A Highly Practical and Affordable Microgrid Design Project for Developing Rural Communities: Case Study in Ghana

Dr. Hossein Salehfar, University of North Dakota

Dr. Hossein Salehfar received his Bachelor of Science (B.S.) degree in electrical engineering from the University of Texas at Austin, and his Master of Science (M.S.) and Doctorate (Ph.D.) degrees both in electrical engineering from the Texas A&M University in College Station, Texas. He was a research assistant with the Electric Power Institute at Texas A&M University during 1985-1990. He was an Assistant Professor of Electrical Engineering at Clarkson University in New York during 1990-1995. Since 1995 he has been with the Department of Electrical Engineering at University of North Dakota, Grand Forks, where he is now a full Professor. Dr. Salehfar served as the Interim Chair of the UND Department of Electrical Engineering from 2010 to 2012 and as the Director of Engineering Ph.D. Programs for several years. Dr. Salehfar worked as a consultant for the New York Power Pool in New York and electric utilities and coal industries in the State of North Dakota. Dr. Salehfar has had active and externally funded multidisciplinary research projects funded by various government and private organizations. He has worked on a number of projects funded by the National Science Foundation (NSF), and the U.S. Department of Energy (DOE). Some of the projects that he has worked on include microgrids, alternative and renewable energy systems, fuel cell technologies, power electronics, electric drives and electric vehicles, wireless power transmission, neuro-fuzzy intelligent systems, smart grid and conventional electric power and energy systems, power systems reliability, engineering systems reliability and security, power systems production costing, energy and load management programs, and energy efficiency. He has supervised several Ph.D. and master's level graduate students and has published his research work extensively in various national and international journals, conferences, and books. During the past several years, Dr. Salehfar has developed and taught numerous courses at undergraduate and graduate levels including various power systems courses, alternative and renewable energy systems, electric drives, power electronics, power and other engineering systems reliability performance and evaluation, engineering statistical data collection and analytics, electric circuits, senior design courses and projects, electromagnetics, control systems, signal processing, signals and systems, etc. Dr. Salehfar has served as an active reviewer of proposals and manuscripts for the National Science Foundation (NSF), the IEEE, various Power Electronics Conferences and several international journals, conferences, and publications. He is a professional member of the American Society for Engineering Education (ASEE) and a senior member of the IEEE. For more details on Dr. Salehfar's research work please visit http://www.h2power.und.edu

Michael Klein, University of North Dakota

Michael Klein holds a Masters Degree in Electrical Engineering from the University of North Dakota and Bachelors Degrees in Electrical Engineering and Mechanical Engineering from the University of North Dakota and Benedictine College, respectively. He is passionate about applying his engineering education to developing affordable, effective, and sustainable access to basic human needs in developing areas. His interests include renewable energy, microgrids, creative power generation and distribution, and hands-on humanitarian engineering. He is currently employed as a substation design engineer for Burns & McDonnell in their Minneapolis-St. Paul office.

A Highly Affordable Microgrid Design Approach for Developing Rural Communities: Case Study in Ghana

Abstract

This paper describes a hands-on student-centered summer project in Africa. Through two separate Graduate and Undergraduate Cooperative Education courses, electrical engineering students at a University in North Dakota have the opportunity for participation and exposure to an early practical and professional work experience closely related to their academic focus area. This simultaneous combination of academic and professional work experience has proven to have a tremendous positive impact on students' learning and enables them to fully develop their professional identity as engineers early before they graduate. At the completion of the courses, students submit a written report and give an oral presentation to a broader audience on details of the work performed and their findings and learning. The experience that students gain through this program directly contributes to the new ABET-EAC Student Outcomes (1) through (7). Using a set of rubrics designed based on the ABET-EAC Students Outcomes and in consultation with the students' academic advisors and work supervisors, the course instructor issues a final course grade for the participating students. This paper presents the work experience of a participating student at the graduate level in a humanitarian community service program in Africa. Through this program, the student successfully designed and built an electrical power system microgrid for a small and remote community in Ghana. The paper first examines the difference between microgrids and centralized power networks and discusses the suitability of microgrids for providing electric power to rural communities in developing countries. Next, the advantages and disadvantages of employing AC and DC power in microgrids for developing regions are discussed with regards to expected loads, generation sources, transmission/distribution efficiency, stability and control, protection and safety, and reliability and maintenance, with the conclusion that DC microgrids are better suited for developing communities. A practical methodology for selecting optimal distribution conductor sizes is presented. The microgrid design principles developed in the first half of the paper are then applied to an actual case study of Lingbinsi, Ghana, an agricultural community consisting of 267 homes. A step-by-step design approach for the microgrid is presented, resulting in a microgrid design using about 13kW rated capacity of photovoltaic panels and about 40 kWh rated capacity of battery storage with a total lifetime cost of about $133,000. The microgrid supplies 15W of power to each home for five hours per day to provide basic lighting and charging needs and delivers power to a water tower pump that provides enough water for the entire village. The microgrid material, maintenance, and installation costs can be supported by household energy payments that are 17-47% less than current average lighting costs in the region, depending on the financing strategy, while also providing enough power for a water pump. This indicates that the microgrid is highly affordable to the community. This project and its practical engineering experience directly contribute to the new ABET Student Outcomes (1) through (7). Therefore, the project and its outcomes can be adapted to serve as a practical undergraduate senior design project or a case study in renewable energy systems courses.

