



**PREDICTING SOLAR PERFORMANCE IN A CONTINGENCY  
ENVIRONMENT TO MEET NET-ZERO FACILITY POWER**

THESIS

Anthony D. Williams, Captain, USAF

AFIT-ENV-MS-17-M-237

**DEPARTMENT OF THE AIR FORCE  
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**Wright-Patterson Air Force Base, Ohio**

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THESIS

Presented to the Faculty

Department of Systems Engineering and Management

Graduate School of Engineering and Management

Air Force Institute of Technology

Air University

Air Education and Training Command

In Partial Fulfillment of the Requirements for the  
Degree of Master of Science in Engineering Management

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Captain, USAF

March 2017

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### **Abstract**

The U.S. government is involved in contingency operations all over the world and these operations require operational support and sustainment in these locations; this includes the reliable delivery of power to base infrastructure. The traditional means of delivering this support requirement in austere environments has been the use of diesel-power generation that has an extensive logistical and economic tail. The research sought out contingency solar applications that may be implemented and operated to offset the facility demand loads in the location to achieve net-zero power. This research explores the technical feasibility of a deployable photovoltaic microgrid to deliver power to a contingency location. The research evaluates the system's potential power performance in six locations throughout the U.S. Central Command (CENTCOM) and U.S. Africa Command (AFRICOM) using probabilistic simulation modeling techniques. The results showed that there is a potential for photovoltaic microgrids to drastically reduce the demand of contingency shelter systems. The research established recommendations for extensive field testing based on the feasibility of said systems to drastically reduce the demand of shelter systems in contingency locations.

## **Acknowledgments**

I would like to express my appreciation to my thesis advisor, Lt Col Chris Stoppel and the members of my thesis committee, Lt Col Clay Koschnick and Dr. Al Thal. Their insight and guidance was instrumental in my research effort. I want to acknowledge all of my family and friends who were my unwavering support system throughout the process.

Anthony Williams

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# **PREDICTING SOLAR PERFORMANCE IN A CONTNGENCY ENVIRONMENT TO MEET NET-ZERO FACILITY POWER**

## **I. Introduction**

### **1.1 Background**

The Department of Defense (DoD) is the largest consumer of energy for buildings among the five federal agencies: DoD, United States Postal Service (USPS), Department of Energy (DOE), the Department of Veterans Affairs (VA), and the General Services Administration (GSA). The DoD's operational and installation energy consumption is 80% of all federal energy consumption ("Department of Defense Annual Energy Management Report Fiscal Year 2015," 2016). The increasing focus over the last couple of decades on how to reduce the amount of energy these buildings consume has driven multiple laws and executive orders to promote the reduction of energy consumption in federal facilities. However, the reach of federal facilities that consume energy is not only limited to the boundaries of the continental United States. According to the DoD, during the height of U.S. combat operations in Iraq and the second Gulf War, there were 505 bases supporting 165,000 service members ("Middle East," 2010). The need for reliable power in these deployed locations drove power generation requirements that are still being met using diesel fuel-powered generators.

The Defense Logistics Agency (DLA) has determined the average commodity price of diesel fuel is \$1.81 per gallon (*DLA Petroleum Standard Price in Dollars*, 2016). The cost of the same fuel can be much higher in a deployed environment due to transportation difficulties and added security risks. The Fully Burned Cost of Fuel

(FBCF) takes into account all of the additional cost factors and has been placed as high as \$600 per gallon (Dimotakis, Abarbanel, Candler, Cornwall, & Ida, 2006).

Executive Order (EO) 13693 directs that any federal building construction on, or after, 2020 be designed and planned to achieve zero net-energy by 2030. EO 13693 defines *net-zero-energy building* as “a building that is designed, constructed, or renovated and operated such that the actual annual source energy consumption is balanced by on-site renewable energy” (Federal Register, 2015). This EO pushes projects to be prioritized based on life-cycle return on investment and use cost-effective and innovative strategies to achieve energy balance (Federal Register, 2015). This energy balance is better defined as a balance between energy taken from and supplied back to the energy grids over a period of time, usually annually (Sartori, Napolitano, & Voss, 2012).

According to an economic viability study comparing stand-alone photovoltaic (PV) systems to diesel-powered systems, PV-powered systems are the lowest cost option at a daily energy demand of up to 15kWh, even in unfavorable conditions (Kolhe, Kolhe, & Joshi, 2002). With the extensive dependency of diesel power generation in contingency operations, there has been limited research conducted to explore the possibility of implementing the concepts of EO 13693 to achieve net-zero facility power. The extent of research regarding power offset by PV systems for USAF contingency assets is limited to the PV Integrated Power Shelter Systems report that only focused on PV shelter flys. This research seeks to gain further understanding of the performance of available stand-alone technology presented to support the endeavor of implementing solar renewable energy to achieve net-zero facility power in contingency locations.

## **1.2 Problem Statement**

While EO 13514 applies to a range of new construction and renovation projects throughout the DoD, this research focuses on accurately predicting the power performance of a deployable PV-microgrid system in a given U.S. Air Force contingency environment. Currently, there is no framework in place for determining the feasibility or economic viability to make an informed decision on whether or not to pursue net-zero initiatives or other high-performance sustainment options in support of contingency operations. The range of built-up infrastructure at various bases in deployed locations throughout the Middle East and Africa varies considerably; the lifespan of these bases varies as well. Bases can be comprised entirely of temporary structures, semi-permanent structures, or permanent hardened shelters; the power that supplies them can be different as well. More established bases may have buildings tied into the host nation's power grids, while less built-up bases may operate on organic power production methods; these are traditionally diesel-powered generators. There is also, at times, a combination of both energy sources on one base. This research focuses on the initial contingency basing locations that are entirely made up of temporary structures, or Basic Expeditionary Airfield Resources (BEAR) infrastructure that rely on organic power production methods.

The Air Force Civil Engineer Center (AFCEC) motivated the research based on a question that was posed to the agency by AFRICOM which was: *Could solar technology be used to power a bare base and, if so, should that renewable energy source be pursued?* Net-zero, even high performance energy shelter systems, would reduce, and potentially eliminate, the enormous logistics chain and financial burden associated with

fossil fuel-powered generators if proven to be technically feasible and economically viable. Currently, there is not an established framework for how and when to implement any sort of net-zero energy system on a bare base or built up base in a contingency environment. A technical feasibility assessment proves useful as a step in the right direction to provide further information to decision-makers on whether to pursue the application of the technology in various contingency environments.

### **1.3 Research Objectives**

Consideration of the interaction between buildings and energy grids varies from country to country and throughout different regions, because each location presents its own unique challenges. Every location must adapt a net-zero energy definition to its own specific conditions and requirements (Sartori et al., 2012). The Air Force is missing a formal, comprehensive, and consistent framework that considers the relevant aspects characterizing net-zero. Creating this framework is essential because it establishes the boundaries of the system given the subjected load requirements. The objective of this study is to analyze the potential for net-zero application for a given contingency site by using a probability-based model that provides predictive outputs based on a stand-alone PV system's parameters, historical weather data, and load characteristics.

This study researches and elaborates on the use of current PV technology and determines how applicable solar microgrid systems can be utilized in a contingency environment. The technology is the baseline application for the probability model that is described in detail in the methodology section of the research. Contingency commanders and Air Force leadership need to be able to make decisions on how to implement the

technology with known and unknown risks and variabilities, and the predictive model serves as a tool to assist with the decision-making process by providing power probabilities and trends within a net-zero power framework. The model uses applicable variables and constraints of the baseline system, as well as historical environmental data, that predicts the hourly power being produced by the system in various contingency locations within CENTCOM and AFRICOM.

#### **1.4 Investigative Questions**

The objective of this research is to create a probabilistic model that evaluates the extent to which a deployed installation may be a suitable candidate for net-zero applications based on the power output of the baseline PV microgrid system. This study utilizes the most significant variables that may be considered for predicting solar power and uses six test sites across CENTCOM and AFRICOM for data collection and implementation reference. The model results further the understanding of potential renewable power availability and its implementation effects for reaching the net-zero power framework established in the research. This information helps minimize the associated risk of unsuccessful implementation. Creating a technical feasibility assessment model represents an important step towards successful future implementation activities. The following investigative questions are addressed in this project.

- i. How feasible is it to achieve net-zero facility power with a photovoltaic renewable microgrid application in a contingency environment?
- ii. What kind of performance can be expected from the implementation of an available photovoltaic microgrid technology for contingency and bare base applications?

### **1.5 Methodology**

The methodology for the study uses a Monte Carlo simulation method to produce an outcome distribution representing the power produced by the established baseline PV microgrid system. This method uses a mathematical model to run thousands of simulations given a set of unknown variables to see how they interact over a given amount of trial and simulation runs. The variables used in the simulation are explained in detail in the literature review and their function in the model is outlined in the methodology. The evaluation model is beneficial in communicating the risk associated with making decisions based on the model's outputs. The cumulative set of outputs will be representative of an expected hourly power expectancy, with a 95% confidence interval, for every location evaluated. This data allows the application of a load-matching formula to be used to determine the probability of meeting net-zero power for the established framework.

## **II. Literature Review**

This chapter defines key terms in relationship with the research areas of net-zero initiatives and establishing power expectancy of solar microgrid systems. Additionally, the chapter establishes the contingency environment used throughout the research. The chapter also elaborates on the relevant technology and prior research efforts that play a role in the research, as well as discussing potential economic assessments. The chapter begins with addressing the directives and guidance that support net-zero implementation and initiatives and how the DoD branches are working to meet the requirements.

After establishing this background, the boundaries of what will be considered a contingency environment in regards to installations supporting contingency operations is covered and then the boundaries of how net-zero is defined for practical application within the research are established. Then the chapter addresses the relevant solar technology used throughout the research and the associated measurements that are considered when predicting the power of the said technology. Finally, the chapter addresses the importance of a full life-cycle assessment to build a complete feasibility model to include economic viability for net-zero implementation.

### **2.1 DoD Directives to Support Renewable Energy in Military Operations**

The turn of the 21<sup>st</sup> century came with a boost to the field of renewable energy when Public Law (Pub.L.) 109-58, (Energy Policy Act of 2005) was passed. Pub.L. 109-58 was a bill passed by the United States Congress that reformed America's energy policy through tax incentives and guaranteed loans for clean energy production endeavors. The bill establishes guidelines for how the DoD will operate with regards to

energy acquisition and consumption. Furthermore, this drove DoD Directive 4180.01, which addresses responsibilities for energy planning, use, and management within the DoD. The DoD policy is established to enhance military capability, improve energy security, and mitigate the associated costs with the use and management of energy (Usdat, 2014).

The Air Force released its Energy Strategic Plan that outlined four priorities that were objectively established to meet two goals. First, reduce energy intensity by 37.5% by 2020 (with 2003 as a baseline) and second, meet a renewable energy consumption goal of 25% across the enterprise by 2025. The four priorities to the plan were to improve resiliency, reduce demand, assure supply, and foster an energy culture (“Air Force Strategic Energy Plan 2013,” n.d.). Enhancing the use of renewable energy will increase operational flexibility and improve energy security. This is especially important in military operations in contingency environments, where the apparent threat levels are increased and resources are constrained.

The United States military operates out of numerous contingency locations around the globe. The energy consumed to support the operations, which includes training, moving, and sustaining military forces and weapons platforms, is described as operational energy (DoD Directive 5134.15, 2011). The DoD considers operational energy and installation energy differently, even though the distinction between the two may, at times, be unclear. However, when it comes to the energy used in direct support of expeditionary or contingency operations, the in-theatre energy consumed by facilities or systems supporting the locations is operational energy (Schwartz, Blakeley, & O’Rourke, 2012). Operational energy accounts for approximately 75% of the DoD’s

total energy consumption on (Schwartz et al., 2012). To transform the way the United States Armed Forces consumes energy, the DoD published the Operational Energy Strategy on June 14, 2011. The goal of the Operational Energy Strategy is to promote energy security for the warfighter through a three-fold approach: reducing demand for energy in military operations, expanding and securing energy supplies for military, and building security into the future force (*Operational Energy Strategy Implementation Plan*, 2012).

## **2.2 Other Service Initiatives towards Net Zero**

The United States Army has created the Army Net Zero initiative in response to additional energy-related federal mandates—including Executive Order 13514, the Energy Policy Act of 2005, and the Energy Independence and Security Act of 2007. The initiative launched with an installation-level pilot program in which 17 Army installations were considered for the net-zero concept. The initial basis for the program relied on the initial definition of a net-zero energy installation. “Defining a Net Zero Energy Military Installation is complicated by the need to consider mission-specific energy requirements in addition to energy used by individual buildings, public facilities, and infrastructure” (*Army Net Zero and Energy Program Summary*, 2013).

Being able to define the net-zero energy goal affects many of the design choices that must be made and the planning factors associated with achieving the set goal (Torcellini, Pless, & Deru, 2006). The U.S. Air Force Energy Strategic Plan defines a zero-net energy building as, “a building that is designed, constructed, and operated to require a reality reduced quantity of energy to operate, meet the balance of energy needs

from sources of energy that do not produce greenhouse gases, and therefore result in no-net emissions of greenhouse gases and be economically viable” (The White House, n.d.; “U.S. Air Force Energy,” 2013). This definition focuses on the energy required to maintain and operate buildings, and the reduction of energy consumption as the first step, but it does not specifically cover the other factors of net-zero, which include water and waste. For this research, only electrical power will be considered.

### **2.3 Meeting Net-Zero**

To achieve a net-zero installation, there must be a tiered effort that should mainly focus on the reduction of energy consumption. This effort may include incorporating more efficient equipment, shelters, and other systems. It will also require a cultural change that promotes energy conservation through daily operations and actions of those involved (Booth et al., 2010). The U.S. Army launched a net-zero initiative that was implemented at the installation level with the goal to produce as much renewable on-site energy as it used over the course of a year (*Army Net Zero and Energy Program Summary*, 2013). The U.S. Army leveraged an approach that emphasized the reduction of the overall energy usage through maximization of energy efficiency, energy recovery, and cogeneration opportunities (*Army Net Zero and Energy Program Summary*, 2013). The plan calls for the remaining demand be offset by the production of renewable energy. Figure 1 is an illustration of the tiered approach the U.S. Army uses as a summation of their net-zero initiative.



**Figure 1 – U.S. Army Net-Zero Approach** (*Army Net Zero and Energy Program Summary*, 2013)

In 2012, Applied Research Associates released the Air Force Research Laboratory sponsored report on PV Integrated Power Shelter Systems (PVIPSS) for Basic Expeditionary Airfield Resources (BEAR) (Keith, Moheisen, Shaaban, & Salavani, 2012). The technical report is a culmination of testing done on various high performance shelter systems. In 2008, AFCEC initiated a BEAR Modernization Plan to explore ways to mitigate the use of diesel fuel use and promote renewable sources to comply with the energy goals, objectives, and metrics of the Air Force. The BEAR Solar Demonstration took place at Holloman AFB, NM in the summer of 2008 and showed that power could be generated from PV integrated shelter flies and ultimately reduce energy demands of the shelter systems (Keith et al., 2012). This demonstration highlighted the importance of making shelter systems more energy efficient (Keith et al., 2012). The research effort aligned with the first pillar of the Air Force Energy Plan 2010: reduce demand, through energy efficient systems. In 2010, follow-on efforts were conducted at the Net-Zero Plus

Joint Capability Technology Demonstration (JCTD) in Ft. Irwin, CA, and in 2012 at the BEAR Parade of Expeditionary Homes at Holloman AFB (Keith et al., 2012).

Additionally, in 2012, a joint proposal with the U.S. Army was funded by the Director of Operational Energy Plans and Programs (DOEPP) in support of Advanced Energy Efficient Shelters. This effort led to a joint installation of shelter testing at Ali Al Salem Air Base, Kuwait, in the summer of 2013, Guam in the summer of 2014, and winter testing at Ellsworth AFB, SD, from 2014-2015.

The technical report was an evaluation of the energy efficient technology and not the evaluation of the shelter manufacturers. The efforts focused on improving the efficiency of soft-wall expeditionary shelter systems to reduce demands (Keith et al., 2012). The components that were examined were shelters (barrel and gable), shade flies, PV covered shade flies (4kW and 5kW), insulated liners, LED lights, Environmental Control Units (ECU), thermal coatings and covers for ECUs and ducts, and insulated vestibules with flies and hard doors. It was determined that with current modernization initiatives, it is possible to reduce the BEAR power demand by ~50%. The breakdown for the reduction is as follows: Energy Efficient Shelter Systems, 20%; Efficient ECUs, 10%; BEAR System for Load and Installation Management (BSLIM) with PV flies, 20% (Keith et al., 2012).

The Applied Research Associates report was focused on integrated PV flies and on no other renewable sources. The reason for the limitation is because AFCEC's initiative was to find a renewable source that would not expand the physical footprint of the current infrastructure. While the PV Integrated Power Shelter Systems for BEAR focused on PV flies that are laid over the shelters, this research focuses on a stand-alone PV system.

However, for the purpose of this research, the data collected from the Energy Efficient Shelter System and ECUs was used for the predictive model demand load assumptions. The reasoning for using this assumption is discussed further in Chapter III Methodology.

Once an energy reduction goal is met, the next phase is the renewable energy acquisition to offset the remaining demand. There are several ways to meet the demand of net-zero on a community level. A net-zero community has greatly reduced energy needs through efficiency gains that help meet the balance of energy within the community that is offset by renewable energy (Carlisle, Geet, & Pless, 2009). A contingency base is considered a community for the research. Torcellini et al. (2006) identifies four definitions on meeting the needs of a net-zero community.

*“Net-Zero Site Energy: The same amount of renewable energy is produced in the community for buildings and infrastructure as is needed by the relative facilities within a year when accounted for at the site.”*

*“Net-Zero Source Energy: A zero energy building produces at least as much energy as it uses in a year from the given source.”*

*“Net-Zero Energy Cost: The amount of money a particular utility company pays the community for the energy generated from the renewable energy source and exports to the grid is at least equal to the amount the utility consumed over a year.”*

*“Net-Zero Energy Emissions: A community is considered net-zero emissions when it produces and uses at least as much emissions-free renewable energy as it uses from emissions-producing energy sources annually.”*

These definitions, or a mixture of the four, explained by Torcellini et al. (2006) could potentially have a role in meeting a net-zero contingency installation. However, the use of net-zero energy cost may become complicated to implement depending on the host nation’s established infrastructure and utility-measuring capabilities. As stated, a net-

zero framework must be established, and this means outlining the system boundaries and conditions.

## **2.4 Defining the System Boundaries and Expeditionary Environment**

Defining the system boundary is essential to the identification of the energy flows being considered across both the physical and balance boundaries of any system being evaluated to achieve net-zero. The physical boundary of a system covers the complete power generation system and all of the associated physical assets, or facilities. The physical boundary helps identify the system's grid properties and operations. The balance boundary establishes the demand sources that are considered in the net-zero balancing equation (Sartori et al., 2012; Torcellini, Pless, Deru, & Crawley, 2006). This study will focus on the physical and balance boundaries associated with the operational facility energy demand for non-enduring locations supporting contingency operations.

To construct the boundaries for this study, a holistic approach must be taken to account for all boundary conditions. First, a contingency environment and a contingency operation must be defined. According to 10 USC 101(a)(13) and FAR 2.101 ("10 U.S. Code § 101 - Definitions," n.d.-a, Federal Acquisition Regulation Subpart 2.1 - Definitions, n.d.-a), a contingency operation is:

*"A military operation that is designated by the Secretary of Defense as an operation in which members of the armed forces are involved in military actions, operations, or hostilities against an enemy of the United States or an opposing force."*

It results in the call or order to active duty of members of the uniformed service members (“10 U.S. Code § 101 - Definitions,” n.d.-b, Federal Acquisition Regulation Subpart 2.1 - Definitions, n.d.-b).

To support the requirements of the contingency operations, there are various requirements that drive contingency basing. Contingency basing is “the life-cycle process of planning, designing, constructing, operating, managing, and transitioning a non-enduring location supporting a Combatant Commander’s requirements” (*DoD Directive 3000.10*, 2013). The United States military services have supported contingency operations around the globe since their inceptions. A contingency location is a non-enduring location that is not within the United States that supports and sustains the contingency operations as it is directed by the appropriate authority where it is categorized by the mission life-cycle requirements (*DoD Directive 3000.10*, 2013). The life-cycle requirements for the contingency locations are broken down into three categories: initial, temporary, or semi-permanent.

*“Initial contingency location: A contingency location occupied by a force in immediate response to a named or unnamed contingency operation and characterized by austere infrastructure and limited services with little or no external support except through Service organic capabilities.”*  
(*DoD Directive 3000.10*, 2013)

*“Temporary contingency location: A contingency location that provides near-term support for a named or unnamed contingency operation and characterized by expedient infrastructure and support services that have been expanded beyond Service organic capabilities.”*  
(*DoD Directive 3000.10*, 2013)

*“Semi-permanent contingency location: A contingency location that provides support for a prolonged named or unnamed contingency operation and characterized by enhanced infrastructure and support services consistent with sustained operations.”*  
(*DoD Directive 3000.10*, 2013)

It is important to define the contingency location, as well as the related facilities and buildings associated with them. Between an initial, temporary, and semi-permanent contingency location, the types of facilities can vary in an extensive manner. This includes the sizes, associated functional systems, and overall efficiency. At times, they may even be a combination of different types of facilities to support an installation in transition between the three or going from non-enduring to enduring. A consistent net zero energy building (ZEB) definition should allow a meaningful comparison between similar buildings in similar climates, as well as between the expected performances of a building (Sartori et al., 2012). Understanding the makeup of the installation by facilities is difficult but must be managed. This research will focus on the initial contingency location with an independent power grid supporting the installation facility or shelter system power demand. Specifically, net-zero balance is established when the energy produced equals (or is greater than) the energy used on a typical day in the established contingency environment. However, there are other realistic concerns for potential system configurations when considering the host nation's electrical supply that should be addressed in this literature review; however, they were not considered in the methodology of this research.

## **2.5 Host Nation Power Considerations**

There are many situations when the host nation's electrical grid is considered highly unreliable; however, for all intents and purposes, the most reliable and cost-effective solution is an entirely isolated grid (*Guidance for DoD Utilization of Host Nation Power*, 2015). When considering the four net-zero measures, each one mean

introduces a potential to incorporate an additional renewable source to the host nation's existing grid. The previous statement would not be true if a completely isolated micro-grid were being used. Through an MIT Lincoln Laboratory and Sandia National Laboratories (2015) study, bases that are properly connected to the host nation's power grid will benefit from reduced energy costs, fossil fuel usage, and increased endurance of the base itself—regardless of the host nation's power grid reliability (*Guidance for DoD Utilization of Host Nation Power*, 2015). This study also addresses qualitative considerations that include the mission assurance needs as it pertains to energy, the local grid capacity and capability, the host nation's interest in grid and power improvement, power reliability and availability (service interruption rates), and the overall grid security. The recommendation from the study was to use the host nation grid, and was specified by the following statement:

*“It is recommended, and should always be the case, that every OCONUS base in the developing world should have on-base generation capability that can meet their full power demand. Once that is in place, a connection to the HN grid will only improve overall energy accessibility by providing a second channel beyond just the fuel supply. In this way, HN power is like other intermittent sources such as solar or wind power. HN power should not be thought of as a replacement for traditional on-base generation, but an augmentation.”*

*(Guidance for DoD Utilization of Host Nation Power, 2015)*

Establishing a contingency location's best method for power supply begins to help form the boundaries for the net-zero system being implemented. As an optimal solution, a contingency base would be connected to the host nation's power grid. Establishing the building or installation system boundary is necessary to identify which energy flows cross the boundary and how these systems cross them as well (Sartori et al., 2012). Both boundary categories must be considered and must coincide to be considered

net-zero. For example, if the airfield lights are not considered with the balance boundary, they are not part of the physical boundary of the system. “The physical boundary is useful to identify so called ‘on-site’ generation systems; so that if a system is within the boundary it is considered on-site, otherwise it is ‘off-site’” (Sartori et al., 2012). The balance boundary will define the energy uses that are considered for the net-zero balance (Sartori et al., 2012).

## **2.6 Energy Consumption for Typical Initial Contingency Location**

The United States’ military CENTCOM presence spiked between 2001 and 2014, as the contingency operations were carried out in support of Operation Iraqi Freedom and Operation Enduring Freedom. For decades, military services have operated out of countries in the Middle East and the Northern Horn of Africa. The main source for powering the infrastructure in these locations has been fossil fuels for the fossil fuel-powered generators. The Defense Logistics Agency (DLA) has determined the average commodity price of diesel fuel is \$1.81 per gallon (*DLA Petroleum Standard Price in Dollars*, 2016). The cost of the same fuel can be much higher in a deployed environment due to transportation difficulties and added security risks. The Fully Burned Cost of Fuel (FBCF) takes into account all of the additional cost factors and has been placed as high as \$600 per gallon (Dimotakis et al., 2006).

Despite the abundant regional solar resource in this part of the world, little solar photovoltaic capacity has been deployed given the significant market growth in 2011 of almost 30 gigawatts (GW) of new solar capacity worldwide (Griffiths, 2013). To begin taking advantage of the resource for military applications, a baseline, or benchmark, for

energy demand must be established. The DoD is the largest consumer of energy through buildings among the five federal agencies (DoD, USPS, DOE, VA, GSA) at 54% (“Buildings Energy Data Book,” 2012) and must consider benchmarking in these contingency locations since the majority of the electrical energy comes from operational usage. For the purpose of this research, the anticipated baseline for an initial contingency location will be the U.S. Air Forces Africa (AFAF) military construction (MILCON) project, AFAF 14-0005

The AFAF MILCON project, AFAF 14-0005, “Construct Airfield and Base Camp”, includes troop labor to construct a 1,830 linear meter asphalt runway and turnarounds capable of supporting C-17 operations, and various light and medium load aircraft (Synovec, 2015). Additionally, the project includes construction of force protection infrastructure; site preparation for life support, operations, and logistics areas; and the associated electrical and utility infrastructure (Synovec, 2015). The bare base supports AFRICOM. The site has limited to no existing utility and electrical access to the closest local infrastructure. The support services (electricity and utilities) will be sustained organically and without reliance on the host nation. The assets in Table 1, list the electrical demands associated with AFAF 14-0005 and can be considered a demand baseline for a typical bare base or initial contingency location that applies to the research.

**Table 1 - Assets and Power Consumption for AB-201**

| <b>Base Asset</b>                                   | <b>Calculated UTCs</b> | <b>Power Consumption (kW)</b> |
|-----------------------------------------------------|------------------------|-------------------------------|
| CE MAINTENANCE (1 MEDIUM SHELTER/ 6 SMALL SHELTERS) | 1                      | 4.6                           |
| ENGINEERING MGT (2 SMALL SHELTERS)                  | 1                      | 6                             |
| TACTICAL EXCHANGE (1 SMALL SHELTER)                 | 1                      | 6                             |
| POSTAL (1 MEDIUM SHELTER; 1 FDECU)                  | 1                      | 6.5                           |
| CHAPLAIN (1 SMALL SHELTER)                          | 1                      | 7.8                           |
| MORTUARY (1 SMALL SHELTER)                          | 1                      | 10.7                          |
| TRAFFIC MANAGEMENT (NO FCY)                         | 1                      | 12                            |
| REMOTE AREA LIGHTING SYSTEM (2 RALS)                | 2                      | 16.8                          |
| FIRE OPS/CRASH RESCUE (4 SMALL SHELTERS)            | 1                      | 18                            |
| 8K DOME (1 SHELTER)                                 | 2                      | 20                            |
| ADR300 REFRIGERATION (1 ADR)                        | 5                      | 20                            |
| PWR PRO/CE SUP/ELECT (3 SMALL SHELTERS)             | 1                      | 22.5                          |
| ADMIN (4 SMALL SHELTERS)                            | 1                      | 23                            |
| VEHICLE MAINTENANCE/OPERATIONS (1 SMALL SHELTER)    | 1                      | 27.5                          |
| 4K DOME (1 SHELTER)                                 | 2                      | 30                            |
| SHOWER/SHAVE/LATRINE (2 SMALL SHELTERS)             | 3                      | 36                            |
| WATER DISTRIBUTION INITIAL                          | 1                      | 36                            |
| WATER PRODUCTION (1500) (2 1500GAL ROWPUs)          | 1                      | 45                            |
| CE INDUSTRIAL (6 SMALL SHELTER/3 MEDIUM SHELTERS)   | 1                      | 51                            |
| KITCHEN                                             | 1                      | 137                           |
| BILLET (12 SMALL SHELTERS)                          | 3                      | 162                           |
| SELF HELP LAUNDRY                                   | 1                      | 172                           |
| FDECU (12 FDECUS)                                   | 7                      | 1302                          |
| <b>TOTAL:</b>                                       |                        | <b>1911.28</b>                |

While the assets in Table 1 give the power requirements, and are useful for planning actions when considering the worst case load demand that must be matched by the power generation sources, it does not provide an accurate trend of actual power usage in the location. Data collected from Ali Al Salem AB (ASAB), Kuwait, provides a better visualization of what the power demand trend looks like. Figure 2 and Figure 3 show the usage on an extreme summer and winter day, respectively.

