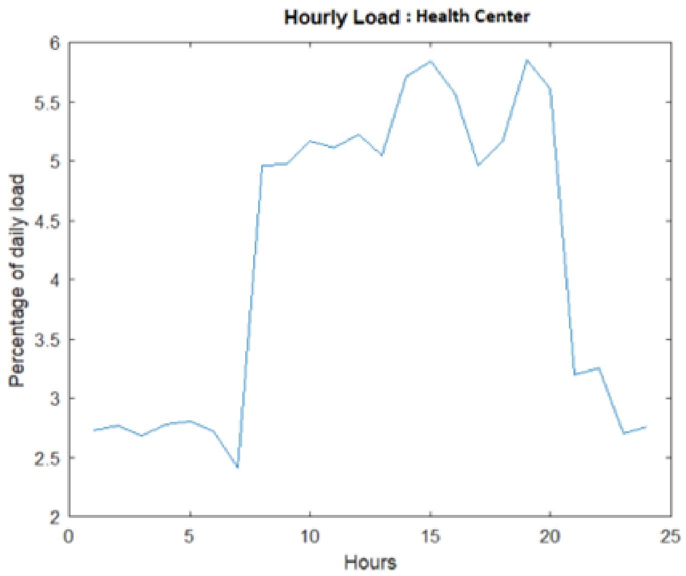

Figure 6: Load Profile for the Health Centre

Table 1: Probability Matrix for Maize Mill

Category	No.	P(W)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Lights	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.13	0.47	0.8	0	0	0	0
Milling machine Low Season	1	10000	0	0	0	0	0	0	0	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.5	0.5	0.5	0	0	0	0	0
Milling machine Mid Season	1	10000	0	0	0	0	0	0	0	0.4	0.4	0.4	0.4	0.4	0.67	0.67	0.67	0.67	0.67	0.67	0.67	0	0	0	0	0
Milling machine High Season	1	10000	0	0	0	0	0	0	0	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0.83	0	0	0	0	0
Phone Charging	2	3	0	0	0	0	0	0	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0	0	0	0	0

Table 2: Hourly Load Matrix for Maize Mill (in kW)

Category	No.	P(W)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
Lights	2	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0.003	0.005	0	0	0	0
Milling machine Low Season	1	10000	0	0	0	0	0	0	0	2.5	2.5	2.5	2.5	2.5	2.5	2.5	2.5	5	5	5	5	0	0	0	0	0
Milling machine Mid Season	1	10000	0	0	0	0	0	0	0	4	4	4	4	4	6.7	6.7	6.7	6.7	6.7	6.7	6.7	0	0	0	0	0
Milling machine High Season	1	10000	0	0	0	0	0	0	0	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	8.3	0	0	0	0	0
Phone Charging	2	3	0	0	0	0	0	0	0	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0	0	0	0
Total (kW)			0	0	0	0	0	0	0	14.801	14.801	14.8	14.8	14.	17.50 1	17.50 1	17.5	20	20.	20.	20.	0.005	0	0	0	0

Table 3: On and Off Days of Operation for Select Appliances

Category	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Lights	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Milling machine Low Season	1	1	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1
Milling machine Mid-Season	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	0	1	0	0
Milling machine High Season	1	1	1	1	1	1	1	0	0	0	0	0	0	1	1	1	0	0	0

Using Load Characteristics for a Known Village to Estimate the Electricity Consumption of Another

This case study intends to show how load characteristics for a known village can be used to estimate the electricity consumption of another. The study has used measurements in [132] carried out for a village in Uganda on three transformers.

In [132] the customers were grouped by their appliances; Group 1: Lighting, radio, TV

Group 2: Lighting, radio, TV, 1 or 2 appliances (fan, fridge, flat iron).

This study has considered the customers connected on Transformer 2 in [132]. The distribution of the customers in each group is as shown in Table 4.

Table 4: Customers Distribution

	Group 1	Group 2
Phase 2Y (Yellow Phase)	4	3
Phase 2R (Red Phase)	2	2
Phase 2B (Blue Phase)	1	4

In this case study, it's assumed that the electrified village consists of customers connected to phases 2Y (Yellow Phase) and 2R (Red Phase) and those in phase 2B (Blue Phase) belong to the unelectrified village. The load profile for phase 2B is then estimated using a MATLAB program.