I. Introduction

The developed world has had reliable access to electric power for decades, and much research is currently focused on the reliability, efficiency, and security of aging grids, harnessing sustainable generation, and integrating “Smart Grid” concepts. However, approximately one billion people still lack access to electricity globally. Access is particularly low in rural areas, where only 63.2% of people in rural areas of developing countries have access to electricity [1], and about half of those without electricity live in Africa, where the 2015 rural electrification rate was only 14% [2]. One proposed solution is the islanded microgrid, which is a small grid that connects consumers with local, small-scale generation. Microgrids may be the only viable option for rural areas. The United Nations states that centralized power is much more expensive in rural areas due to low population densities, "peaky" demand profiles, high line losses, and inefficient use of power line capacity [3], as well as low initial energy consumption [4]. Furthermore, incrementally extending centralized grids to rural areas “causes lines to be strung haphazardly, resulting in greater losses” [3]. Therefore, the International Energy Agency predicts that 70% of rural areas must be electrified by “mini-grids” [5]. However, microgrids designed to meet the demands of the developed world often use sophisticated/expensive equipment, making them impractical for developing areas. The objective of this paper is to provide a methodology for designing affordable microgrids for low-income rural areas of developing countries.

II. Basic Design Choices

A DC network powered by photovoltaic (PV) arrays was selected as the basic design for rural microgrids based on the following criteria:

Expected Loads. Expected uses of electricity in rural areas are for lighting, communication, refrigeration, and small motors [3], which are likely the only loads that are financially feasible [6]. These loads typically directly operate on DC power [7] [8].

Transmission Efficiency. In general, DC power transmission is more efficient than AC [7] [8] [9] [10] [11], and DC loads are more efficiently served by a DC grid [11] [12]. Studies have also found that DC microgrids have a reduced number of power converters that are also simpler and cheaper [9] [13].

Stability and Control. DC control is simpler and cheaper due to the lack of frequency and reactive power control [8] [9].

Safety and Protection. AC protection systems are better-understood and have smaller fault currents. However, low voltage DC wires can be touched without harm [7] [9] [14].

Reliability and Maintenance. The superiority of AC or DC power systems in terms of reliability is controversial [7] [9] [13]. However, DC systems tend to be simpler to set up and can be serviced by local people with little training [12] [14].

Generation Sources. PV generation was selected because:

1. PV cells can connect directly to a DC power system
2. PV cells require minimal maintenance.
3. The levelized cost of electricity (LCOE) for PV cells is slightly higher than other sources [1] [15] but is likely competitive in developing countries where PV cells are already popular and require simple installation [16].
4. Modular PV cells can be easily scaled for demand growth.
5. PV cells are efficiently used with battery energy storage.

6. PV cells can be installed in almost any geographic location.
7. PV cells do not require a fuel source.

III. Case Study – Lingbinsi, Ghana

The microgrid design process will be demonstrated in Lingbinsi, Ghana, where the student author visited in 2016 to install a water tower and borehole well. Lingbinsi (9.575°N, 1.41°W) is in the northern part of Ghana in the North Gonja District. Pertinent climate and socioeconomic data are shown in Table 1. According to the student author's most recent correspondence with the village, the village was also working to install a pump to mechanize the borehole well.

TABLE 1: BASIC DESIGN PARAMETERS FOR LINGBINSI, GHANA

Parameter	**Value** [17] [18] [19]
Temperature Range	81 - 95°F (27.4 - 35°C)
Average Hourly Wage	GH¢0.49/hour
Methods of Lighting (Percentage of people who were using the method)	Kerosene (40-80%) Battery Flashlight (Up to 40%) Other Electricity (13-16%)
Annual Household Lighting Costs	GH¢76
Population with Cell Phones	9.3%
Population working in Agriculture	83-90%
Total Population	4,104
Houses	267

Due to the wide scope of designing an entire electric grid, it will be necessary to make several assumptions in this case study that will be noted in the following sections.

A. Load Estimate

To properly size the microgrid to meet the needs of the village, the expected demand or load of the village must first be estimated. Electronic devices are rare in the region [17], which may be due to the lack of an established electric grid. However, as noted in Table 1, the high usage of flashlights for lighting shows a desire for electric lighting, and the relatively small part of the population currently using cell phones may quickly increase if charging power is made available. Therefore, the grid will provide power for lighting and phone charging, a water pump for the borehole well, and a few small appliances. Most homes in the region have two rooms [20], so if each house uses two 5W LED light bulbs and charges a phone (4W-7W [21]), it will consume about 15W.