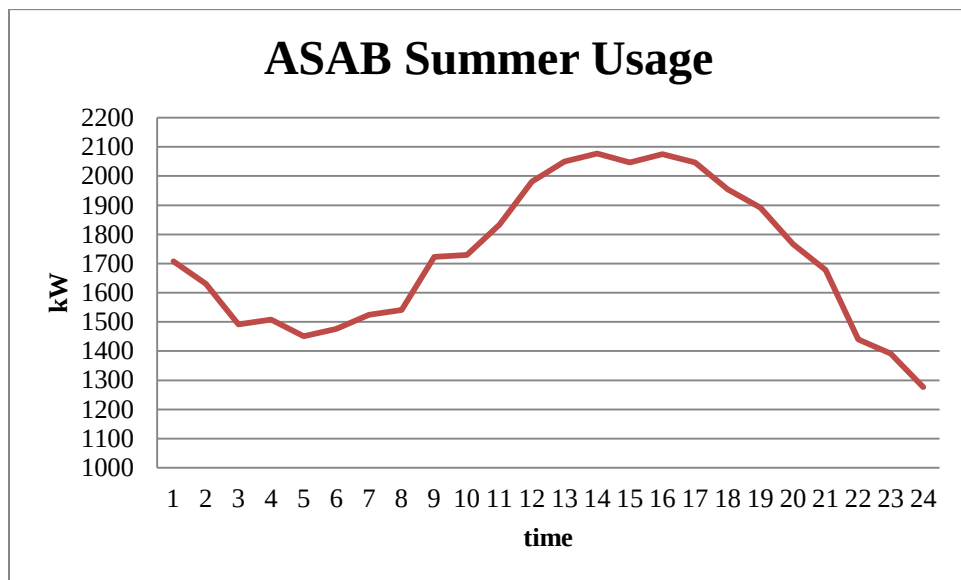


**Figure 2 - Summer Power Usage at Ali Al Salem AB, Kuwait**

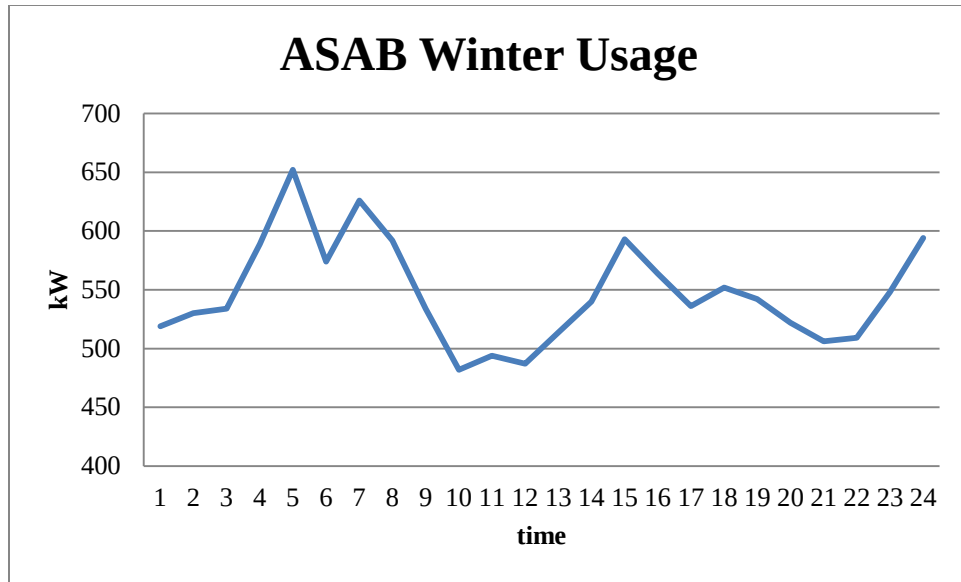


**Figure 3 - Winter Power Usage at Ali Al Salem AB, Kuwait**

The power generation systems in ASAB provide energy on a much greater scale than what would be required at an initial contingency location. However, the types of usage and the loads on both systems are similar because both use Mobile Electric Power (MEP) series generators that are integrated into the BEAR infrastructure, it is just the sizes of the applications that are different. A scaling method was used to right-size the demand curves in Figure 2 and Figure 3 to what may be appropriate for an initial contingency location, as a high level estimate. This is done by taking the power generation capability of the ASAB data and the power generation capability in the Agadez location and creating a scaling ratio as shown in Table 2:

**Table 2 - Sizing Ratio for Contingency Location Types**

|              |               |
|--------------|---------------|
| ASAB         | 3200 kW       |
| AB-201       | 1560 kW       |
| <b>ratio</b> | <b>0.4875</b> |

The ratio can be applied to scale the demand loads represented in Figure 2 and Figure 3 to provide a better understanding of the demand trends that can be expected at an initial contingency location application. The power generation capability for each base, ASAB and AB-201, is the total wattage for all available MEP generator assets on each base.

## **2.7 Renewable Energy Sources**

Renewable energy is a challenge for power generation because it behaves very differently than typical power sources. Many of the traditional systems have a predictable stochastic mannerism to them. However, renewable energy sources are a considerable degree less predictable and can be extremely variable. The various factors that dictate the amount of useable power are at times uncontrollable and all locations do not provide the same characteristics. Hence, a single renewable energy system will not operate and perform the same from one location to another.

When considering renewable options to achieve net-zero, the energy grid being used is critical. The energy grid is the supply system of energy, whether it is electricity or other energy sources. The grid may be two-way, unless isolated microgrids are considered, and in this configuration the energy is delivered to the building(s) via the grid; the grid also receives energy being generated on the site (Sartori et al., 2012). A micro-grid system is isolated from the host nation's grid and solely supplies the buildings

under its load. The micro-grid concept takes a cluster of buildings and/or loads operating as a single controllable system that provides the required power to the area (Lasseter, n.d.).

This research will focus on the micro-grid system because by definition it is most comparable to a system that is used in an initial contingency location where power supply is going to be organically generated and independent from a larger grid. Moreover, this study will utilize the relevant criteria for predicting a solar renewable energy system's power performance to meet the net-zero.

## **2.8 Solar and PV System Technology**

Photovoltaic technology uses ultraviolet radiation from the sun as an initial energy source to be converted into electrical energy (Green, 1982). The PV array is made up of multiple modules that convert the solar radiation to direct current (DC) electricity. A typical PV system produces DC power supply from the PV cell array. In most cases, the demand load must be supplied through alternating current (AC) power because most assets, appliances, and other systems require AC supply. To accomplish a conversion from DC to AC power, the PV system contains an inverter that functions as the load converter between the PV array and the demand source. A basic PV system will typically contain a PV array, battery storage, a controller, and an inverter (Sukamongkol, Chungpaibulpatana, & Ongsakul, 2002) as shown Figure 4.

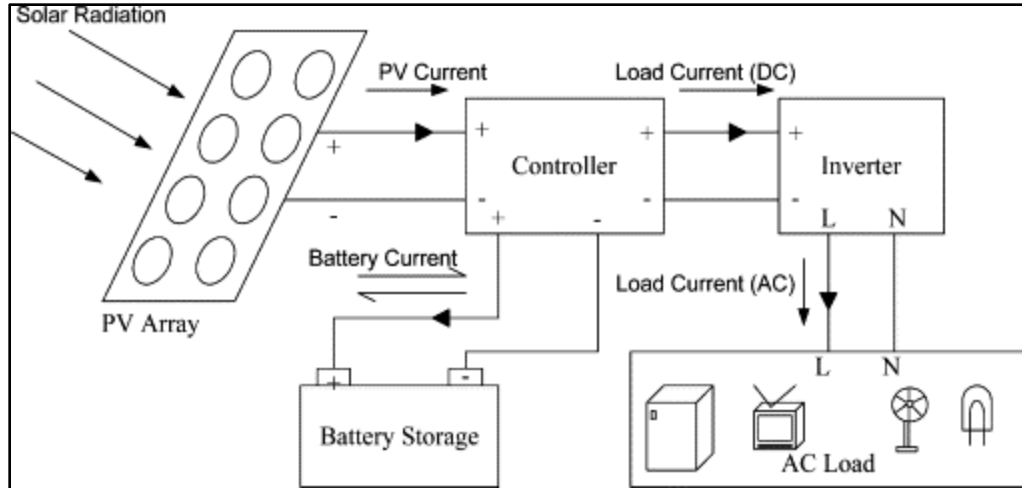


**Figure 4 - Typical stand-alone PV configuration(Sukamongkol et al., 2002)**

Determining the overall performance of a stand-alone system like Figure 4 requires the characteristic performance of each of the individual components of the PV system (Sukamongkol et al., 2002). Each of the component's performance measures are able to be identified. The PV array's output current is fixed at the system's operating voltage and is measured with  $I_p = \text{output current of panel}$ . The charge controller acts as a regulator to prevent overcharge of the battery and supplies the battery with recharging voltage when the load demand is low enough to do so (Sukamongkol et al., 2002). The charge controller must be able to determine the battery current, and this relationship is measured with  $I_B = \text{battery current}$ .

The battery storage performance measures are the battery's terminal voltage, or the voltage at the terminals, and the state of charge (Sukamongkol et al., 2002). The respective measures are  $V_B = \text{battery terminal voltage}$  and  $SOC = \text{State of Charge}$ . The performance of the inverter, which converts the electricity from a

DC input from the battery into an AC output, can be measured by the relationship between the inverter input and its output power. There will be a power loss between two components as a result of the switching circuit and the step-up transformer. The power losses can be broken down into various categories but ultimately the core loss is fixed as long as voltage is maintained (Sukamongkol et al., 2002).

The strongest atmospheric dependency for solar power is solar radiation (Boxwell, 2016). The environmental scenario that provides the optimal solar-power production would be consistent with the following: no clouds, minimal aerosols, and the panel's maximum ambient temperature of 77°F (25°C). According to Boxwell (2013), every 1°C deviation, above or below, from the ideal ambient temperature of 25°C will lose or gain, respectively, an efficiency of 0.5%. To adjust to these constraints, there are available systems that utilize cooling technologies that will help regulate the surface temperatures of the panels to maintain the ideal temperature. However, these systems require additional electrical power to operate the required pumps and/or compressors. Another ideal feature would suggest a PV panel would be able to rotate with the sun's progress through the sky so that the sun's rays are constantly orthogonal to the plane of the panel and PV modules. Unfortunately, these systems can be expensive and will also require additional power to run motors and other electrical components. In an effort to minimize the cost and power consumption, designers typically use an averaged azimuth and elevation angles for the panel orientation (Boxwell, 2016).

## **2.9 Solar Radiation**

Solar radiation is measured in solar irradiance, or the power per unit area received from the sun in the form of electromagnetic radiation in space or on the earth's surface (Iqbal, 1983a). Hourly solar irradiation varies approximately  $\pm 45 \text{ W/m}^2$  over the span of a year (Kharseh, n.d.). The hourly solar irradiance is calculated using the formula:

$$I = I_b + I_d \quad (1)$$

where  $I_b$  is the beam component and  $I_d$  is the diffuse component. The beam radiation ( $\tau_{cb}$ ) is the accumulation of solar rays that reach the ground without change in direction, which is also considered direct radiation (Iqbal, 1983b). The diffuse radiation ( $\tau_{cd}$ ) is the solar rays that reach the ground after a change in direction by particles in the atmosphere (Iqbal, 1983b). The beam and diffuse radiations are the ratios of the transmitted direct radiation to the total radiation incident at the top of the atmosphere ( $G_0$ ). Each component, beam and diffuse irradiation, is measured by the following equation for hourly radiation on a ground surface for a clear day:

$$I = \frac{12 \cdot 3600}{\pi} \cdot (\tau_b + \tau_d) \cdot G_{sc} \cdot \left(1 + 0.033 \cdot \cos \frac{360 \cdot n}{365}\right) \cdot (\cos \varphi \cdot \cos \delta \cdot (\sin \omega_2 - \sin \omega_1) + \frac{\pi \cdot (\omega_2 - \omega_1)}{180} \cdot \sin \varphi \cdot \sin \delta) \quad (2)$$

Each variable will in Equation 2 is described in the remainder of this section.

The concept of measuring solar irradiance begins with the solar constant. The solar constant is the intensity of the solar radiation hitting one square meter of the earth at the mean distance from the sun (Kharseh, n.d.). The solar constant is calculated to be  $1367 \text{ W/m}^2$  from:

$$G_{sc} = \sigma T^4 \left( \frac{4\pi R}{4\pi D} \right)^2 \quad (3)$$

where  $\sigma$  is the Stefan-Boltzmann constant ( $5.67 \cdot 10^{-8} W/m^2 \cdot K$ ),  $R$  is the sun's radius ( $696 \cdot 10^6 m$ ),  $D$  is the average distance between the sun and the earth ( $150 \cdot 10^9 m$ ), and  $T$  is the temperature of the sun ( $5785^\circ K$ ).

There are four major angles that are used to calculate the hourly solar irradiance: latitude, longitude, declination, and hour angle (Iqbal, 1983c). Latitude ( $\phi$ ) and longitude ( $L$ ) are both used to calculate solar irradiation. The latitude ( $\phi$ ) is the angle measured at the centre of the Earth, and where a given location is with respect to the equator. The longitude ( $L$ ) is the angle measured at the centre of the earth, and where a given location is with respect to the Greenwich meridian. The Greenwich meridian is the 0 degree measurement with locations west being negative and east being positive. Additionally, the measure of declination ( $\delta$ ) is the angle made between the plane of the equator and the line that joins the two centres of the earth and the sun (Iqbal, 1983c).

$$\delta \approx 23.45 \cdot \sin \left( \frac{284+n}{365} \right) \quad (4)$$

The variable ( $n$ ) for all parts of applications of calculating solar irradiance is, the day of the year (1-365). The hour angle is the Sun's angular deviation from south given by the formula:

$$\omega = 15^\circ \cdot (\text{solar time} - 12) \quad (5)$$

where,

$$\text{solar time} = \text{standard time} + \frac{4 \cdot (L_{st} - L_{loc}) + E}{60} \quad (6)$$

and,

$$E = 229.2 \cdot \left( 0.000075 + 0.001868\cos B - 0.0302077\sin B - 0.014615\cos 2B - 0.04089\sin 2B \right) \quad (7)$$

And,

$$B = (n - 1)360/365 \quad (8)$$

Other considerations include the solar azimuth ( $\gamma$ ) which is the angle of projection of the straight line that joins the considered site with the centers of the sun on the horizontal plane and due south (Kharseh, n.d.). The incident beam radiation ( $\theta$ ) is the radiation at the angle at which the beam radiation meets the measureable surface (Kharseh, n.d.). The Zenith angle  $\theta_z$  is the incidence angle of the sunbeam on a horizontal surface on any given latitude (Kharseh, n.d.).

## **2.10 Köppen-Geiger Climate Maps**

Besides the geographical location of a site and its relative position to the sun, climate characteristics can have a role in the effectiveness of a solar power source. There is a wide span of variance in the different types of climates around the globe, and being able to sample from each relevant type of climate in the research is essential to gaining a better understanding of how a system may behave in the full spectrum. The Köppen-Geiger Climate map provides a recognized categorized climate map to assist with sampling various locations to obtain breadth in the research.

The Köppen-Geiger map is the most frequently used climate classification map by Wladimir Köppen. The latest version was jointly adjusted in 1961 along with Rudolf Geiger (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006a). The Köppen-Geiger climate classes are coded in a way that describes a location's main climate type, precipitation, and temperature to the 0.5 degree for latitude and longitude grid accuracy (Kottek et al.,

2006a). Applications to climate modeling and greenhouse gas warming simulations have incorporated the Köppen-Geiger climate classification. By sampling from the various climate classifications within the CENTCOM and AFRICOM areas of responsibility (AOR), a full spectrum can be represented in the model. Figure 5 is the world map of Köppen-Geiger Climate Classification.

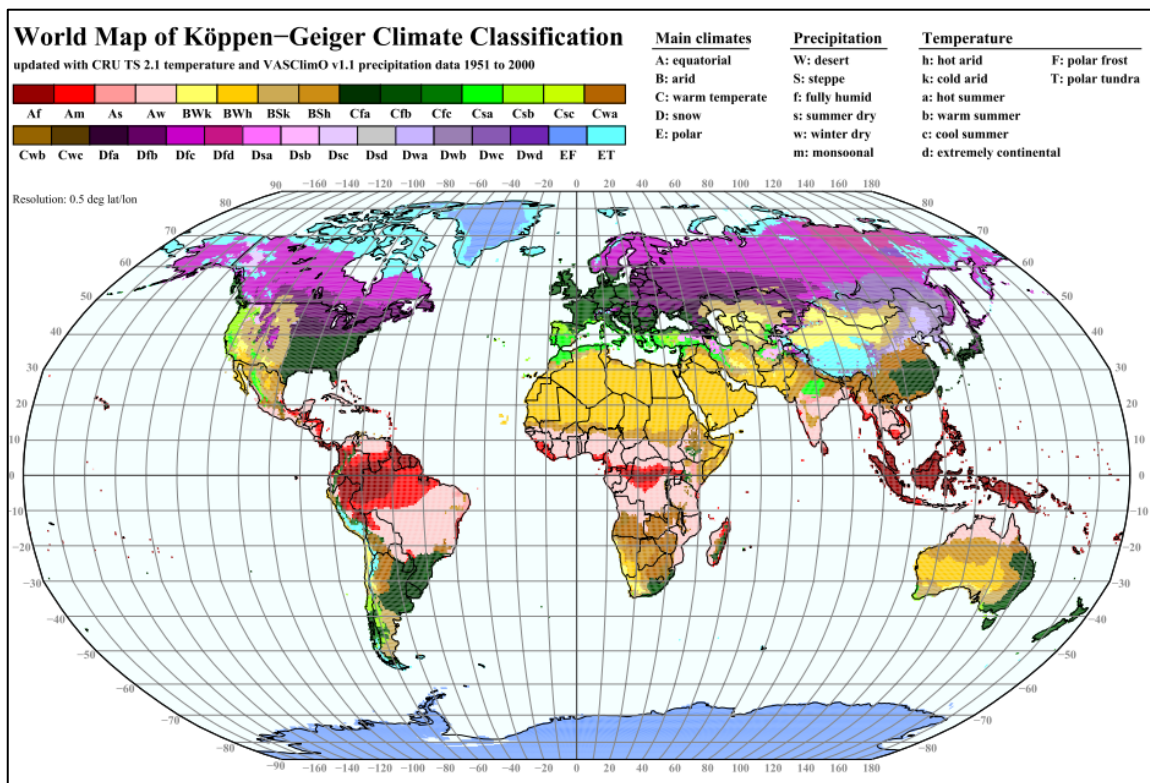


**Figure 5 - Köppen-Geiger Climate Classification Map (Kottek, Grieser, Beck, Rudolf, & Rubel, 2006b)**

### **2.11 Economic Feasibility Models**

To properly disseminate the renewable energy systems to a given location, there must be an evaluation of the system's technical appropriateness as well as the economic viability (or feasibility) for the subject location (Kaundinya, Balachandra, & Ravindranath, 2009). Economic feasibility is the analysis of a project's costs and revenues in an effort to determine whether or not it is logical and possible to complete ("Economic Feasibility," n.d.). There are many models that are used to execute a feasibility analysis, specifically as they pertain to renewable energy and net-zero initiatives. Sesana and Salvalai (2013) provide an overview of the main life-cycle methodologies used to evaluate net-zero energy buildings with the objective to understand how net-zero design is interpreted in the economic field. They argue that the consideration of the entire system's life-cycle must be considered through the life cycle methodologies: life-cycle assessments (LCA), life-cycle energy analysis (LCEA), life-cycle ZEB (LC-ZEB) and life-cycle costs (LCC). The literature captured from the paper expresses that LCC analysis as the best tool to defining the lowest cost of a sustainable or net zero system. The LCC has limitations due to the lack of reliable information and difficulty in forecasting over a long period of time factors (Sesana & Salvalai, 2013). To consider the forecasting problems, there are various risk assessment techniques that are used. The most accepted techniques are sensitivity analysis (deterministic approach), Monte Carlo simulation (probabilistic approach), and fuzzy set theory (Sesana & Salvalai, 2013).

Kolhe et al. (2002) argue one way to determine the economic viability is to compare the stand-alone system with the most likely alternative source, which would be a diesel-

powered system in a contingency location. Kolhe et al. (2002) compare a solar PV system with a diesel-powered system for an energy demand using a sensitivity analysis via life-cycle cost computation based on country-specific parameters. The model that was applied for the comparison estimates the comparative viability of the PV system, worst case and best case, against the conventional diesel-powered system based on their respective life-cycle costs.

Fuller (2010) defines a life-cycle cost analysis as “a method for assessing the total cost of facility (infrastructure). It takes into account all costs of acquiring, owning, and disposing of a building or building system.” The costs associated with the cash flow for a life-cycle cost analysis (LCCA) may include: initial costs, fuel costs, operation and maintenance (O&M, and repair costs, replacement costs, resale or salvage values and disposal costs (residual values), finance charges, and other miscellaneous costs (Fuller, 2010). Another definition of a total life-cycle cost (TLCC) analysis is given by (Brown & Yanuck, 1980) where the TLCCs are the costs incurred through the ownership of an asset over an asset’s life span or the time or period of subject interest. While The TLCC considers all significant costs associated with the life of the project, the TLCC is not recommended for an economic evaluation to decide one alternative over another because there is no frame of reference for what are acceptable and unacceptable costs. Additionally, TLCC does not take benefits and returns into account; however, TLCC can be used to ranked mutually exclusive alternatives with the same economic benefits and returns (Short, Packey, & Holt, 2005). An LCCA is typically conducted for the purpose of further understanding of the LCC associated with a potential stand-alone system in a

ranking comparison to the other alternatives in a contingency environment (i.e. diesel power production) using the following formula (Short et al., 2005):

$$TLCC = I + PVOM \quad (9)$$

where,

$I$  = initial investment

$PVOM$  = present value of all O&M costs, or

$$PVOM = \sum_{n=1}^N \frac{O\&M_n}{(1+d)^n} \quad (10)$$

The O&M costs associated with standard (grid connected) solar PV systems are generally lower than other renewable systems and are significantly lower than diesel powered generation system O&M costs. The world mean estimate for O&M costs for a PV system is 1.5% of the total initial investment cost of the PV system (Jaeger-Waldau, 2013). However, there have been very few studies done to establish recent estimates for the annual costs of O&M for off-grid or stand-alone PV systems.

Another viability method is the comparison of the levelized cost of energy (LCOE) between the PV renewable method and the diesel fuel operation. LCOE allows a comparison of the alternatives where there are different scales of operation and potentially different investment and operating time periods. The LCOE is the cost assigned to every unit of energy produced (or saved) by the observed system over the analysis period, which will equal the TLCC when discounted back (Short et al., 2005) by using the following formulas:

$$\sum_{n=1}^N \frac{Q_n \times LCOE}{(1+d)^n} = TLCC, \text{ or}$$

$$LCOE = TLCC \div \{[Q_n \div (1 + d)^n]\} \quad (11)$$

Where,

LCOE = levelized cost of energy

TLCC = total life-cycle cost

$Q_n$  = energy output or saved in year  $n$

$d$  = discount rate

$N$  = analysis period

## **2.12 Uncertainty and Risk**

When predicting the technical and economic performances of a solar system, there are variables that have levels of uncertainty. The uncertainty refers to the state of information about a given variable or parameter of interest when the quantity cannot be known perfectly (Short et al., 2005). The concept of variability aligns with uncertainty as it describes how a parameter may vary across a group. The concept of risk refers to the level of uncertainty with a significant measure (Short et al., 2005). The uncertainty related to the performance of the system comes from the uncertainty in weather conditions such as solar irradiance, temperature, and wind conditions. These conditions are not perfectly predictable and are direct factors in predicting the solar output of a given system. This research acknowledges the uncertainty associated with implementing a

renewable power system, and it is the basis for using simulation methods to consider the uncertainties.

### **III. Methodology**

The objective of the study is to model the operational performance of a deployable photovoltaic (PV) microgrid and how it will reduce net loads to achieve net-zero facility power in a given contingency location. The model takes named, but unknown, variables and creates distributions for expected power production outcomes based on the model inputs. The outputs are the results of the Monte Carlo simulation and are displayed as probable power production over the course of a set day. The predicted power outputs are compared against the established power demand trends to display the net loads of production. The model is used to evaluate various contingency locations within the U.S. Central Command (CENTCOM) and U.S. Africa Command (AFRICOM) areas of responsibility (AOR) and determine a PV system's predicted performance and compare it to a typical contingency operations facility power usage to help determine which locations are best candidates for net-zero power implementation. The Köppen-Geiger Climate Classification map is used to select various locations to obtain a wide spectrum of sites in the AORs for simulation testing and evaluation.

#### **3.1 Simulation Theory**

The Monte Carlo method has been used to solve complicated problems in the fields of science, engineering, biology, and physics. The applications have grown rapidly since its inception in the 1940s (Metropolis, 1987). The Monte Carlo method is a statistical sampling technique that has grown and become more sophisticated as the computer codes that are utilized have evolved (Eckhardt, 1987). To run the statistical samplings, Monte Carlo uses different iterations of random variables. Random numbers

are generated from a source of distributed pseudo-random numbers using a common algorithm for generating the numbers (Metropolis, 1987). Even though the variables are random, there is an established set of constraints that bound the randomization, such as mean and standard deviations in the case of a normally distributed set of variables (Lomas & Eppel, 1992). This input information may be derived from historical data and experiences.

A Monte Carlo simulation performs risk analysis by building models of possible results through a mathematical technique that substitutes probability distributions for factors with inherent uncertainty (“Monte Carlo Simulation,” 2016). The Monte Carlo method can be approached two different ways. The first approach finds the end point as a fixed but unknown value. The other approach states the end point as an unknown distribution of values (Hoffman & Hammonds, 1994) which is the approach utilized for this research. The endpoints (outputs) for the study will be potential power generation of the renewable PV system.

The predictions produced by the unique set of input data is saved and the process is repeated many times, using a different, yet unique, set of inputs on each occasion (Lomas & Eppel, 1992). The comprehensive output distribution may explain how likely a particular event may occur given there are a large number of inputs, and it should most likely be normally distributed regardless of the individual input distributions (Lomas & Eppel, 1992; “Monte Carlo Simulation,” 2016). By using Monte Carlo simulations in this study, various locations can be analyzed collectively when all of the necessary parameters are known and historical data for the parameters exists, but their future

implementation values are unknown. The model parameters are identified in section 3.5.1.

### **3.2 Model Development**

To develop a simulation model that incorporates all of the significant parameters to predict the performance of a given PV system, the research uses references outlined in the NREL PVWatts® Version 5 Manual as a developmental baseline. The NREL PVWatts® calculator is a web-based application that estimates the electricity production of a grid-connected PV system based on a few simple inputs (Dobos, 2014). While the program was meant for grid-connected systems, a standalone application is used in the researcher's model and certain aspects of the research model are adjusted or assumed as necessary. The results from PVWatts®, and inherently the research model, are estimates and are representative of a year with typical weather and actual performance measures that may deviate as much as  $\pm 20\%$  from the annual long-term averages and  $\pm 40\%$  for monthly values (Dobos, 2014). The stated error margins, are deemed acceptable due to the countless variables that may affect the actual performance of a given system over that length of time.

PVWatts® uses a set of PV system specifications that are the minimal requirements necessary to obtain expected output. To generate useful outputs from the research model, a baseline PV system needs to be established. This system serves as the hypothetical microgrid PV system that would be implemented in the given contingency location, and it was assumed to be a typical technology that could be deployed and seamlessly integrated with the BEAR assets currently in use. The baseline system

specifications used in the researcher's model come from the ZeroBase MX-SERIES 100 power system which is a microgrid for remote and austere environments ("MX-SERIES 100," n.d.). The system is an expeditionary mobile microgrid that produces solar renewable power for contingency shelters and basing. This research is not an evaluation on the MX-SERIES' performance; however it provides validated system performance data that can, in-turn, be used as a baseline input for the model. The maximum module efficiency for the baseline system is calculated using the efficiency equation ("Measuring PV Efficiency," n.d.)

$$\eta_{max}(\text{max efficiency}) = \frac{P_{max}(\text{max power output})}{(E_{S,\gamma}^{SW}(\text{incident radiation flux}) * A_c(\text{area of collector}))} \quad (12)$$

The baseline system size is the  $P_{max}$ , as is it is the maximum power output of the array at the irradiance or the incident radiation flux. The assumed incident radiation flux under standard testing conditions (STC) is 1000W/m<sup>2</sup>. The area is considered the total surface area of the module array in square meters. The efficiency breakdown for the baseline system is outlined in Table 3. While the system uses the most well-known and developed module types, mono-crystalline, its efficiency falls behind what is typical industry efficiencies of 14-15%

**Table 3 - Baseline System Efficiency Breakdown**

|              |              |
|--------------|--------------|
| $P_{max}$    | 8600 Watts   |
| $A_c$        | 113.48 $m^2$ |
| $\eta_{max}$ | 7.6%         |

**Table 4 - Baseline System Model Inputs**

| Input Parameter     |                                                                        |                                                          |
|---------------------|------------------------------------------------------------------------|----------------------------------------------------------|
| Field               | Units                                                                  | Value                                                    |
| System Size         | kW (DC)                                                                | 8600                                                     |
| Module Type         | Standard, Premium, or thin film                                        | Standard                                                 |
| System losses       | %                                                                      | 14*                                                      |
| Array type          | Fixed open rack, fixed roof mount, 1-axis, bracketed 1-axis, or 2-axis | Fixed open rack                                          |
| Tilt angle          | Degrees                                                                | Site Latitude**                                          |
| Azimuth             | Degrees                                                                | 180° in northern hemisphere, 0° in southern hemisphere** |
| DC/AC ratio         | Ratio                                                                  | 1.1*                                                     |
| Inverter efficiency | %                                                                      | 96*                                                      |

The probability model requires certain baseline system parameters and assumptions be identified. Table 4, displays the basic model inputs for the baseline system that is relevant to the model. The “standard” module type is representative of a typical poly- or mono-crystalline silicon module configuration and is reflective of the baseline PV system. While there was information provided in the manufacturer specifications that was useful, there were fields that required assumptions based on the limitation of data availability. The assumptions that were made about the system were taken from default settings of PVWatts®. These default values are close to the industry

standards for typical PV systems. Table 5, gives an overview of the variables that are considered in the model's output function, Equation (13) (Dobos, 2014; Sukamongkol et al., 2002). The variables  $I_b$ ,  $I_d$ , and  $T_a$  are the variables in the model that are not static and have distributions built for them based on the data collected and are subject to the Monte Carlo sampling method used in the model.