The following assumptions have also been made:

i) The hourly appliance usage for lighting, TV, radio, fridge, fan and flat iron are same as [134].

ii) The daily load consumption for Group 1 is estimated to be uniformly distributed between 5.7kW and 7 kW and that for group 2 between 7kW and 8.5kW. This assumption is made based on measurements for phases 2Y and 2R in [132].

Using a MATLAB toolkit based on the algorithm, the load profile for each group is determined. This profile shows the hourly load as a percentage of the daily load.

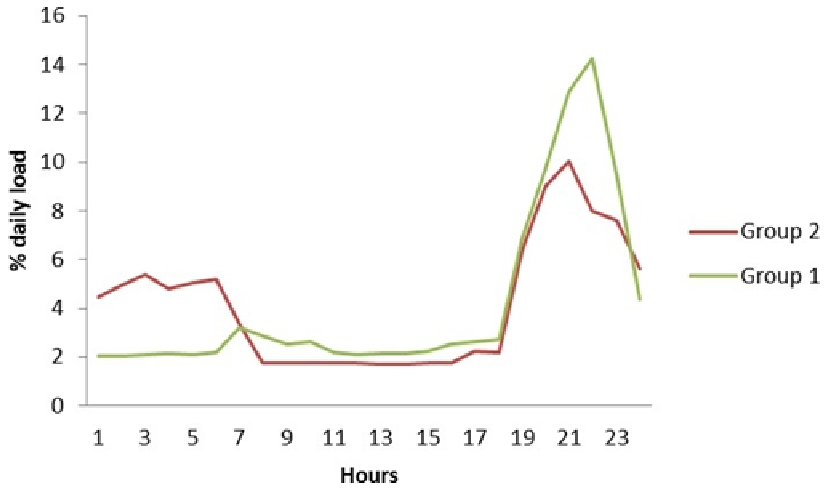

Figure 7: Percentage of daily load for Group 1 and Group 2

Assuming that customers in phase 2B belong to the unelectrified village, the load profile is estimated using a MATLAB toolkit based on the algorithm. The load profiles for the measured data for phase 2B and the generated profile from MATLAB are shown in Figure 7.

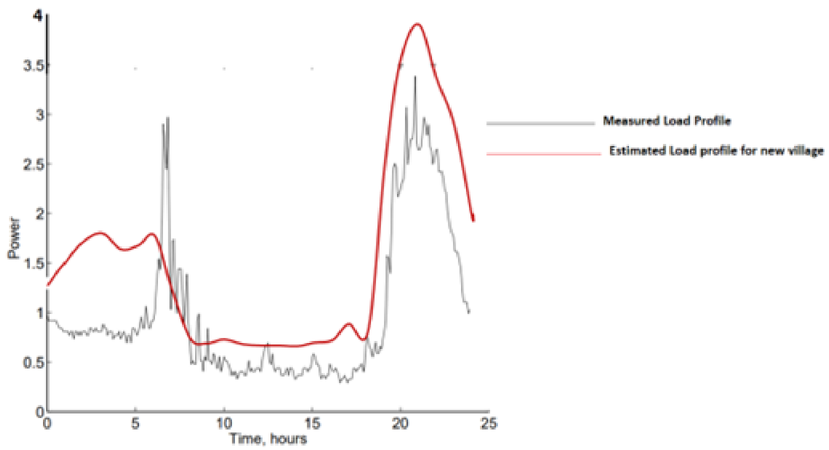

Figure 8: Comparison Between the Measured Load profile from [132] and the Estimated Load Profile for New Village to Be Electrified

It can be noted that the profiles are similar apart from the morning peak. The average power calculated over a year is 37.3kW. This is close to the average of 32.3kW obtained after two days of measurements. This shows that data from a proxy village can be used to estimate with minimal error the load in an unelectrified village.

CONCLUSIONS

To electricity with many of them living in rural and remote areas that are far away from the main grid. Specifically, the challenge faced with measuring sustainability of rural electrification projects was addressed by investigating the factors that need to be considered when determining sustainability of such projects. This thesis filled that gap by proposing an improved approach to load estimation that enhances existing methods, incorporates gender aspects in the load assessment process and estimates yearly change in the load. This approach enables the microgrid planner to determine the percentage of people in the community who will connect and utilize the microgrid service in a given year.

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