The pump power depends on the water capacity and flow rate required by the village. About 13.2 gal (50L) of water per person per day is essential for basic health [23], so the village of 4,104 people needs 52,834 gallons/day. Assuming the pump primarily runs during daylight hours for 11 hours each day (6:30AM-5:30 PM), it must operate at about 80 GPM. A DC pump like the

SQFlex 60 SQF-3 can provide 15ft of head (low head due to the nearby river) at 80GPM, consuming 1.41kW [24].

During this 11-hour period, the pump will consume 15.4 kWh. Assuming that all 267 homes participate in the grid and draw 15W for 5 hours each day, the grid must supply 20 kWh every day for lighting/charging. Adding the use of some small appliances such as 1-2 DC refrigerators and televisions increases the estimate to about 21 kWh at 4.1 kW. Therefore, the total daily energy usage of the village is approximately 36 kWh with a peak load of 4.1 kW. To contain the scope of this case study, it will be assumed that this load does not grow over time.

Ghana typically experiences 12 hours of daylight year-round from 6AM-6PM [22]. The greatest lighting/charging demand will occur from 6-10PM when most people are home and from about 5-6AM as people begin work before sunrise. The pump should not be operated during these times of high demand but rather should fill the water tower during the day when most people are at work, which is also advantageous because power produced from the PV cells can be used immediately, avoiding battery losses. This load schedule is summarized in Table 2.

TABLE 2: DAILY LOAD PROFILE FOR LINGBINSI, GHANA

Time	Main Load	Power	Energy
12AM-5AM	Little to None	~0	~0
5AM-6AM	Lighting/Charging	4.1 kW	4.1 kWh
6:30AM-5:30 PM	Water Pumping	1.41 kW	15.4 kWh
6PM-10PM	Lighting/Charging	4.1 kW	16.4 kWh
10PM-12AM	Little to None	~0	~0
		Total:	**35.9 kWh**

B. Distribution System

Following an estimation of the village load, the physical layout of the microgrid must be established, which will permit the power losses on the conductors to be estimated. Reference [25] shows how dividing the generation into two sites on opposite sides of a village and using an O-shaped distribution layout reduces voltage dip, conductor cost, and PV/battery sizes compared to a single location. The largest load in Lingbinsi is the pump, so one PV-battery section will be placed by the water tower and the other on the north side of the village as shown in Figure 1, making an O-shape and keeping the PV cells out of the floodplain on the east side of the village and away from roads, minimizing dust buildup.

The main grid consists of Lines A and B, where Line B is divided into three sub-sections. The village was also divided into sectors served by each distribution line shown by the shaded areas. Homes are connected to the main line through feeder cables, and a tie line is shown, which will be discussed in a following section.