**Table 5 - Variables for DC Power Output**

| Variable                             | Unit                          | Source                                                                                       |
|--------------------------------------|-------------------------------|----------------------------------------------------------------------------------------------|
| Direct Irradiance ( $I_b$ )          | $\text{w/m}^2$                | 14 <sup>th</sup> Weather Sq                                                                  |
| Diffuse Irradiance ( $I_d$ )         | $\text{w/m}^2$                | 14 <sup>th</sup> Weather Sq                                                                  |
| Ground Irradiance ( $I_g$ )          | $\text{w/m}^2$                | PVWatts assumption                                                                           |
| Ambient Temperature ( $T_a$ )        | $^{\circ}\text{C}$            | 14 <sup>th</sup> Weather Sq                                                                  |
| Cell Temperature ( $T_{cell}$ )      | $^{\circ}\text{C}$            | $T_{cell} = T_a + (NOCT - 20^{\circ}\text{C}) \left( \frac{I_{tr}}{800\text{W/m}^2} \right)$ |
| Nameplate DC rating ( $P_{dc0}$ )    | Watts                         | Zerobase MXSeries specifications                                                             |
| Temperature coefficient ( $\gamma$ ) | $\text{-\%/}^{\circ}\text{C}$ | PVWatts assumption                                                                           |
| Reference Cell Temperature           | $^{\circ}\text{C}$            | Standard Test Conditions                                                                     |

The research model focuses on estimating the potential power production during the producible hours of the day, which is categorized as the period of time that the solar radiation has a positive effect on the system. The following equation is used to model the module power generation at a given hour (Dobos, 2014; Sukamongkol et al., 2002):

$$P_{dc} = \frac{I_{poa}}{1000} P_{dc0} \left( 1 + \gamma (T_{cell} - T_{ref}) \right) \quad (13)$$

where  $P_{dc}$  is the DC power generated from the solar array. The plane-of-array incident,  $I_{poa}$ , is the sum of the three components in the equation (Dobos, 2014), similarly noted in Chapter II:

$$I_{poa} = I_b + I_d + I_g \quad (14)$$

The direct irradiance,  $I_b$ , and diffuse irradiance,  $I_d$ , are both sources of data obtained from the 14<sup>th</sup> Weather Squadron. These inputs serve as two out of the three unknown, but named, variables in the Monte Carlo Simulation which is explained in further detail in this chapter. The ground reflectance,  $I_g$ , is an assumed  $0.2W/m^2$  to maintain consistency without accounting for such a large variation of ground and soil type scenarios. The variable,  $P_{dc0}$ , is the manufacturer specified nameplate DC rating for the array. The nameplate DC rating for the baseline system array is  $P_{dc0} = 8.6 kW$ .

The temperature coefficient,  $\gamma$ , governs the module's efficiency, which is assumed to decrease at a linear rate as a function of temperature rise.  $T_{cell}$  is the cell temperature, or the current operating temperature of the modules.  $T_{ref}$  is the reference cell temperature, which is a constant  $25^\circ C$ , with the reference irradiance being  $1000 w/m^2$ , as these parameters are the standard testing conditions (STC) for solar panels (Fuentes, 1987). The temperature coefficient,  $\gamma$ , is based on the module cover type. The baseline PV system uses a "standard" module type with a glass cover. The researcher used the PVWatts® calculator assumption was used for the temperature coefficient,

which is,  $\gamma = -0.47\%/^{\circ}\text{C}$  (Skoplaki & Palyvos, 2009). The solar cell temperature is calculated using the following equation (Fuentes, 1987; Ross Jr, 1980):

$$T_{cell} = T_a + (NOCT - 20^{\circ}\text{C}) * \frac{I_{poa}}{800\text{W}/\text{m}^2} \quad (15)$$

The ambient dry bulb temperature,  $T_a$ , is the third input variable in the Monte Carlo Simulation. The nominal operating cell temperature (NOCT) is the temperature reached by open circuited cells in a module under the following standardized conditions: 1) Irradiance on cell surface =  $800\text{W}/\text{m}^2$ , 2) Air Temperature =  $20^{\circ}\text{C}$ , 3) Wind Velocity =  $1\text{m}/\text{s}$ , and 4) Mounting = open back side (Fuentes, 1987; Ross Jr, 1980). The most optimal module operates at a NOCT of  $33^{\circ}\text{C}$ , the worst at  $58^{\circ}\text{C}$ , and the typical module at  $48^{\circ}\text{C}$  (Ross Jr, 1980). Since there was limited data on the exact NOCT of the baseline system, the typical NOCT of  $48^{\circ}\text{C}$  was used in the model.

To gain an understanding of the estimated production over an entire year, a year was categorized as twelve days that are representative of each given month. This facilitates the evaluation of patterns in a potential location efficiently without analyzing 365 simulated twelve-hour days. Instead, the analysis covers twelve typical days (one day per month), each over a simulated twelve-hour timeframe. No adjustments are made for leap years or daylight savings time which leaves 288 estimated power outputs per year (144 DC and 144 AC). This was considered the most efficient method to obtain enough data points for the purpose of the research effort.

There are three significant solar and weather variables that are required for the PVWatts® calculator on an hourly basis: two components of solar irradiance (beam and diffuse), ambient dry bulb temperature, and wind speed at 10m above ground (Dobos, 2014). It is assumed that the solar array will be erected on the ground and remain there in application as the baseline PV system is a ground-mounted solar array (“MX-SERIES 100,” n.d.). With the assumption that the solar array is ground-mounted, wind speed was excluded as a contributing weather factor since the PV Watts® calculator assumes wind is a factor when arrays are mounted 10m above ground level. This leaves the research model with three main solar and weather factors to influence the power production of the PV system: beam (direct) irradiance, diffuse (indirect) irradiance, and ambient dry bulb temperature.

As described in the microgrid system in Chapter II, the inverter converts the DC power to AC power, and the total system losses are captured in the model. Based on an analysis of the California Energy Commission (CEC) inverter performance data, a “typical” inverter was selected to use for the PVWatts® calculator (Dobos, 2014). The “typical” inverter was selected by calculating an average part-load efficiency curve and then finding the inverter in the dataset whose actual efficiency curve best fit the average (Dobos, 2014). The “typical” inverter nominal efficiency  $\eta_{nom}$ , is 0.96, and is the value used in the model due to the lack of information provided in the baseline system’s manufacturer specifications.

### **3.3 Simulation**

Two Microsoft Excel add-ins were used for the analysis. To best fit the variable data into distributions for the Monte Carlo simulations, the @Risk® add-in is utilized. The program uses the Akaike Information Criterion (AIC) to select a distribution model from the dataset that best minimizes the Kullback-Leibler distance between the model and the truth (Burnham & Anderson, 2002). The distribution with the highest AIC score and makes logical sense using best judgement based on the data was applied. Each distribution is adjusted to fit logical conditions and the minimum and maximum ranges of the data. The variables that require parameter adjustments in the model are the direct and diffuse irradiance variables.

The second tool is the Analytic Solver® Platform, which is used to conduct the Monte Carlo simulations. Simulations were run on a quarterly data because of the limited capability of Analytic Solver® Platform. The version of the add-in used in the research, is capable of processing no more than 200 unknown variables in the simulation. By breaking the data into quarters, the number of variables remains around 168 for each simulation. The simulation is set to run 10,000 iterations and the output value is the DC power. Confidence intervals are also determined with the output values. Confidence levels for the parameter is an interval computed for the sample data that is said to have a probability of producing a true value within that interval for the parameter (Calder, 1953).

To ensure the model is weighting the variables in accordance with literature review, a sensitivity analysis is run on the outputs to ensure the correct parts of the system, if adjusted, have the most impact on increasing the estimated power output. The

simulation results are broken down into summer months and winter months. This facilitates the analysis on the estimated energy production over a year, and the two major seasons.

### **3.4 Solar and Weather Data**

The research model is populated with solar and weather data from the 14<sup>th</sup> Weather Squadron. The 14<sup>th</sup> Weather Squadron is the Air Force's sole climate operations unit that collects and exploits climate data to optimize military and intelligence operations and planning ("14th Weather Squadron," n.d.). The 14<sup>th</sup> Weather Squadron developed a solar database specifically for solar and photovoltaic research, which is the source for all historical solar irradiance and ambient temperature data. The theory and calculations for computing solar irradiance are covered in Chapter II.

The 14<sup>th</sup> Weather Squadron provided data for 153 possible sites to be evaluated for the analysis. Each site contains hourly data for parameters such as temperature, wind speed, and solar irradiance. A site has to have at least 1,200 observations to count as a good year to be used in the model. Additionally, the site has to have at least 10 consecutive good years to be analyzed. The optimal dataset for a location will have at least 87,600 data points for each parameter of the data.

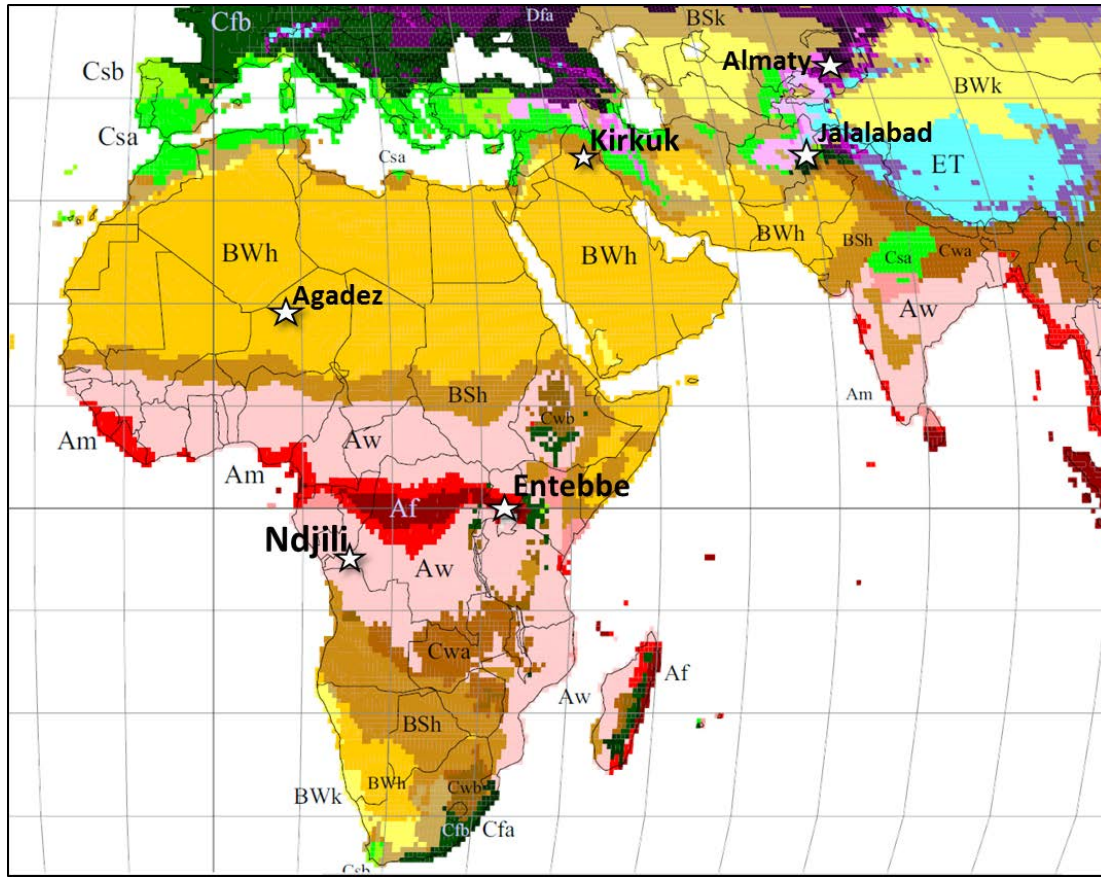
### **3.5 Test Locations**

The locations evaluated using the simulation model are chosen using the Köppen-Geiger map as a guiding tool. It is used to ensure the spectrum of climate types in the CENTCOM and AFRICOM AORs. The most robust datasets for each climate type in the AORs are used as a representative of that climate type. To determine the final list of

sites, the researcher took the available data provided by the 14<sup>th</sup> Weather Squadron were separated for each site by its Köppen-Geiger classification. Then, the site from each climate classification that had the most years of consecutive years of data available through 2015 were considered. Finally, the data for each of the considered sites were screened to ensure the site had a collection of data points for every relevant hour of every day of every month for every year. The final list of sites that will be evaluated in the analysis are outlined in Table 6 and are mapped on the Köppen-Geiger map in Figure 6. The test sites selected are considered a diverse representation of the AORs.

**Table 6 - Test Site Information**

| <b>Location Name</b> | <b>Latitude</b> | <b>Longitude</b> | <b>Elevation (meters)</b> | <b>K-G Climate</b> |
|----------------------|-----------------|------------------|---------------------------|--------------------|
| Kirkuk               | 35.47           | 44.35            | 323.39                    | Bsh                |
| Jalalabad            | 34.4            | 70.48            | 566.93                    | Cfa                |
| Agadez               | 16.97           | 7.97             | 505.05                    | Bwh                |
| Almaty               | 43.35           | 77.04            | 680.92                    | Dfb                |
| Entebbe              | 0.04            | 32.44            | 1152.75                   | Am                 |
| Ndjili               | -4.39           | 15.44            | 313.02                    | AW                 |



### **3.6 Demand and Usage Data**

As addressed in Chapter II, the Photovoltaic Integrated Powered Shelter Systems (PVIPSS) study on the power demand of and ECU-E on two gable shelter systems were used as the demand load for the research. It was assumed that the baseline system would have to be used on a smaller scale like the one tested in the PVIPSS study and assumedly, could be implemented with the AFCEC configuration across the contingency locations. The limitation is that the available data only covers summer demand conditions, so the load matching determination is only conducted with the simulation outputs from the

summer months. The results for the AFCEC study described in Chapter II are provided in Figure 7.

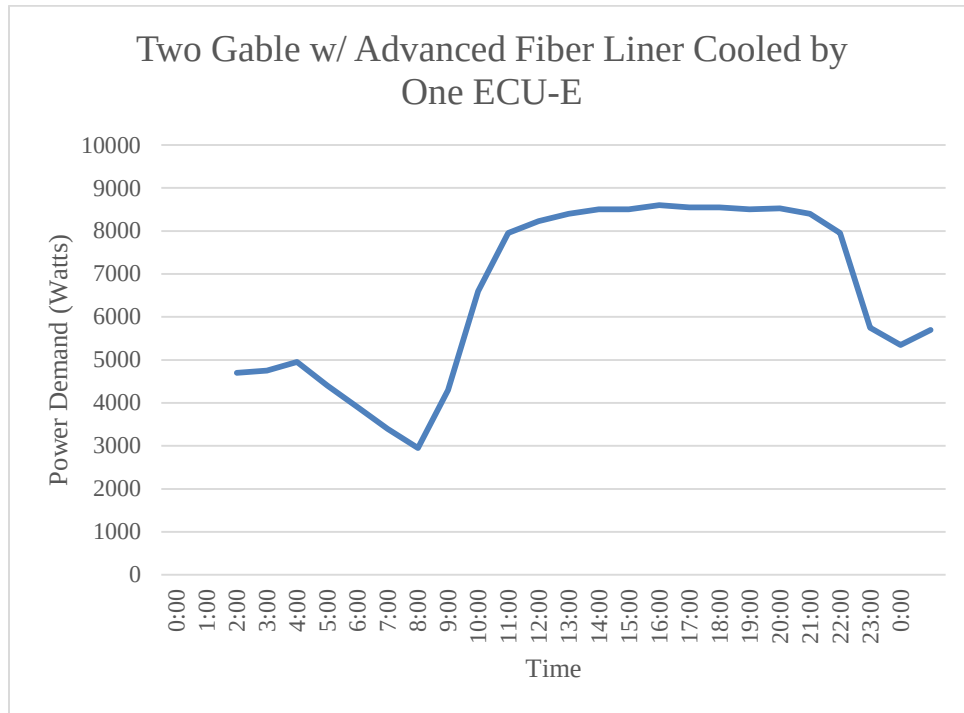


**Figure 7 - Average Hourly ECU Power Demand at Holloman**

The demand curve in Figure 7 is used as a base case scenario for the baseline system's simulation results. The summer means all of the sample mean outputs from the simulation model are compiled and integrated with the demand load. The baseline system output data will reduce the demand curve, and the load matching capability of the system is calculated. The reasonable calculation for measuring the load-matching capability of the system is measured by (Voss et al., n.d.)

$$f_{load,i} = \frac{g_i}{l_i} \cdot 100 \text{ [\%]} \quad (16)$$

where  $g$  and  $l$  are the on-site generation from the microgrid and the demand load, respectively, and  $i$  is the time interval that is used (hours). Voss et al. uses a minimizing function that does not apply to the research and was excluded.

The hourly results using the load matching equation dictates the percentage of the demand load that will be reduced due to the renewable power offset. The cumulative results for the summer months for each site are utilized to evaluate how effective the microgrid will offset the sample demand load. However, because of the limited environment the demand load data was collected in, it cannot be assumed that all of the test sites will accurately reflect a similar scenario.

### **3.7 Temperature Comparison**

To ensure the sites that are being applied to the demand load are accurately comparable, several statistical tests were conducted. The first test is a correlation test to support the assumption that during the summer months the temperature has a strong positive correlation with the power consumption of the ECUs. The winter temperatures were not included in the correlation because of the limitation of the PVIPSS study, which only tested during the summer months. To measure the strength of this linear relationship, a correlation coefficient is calculated. The Pearson's correlation coefficient is the most frequently used method to determine the strength of the relationship between two variables using a value between -1 and 1; -1 is a perfect negative correlation and 1 is a perfect positive correlation (Doyle, 2011). The correlation between the demand load

(kW) and Temperature (°F) are tested and yield a 0.9563 correlation, which confirms the assumption that there is a very strong positive correlation between the temperature and demand load of the ECU.

**Table 7 - Pearson's Correlation between power used by ECU and Temperature**

|           | <i>kW</i> | <i>°F</i> |
|-----------|-----------|-----------|
| <i>kW</i> | 1         |           |
| <i>°F</i> | 0.956344  | 1         |

With this correlation confirmed, the researcher uses temperature data for the test sites to determine if there is any statistical differences in their mean summer temperatures and the temperatures observed in the AFCEC demand load study. This comparison is accomplished using the Tukey-HSD test, which is a method of multiple comparisons in which a set of group means are ranked from smallest to largest, and the statistical difference between pairs of means is computed based on the number of steps between the means in rank order (Colman, 2008). The test sites that fall within the AFCEC demand load rankings are considered acceptable to apply the load matching formula because there is no statistical difference in the temperatures, so it is assumed that the demand loads would hypothetically be similar. The test locations that are statistically different are not load matched to the baseline demand curve.

## **IV. Results**

This section addresses the results of the simulation for each of the sites outlined in Section 3.6. Significant findings of the results from the simulation are also explained. This section provides the results of the load matching examination outlined in Section 3.7. Appendix A provides monthly output sample means for each test site along with the AC power expectancy. Appendix B provides confidence intervals of outputs.

### **4.1 Agadez Results**

The results for the hourly mean power expectancy for the Agadez location is outlined in Figure 8. There is an expected eleven-hour period for power to be produced by the baseline system in the winter months and a twelve-hour period for the summer months. There is a moderately small difference in the power produced during the summer months and the winter months with the largest difference being 968 watts at hour 0800 with a mean difference of 453 watts throughout the producible day. The maximum expected wattages for the winter and summer months, respectively, are 5,777 watts at hour 1300 and 6,017 watts at hour 1100.

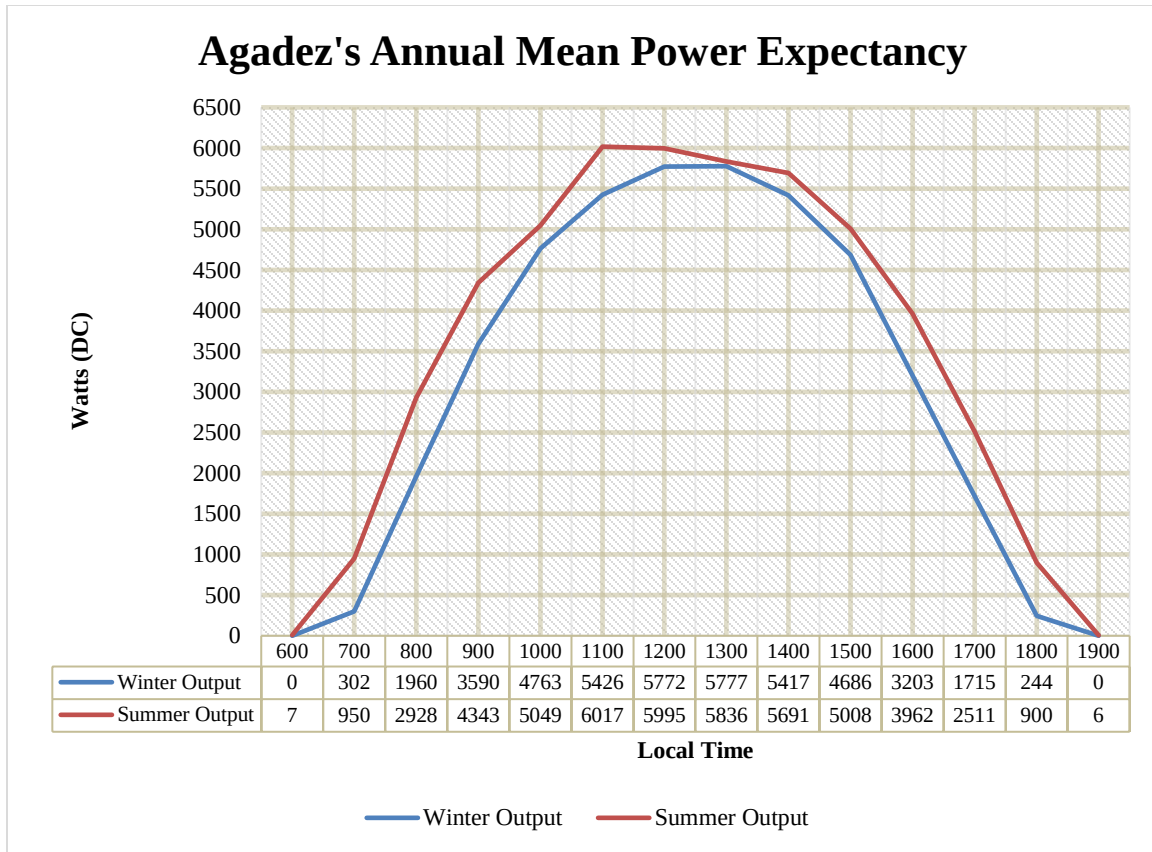


**Figure 8 - Agadez's Annual Mean Power Expectancy**

## **4.2 Kirkuk Results**

The results for the hourly mean power expectancy for the Kirkuk location is outlined in Figure 9. There is an expected twelve-hour period for power to be produced by the baseline system in the winter months and an eleven-hour period for the summer months. There is a significantly sizeable difference in the power produced during the summer months than the winter months with the largest difference being 1,804 watts at hour 0800 with a mean difference of 1,114 watts throughout the producible day. The

maximum expected wattages for the winter and summer months, respectively, are 4,363 watts at hour 1100 and 5,290 watts at hour 1300.

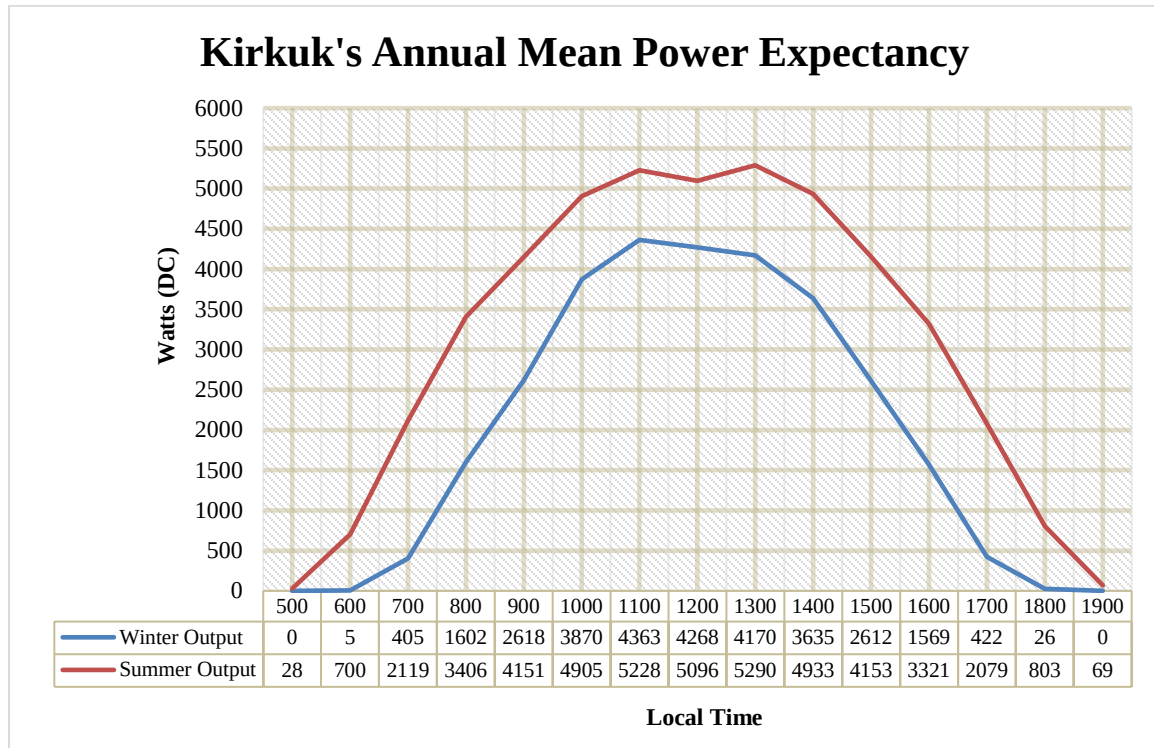


**Figure 9 - Kirkuk's Annual Mean Power Expectancy**

### **4.3 Entebbe Results**

The results for the hourly mean power expectancy for the Entebbe location is outlined in Figure 10. There is an expected twelve-hour period for power to be produced by the baseline system in the winter months and an eleven-hour period for the summer months. There is a marginally small difference in the power produced during the summer months and the winter months with the exception between the hours of 1100 and 1500 where there is a moderately small difference. The research identifies the summer and

winter months as the seasons as a result of the tilt of the Earth's rotational axis with relation to the orbital plane. Locations near the equator have decreased seasonal effect amplitude and directly on the equator these effects completely vanish. This means that the summer and winter seasonal effects are reversed for locations on the southern hemisphere. This explains why the winter months, as the research describes them, have more irradiance intensity, and produce more energy during the season. The largest difference between the summer and winter months is 608 watts at hour 1400 with a mean difference of 201 watts throughout the producible day. The maximum expected wattages for the winter and summer months, respectively, are 5,900 watts at hour 1400 and 5,440 watts at hour 1300.

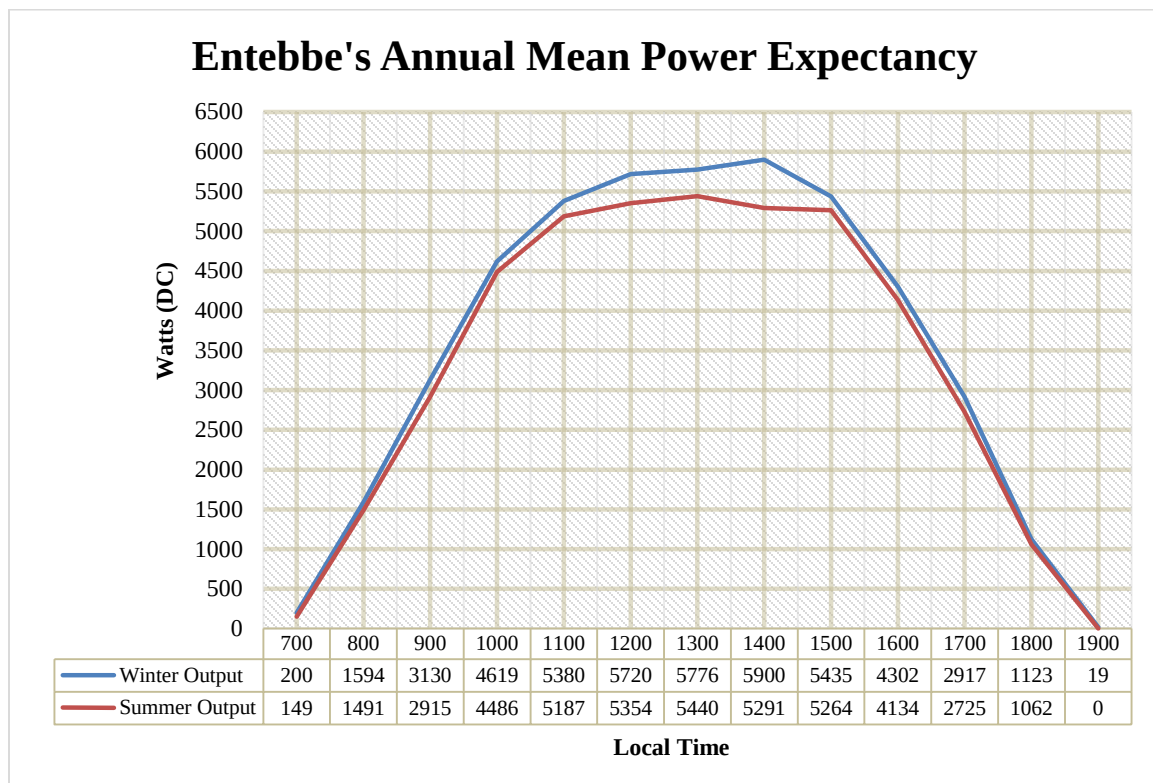


**Figure 10 - Entebbe's Annual Mean Power Expectancy**

#### **4.4 Jalalabad Results**

The results for the hourly mean power expectancy for the Jalalabad location is outlined in Figure 11. There is an expected eleven-hour period for power to be produced by the baseline system in the winter months and a thirteen-hour period for the summer months. There is a significantly sizeable difference in the power produced during the summer months than the winter months with the largest difference being 1,695 watts at hour 1600 with a mean difference of 1,155 watts throughout the producible day. The maximum expected wattages for the winter and summer months, respectively, are 4,290 watts at hour 1100 and 5,322 watts at hour 1100.