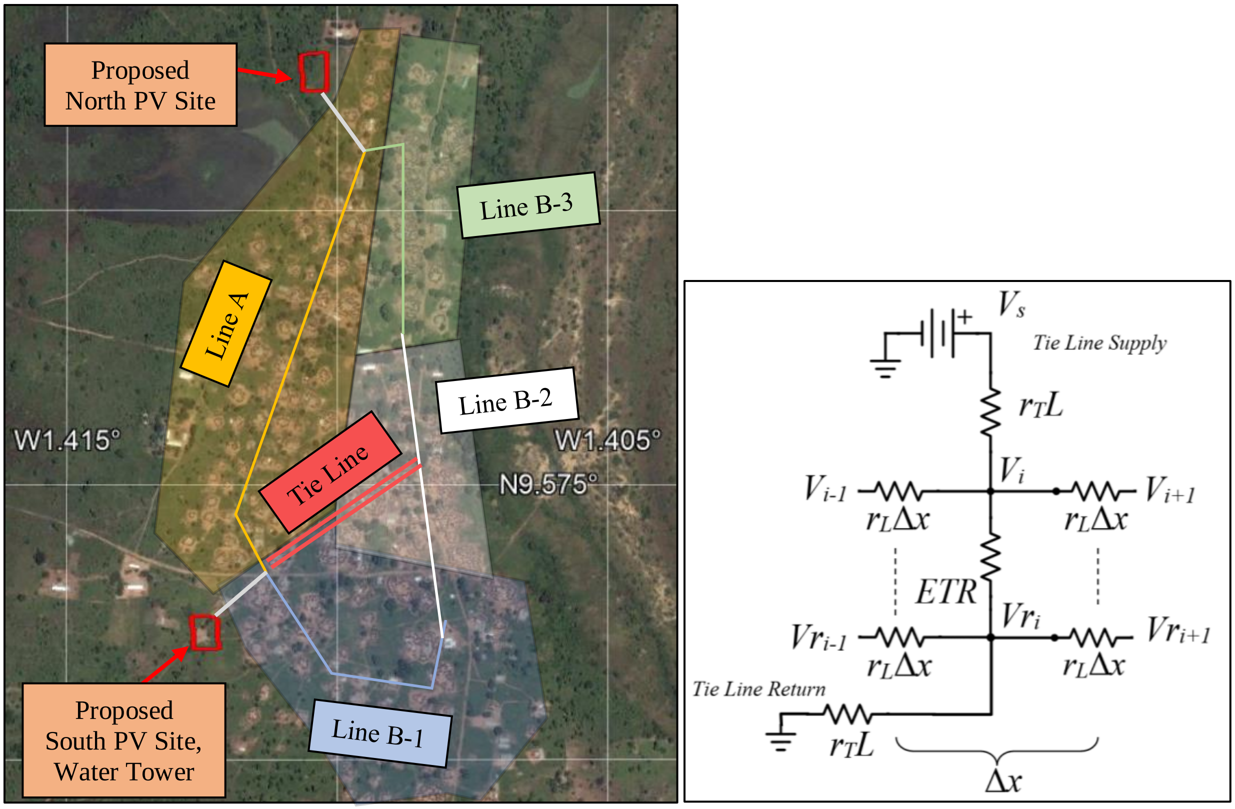

Figure 1. Proposed microgrid layout for Lingbinsi, Ghana with tie line added for better distribution performance (left). Nodal circuit model for connection point of tie line with Line B (right).

Estimates of the physical parameters of the network are shown in Table 3. Due to the relatively short length of the distribution lines, the sag of the conductors is assumed to add negligible length. The Homes/Mile of each distribution line section (*HPM*) was computed by dividing the estimated number of homes in each distribution service sector by the length of the main distribution line passing through the sector. A nominal distribution voltage of 48V was selected as this voltage is easily attainable with typical 12V PV cells and batteries, is safe to touch [7] [9] [14], and minimizes voltage dip, power loss, costs, and generation sizing [25]. The voltage will be converted down to a lower voltage of 12V or 5V by DC/DC converters in each home. The design of these converters is covered in a separate paper.

TABLE 3: DISTRIBUTION LINE ESTIMATES

Parameter	**Line**			
	A	**B-1**	**B-2**	**B-3**
Length (mi)	0.8	0.55	0.35	0.5
Estimated Number of Homes	107	64	64	32
Homes/Mile of Line (HPM)	134	117	183	64
Feeder Cable /Mile of Main Line (ft/mile)	25,550			
Feeder Cable Length/Home (ft/mile)	191	218	140	400
Nominal Distribution Voltage	48V			

It will be assumed that the main distribution line has two conductors, the supply and return line, and that Single Wire Earth Return (SWER), in which only a single supply line is used and the earth acts as the return path, will not be considered due to uncertainties about soil characteristics and about its practicality in a low voltage system. A home is connected to the main distribution lines by feeder lines, where the voltage between the supply and return lines at the connection of the feeder to the distribution line is V_{Li}. The supply and return feeder lines each have a resistance $r_f \Delta x_f$, where r_f is the resistance/length of the feeder and Δx_f is the feeder length. The home consumes current I_H, and the voltage at the point of connection with the home is V_H. These resistances can be combined into the Total Single-Home Resistance (*TSHR*):

$$TSHR = 2r_f \Delta x_f + Z_{Converter} \tag{1}$$

$Z_{Converter}$ is the input impedance of the home's DC/DC converter that is assumed to provide a constant power P of 15W. This impedance changes depending on the distribution line voltage as given by:

$$Z_{Converter} = \frac{V_{Li}^2}{P} \tag{2}$$

In a segment of length Δx of the distribution line, the total number of homes served by the line segment is equal to $HPM \times \Delta x$ (in miles). The houses are connected in parallel, so the Equivalent Total Resistance (*ETR*) of the homes connected to a segment of the line is:

$$ETR = \frac{1}{HPM \times \Delta x \times 1/TSHR} \tag{3}$$

With this model, the entire distribution line can be divided into sections Δx in length. This circuit is shown in Figure 2. The node voltage in relation to ground is V_i at the point where the i^{th} *ETR* connects to the supply line and Vr_i where it connects to the return line. The nodes are connected through the resistance of the distribution conductors $r_L \Delta x$, where r_L is the conductor resistance/length. PV sites are shown as voltage sources at either end of the line.

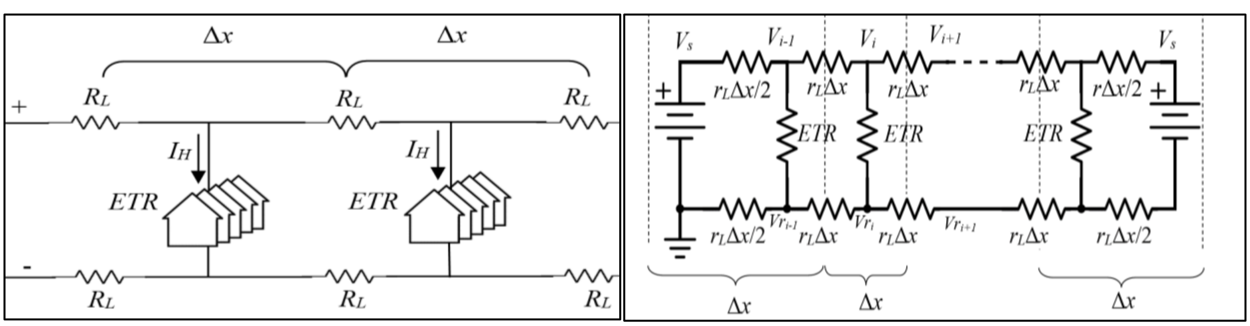

Figure 2. Circuit model for consecutive segments of the distribution line, where the homes connected to the line in each line segment have a resistance *ETR* and consume current I_H, and the distribution line segments have resistance R_L (left). Formal circuit model for the distribution line (right).

To solve for the voltages at each node, the node voltage equations for the i^{th} supply connection node can be written as:

$$\frac{V_{i-1} - V_i}{r_L \Delta x} + \frac{V_{i+1} - V_i}{r_L \Delta x} + \frac{Vr_i - V_i}{ETR} = 0 \tag{4}$$

Similar equations can be found for the return line. For the nodes adjacent to the sources, the appropriate Δx in the denominators must be divided by two, as the *ETR* is assumed to lie in the middle of each Δx segment of line (with $\Delta x/2$ on either side of the *ETR*). The nodal voltages must be solved iteratively because the *ETR* for each node depends on $Z_{Converter}$, which in turn depends on V_i and Vr_i as described by (2).

This iterative procedure was executed with the values in Table 3, allowing the power provided to each home to vary from 14.0-15.1W to allow the iterative solver to converge to a solution. The results are shown in Figure 3, where V_H is shown along the length of the line. The results are presented for varying main distribution line sizes. The feeder size was also varied but had negligible effects.

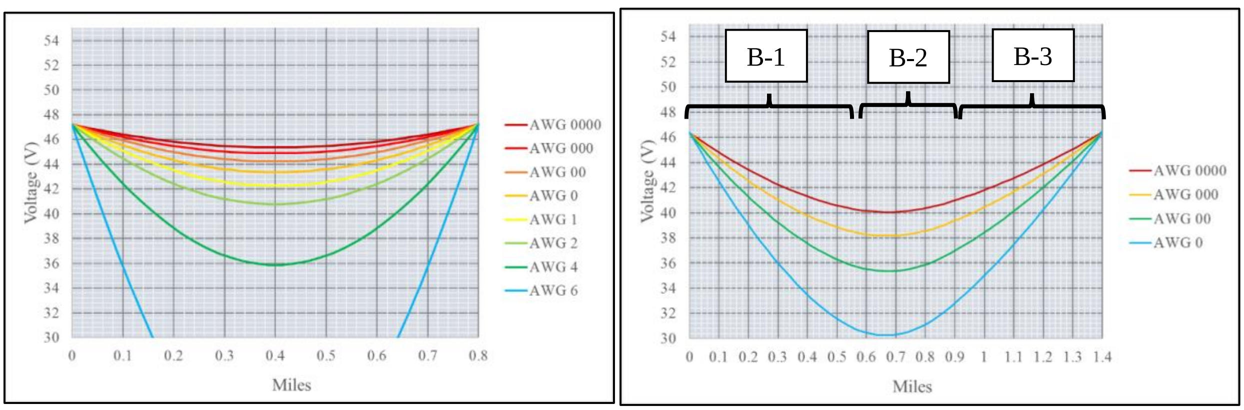

Figure 3. Voltage profile for Line A (left) and B (right). The south PV site is at Mile 0.

With these voltage profiles, the cost of the generation that must be added to cover the distribution loss can be computed. The power loss in the supply and return cables is given by:

$$P_{Loss} = \sum_{i=1}^{n} \left(\frac{(V_i - V_{i-1})^2}{r_L \Delta x} + \frac{(Vr_i - Vr_{i-1})^2}{r_L \Delta x} \right) \tag{5}$$

The equation must be slightly modified for the nodes adjacent to the sources as described previously.

For the cost analysis, the cost of distribution power losses was estimated as $8.34/W as will be described in further detail in following sections. It was also assumed that the lines were used for 5 hours/day while the pump was not running (see Table 2). The resulting plots for distribution line B are shown in Figure 4 [25].

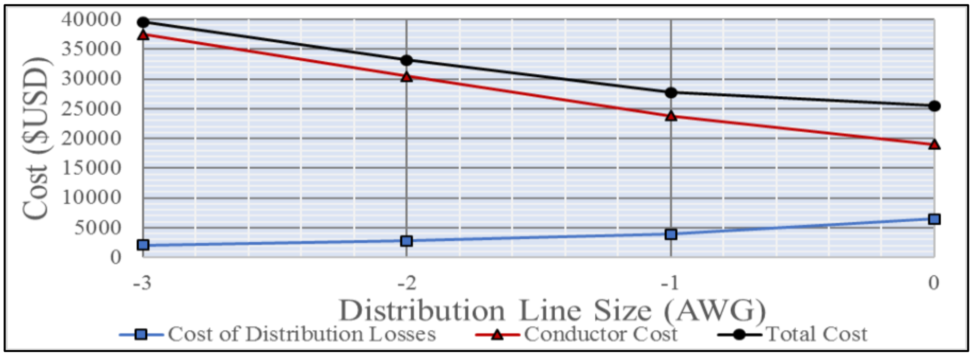

Figure 4. Line B loss, conductor, and total cost curves.