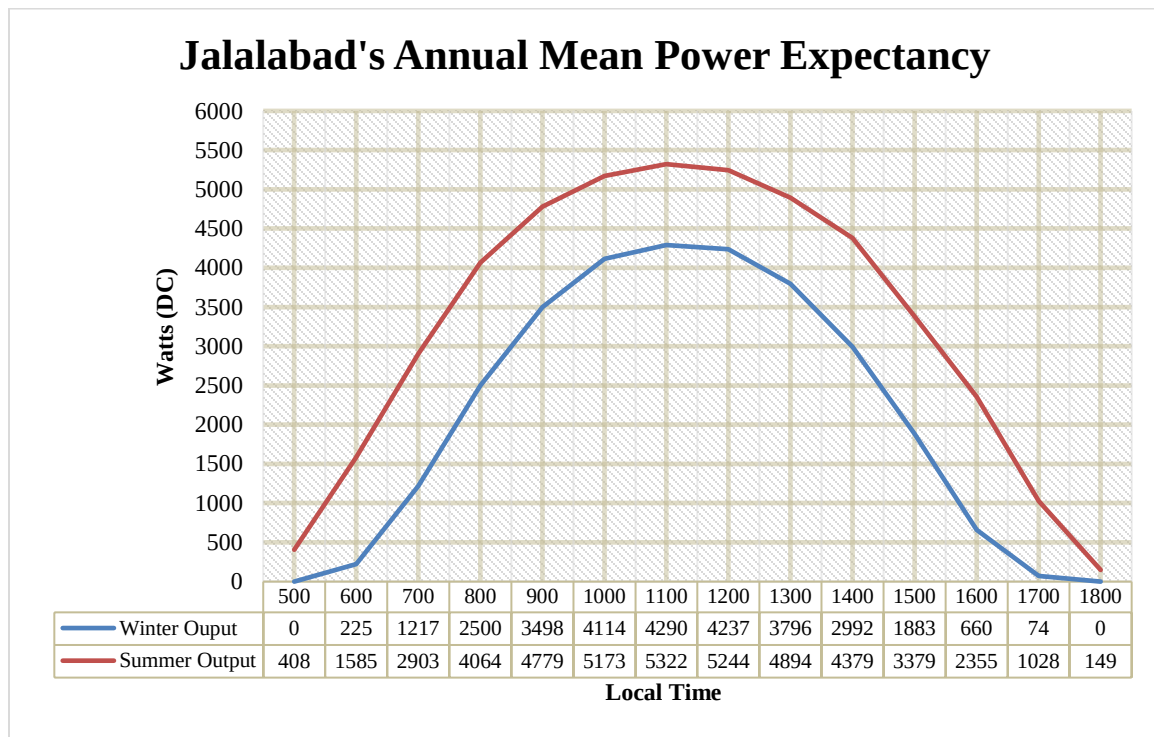


**Figure 11 - Jalalabad's Annual Mean Power Expectancy**

#### **4.5 Ndjili Results**

The results for the hourly mean power expectancy for the Ndjili location is outlined in Figure 12. There is an expected twelve-hour period for power to be produced by the baseline system in both the winter and the summer months. There is a relatively small difference in the power produced during the summer months and the winter months with the exception between the hours of 1300 and 1600 where there is a moderately greater difference. Locations near the equator have decreased seasonal effect amplitude and directly on the equator these effects completely vanish. This means that the summer and winter seasonal effects are reversed for locations on the southern hemisphere. This explains why the winter months, as the research describes them, have more irradiance intensity, and produce more energy during the season. The largest difference between the summer and winter months is 480 watts at hour 1300 with a mean difference of 307 watts throughout the producible day. The maximum expected wattages for the winter and summer months, respectively, are 5,784 watts at hour 1300 and 5,536 watts at hour 1200.

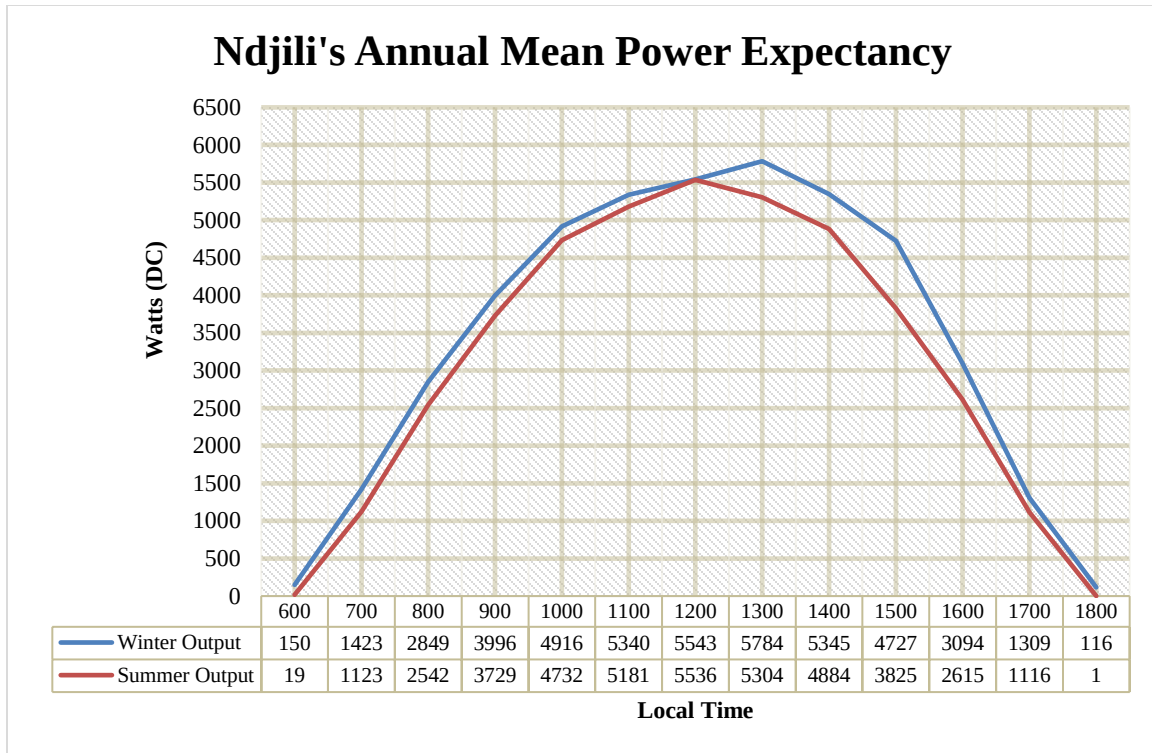


**Figure 12 - Ndjili's Annual Mean Power Expectancy**

#### **4.6 Almaty Results**

The results for the hourly mean power expectancy for the Almaty location is outlined in Figure 13. There is an expected twelve-hour period for power to be produced by the baseline system in the winter months and a fourteen-hour period for the summer months. There is a significantly sizeable difference in the power produced during the summer months than the winter months with the largest difference being 2,143 watts at hour 1700 with a mean difference of 1,503 watts throughout the producible day. The maximum expected wattages for the winter and summer months, respectively, are 3,671 watts at hour 1300 and 5,228 watts at hour 1300.

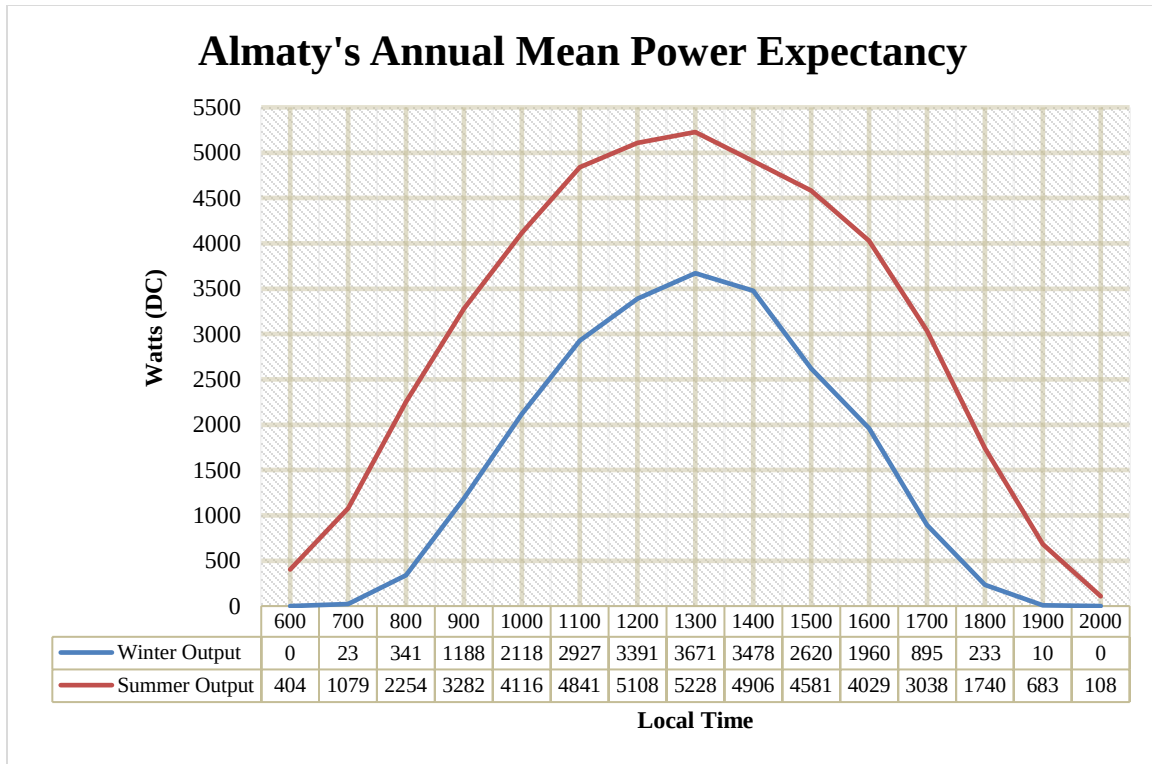


**Figure 13 - Almaty's Annual Mean Power Expectancy**

#### **4.7 Temperature Comparisons**

The hourly ambient summer temperatures for each of the test sites are compared to the hourly Holloman ambient summer temperature data that was collected from the PVIPSS study. The complete collection of summer temperatures for each of the test sites is outlined in Figure 14. The large circle on the right represents the grouping from the Tukey-HSD test and the three points (Ndjili, Entebbe, and Almaty) outside of the larger circle, in smaller circles, have means that are considered statistically different than the baseline (Holloman) mean temperatures and are not used in the load matching survey.

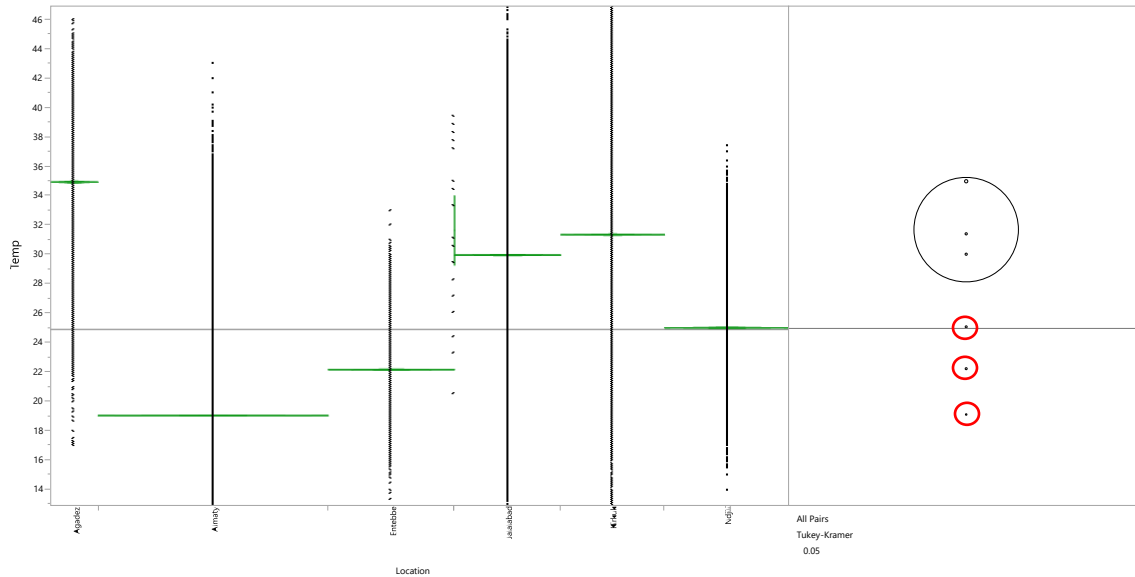


**Figure 14 - Tukey-HSD Test Results Comparing Temperatures of Test Sites to Holloman**

Table 8 shows the lettered grouping for the Tukey-HSD test which is another representation of how the ANOVA groups the data. This means there are no statistical differences in temperatures within the grouped locations. Locations outside of the grouping will not be used in the load matching analysis because the baseline demand load conditions would not be representative for those locations. Appendix C provides the complete summary of the test results.

**Table 8 - Tukey-HSD Test Lettered Grouping**

| Level                 | Mean      |
|-----------------------|-----------|
| Agadez <b>A</b>       | 34.958847 |
| Holloman <b>A B C</b> | 31.665000 |
| Kirkuk <b>B</b>       | 31.379553 |
| Jalalabad <b>C</b>    | 29.992854 |
| Ndjili <b>D</b>       | 25.047012 |
| Entebbe <b>E</b>      | 22.197513 |
| Almaty <b>F</b>       | 19.077924 |

#### **4.8 Agadez Load Matching Results**

The mean annual summer output data is applied to the established baseline demand curve and the new demand curve is outlined in Figure 15. While there is a substantial reduction in the overall demand with the implementation of the baseline system, at no point is the system achieving a 100% load matching capability. The representation is, however, limited to the confines of the research model outputs. The results may prove that incorporating battery storage capability, with accurate charge and discharge rates, may mean that reaching net-zero could become possible. The maximum load matching capability on a continuous hourly basis is outlined in Table 9.

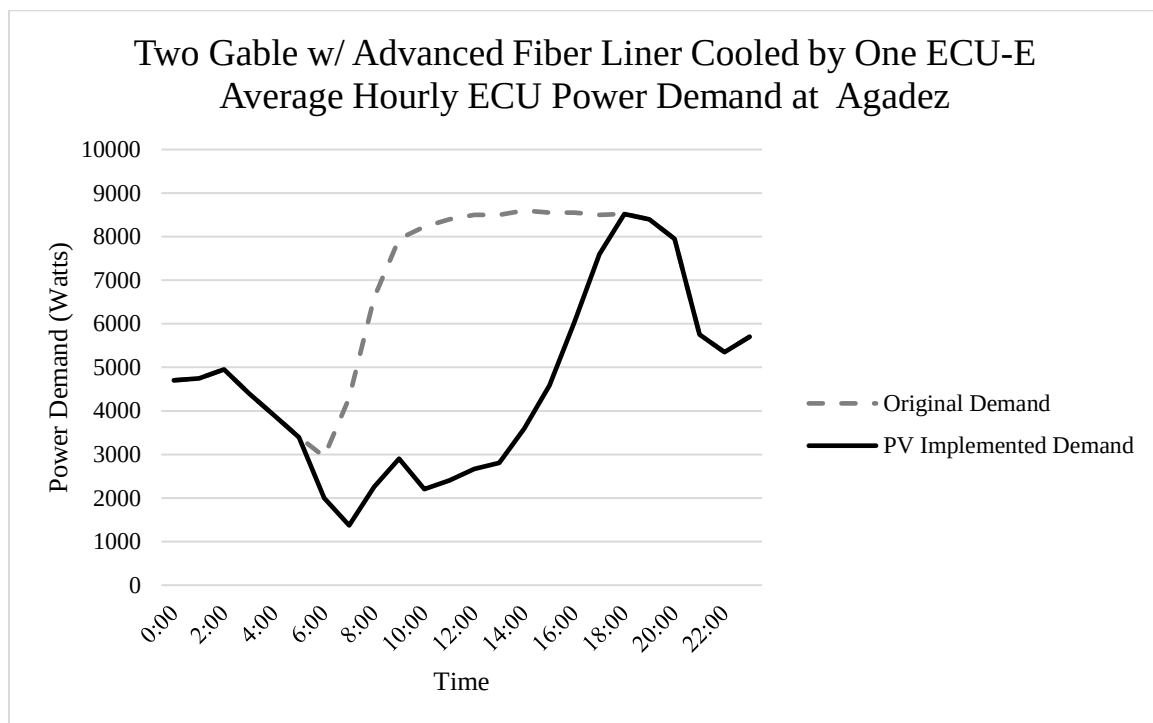


**Figure 15 - Potential Demand Load Reduction in Agadez**

**Table 9 - Hourly Load Matching Capability in Agadez**

| Time  | Load Matching Capability |
|-------|--------------------------|
| 1:00  | 0%                       |
| 2:00  | 0%                       |
| 3:00  | 0%                       |
| 4:00  | 0%                       |
| 5:00  | 0%                       |
| 6:00  | 0%                       |
| 7:00  | 29%                      |
| 8:00  | 68%                      |
| 9:00  | 65%                      |
| 10:00 | 62%                      |
| 11:00 | 74%                      |
| 12:00 | 71%                      |
| 13:00 | 68%                      |
| 14:00 | 68%                      |
| 15:00 | 58%                      |
| 16:00 | 46%                      |
| 17:00 | 30%                      |
| 18:00 | 12%                      |
| 19:00 | 1%                       |
| 20:00 | 0%                       |
| 21:00 | 0%                       |
| 22:00 | 0%                       |
| 23:00 | 0%                       |
| 0:00  | 0%                       |

#### **4.9 Kirkuk Load Matching Results**

The mean annual summer output data is applied to the established baseline demand curve and the new demand curve is outlined in Figure 16. While there is a substantial reduction in the overall demand with the implementation of the baseline system, at no point is the system achieving a 100% load matching capability. The

representation is, however, limited to the confines of the research model outputs. The results may prove that incorporating battery storage capability, with accurate charge and discharge rates, may mean that reaching net-zero could become possible. The maximum load matching capability on a continuous hourly basis is outlined in Table 10.

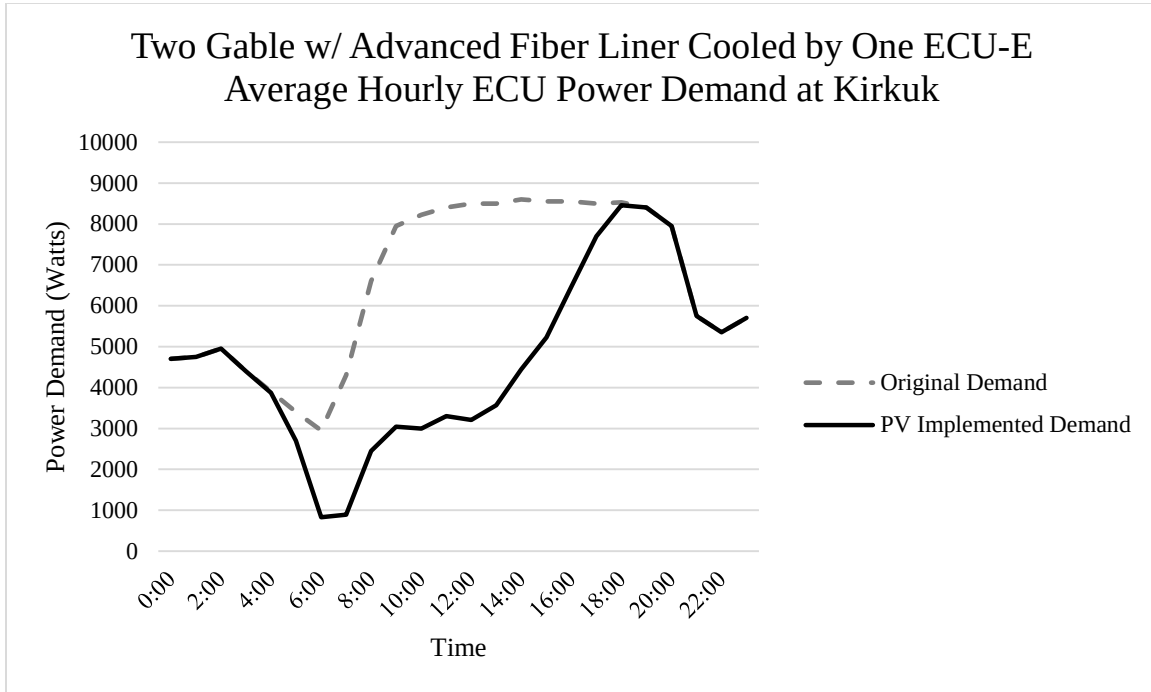


**Figure 16 - Potential Demand Load Reduction in Kirkuk**

**Table 10 - Hourly Load Matching Capability in Kirkuk**

| Time  | Load Matching Capability |
|-------|--------------------------|
| 1:00  | 0%                       |
| 2:00  | 0%                       |
| 3:00  | 0%                       |
| 4:00  | 0%                       |
| 5:00  | 1%                       |
| 6:00  | 21%                      |
| 7:00  | 72%                      |
| 8:00  | 79%                      |
| 9:00  | 63%                      |
| 10:00 | 62%                      |
| 11:00 | 64%                      |
| 12:00 | 61%                      |
| 13:00 | 62%                      |
| 14:00 | 58%                      |
| 15:00 | 48%                      |
| 16:00 | 39%                      |
| 17:00 | 24%                      |
| 18:00 | 9%                       |
| 19:00 | 1%                       |
| 20:00 | 0%                       |
| 21:00 | 0%                       |
| 22:00 | 0%                       |
| 23:00 | 0%                       |
| 0:00  | 0%                       |

#### **4.10 Jalalabad Load Matching Results**

The mean annual summer output data is applied to the established baseline demand curve and the new demand curve is outlined in Figure 17. While there is a substantial reduction in the overall demand with the implementation of the baseline system, at no point is the system achieving a 100% load matching capability. The

representation is, however, limited to the confines of the research model outputs. The results may prove that with incorporating battery storage capability, with accurate charge and discharge rates, may mean that to reaching net-zero could become possible. The maximum load matching capability on a continuous hourly basis is outlined in Table 11.

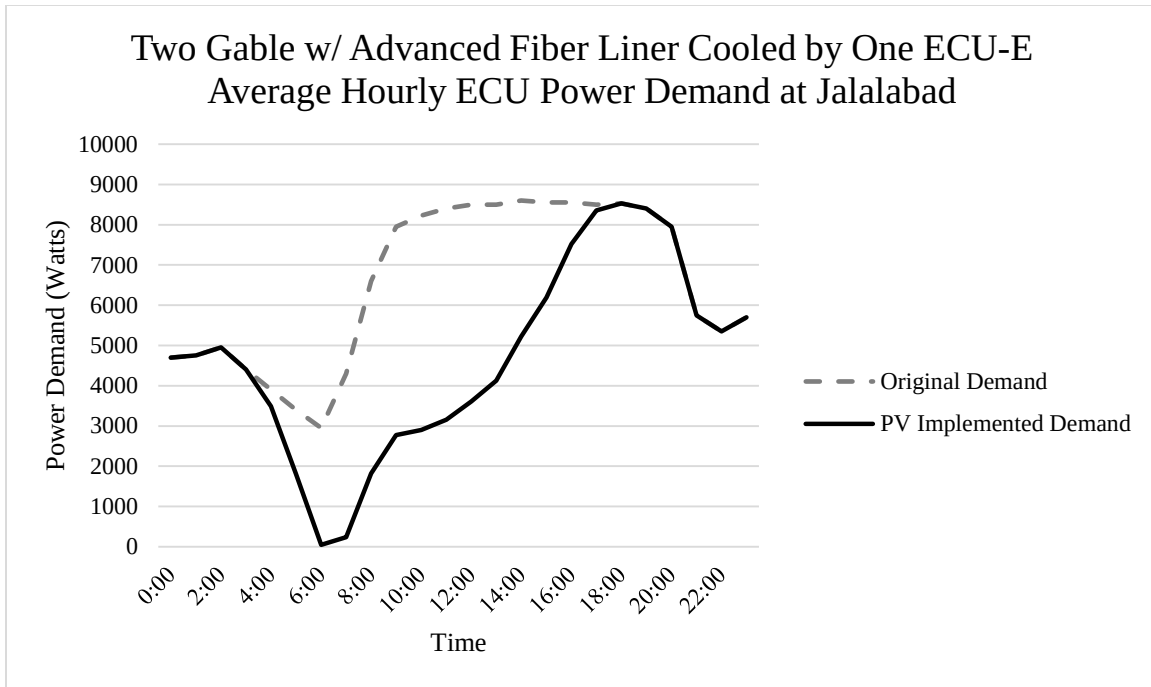


**Figure 17 - Potential Demand Load Reduction in Jalalabad**

**Table 11 - Hourly Load Matching Capability in Jalalabad**

| Time  | Load Matching Capability |
|-------|--------------------------|
| 0:00  | 0%                       |
| 1:00  | 0%                       |
| 2:00  | 0%                       |
| 3:00  | 0%                       |
| 4:00  | 0%                       |
| 5:00  | 10%                      |
| 6:00  | 47%                      |
| 7:00  | 98%                      |
| 8:00  | 95%                      |
| 9:00  | 72%                      |
| 10:00 | 65%                      |
| 11:00 | 65%                      |
| 12:00 | 62%                      |
| 13:00 | 58%                      |
| 14:00 | 52%                      |
| 15:00 | 39%                      |
| 16:00 | 28%                      |
| 17:00 | 12%                      |
| 18:00 | 2%                       |
| 19:00 | 0%                       |
| 20:00 | 0%                       |
| 21:00 | 0%                       |
| 22:00 | 0%                       |
| 23:00 | 0%                       |
| 0:00  | 0%                       |

#### 4.11 Summary of Load Matching Capability

| Time  | Load Matching Capability |        |        |
|-------|--------------------------|--------|--------|
|       | Jalalabad                | Kirkuk | Agadez |
| 0:00  | 0%                       | 0%     | 0%     |
| 1:00  | 0%                       | 0%     | 0%     |
| 2:00  | 0%                       | 0%     | 0%     |
| 3:00  | 0%                       | 0%     | 0%     |
| 4:00  | 0%                       | 0%     | 0%     |
| 5:00  | 10%                      | 1%     | 0%     |
| 6:00  | 47%                      | 21%    | 0%     |
| 7:00  | 98%                      | 72%    | 29%    |
| 8:00  | 95%                      | 79%    | 68%    |
| 9:00  | 72%                      | 63%    | 65%    |
| 10:00 | 65%                      | 62%    | 62%    |
| 11:00 | 65%                      | 64%    | 74%    |
| 12:00 | 62%                      | 61%    | 71%    |
| 13:00 | 58%                      | 62%    | 68%    |
| 14:00 | 52%                      | 58%    | 68%    |
| 15:00 | 39%                      | 48%    | 58%    |
| 16:00 | 28%                      | 39%    | 46%    |
| 17:00 | 12%                      | 24%    | 30%    |
| 18:00 | 2%                       | 9%     | 12%    |
| 19:00 | 0%                       | 1%     | 1%     |
| 20:00 | 0%                       | 0%     | 0%     |
| 21:00 | 0%                       | 0%     | 0%     |
| 22:00 | 0%                       | 0%     | 0%     |
| 23:00 | 0%                       | 0%     | 0%     |
| 0:00  | 0%                       | 0%     | 0%     |

The summary of the baseline system's ability to match the baseline demand in the locations tested are shown in Table 12. The system is projected to reduce the demand in Jalalabad and Agadez by 50% during the producible hours of the system. Kirkuk has the longest power production duration of the three locations but is expected to reduce the

demand load 44%. The closest the baseline system got to completely matching the demand was in Jalalabad between 0700 and 0800 hours but approached and declined from that maximum in a steep pattern. The maximum load matching capability for Kirkuk is 72-79% between 0700 and 0800 hours and 71-74% for Agadez between 0900 and 1000 hours.

## **V. Limitations and Conclusions**

This chapter presents the conclusions from this research and elaborates on the limitations of the research. The significance of the research is discussed along with specific actions regarding how to implement the research's findings. Finally, future research is identified to strengthen the model's results.

### **5.1 Significance of Research**

The research showed there is an application to drastically reduce the use of diesel generation in various contingency locations and environments through the use of PV microgrid technology. Implementing a PV microgrid makes the contingency bases more adaptive and efficient by reducing the logistical burden required for diesel-powered generators. Ultimately, any PV implementation will enhance the installation resiliency by diversifying the electrical and power production infrastructure. The model results in this research provide an outlook of the expected power production on an hourly basis of a PV microgrid that can be integrated into the current BEAR asset inventory.

Additionally, the ability to reach net-zero facility power may not be achievable by solely implementing solar energy but is a significant contributing factor when moving towards net-zero. Continuing to improve the efficiencies of shelter systems and ECUs is critical to meeting net-zero as well. Based on the baseline system in the research, a microgrid system that can be deployable and re-deployable is limited to smaller scale applications and may be limited in space availability. The baseline system is also limited in its efficiency and more efficient technology may prove to show improved results. As the size of the PV system expands, they will require additional land area for the array

panels. Depending on the characteristics of the location, and its available land area, this constraint may prove problematic. However, the use of a PV microgrid, may add a layer of energy security through redundancy, which would ultimately enhance the resiliency of the contingency installation through power generation system diversity.

## **5.2 Limitations**

The research and the research model have several notable limitations that need to be addressed. One of the main limitations was the availability of the baseline system data. While the manufacturer specifications that were used were sufficient to provide information for the model, more detailed design specifications would have limited the number of assumptions and the battery performance would have expanded the breadth of the performance analysis. Without that specific data, the research approach was to calculate production rates in the model excluding the battery and controller affects, and assuming a standard converter efficiency. This limitation makes the model a reflection of a worst-case situation, where the system has no energy storage capability and is directly supplying the demand load. Additionally, the baseline system was not very efficient in comparison to the efficiency available for monocrystalline modules in the market. A more efficient system would yield higher load matching capability results.