To reduce the cost of Line B, a tie line was added as shown in Figure 1. This line will not serve any homes but will be a connection between the PV site and line B-2. The nodal equation at the tie line connection was modified according to Figure 1, and the total costs were computed for distribution line sizes of 4/0 – 2 AWG and tie line sizes of 4/0 – 6 AWG. Results are shown in Table 4. Implementing the tie line leads to the minimized combined cost of Lines A and B.

TABLE 4: OPTIMAL CONDUCTOR SIZING

Parameter	**Line A**	**Line B w/o Tie**	**Line B w/ Tie**
Optimal Distribution Conductor	**4 AWG**	**0 AWG**	**2 AWG**
Optimal Tie Line Conductor	N/A	N/A	**2 AWG**
Distribution Power Loss (W)	307.58	776.49	490.64
Tie Line Power Loss (W)	N/A	N/A	104.13
Total Power Loss (W)	**307.58**	**776.49**	**594.77**
Lowest V_H (V)	35.87	30.29	30.72
Cost of Dist. Power Loss (USD)	$2,565	$6,475	$4,960
Cost of Tie Line Power Loss (USD)	N/A	N/A	$3,341
Cost of Dist. Conductor (USD)	$9,092	$37,988	$24,683
Cost of Tie Line Conductor (USD)	N/A	N/A	$6,171
Cost of 18AWG Feeder Cable (USD)	$3,581	$3,581	$3,581
Total Conductor Cost (USD)	**$12,673**	**$41,569**	**$34,435**
Energy Loss (kWh/day)	1.55	3.88	2.97

When the system is loaded, the lines draw currents of 37.59-55.79A. To provide basic protection for the system, circuit breakers will be added with ratings near the maximum current, costing about $130 [26].

The distribution network will also require some method to physically support the conductors. The conductors could be buried, but this would require a significant increase in conductor cost due to insulation requirements. A possible solution is to build small "power towers" from mud or locally harvested wood, which are the most common building materials in the area. The only cost therefore is labor, which can be roughly estimated as about GH¢800 or about USD $550.

C. Generation

The two PV-battery sites must provide enough energy to serve the loads of the village, which are combined with the power losses of the conductors in Table 5. The division of energy for the sites was found using the current drawn from each site. For example, the south PV site provided 64.3% of the total current, so it was assigned 64.3% of the load.

Because the lighting/charging loads in the village occur at night, the load must be served from batteries. Sizing the battery system requires the battery characteristics shown in Table 6. Lithium-ion batteries will be used because of their competitive lifetime cost, suitability to hot climates, lower weight (easier transport), lower maintenance, and greater depth of discharge. Assuming the combined battery/controller efficiency is 85%, the north site requires 9.11kWh/0.85 = 10.72kWh of storage. However, only 80% of the rated capacity is usable, so the required rated capacity for the north site is 10.72 kWh/0.8 = 13.4 kWh. Similarly, 24.14 kWh of storage is required at the south site.

TABLE 5: MICROGRID ENERGY CONSUMPTION

	Total	**North**	**South**
Lighting/Charging Load			
Homes	21 kWh	7.5 kWh	13.5 kWh
Line A	1.55 kWh	0.56 kWh	0.99 kWh
Line B	2.97 kWh	1.06 kWh	1.91 kWh
Total	**25.52 kWh**	**9.11 kWh**	**16.41 kWh**
Pumping Load			
Pump	15.4 kWh	N/A	15.4 kWh

TABLE 6: BATTERY TYPE COMPARISON

Parameter	**Lead Acid** [27]	**Lithium Ion** [28] [27]
Charge/Discharge Efficiency	80-90%	80-90%
Depth of Discharge (DoD)	50%	80%
Performance Degradation Temperature	25°C	45°C
Initial Cost ($/kWh)	131	471
Lifetime Cycles	200-1000	1000-4000
Regular Maintenance Required	Yes	No
Energy Density (Wh/kg)	50	190
Charge Controller Efficiency	98%	98%

PV panel sizing depends on several factors such as irradiation, celestial mechanics, and panel orientation, which are beyond the scope of this paper. Instead, the PV Watts Calculator from the National Renewable Energy Laboratory [18] was used to estimate system output. The optimum panel tilt angle in Ghana is 6°, and irradiation ranges from 4.5 kW/m^2/day during the cooler wet season to 6 kWh/m^2/day during the hotter dry season. In the area, a panel rated at 1 kW therefore produces 1,495 kWh/year [18], (about 4.1 kWh/day). However, during the wet season, the output may drop to 3.6 kWh/day, so this "worst-case" value is used for sizing the panels.

The ambient temperature in the region can cause an additional ~5% loss in PV output during the dry season. However, temperatures are lower during the wet season, so the "worst case" output of 3.6 kWh/day should not drop any further.

The north PV panels must provide 13.4 kWh to the batteries every day. Therefore, the site requires a rated PV capacity of (13.4/kWh/day) / (3.6 kWh/day/kW) = 2.98 kW. Similarly, 5.36 kW rated capacity is required at the south site. It should be noted that although the worst-case value for solar irradiation was used in sizing the system, the sizing of the PV panels and batteries assumes that no additional generation or storage capacity is required to account for prolonged periods of below-average solar irradiation due to unusually cloudy conditions.