The second most prominent limitation of the research was the lack of available demand load data. There was not an abundant amount of actual contingency usage data to apply to the model results. The data that is used in the research is a collection of test points from a controlled experiment. The tests did not account for the increase of the

power demand due to people living and operating out of the shelter. Additionally, the data did not cover winter months and lacked location and climate diversity.

### **5.3 Recommendations for Action**

The opportunity to exploit the availability of renewable energy technology must be seized in order to propel energy assurance and reduce the extensive logistical chain that comes with using diesel power. It is recommended that AFCEC conduct field tests of similar deployable microgrid systems to gain accurate knowledge of their capabilities and further explore their maintenance demands prior to implementation. This study will provide further validation of the predictive model as well as provide additional insight into whether there is a net benefit to implementing these systems.

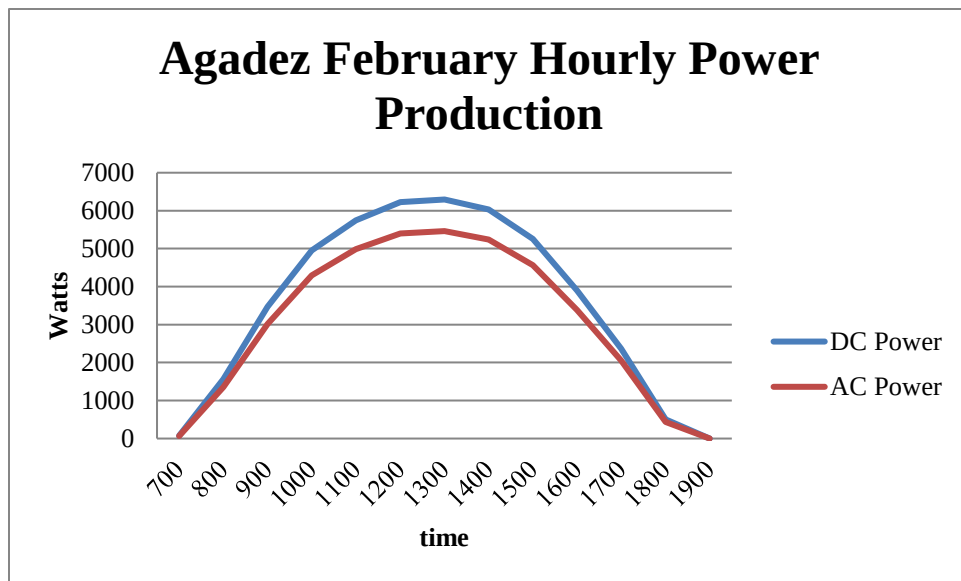
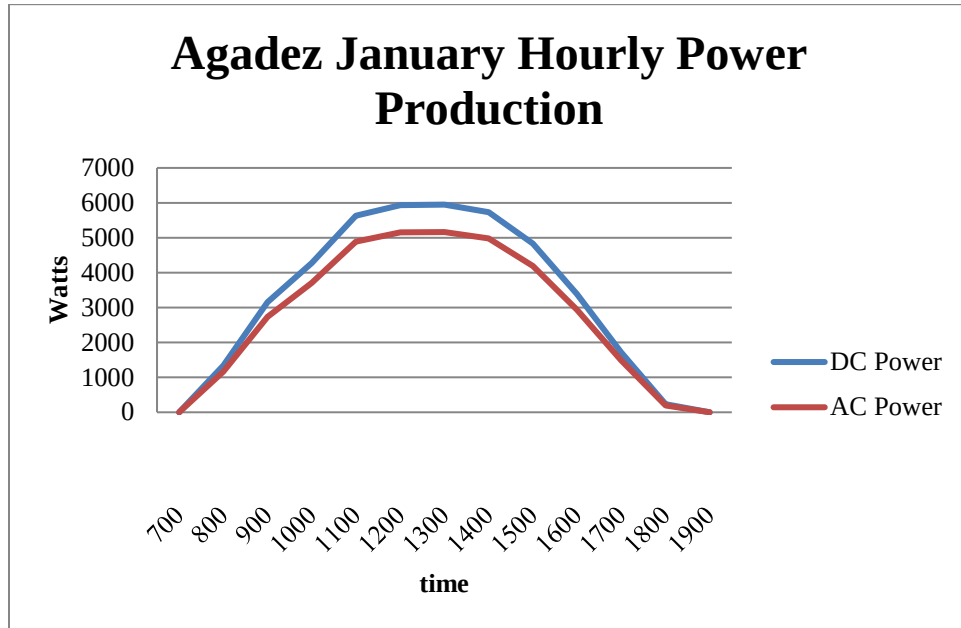
### **5.4 Recommendations for Future Research**

Future research would include adding to the robustness of the model by collecting more data on various microgrid systems and implementing more system parameters to include battery and storage characteristics. This would improve the model complexity because it would incorporate accurate system losses and charging and discharging rates of the battery. To complement the addition of detailed system design specifications, collecting actual field data to create an accurate hourly demand curve that reflects the facility power usage in a contingency location should be researched. This would add complexity to the model and give a more accurate depiction of the power production and storage capabilities of the system during implementation, as well as its ability to help achieve net-zero power.

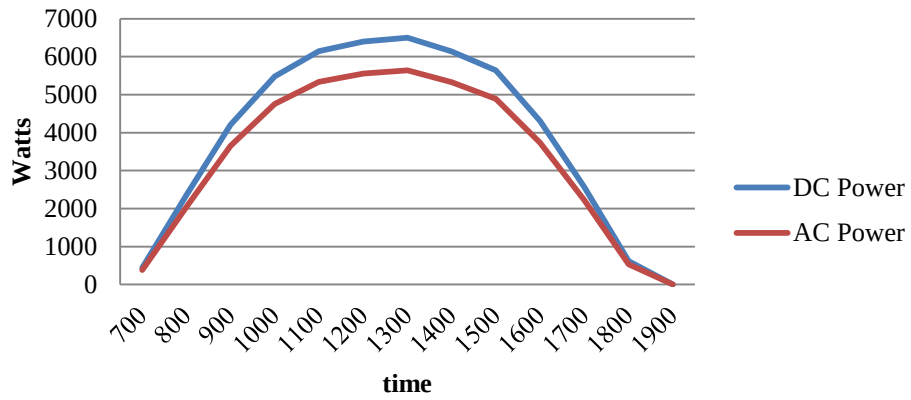
Additionally, a full economic feasibility study can be conducted on the implementation of bringing a PV microgrid array into the BEAR inventory. This study would include a full LCC analysis on the system as well as evaluate the LCOE when comparing the solar source to the traditional diesel source. This would be a critical research line as it would quantify the logistical and economic chain that is tied to using diesel power and how much it can be reduced by the augmentation of a renewable source like solar energy.

## Appendix A

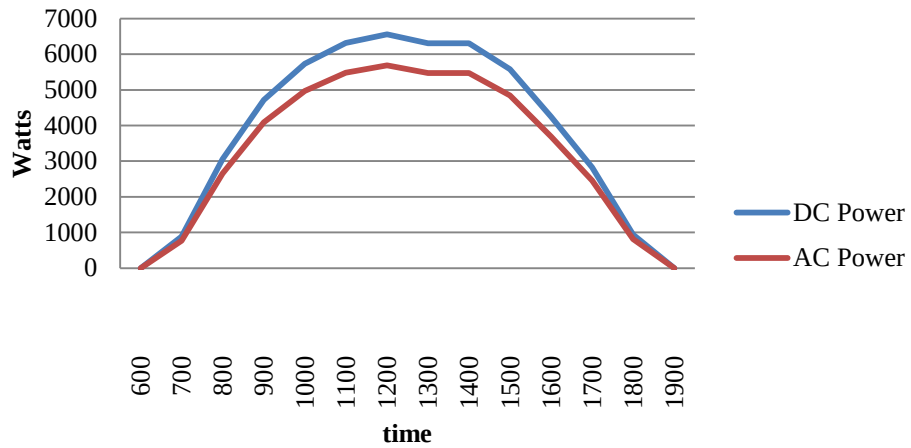
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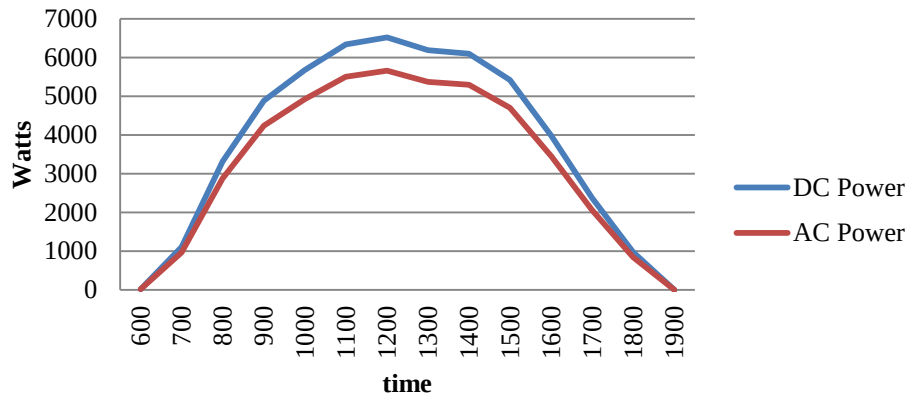
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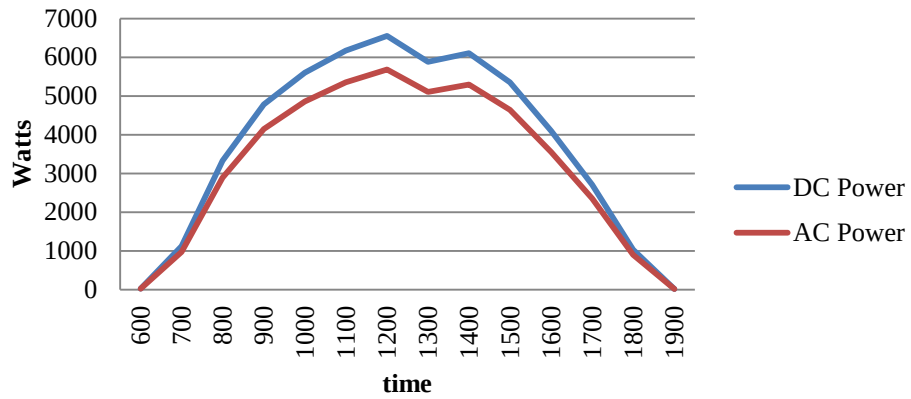
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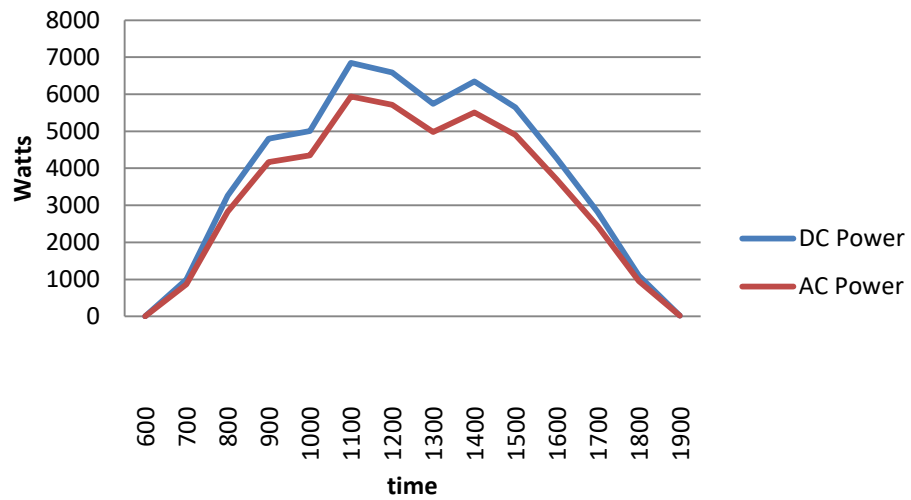
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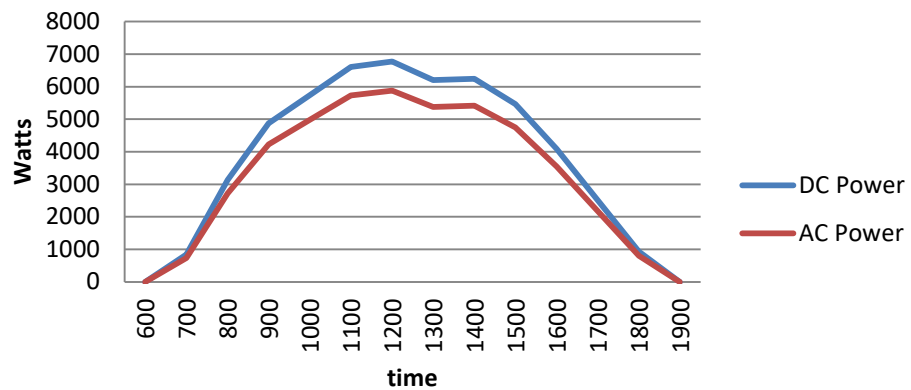
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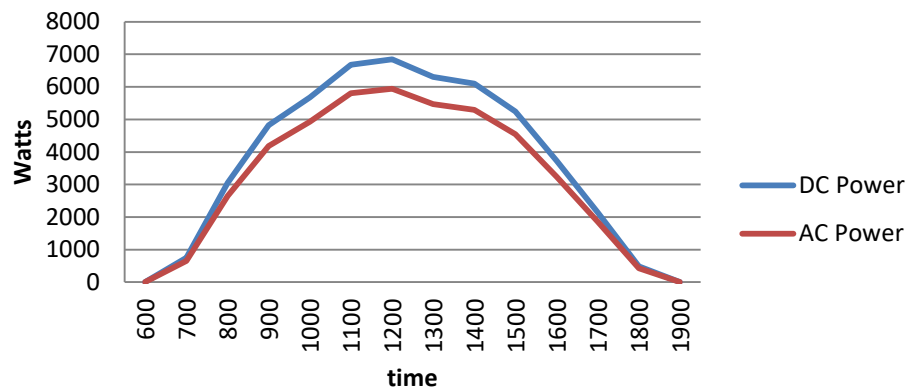
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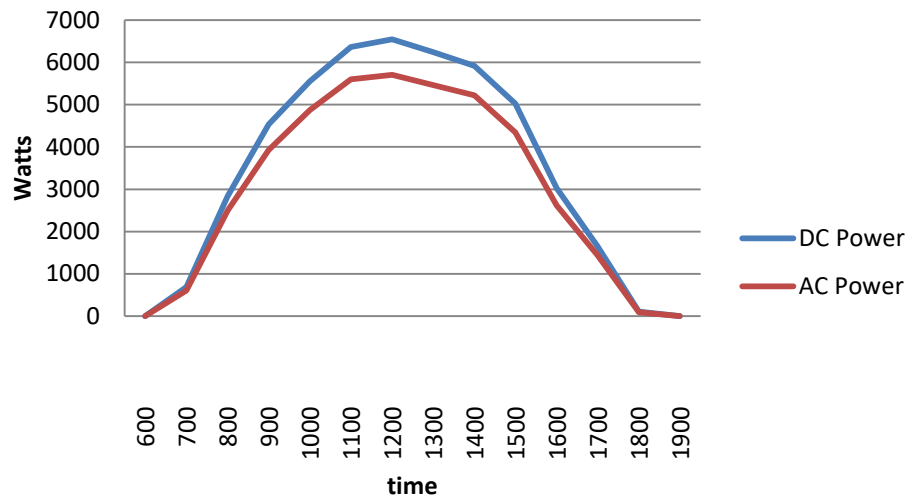
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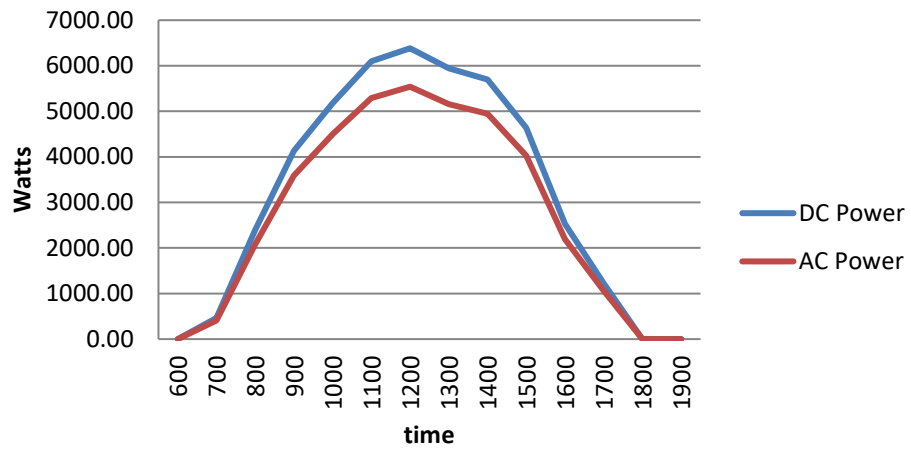
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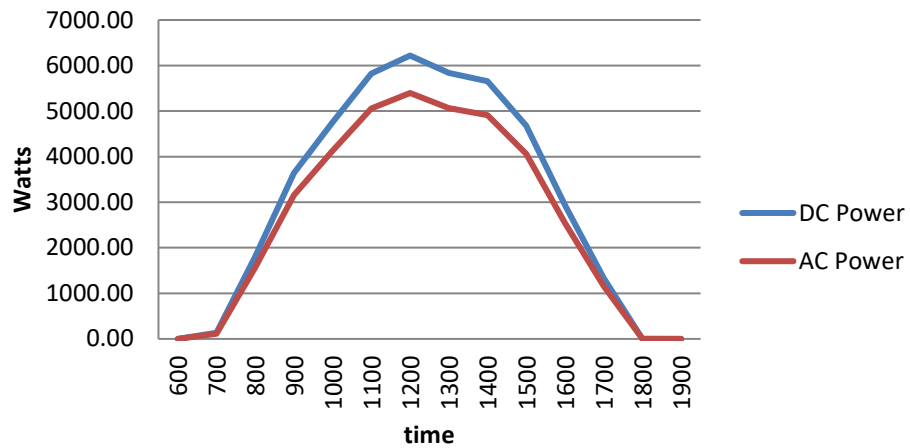
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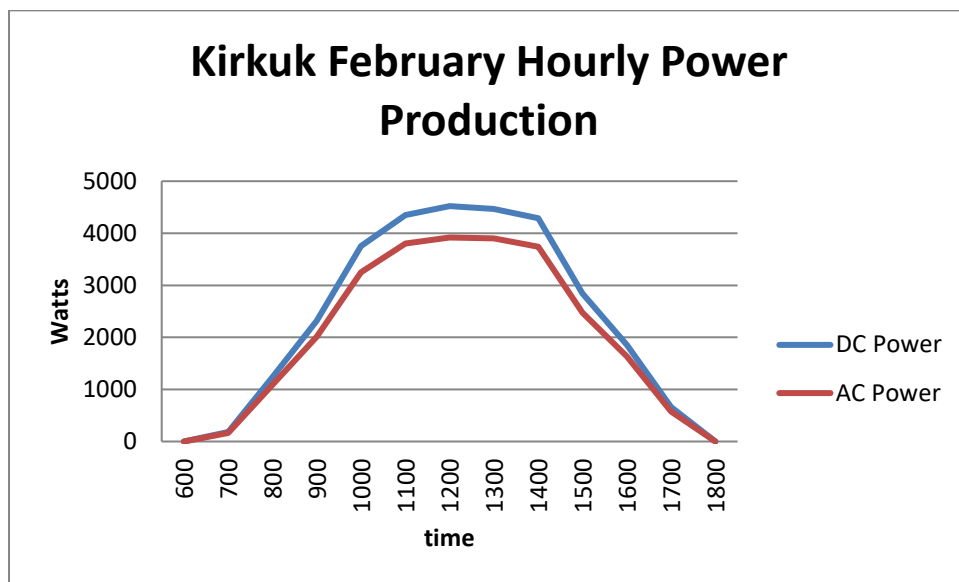
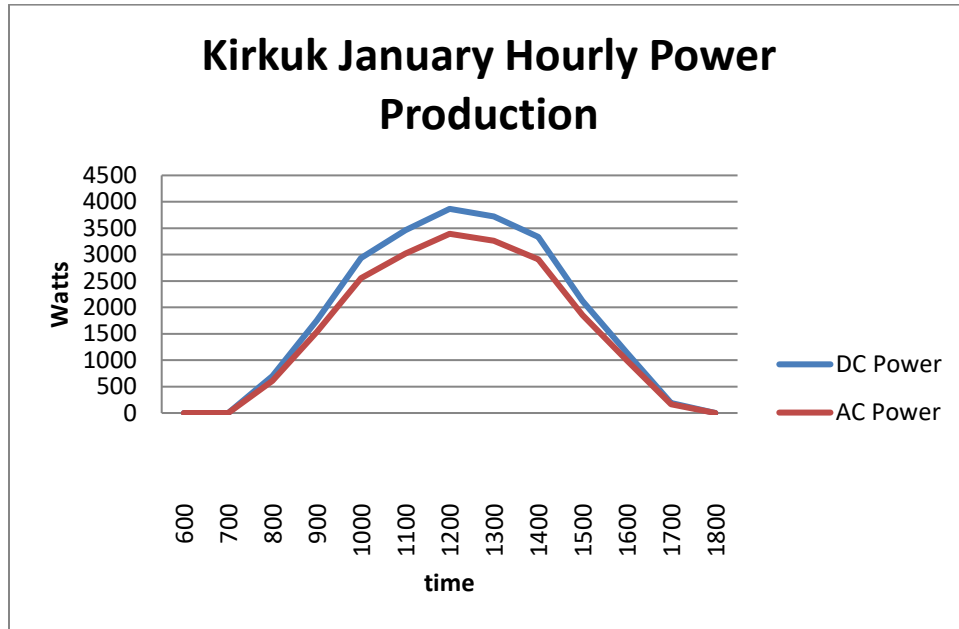
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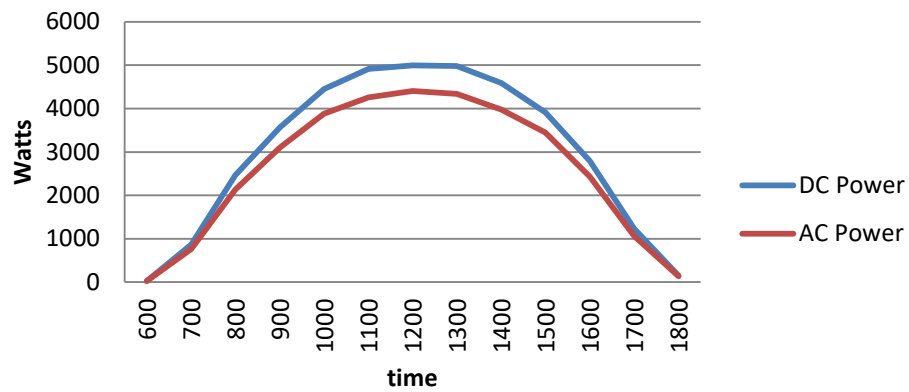
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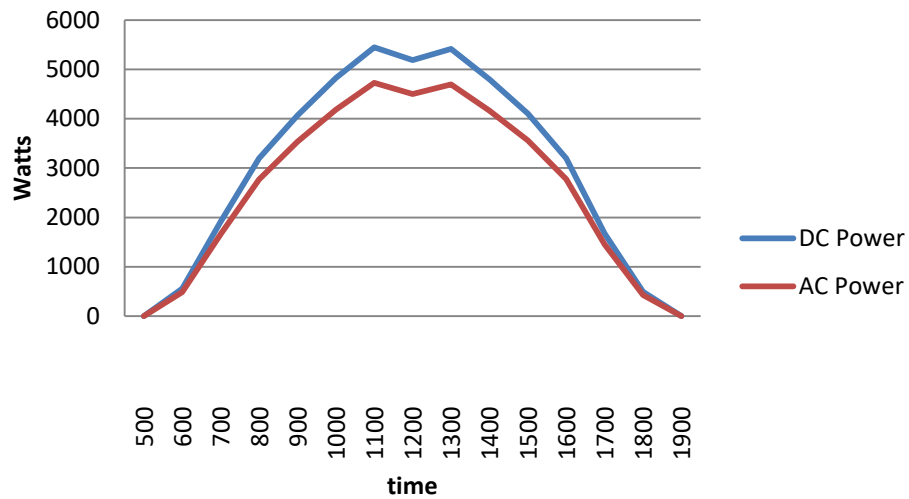
ii. **Kirkuk**



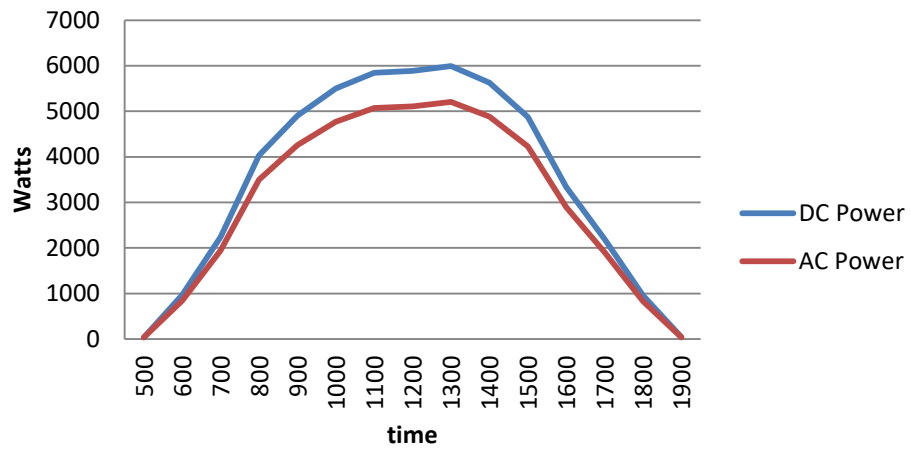
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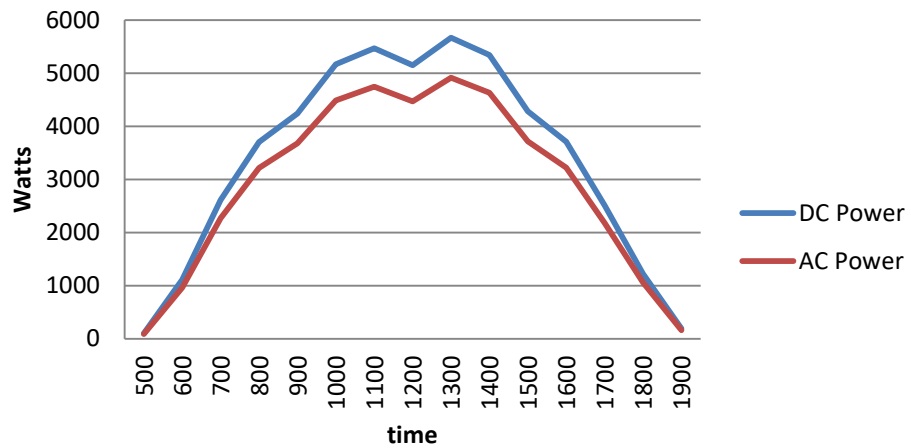
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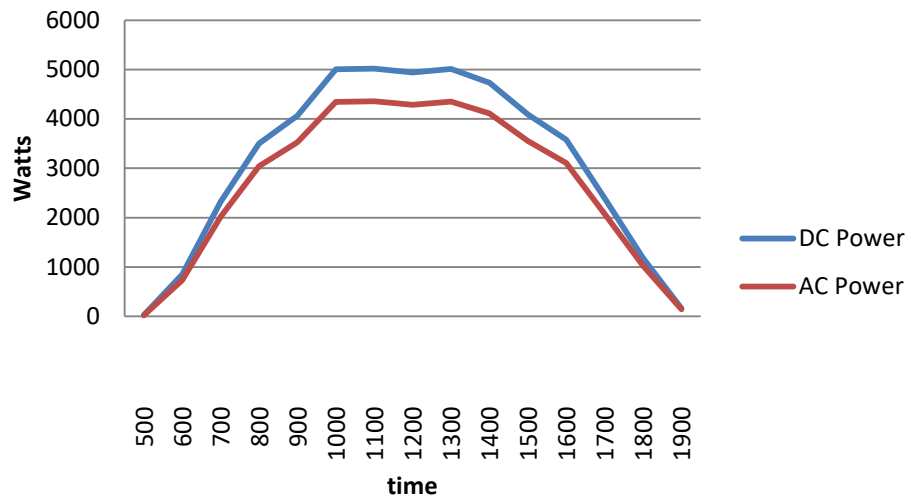
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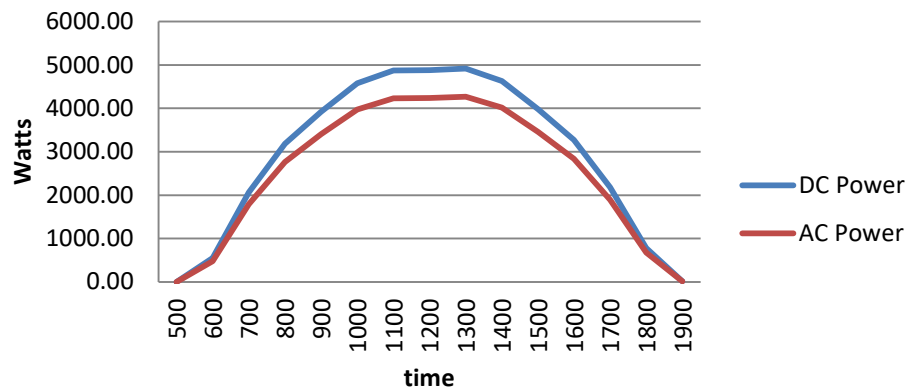
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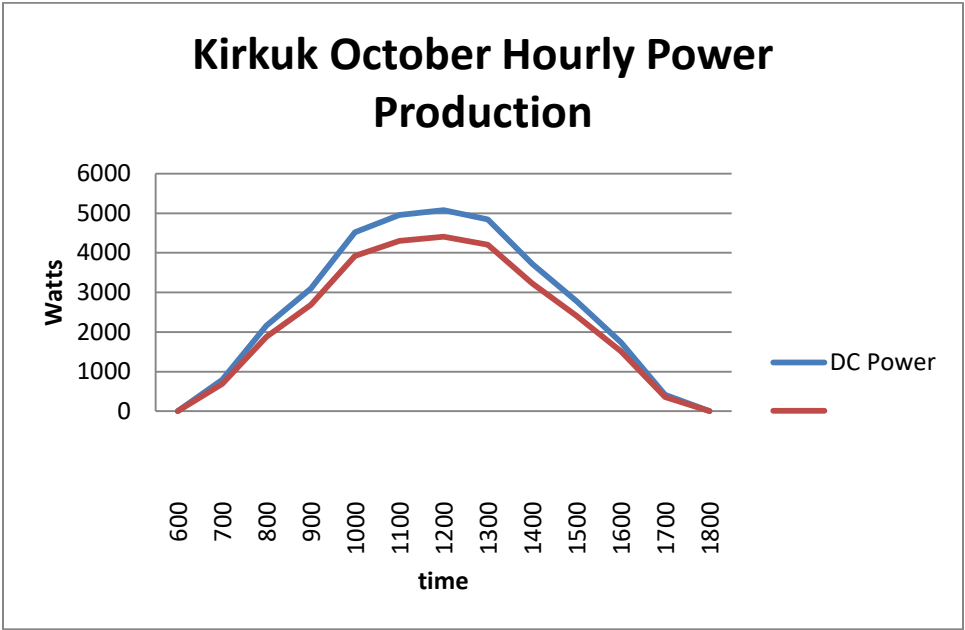
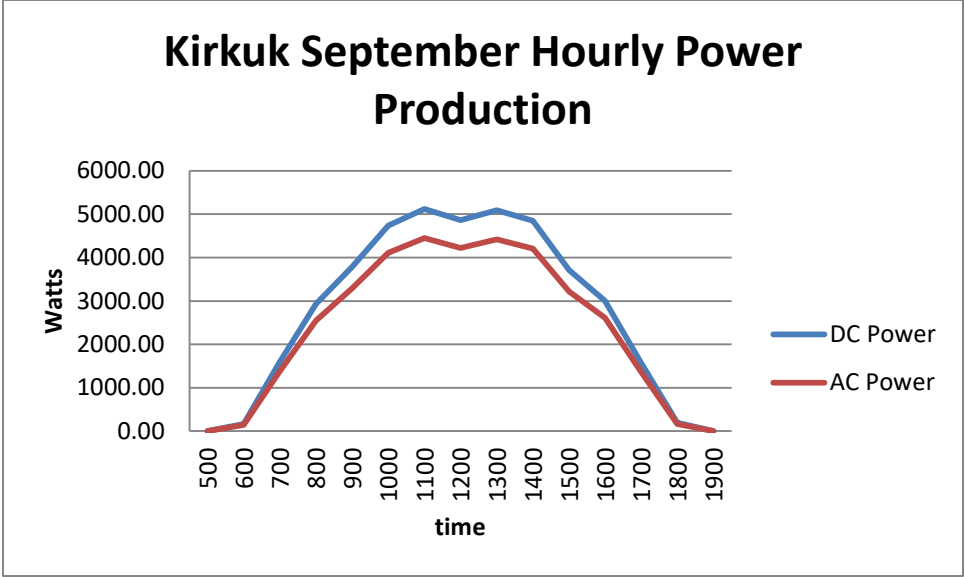


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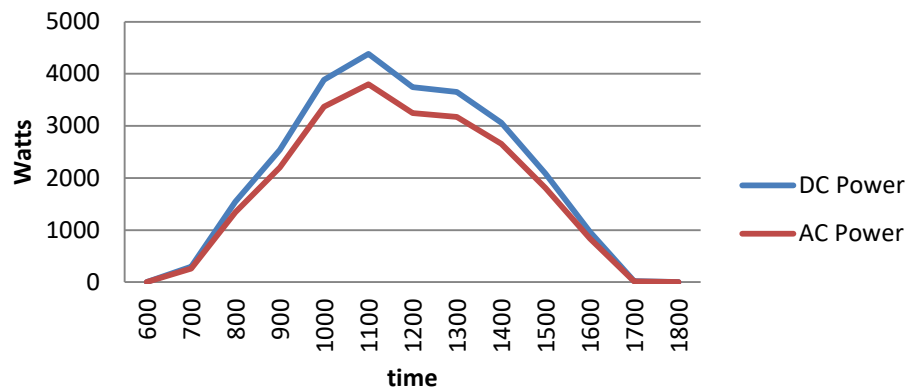


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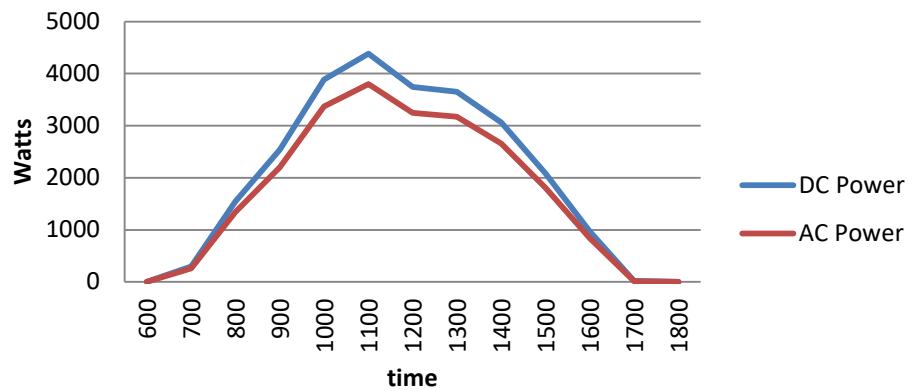




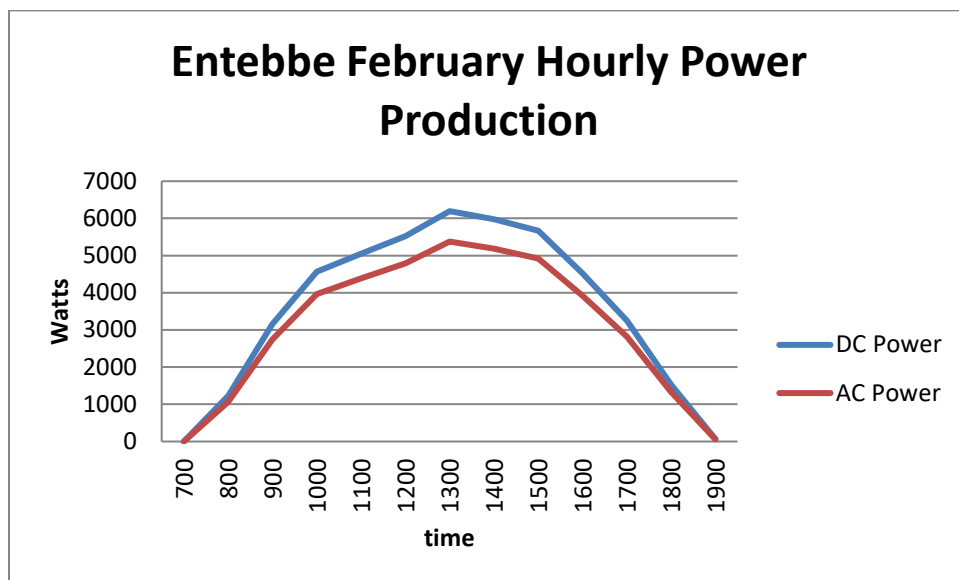
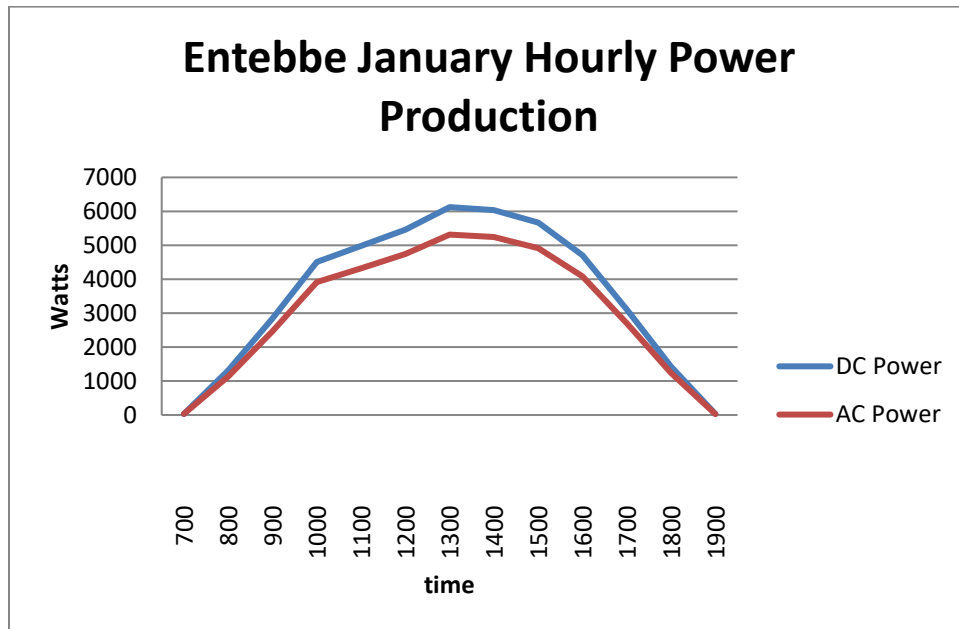
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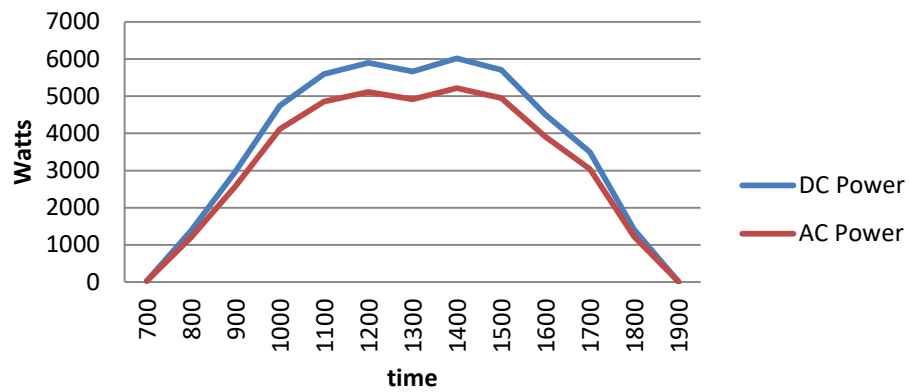
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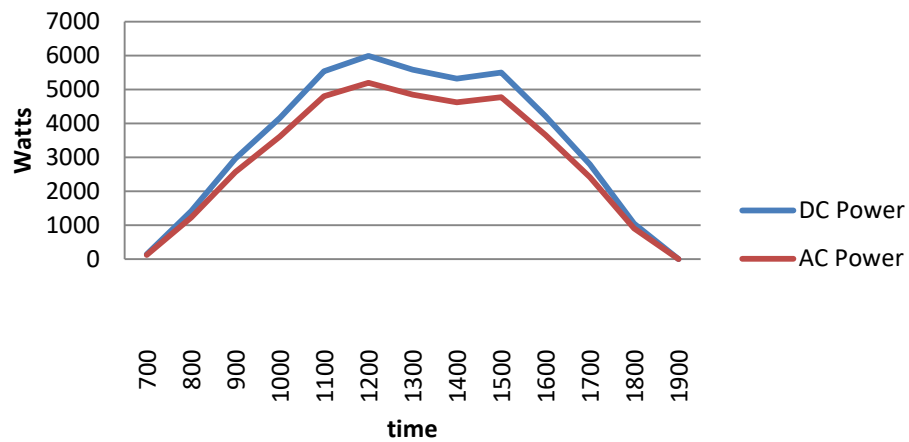
iii. Entebbe