The combined cost for PV panels and mounting hardware is about $1,000/kW [29], and the cost of lithium-ion batteries is $471/kWh [28]. Assuming the batteries are cycled once per day, they must be replaced after about ten years (3,650 cycles). Therefore, for a 30-year system life, the batteries must be replaced twice. The present worth of the initial batteries and replacement sets is $790/kWh, assuming an interest rate of 8%. Table 7 shows the total cost of the PV-battery sites.

TABLE 7: PV/BATTERY COSTS FOR LIGHTING/CHARGING LOADS

Parameter	North Site	South Site
PV cost	$2,980	$5,360
Battery Cost	$10,586	$19,071
Total Lighting/Charging Generation Cost	**$13,566**	**$24,431**

This data was used to calculate the cost of transmission power loss used above in Section III-B. For every 1 kW of power lost on the lines, the line consumes 5 kWh of energy per day, which must be made up by an additional 5 kWh / (0.85 efficiency) / (0.8 Depth of Discharge) = 7.81 kWh of battery storage and an additional 7.81 kWh / (3.6 kWh/day) = 2.17 kW of PV capacity. Therefore, each kW of loss costs (7.81 kWh of battery storage) x ($790/kWh) + (2.17 kW) x ($1,000/kW) = $8,340, equivalent to $8.34/W, which was the cost of power loss used in Figure 4.

The south site needs additional generation to power the pump. Solar radiation has an approximately parabolic relationship with time with a maximum at solar noon and zeros at sunrise and sunset [30]. Assuming PV power output is proportionate to irradiation, power output can also be represented by a parabola. Integrating the power output curve with respect to time should give the daily energy output, so the estimated output curve for a 1kW panel is given by $y = -0.0125t^2 + 0.3t - 1.35$, which, when integrated from t = 6 to t = 18 (sunrise to sunset in Ghana), gives 3.6 kWh, the daily "worst-case" PV energy output in Ghana. Similar curves can be found for panels of other sizes.

The pump consumes 1.4 kW (assumed constant) from 6:30 AM to 5:30 PM. Overlaying this load on a PV output curve results in Figure 5. When the PV cells produce more power than the pump consumes, the batteries charge (green region). When less power is generated than the pump consumes, the batteries provide power to the pump, (violet regions). The PV panels and batteries must be large enough to charge the batteries with the energy that the batteries discharge to the pump each day.

The cost of the pump PV-battery system was optimized by varying the capacity of the PV panels and computing the total cost of the PV panels and the required battery storage using the costs from Table 7. The power curves and energy flows for the resulting cost-optimized system are shown in Figure 5. The optimized PV-battery site has 4.4 kW of PV capacity and 2.25 kWh of battery capacity, costing a total of $6,178.

A final note is merited regarding emergency pumping power from the north site. With the pump connected to the north site through the distribution network, the north site can provide a maximum of 688W to the pump while 688W is lost on the lines for a total of 1.376 kW. The site has enough energy to provide 6.6 hours of pumping power at 60 GPM (9.11 kWh / 1.376 kW) for a total of 23,760 gal/day, 45% of the normal requirement.

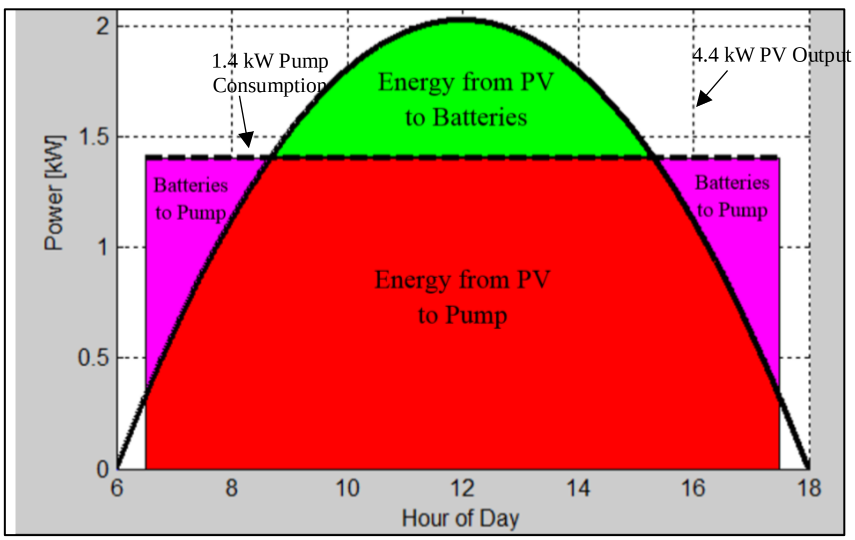

Figure 5. Power curves and energy flow for optimized pump PV-battery system.

D. Summary

The microgrid is shown in Figure 1 and summarized in Table 8. The estimated lifetime cost of the system is presented in Table 9. The cost of one employee who will clean and maintain the PV is included, assuming he/she works 50 hours/month with the average wage from Table 1 of GH¢0.49/hr and a 4% raise every year for 30 years.