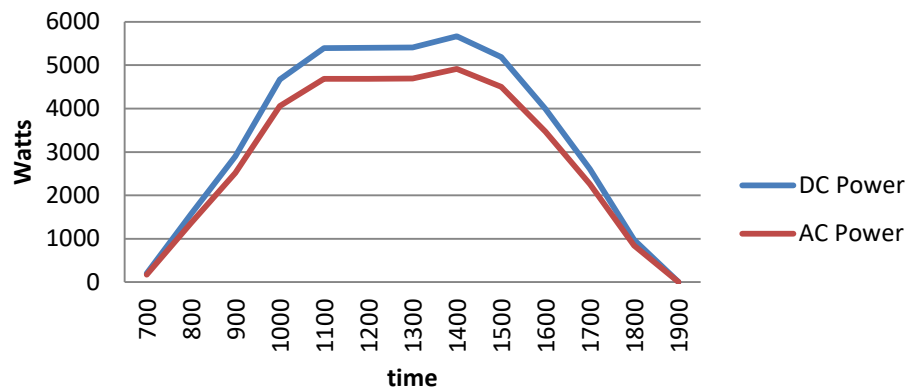
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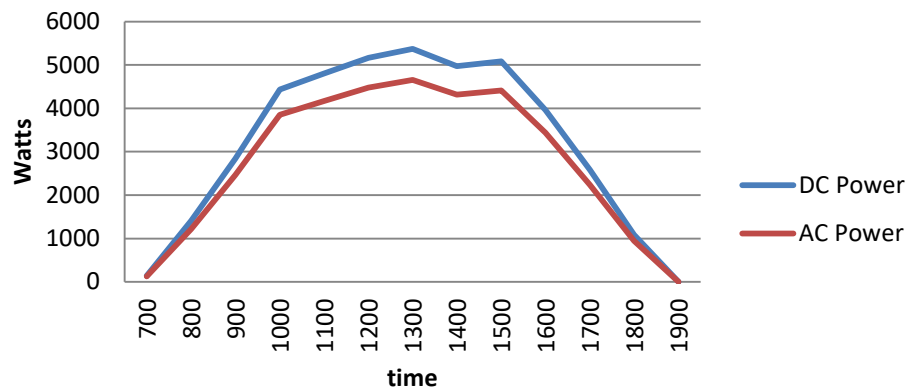
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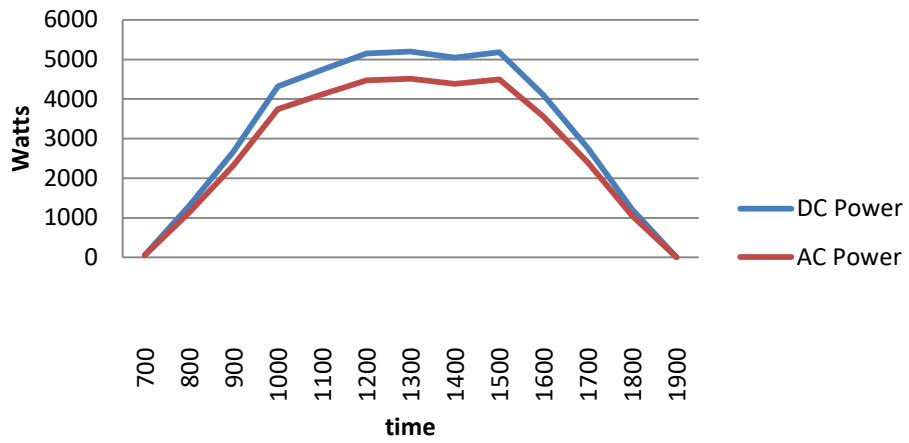
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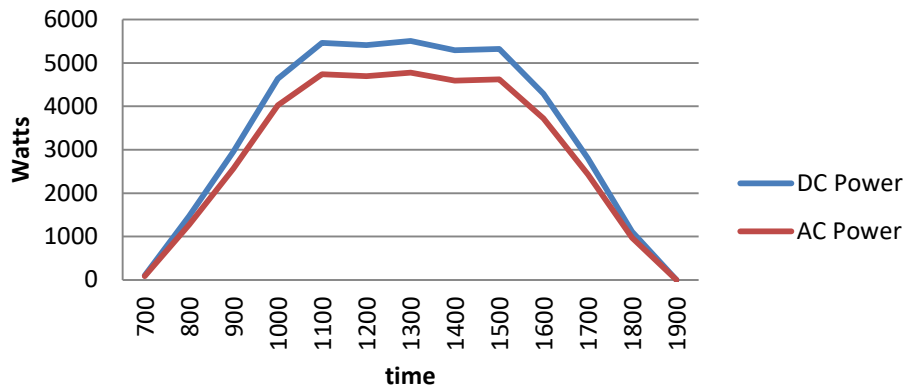
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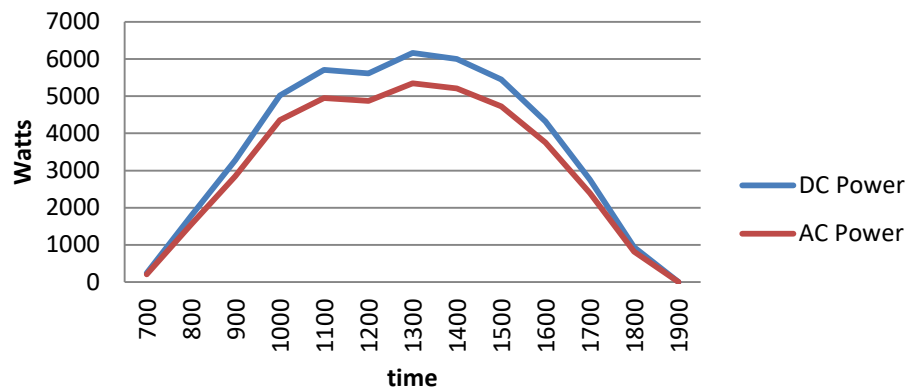
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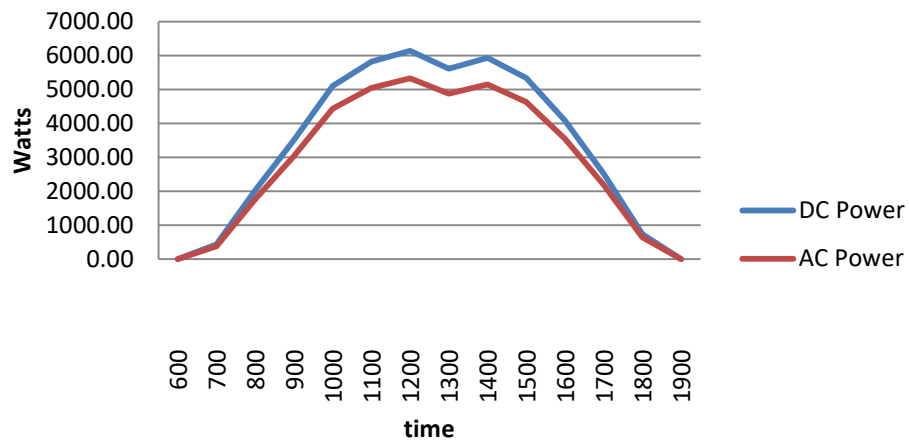
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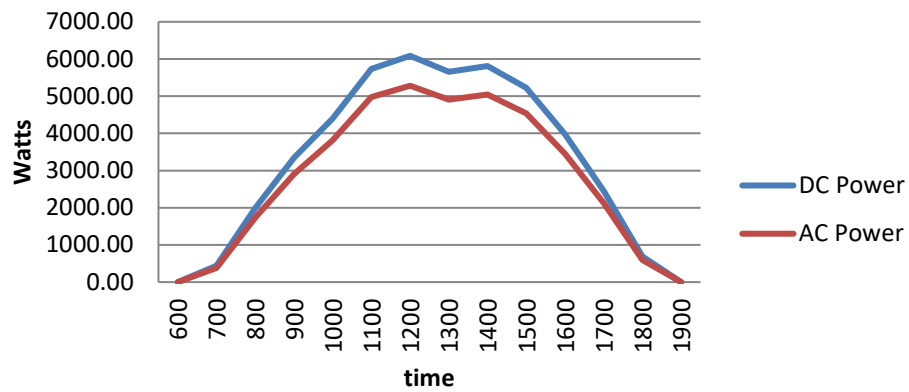
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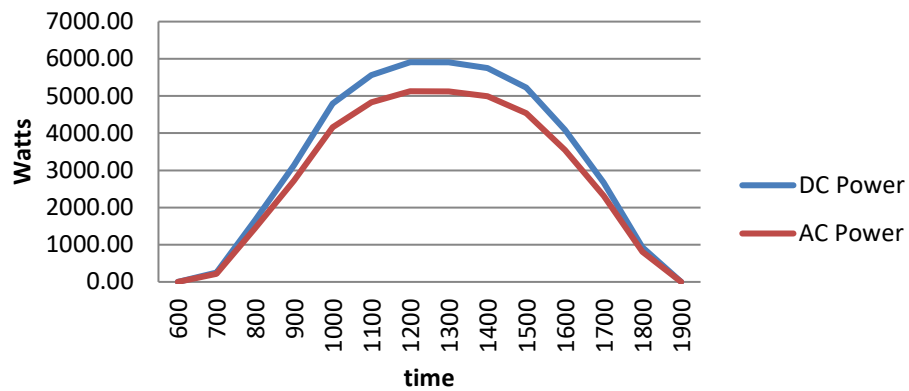
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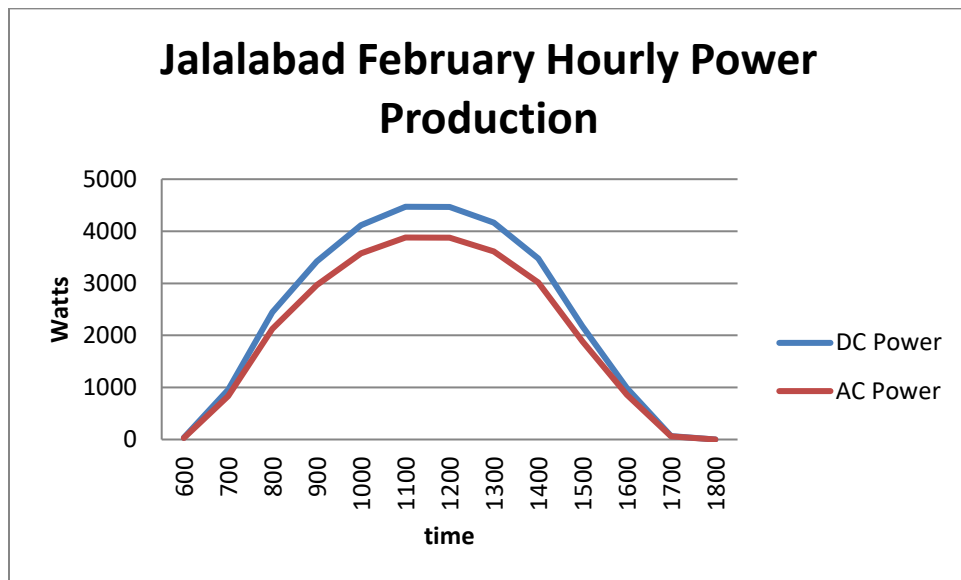
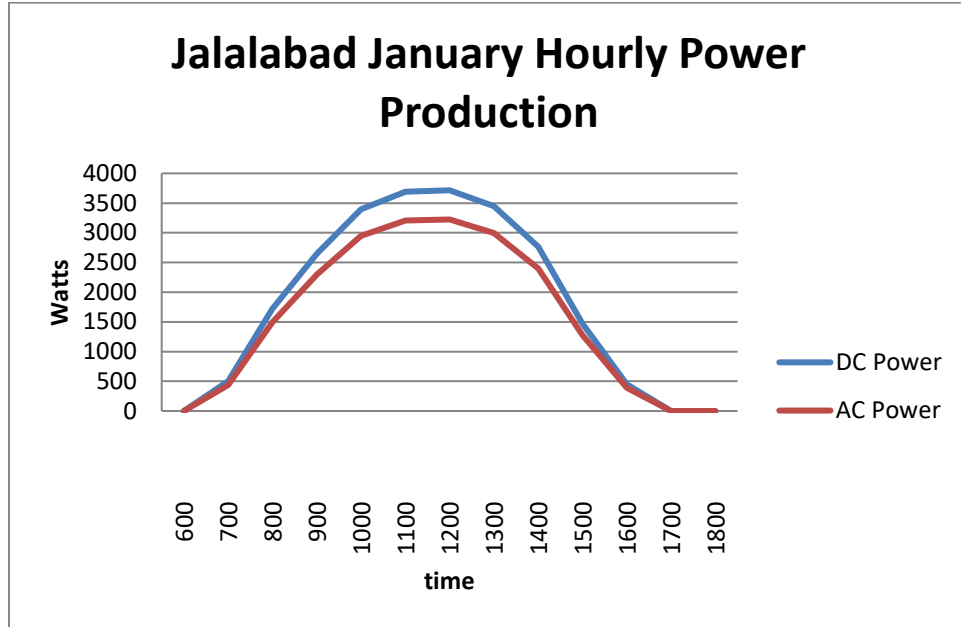
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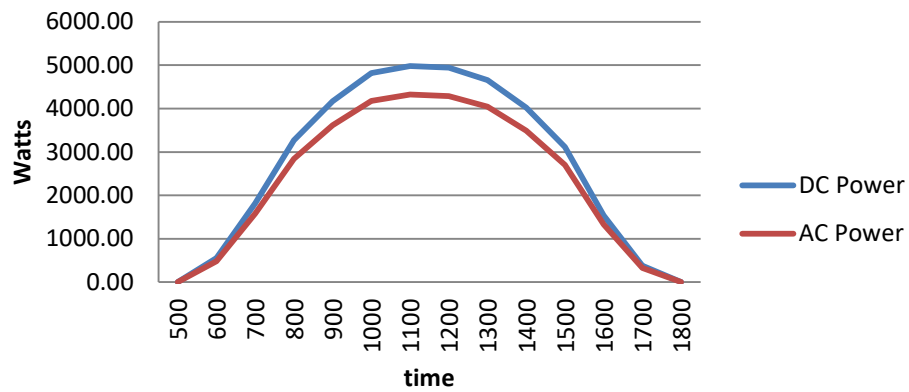
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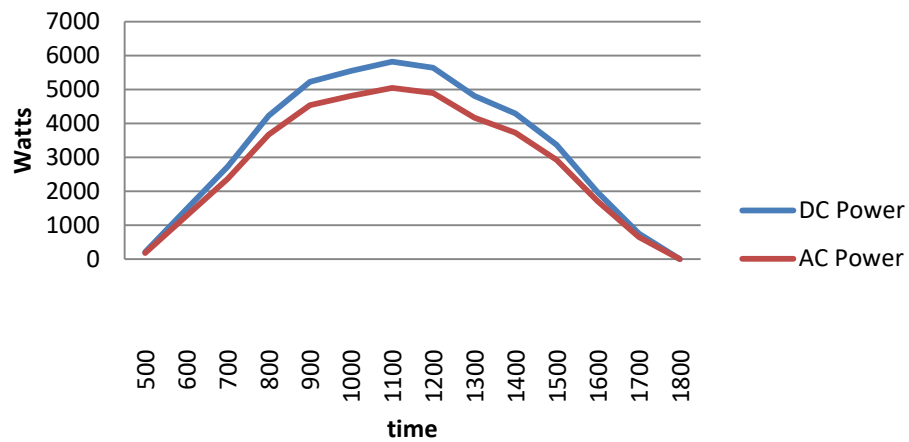
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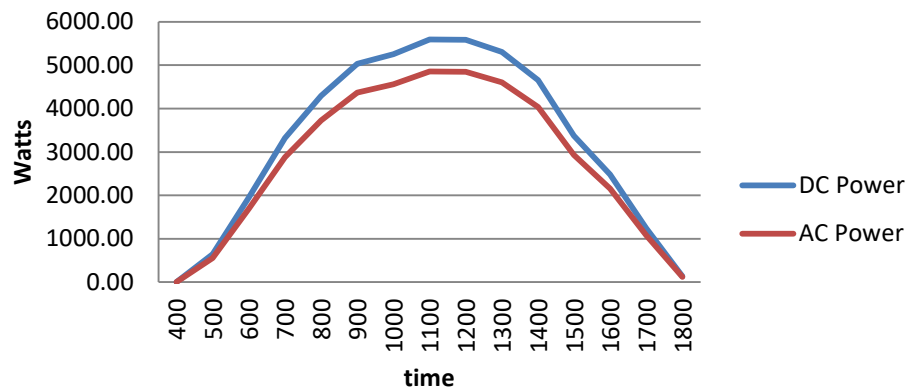
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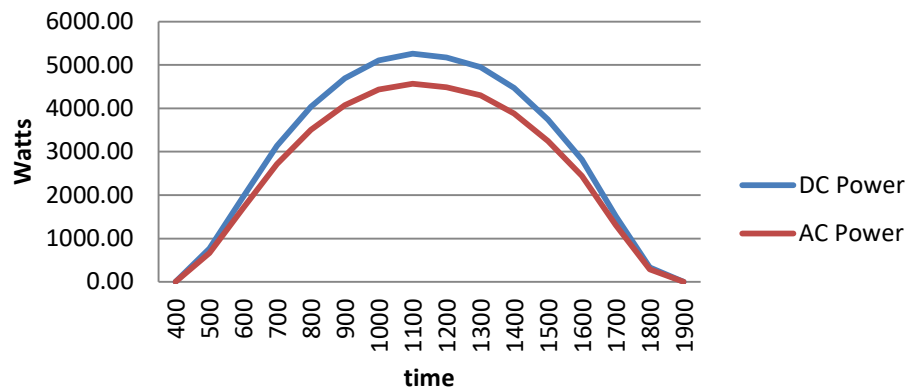
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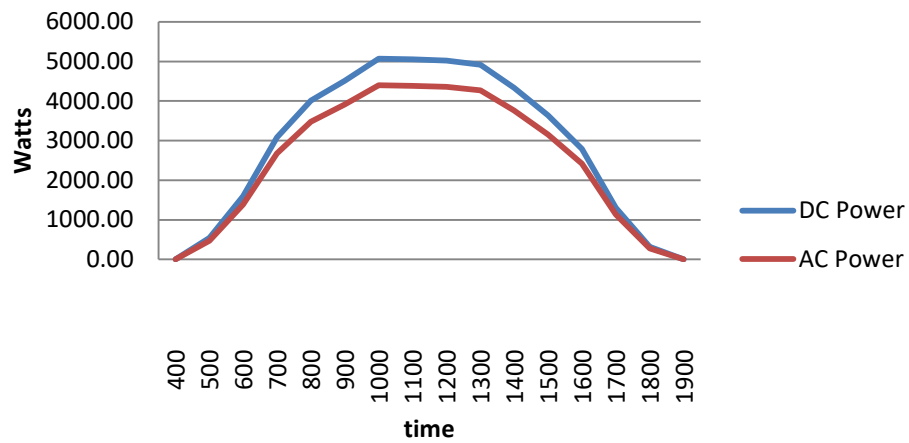
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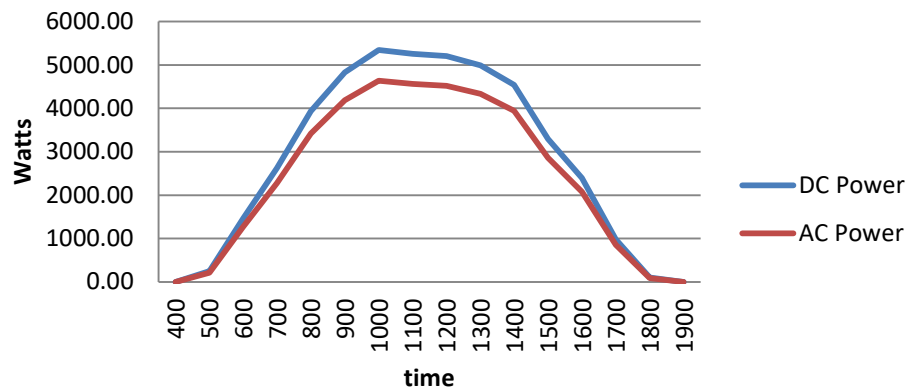
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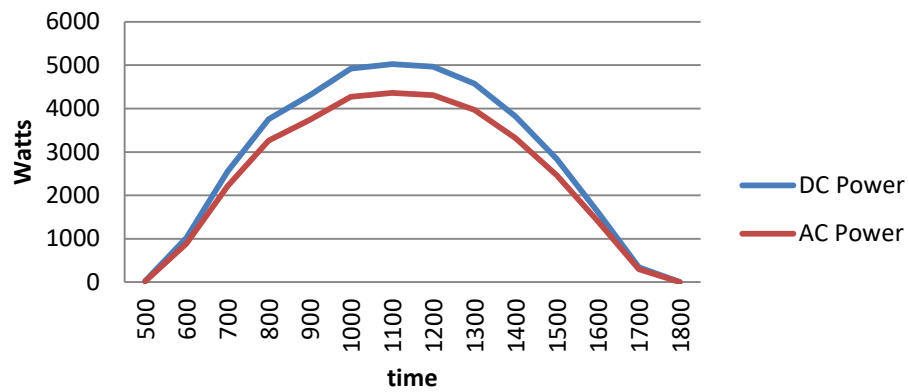
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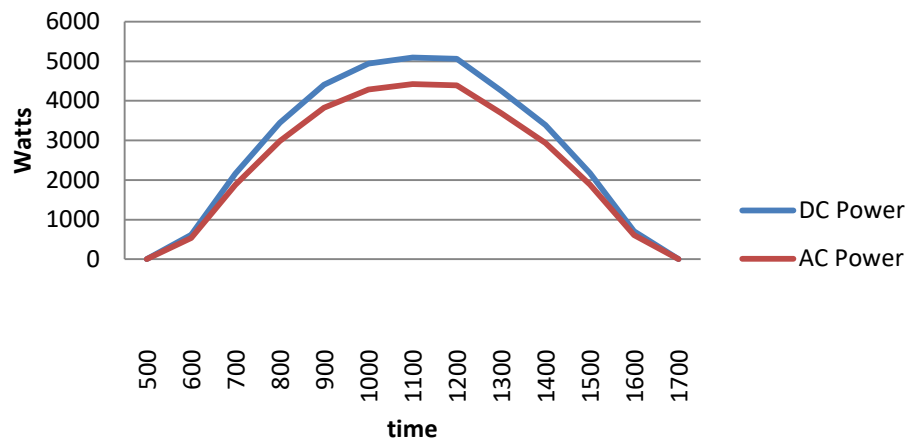
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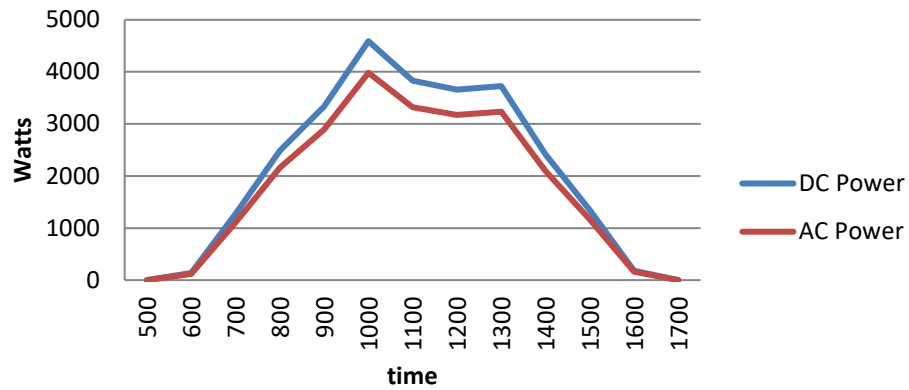
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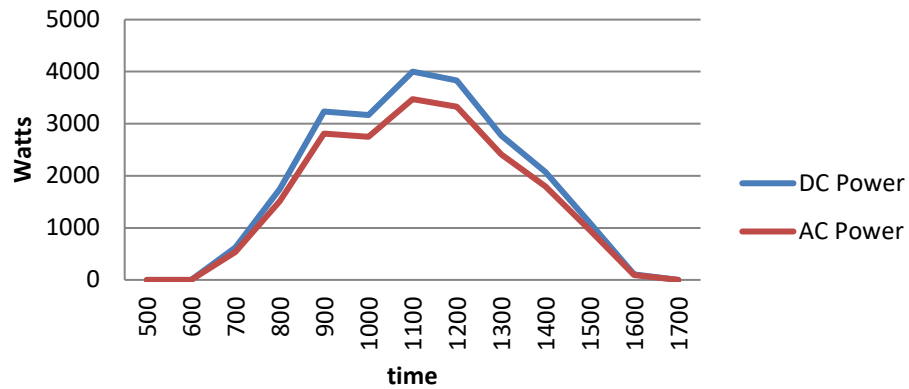
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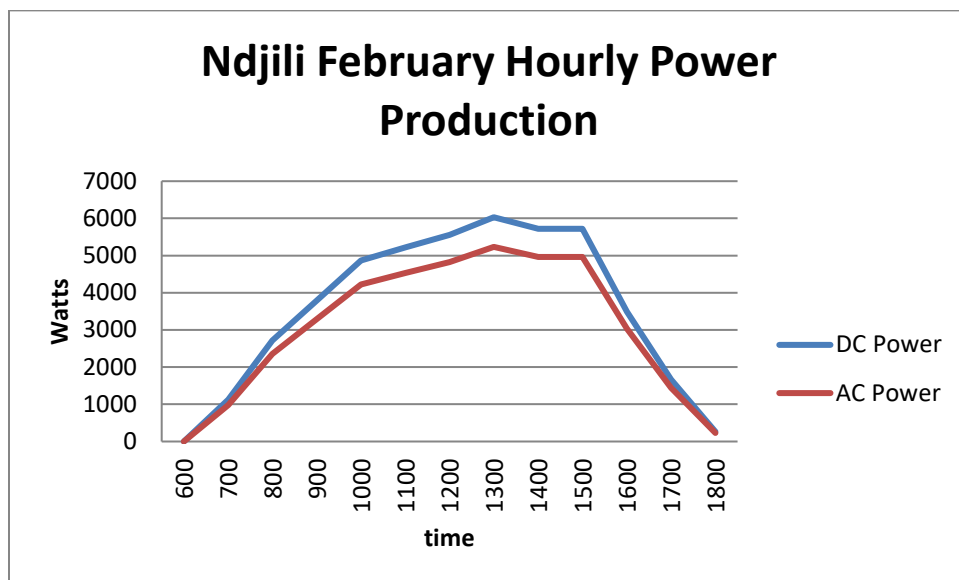
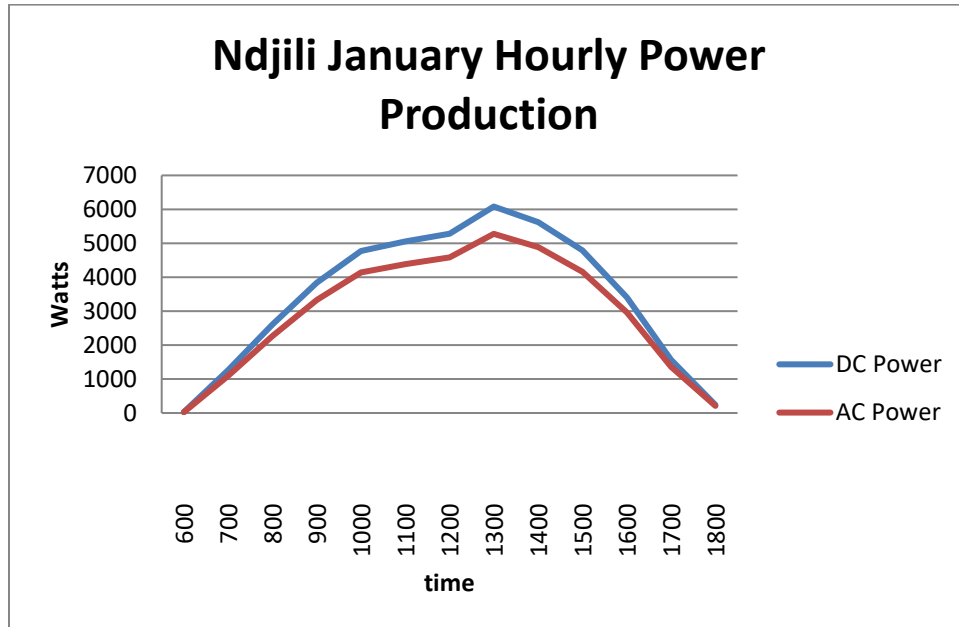
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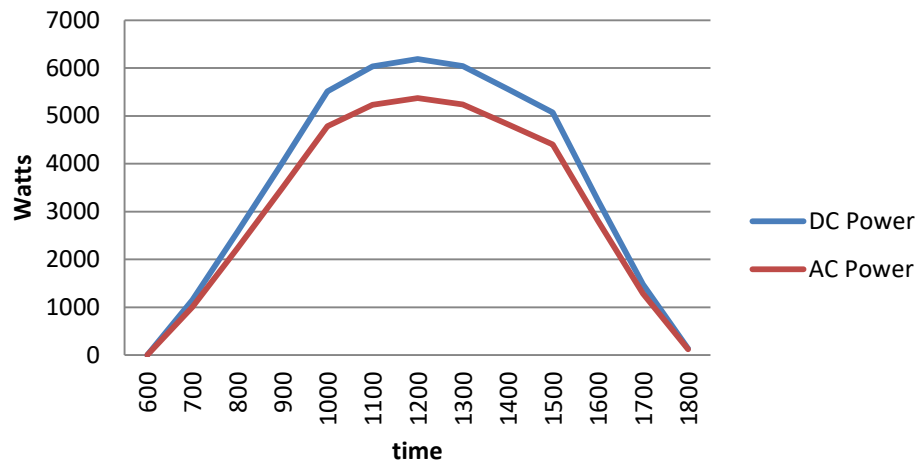
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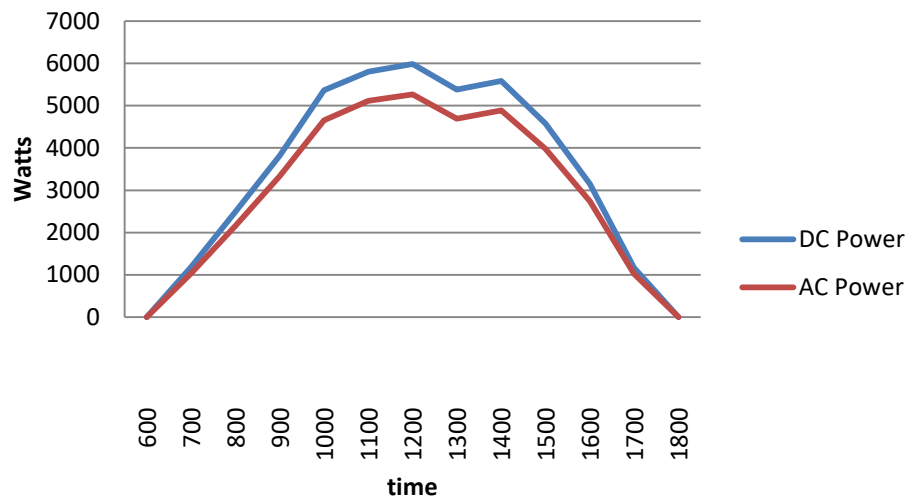
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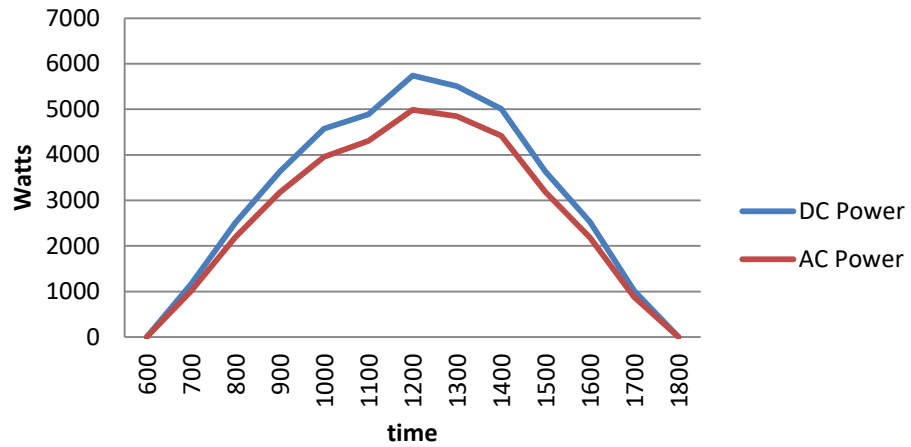
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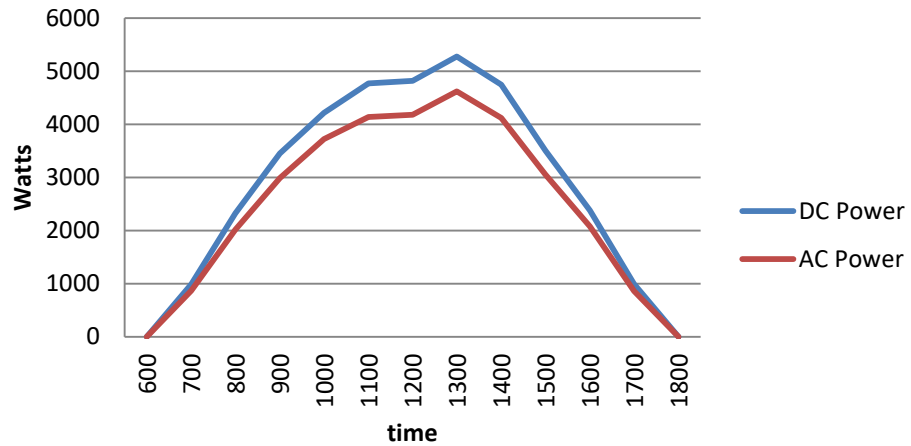
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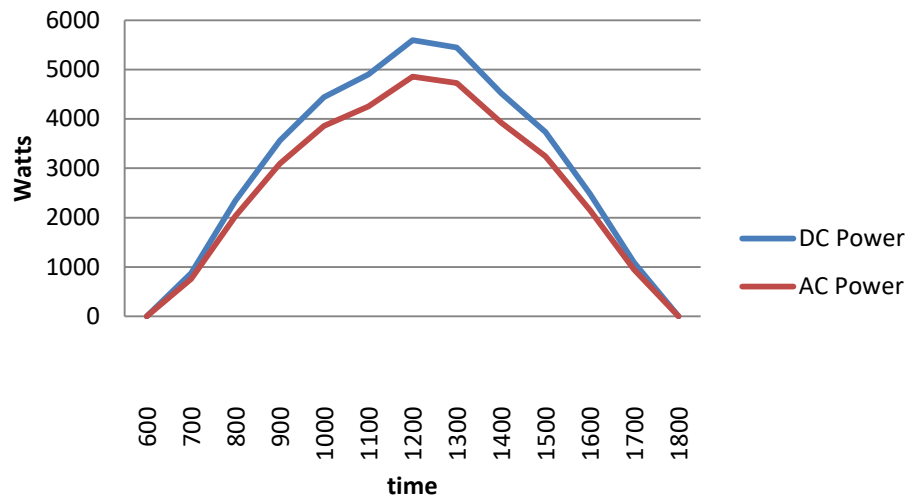
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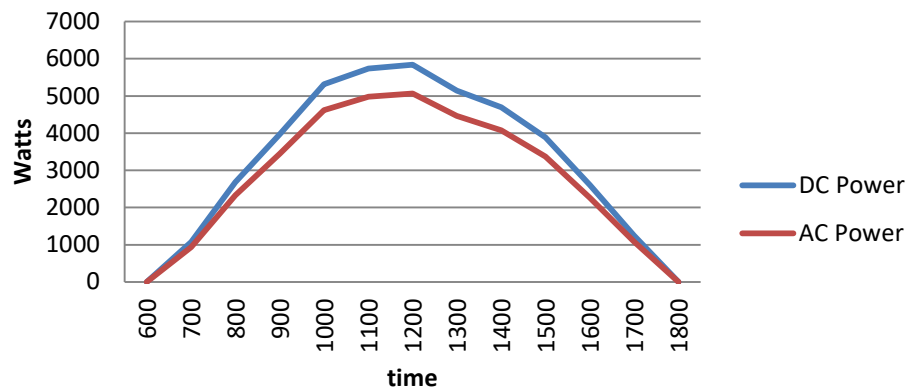
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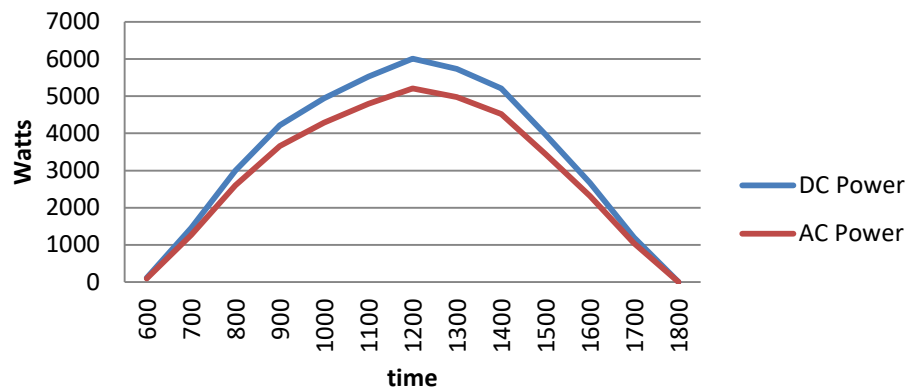
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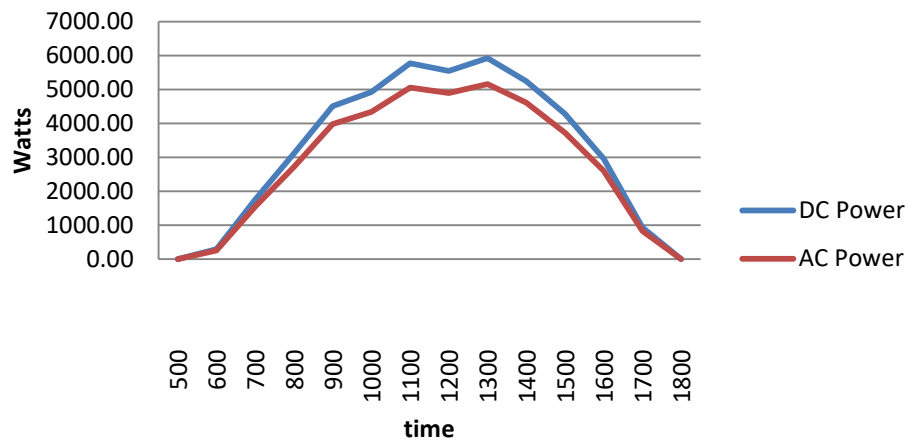
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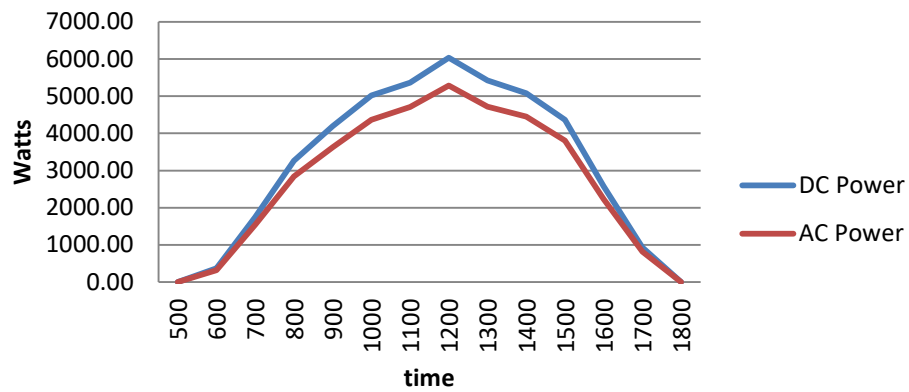
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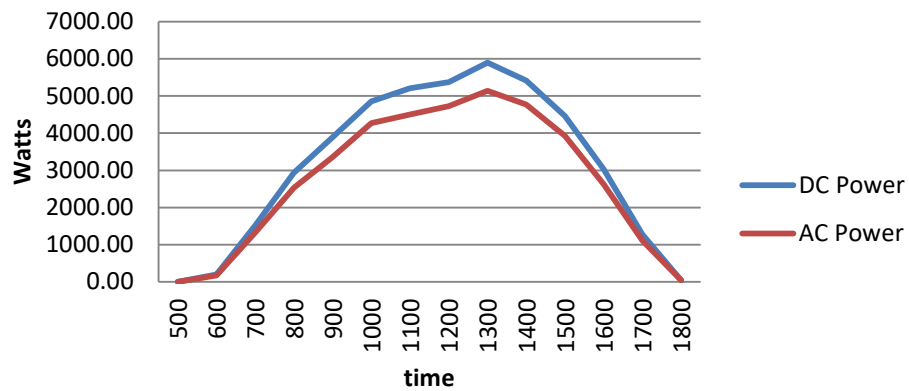
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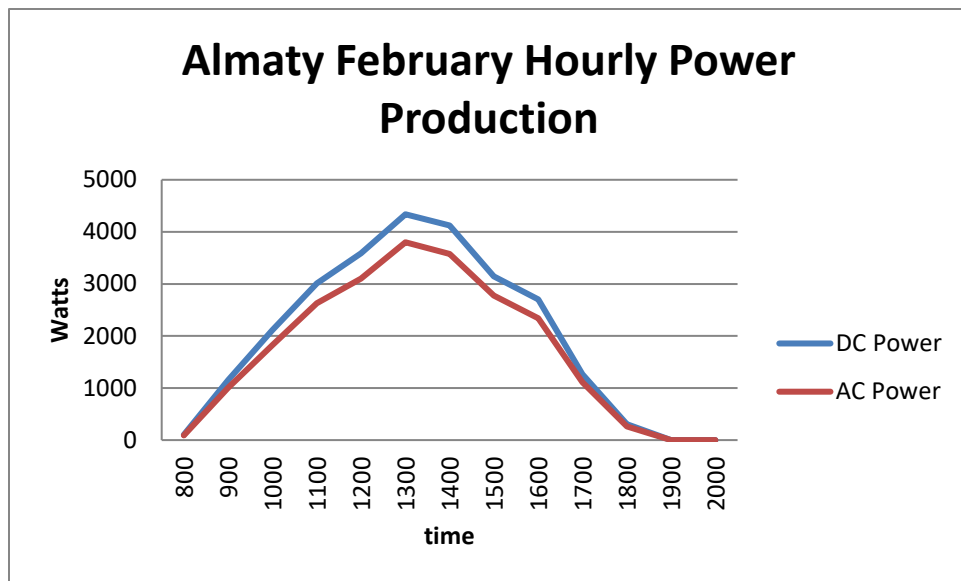
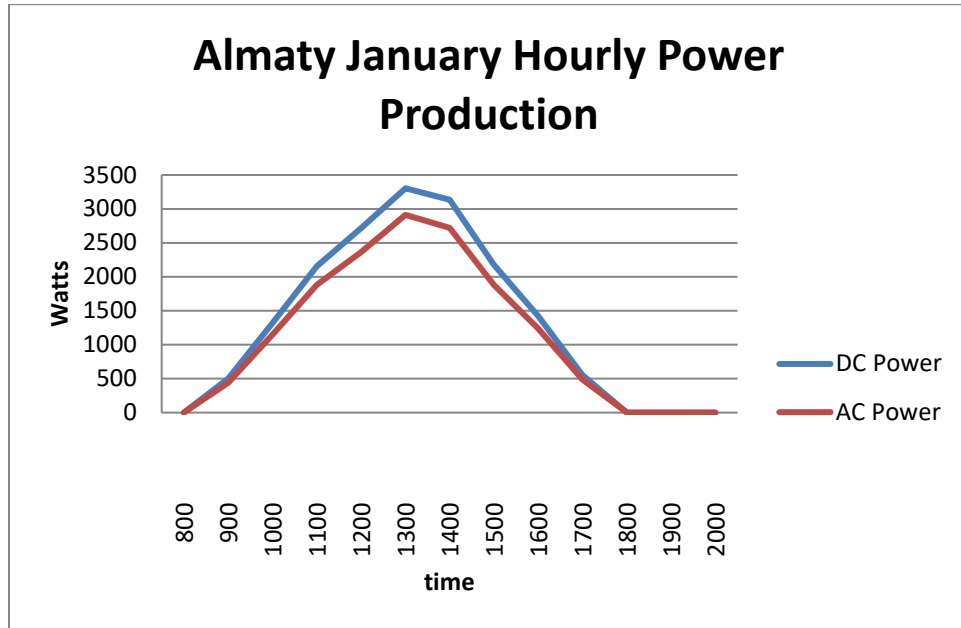
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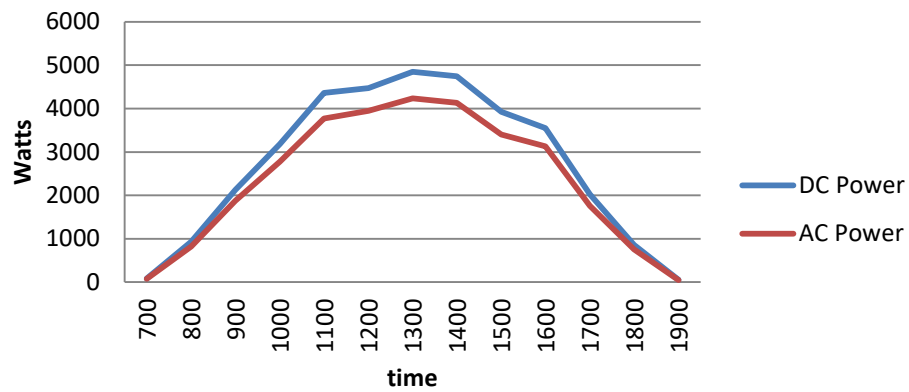
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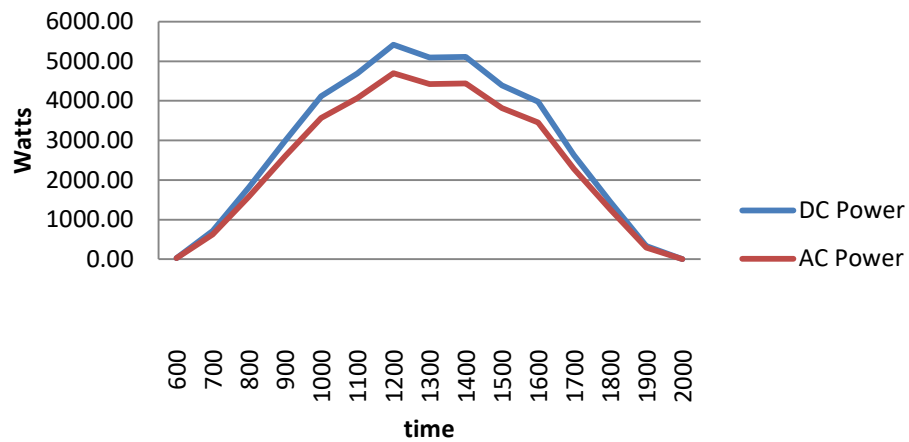
vi. Almaty