TABLE 8: SUMMARY OF LINGBINSI MICROGRID

Characteristic	Value
Generation	
North Site Rated PV Capacity (kW)	2.98
North Site Battery Storage Rated Capacity (kWh)	13.4
South Site Rated PV Capacity (kW)	9.76
South Site Battery Storage (kWh)	26.39
Distribution	
Line A Conductor	0.8 mi of 4 AWG
Line B Conductor	1.4 mi of 2 AWG
Tie Line Conductor	0.35 mi of 2 AWG
Feeder Conductor	10.7 mi of 18 AWG
DC Circuit Breakers	5 x 40-60A
Daily Load Capabilities	
Nominal Home Power for 267 Homes	15W for 5hrs/day
Pumping Capacity (11 hours/day)	52,800 gal/day
Emergency Capability with South Site offline	23,760 gal/day

TABLE 9: LINGBINSI MICROGRID COST ESTIMATE

Item	Cost
Generation	
North Site Batteries	$10,586
North Site PV and mounting hardware	$2,980
South Site Batteries	$19,071
South Site Batteries (Pump)	$1,778
South Site PV and mounting hardware	$5,360
South Site PV and mounting hardware (Pump)	$4,400
Charge Controllers	$3,000
Distribution	
Main Distribution Line Conductor	$39,946
Feeder Cable	$3,581
Protection and Conductor Supports	$680
Home Hookup Modules/Power Meters	$7,743
Material Cost Subtotal	**$99,080**
Employee	$3,150
Maintenance (~5% of Material Cost)	$5,000
Installation (~$2/W installed) [29]	$26,000
Grand Total	**$133,275**

Each home consumes 75Wh/day. For all 267 homes, the total village consumption totals to 7,309 kWh/year or 609 kWh/month. Assuming the village obtains a loan for the total cost of the system without any outside charitable aid and that the credit has a 4% annual interest rate, the village can pay off the loan in the payoff periods with the monthly payments shown in Table 10. The required cost per kWh can then easily be calculated.

TABLE 10: HOUSEHOLD ENERGY COSTS BASED ON LOAN LENGTH

Payoff Period (years)	Monthly Payment	Monthly Energy Use (kWh)	Energy Cost ($/kWh)	Annual Household Energy Cost
15	$990	609	$1.63	$44.62 (GH¢63.56)
30	$636	609	$1.04	$28.47 (GH¢40.56)

In the region, the average household currently spends GH¢76 ($53.50) on lighting annually [20]. If the village implements the microgrid, the average household can save 17-47% (depending on the loan duration) on annual lighting costs while also obtaining household charging capability and the power required for the water pump, making the microgrid highly affordable.

IV. Conclusions

Two separate Graduate and Undergraduate Cooperative Education courses of electrical engineering at a University in North Dakota provide the opportunity for students to be a part of professional engineering work experience closely related to their academic focus areas. The simultaneous combination of academic and professional work experience has proven to have a tremendous positive impact on students' learning and enables them to fully develop their professional identity as engineers early before they graduate. At the completion of these courses, students submit written reports and give oral presentations to a broader audience on their experience and lessons learned. This hands-on experience directly contributes to the new ABET-EAC Student Outcomes (1) through (7). Using rubrics developed based on ABET-EAC Student Outcomes, student written reports, oral presentations, academic advisors' input, and work supervisor surveys, the course instructor issues final course grades.

This paper reported on the work experience of a participating student in a summer humanitarian community service program in Africa. Through this cooperative education course and the sponsoring community outreach program, the student successfully designed and built an electrical power system microgrid for a small and remote community in Ghana. This project resulted in the successful design of a complete rural electric delivery system that provides basic electric services at a cost lower than current average household lighting costs. In brief, the project accomplished the following:

- Demonstrated a logical approach for the selection of overall grid characteristics for a rural village, including justification of a microgrid system and the development of selection criteria for AC vs. DC power and an electric generation source.
- Provided a reasonable estimation of a village's electrical load and its variation with time based on socioeconomic and climate factors.
- Developed an effective circuit model for a DC distribution microgrid to account for conductor power loss, voltage sag, and the variable impedance of home DC/DC converters.

- Employed this circuit model to analyze power loss and voltage sag in the microgrid in order to make improvement to the grid configuration.
- Developed a cost model that accounts for both the conductor cost and conductor power loss to optimize the distribution conductor size and configuration.
- Developed and successfully implemented a methodology to select and size the required battery storage for a village.
- Developed and successfully implemented a methodology to size PV generation for a village, including consideration of the variation of load and solar irradiation throughout the day.
- Successfully demonstrated how strategic financing of the project can ultimately provide the village with household lighting and charging capabilities and an electrified water pumping system that will cost less than current household lighting practices.

The project succeeded in its goal of developing an electric grid that is truly affordable for a developing community. This case study can be adapted as a template for grid designs for developing areas, and can be expanded in future works to explore additional topics such as load growth, Single Wire Earth Return, urban communities, and more advanced financial analysis.

V. References

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