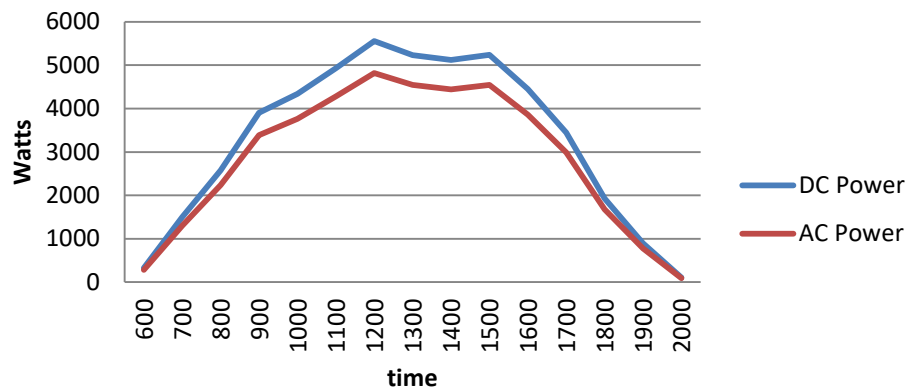
### Almaty March Hourly Power Production



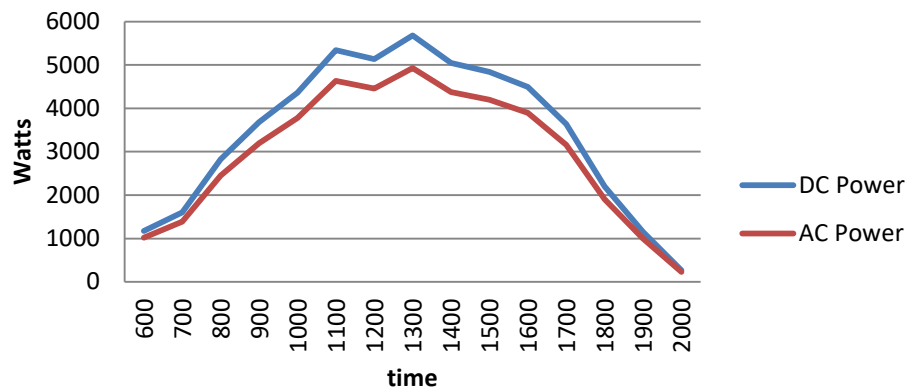
### Almaty April Hourly Power Production



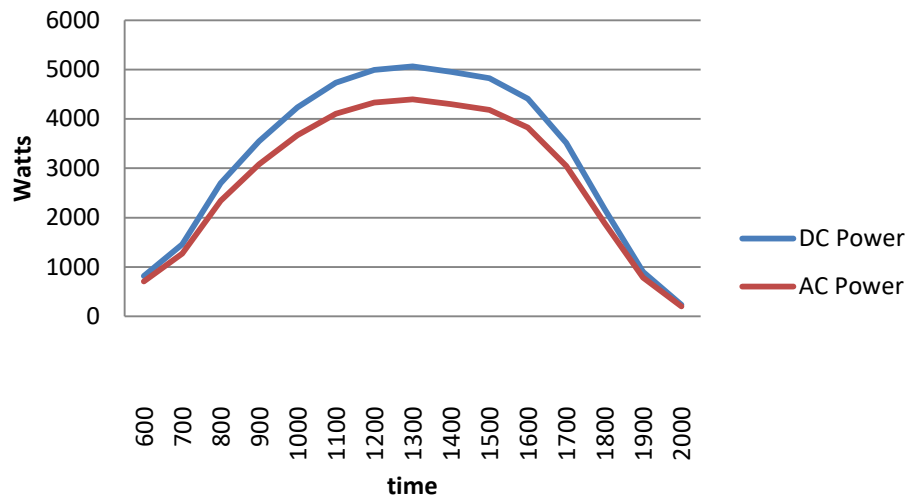
### Almaty May Hourly Power Production



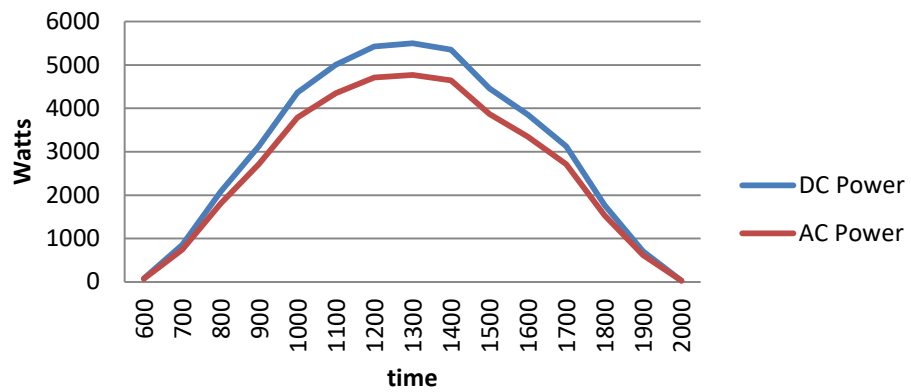
### Almaty June Hourly Power Production



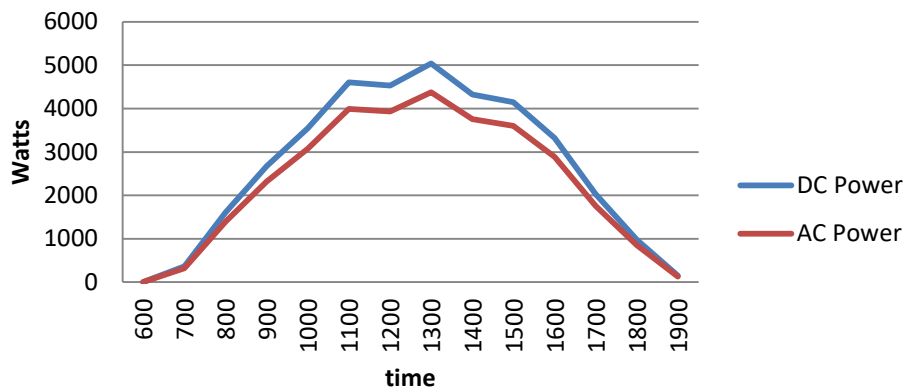
### Almaty July Hourly Power Production



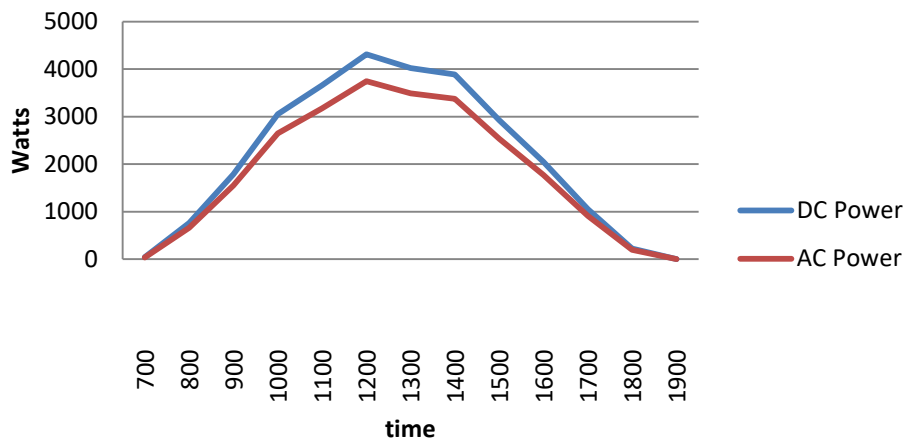
### Almaty August Hourly Power Production



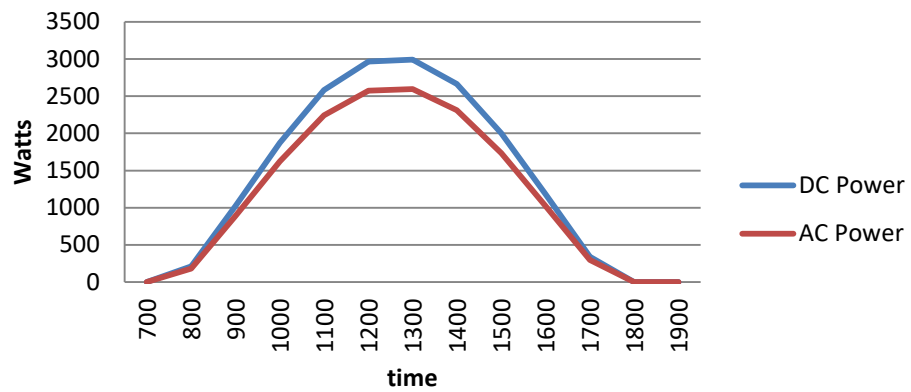
### Almaty September Hourly Power Production



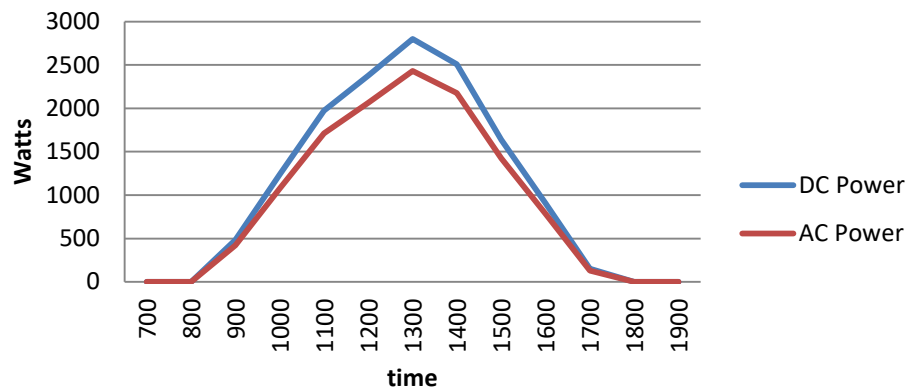
### Almaty October Hourly Power Production



### Almaty November Hourly Power Production



### Almaty December Hourly Power Production



## Appendix B

### i. Agadez

|        |             | Time |      | 600  |      | 700  |      | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      | 1900 |      |
|--------|-------------|------|------|------|------|------|------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|------|------|------|------|------|
|        |             | S.M. | C.I. | S.M. | C.I. | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. | S.M. | C.I. |
| Agadez | January     | 0    | n/a  | 0    | n/a  | 1235 | 3.66 | 2816 | 8.97  | 4259 | 22.62 | 4865 | 17.53 | 5209 | 18.05 | 5489 | 23.94 | 5123 | 16.81 | 4396 | 13.5  | 3229 | 15.16 | 1629 | 6.24  | 229  | 1.81 | 0    | n/a  |      |      |
|        | February    | 0    | n/a  | 74   | 0.75 | 1464 | 6.34 | 3162 | 11.01 | 4539 | 22.1  | 5018 | 18.73 | 5493 | 17.99 | 5829 | 24.35 | 5369 | 16.36 | 4713 | 13.96 | 3600 | 18.8  | 2170 | 7.14  | 504  | 2.61 | 0    | n/a  |      |      |
|        | March       | 0    | n/a  | 438  | 3.02 | 2201 | 8.75 | 3820 | 13.6  | 5114 | 20.84 | 5309 | 20.83 | 5608 | 18.86 | 6135 | 21.8  | 5376 | 17.17 | 4985 | 14.48 | 4031 | 17.26 | 2323 | 6.64  | 612  | 3.34 | 0    | n/a  |      |      |
|        | April       | 0    | n/a  | 888  | 4.88 | 2819 | 8.09 | 4216 | 12.42 | 5299 | 21.16 | 5594 | 15.32 | 5741 | 17.65 | 5836 | 25.09 | 5591 | 15.39 | 4879 | 15.13 | 3870 | 18.64 | 2577 | 5.86  | 885  | 2.4  | 0    | n/a  |      |      |
|        | May         | 18   | 0.16 | 1108 | 5.98 | 2926 | 8.39 | 4351 | 10.87 | 5185 | 21.68 | 6281 | 21.97 | 5781 | 16.78 | 5808 | 23.64 | 5456 | 18.03 | 4846 | 17.49 | 3956 | 19.99 | 2371 | 12.68 | 970  | 4.49 | 0    | n/a  |      |      |
|        | June        | 25   | 0.18 | 1119 | 6.18 | 3041 | 6.87 | 4242 | 12.3  | 5063 | 23.2  | 5497 | 14.09 | 5929 | 14.19 | 5802 | 26.69 | 5611 | 15.44 | 4926 | 18.17 | 4071 | 20.17 | 2697 | 14.41 | 1027 | 6.85 | 13   | 0.11 |      |      |
|        | July        | 0    | n/a  | 995  | 5.05 | 3041 | 5.73 | 4421 | 8.55  | 4434 | 21.69 | 6244 | 16.68 | 5876 | 17.14 | 5686 | 14.8  | 5911 | 18.99 | 5291 | 19.42 | 4092 | 17.58 | 2796 | 16.45 | 1097 | 7.35 | 20   | 0.16 |      |      |
|        | August      | 0    | n/a  | 842  | 4.02 | 2904 | 5.77 | 4428 | 10.9  | 5206 | 24    | 5951 | 17.98 | 6110 | 20.7  | 5864 | 25.84 | 5802 | 19.9  | 5081 | 20.75 | 4068 | 19.13 | 2494 | 17.2  | 935  | 5.86 | 0    | n/a  |      |      |
|        | September   | 0    | n/a  | 747  | 3.55 | 2834 | 4.89 | 4398 | 9.37  | 5106 | 21.78 | 6536 | 6.6   | 6532 | 8.8   | 6017 | 19.19 | 5777 | 16.08 | 5023 | 15.9  | 3717 | 18.47 | 2132 | 11.8  | 486  | 3.53 | 0    | n/a  |      |      |
|        | October     | 0    | n/a  | 701  | 2.75 | 2740 | 3.9  | 4246 | 7.95  | 5150 | 18.1  | 6086 | 6.94  | 6181 | 9.66  | 5910 | 20.38 | 5650 | 9.74  | 5003 | 7.7   | 3019 | 16.1  | 1642 | 5.01  | 110  | 1.06 | 0    | n/a  |      |      |
|        | November    | 0    | n/a  | 465  | 2.2  | 2327 | 3.94 | 3949 | 6.49  | 5022 | 12.15 | 5821 | 7.13  | 6243 | 4.74  | 5751 | 14.21 | 5584 | 4.39  | 4445 | 5.66  | 2529 | 12.24 | 1195 | 1.78  | 0    | n/a  | 0    | n/a  |      |      |
|        | December    | 0    | n/a  | 132  | 1.28 | 1791 | 3.31 | 3544 | 5.3   | 4494 | 14.17 | 5457 | 9.04  | 5897 | 7.23  | 5546 | 14.49 | 5398 | 5.44  | 4576 | 3.7   | 2808 | 9.56  | 1333 | 2.07  | 6    | 0.04 | 0    | n/a  |      |      |
|        |             |      |      |      |      |      |      |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |      |      |      |      |      |
|        |             | Time |      | 600  |      | 700  |      | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      | 1900 |      |
|        |             | S.M. | C.I. | S.M. | C.I. | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. | S.M. | C.I. |
|        | Winter Mean | 0    | n/a  | 302  | 2.00 | 1960 | 4.98 | 3590 | 8.89  | 4763 | 18.33 | 5426 | 13.37 | 5772 | 12.76 | 5777 | 19.86 | 5417 | 11.65 | 4686 | 9.83  | 3203 | 14.85 | 1715 | 4.81  | 244  | 1.77 | 0    | n/a  |      |      |
|        | Summer Mean | 7    | 0.17 | 950  | 4.94 | 2928 | 6.62 | 4343 | 10.74 | 5049 | 22.25 | 6017 | 15.44 | 5995 | 15.88 | 5836 | 22.54 | 5691 | 17.31 | 5008 | 17.81 | 3962 | 19.00 | 2511 | 13.07 | 900  | 5.08 | 6    | 0.14 |      |      |

## ii. Kirkuk

|        | Time        | 500  |      | 600  |      | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |       | 1800 |      | 1900 |      |
|--------|-------------|------|------|------|------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|------|------|------|
|        |             | S.M. | C.I. | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
| Kirkuk | January     | 0    | n/a  | 0    | n/a  | 0    | n/a   | 697  | 4.37  | 1756 | 13.41 | 2904 | 21.3  | 3427 | 26.57 | 3858 | 28.38 | 3699 | 27.13 | 3277 | 23.63 | 2106 | 15.98 | 1128 | 7.8   | 190  | 1.85  | 0    | n/a  | 0    | n/a  |
|        | February    | 0    | n/a  | 0    | n/a  | 183  | 1.79  | 1228 | 8.56  | 2319 | 19.25 | 3732 | 26.77 | 4326 | 30.91 | 4447 | 33.07 | 4384 | 31.89 | 4283 | 28.55 | 2804 | 22.38 | 1833 | 12.9  | 664  | 4.59  | 0    | n/a  | 0    | n/a  |
|        | March       | 0    | n/a  | 28   | 0.3  | 858  | 6.555 | 2463 | 17.69 | 3536 | 27.45 | 4381 | 31.89 | 4850 | 34.34 | 4884 | 36.74 | 4918 | 34.79 | 4530 | 32.53 | 3858 | 27.67 | 2777 | 19.35 | 1225 | 8.78  | 153  | 1.48 | 0    | n/a  |
|        | April       | 0    | n/a  | 560  | 4.11 | 1917 | 13.06 | 3161 | 22.69 | 4014 | 30.51 | 4738 | 33.76 | 5364 | 35.15 | 5070 | 37.58 | 5339 | 35.04 | 4728 | 32.92 | 4019 | 29.66 | 3145 | 22.09 | 1662 | 12.02 | 493  | 3.49 | 0    | n/a  |
|        | May         | 40   | 0.38 | 969  | 6.66 | 2227 | 15.6  | 3998 | 19.73 | 4831 | 25.44 | 5409 | 28.37 | 5750 | 29.07 | 5778 | 29.64 | 5917 | 27.83 | 5563 | 26.28 | 4832 | 24.83 | 3284 | 23.3  | 2182 | 15.08 | 959  | 6.25 | 41   | 0.4  |
|        | June        | 102  | 0.43 | 1113 | 5.72 | 2609 | 12.22 | 3693 | 19.64 | 4253 | 23.3  | 5098 | 26.26 | 5388 | 27.53 | 5111 | 27.66 | 5600 | 25.75 | 5271 | 24.9  | 4284 | 23.02 | 3693 | 19.3  | 2498 | 13.47 | 1218 | 6.36 | 191  | 0.92 |
|        | July        | 26   | 0.25 | 847  | 5.96 | 2318 | 11.6  | 3474 | 18.49 | 4095 | 22.65 | 4945 | 25.34 | 4972 | 25.79 | 4927 | 26.56 | 4966 | 25.68 | 4682 | 24.43 | 4119 | 22.14 | 3548 | 18.78 | 2392 | 12.62 | 1180 | 6.06 | 166  | 1.03 |
|        | August      | 0    | n/a  | 544  | 3.74 | 2050 | 9.46  | 3173 | 16.6  | 3921 | 21.44 | 4535 | 23.88 | 4829 | 24.9  | 4852 | 25.93 | 4879 | 24.8  | 4574 | 23.73 | 3978 | 21.91 | 3259 | 17.26 | 2174 | 11.04 | 777  | 5.64 | 14   | 0.12 |
|        | September   | 0    | n/a  | 167  | 1.61 | 1590 | 7.25  | 2936 | 14.84 | 3789 | 20.76 | 4706 | 24.58 | 5062 | 26.18 | 4837 | 26.18 | 5040 | 25.99 | 4778 | 23.63 | 3688 | 20.22 | 2995 | 14.58 | 1568 | 7.58  | 191  | 1.87 | 0    | n/a  |
|        | October     | 0    | n/a  | 0    | n/a  | 796  | 5.4   | 2139 | 14.98 | 3049 | 24.03 | 4482 | 23.66 | 4880 | 25.68 | 5044 | 26.05 | 4795 | 25.25 | 3669 | 26.72 | 2757 | 21.24 | 1744 | 12.22 | 413  | 3.5   | 0    | n/a  | 0    | n/a  |
|        | November    | 0    | n/a  | 0    | n/a  | 295  | 2.52  | 1545 | 10.24 | 2527 | 19.41 | 3871 | 20.54 | 4340 | 23.17 | 3702 | 28.77 | 3605 | 25.98 | 3027 | 21.61 | 2077 | 14.82 | 965  | 6.01  | 20   | 0.2   | 0    | n/a  | 0    | n/a  |
|        | December    | 0    | n/a  | 0    | n/a  | 296  | 2.51  | 1537 | 10.32 | 2521 | 19.5  | 3849 | 20.6  | 4353 | 23.21 | 3674 | 28.77 | 3618 | 25.98 | 3025 | 21.66 | 2069 | 14.82 | 966  | 6.08  | 20   | 0.2   | 0    | n/a  | 0    | n/a  |
|        |             |      |      |      |      |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |      |      |      |
|        | Time        | 500  |      | 600  |      | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |       | 1800 |      | 1900 |      |
|        |             | S.M. | C.I. | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
|        | Winter Mean | 0    | n/a  | 5    | 0.3  | 405  | 3.8   | 1602 | 11.0  | 2618 | 20.5  | 3870 | 24.1  | 4363 | 27.3  | 4268 | 30.3  | 4170 | 28.5  | 3635 | 25.8  | 2612 | 19.5  | 1569 | 10.7  | 422  | 3.2   | 26   | 1.5  | 0    | n/a  |
|        | Summer Mean | 28   | 0.35 | 700  | 4.6  | 2119 | 11.5  | 3406 | 18.7  | 4151 | 24.0  | 4905 | 27.0  | 5228 | 28.1  | 5096 | 28.9  | 5290 | 27.5  | 4933 | 26.0  | 4153 | 23.6  | 3321 | 19.2  | 2079 | 12.0  | 803  | 4.9  | 69   | 0.62 |

### iii. Entebbe

|         | Time        | 700  |      | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |         | 1500 |       | 1600 |       | 1700 |       | 1800 |      | 1900 |      |
|---------|-------------|------|------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|---------|------|-------|------|-------|------|-------|------|------|------|------|
|         |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.    | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
| Entebbe | January     | 36   | 0.42 | 1299 | 7.74  | 2808 | 19.72 | 4459 | 29.95 | 4920 | 35.8  | 5372 | 37.83 | 6094 | 34.72 | 6003 | 33.16   | 5633 | 30.08 | 4684 | 25.69 | 3113 | 16.64 | 1428 | 8.25 | 31   | 0.29 |
|         | February    | 0    | n/a  | 1224 | 6.91  | 3129 | 20.49 | 4518 | 29.97 | 4961 | 36    | 5400 | 38.56 | 6179 | 34.92 | 5957 | 33.17   | 5642 | 32.1  | 4493 | 24.85 | 3257 | 17.29 | 1526 | 8.89 | 67   | 0.3  |
|         | March       | 29   | 0.35 | 1376 | 8.08  | 2943 | 19.94 | 4657 | 30.86 | 5545 | 35.23 | 5778 | 38.08 | 5541 | 39.83 | 5995 | 33.4145 | 5638 | 30.27 | 4472 | 24.06 | 3482 | 11.64 | 1434 | 6.71 | 15   | 0.16 |
|         | April       | 149  | 1.01 | 1413 | 9.91  | 2963 | 21.11 | 4102 | 30.14 | 5482 | 36.18 | 5904 | 37.55 | 5465 | 39.66 | 5250 | 38.54   | 5524 | 30.03 | 4234 | 23.67 | 2795 | 14.87 | 1049 | 6.09 | 0    | n/a  |
|         | May         | 199  | 0.94 | 1570 | 9.03  | 2879 | 20.47 | 4617 | 30.71 | 5278 | 35.33 | 5302 | 37.78 | 5292 | 38.72 | 5573 | 33.39   | 5135 | 28.67 | 3973 | 22.27 | 2587 | 13.95 | 973  | 4.49 | 0    | n/a  |
|         | June        | 145  | 0.84 | 1412 | 7.95  | 2823 | 20.19 | 4394 | 29.03 | 4716 | 34.74 | 5091 | 37.17 | 5246 | 38.66 | 4839 | 35.61   | 5075 | 28.89 | 3957 | 22.7  | 2608 | 14.21 | 1087 | 5.91 | 0    | n/a  |
|         | July        | 58   | 0.32 | 1298 | 7.25  | 2641 | 19.67 | 4292 | 29.07 | 4670 | 34.55 | 5067 | 37.05 | 5087 | 37.24 | 4941 | 36.19   | 5188 | 29.97 | 4103 | 24.23 | 2792 | 15.6  | 1206 | 6.8  | 0    | n/a  |
|         | August      | 98   | 0.64 | 1479 | 8.45  | 2936 | 20.63 | 4581 | 30.2  | 5368 | 34.89 | 5295 | 37.74 | 5378 | 38.58 | 5177 | 37.32   | 5217 | 32.32 | 4231 | 26.34 | 2786 | 18.51 | 1116 | 6.31 | 0    | n/a  |
|         | September   | 242  | 1.3  | 1774 | 10.2  | 3247 | 22.64 | 4930 | 32.17 | 5605 | 36.26 | 5462 | 38.6  | 6173 | 34.98 | 5968 | 33.67   | 5446 | 29.5  | 4303 | 24.25 | 2782 | 14.57 | 943  | 5    | 0    | n/a  |
|         | October     | 435  | 2.1  | 2022 | 11.25 | 3467 | 23.28 | 5014 | 32.45 | 5719 | 36.11 | 6016 | 37.63 | 5476 | 38.83 | 5887 | 32.45   | 5315 | 29.49 | 4081 | 21.99 | 2526 | 12.8  | 731  | 3.56 | 0    | n/a  |
|         | November    | 444  | 2.07 | 1984 | 11.4  | 3308 | 23.46 | 4336 | 30.99 | 5647 | 35.87 | 5947 | 37.19 | 5549 | 38.47 | 5805 | 31.66   | 5182 | 28.76 | 3996 | 21.85 | 2458 | 12.15 | 689  | 3.27 | 0    | n/a  |
|         | December    | 253  | 1.69 | 1657 | 10.1  | 3125 | 20.87 | 4731 | 30.84 | 5486 | 35.1  | 5806 | 36.88 | 5818 | 37.1  | 5751 | 32.5    | 5200 | 28.5  | 4085 | 21.35 | 2663 | 13.6  | 930  | 5.29 | 0    | n/a  |
|         |             |      |      |      |       |      |       |      |       |      |       |      |       |      |       |      |         |      |       |      |       |      |       |      |      |      |      |
|         | Time        | 700  |      | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |         | 1500 |       | 1600 |       | 1700 |       | 1800 |      | 1900 |      |
|         |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.    | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
|         | Winter Mean | 200  | 1.33 | 1594 | 9.25  | 3130 | 21.29 | 4619 | 30.84 | 5380 | 35.69 | 5720 | 37.70 | 5776 | 37.31 | 5900 | 32.73   | 5435 | 29.87 | 4302 | 23.30 | 2917 | 14.02 | 1123 | 6.00 | 19   | 0.25 |
|         | Summer Mean | 149  | 0.84 | 1491 | 8.80  | 2915 | 20.79 | 4486 | 30.22 | 5187 | 35.33 | 5354 | 37.65 | 5440 | 37.97 | 5291 | 35.79   | 5264 | 29.90 | 4134 | 23.91 | 2725 | 15.29 | 1062 | 5.77 | 0    | n/a  |

#### iv. Jalalabad

|           | Time        | 500  |      | 600  |        | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      |
|-----------|-------------|------|------|------|--------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|------|------|------|
|           |             | S.M. | C.I. | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
| Jalalabad | January     | 0    | n/a  | 0    | n/a    | 504  | 3.11  | 1716 | 11.67 | 2618 | 20.53 | 3335 | 26.12 | 3651 | 28.59 | 3694 | 28.65 | 3421 | 25.56 | 2749 | 19.78 | 1460 | 10.68 | 447  | 3.47  | 0    | n/a  | 0    | n/a  |
|           | February    | 0    | n/a  | 37   | 0.412  | 957  | 6.98  | 2436 | 17.75 | 3367 | 26.52 | 4038 | 32.01 | 4425 | 33.3  | 4440 | 33.1  | 4132 | 30.55 | 3442 | 25.73 | 2158 | 16.37 | 985  | 6.84  | 66   | 0.64 | 0    | n/a  |
|           | March       | 0    | n/a  | 554  | 4.83   | 1808 | 14.41 | 3253 | 25.1  | 4101 | 31.85 | 4728 | 34.92 | 4873 | 36.27 | 4847 | 35.52 | 4568 | 33.62 | 3946 | 29.53 | 3086 | 21.79 | 1534 | 10.48 | 377  | 2.74 | 0    | n/a  |
|           | April       | 210  | 2.02 | 1474 | 10.23  | 2706 | 20.98 | 4276 | 26.31 | 5240 | 28.82 | 5573 | 32.12 | 5830 | 31.73 | 5623 | 32.9  | 4722 | 34.19 | 4231 | 30.08 | 3298 | 24.49 | 1958 | 13.59 | 757  | 4.63 | 0    | n/a  |
|           | May         | 642  | 3.93 | 1983 | 11.48  | 3302 | 20.45 | 4289 | 26.03 | 5018 | 28.89 | 5251 | 28.93 | 5541 | 31.67 | 5555 | 31.09 | 5284 | 30.36 | 4701 | 28.06 | 3339 | 25.39 | 2476 | 17.26 | 1235 | 7.91 | 137  | 1.32 |
|           | June        | 778  | 3.6  | 1974 | 11.29  | 3136 | 18.28 | 4015 | 23.78 | 4689 | 26.45 | 5026 | 26.85 | 5215 | 28.37 | 5146 | 28.74 | 4943 | 27.19 | 4508 | 25.81 | 3752 | 21.98 | 2817 | 15.44 | 1540 | 8.44 | 334  | 2.24 |
|           | July        | 547  | 3.84 | 1601 | 12.385 | 3133 | 19.45 | 4049 | 25.59 | 4577 | 27.6  | 5039 | 28.8  | 5094 | 29.79 | 5022 | 29.94 | 4915 | 27.56 | 4404 | 26.9  | 3717 | 22.77 | 2818 | 16.08 | 1313 | 9.55 | 320  | 2.27 |
|           | August      | 248  | 1.89 | 1460 | 9.76   | 2582 | 19.6  | 3979 | 24.57 | 4816 | 27.24 | 5283 | 29.01 | 5248 | 29.35 | 5182 | 28.79 | 4971 | 27.27 | 4555 | 26.84 | 3260 | 24.86 | 2420 | 13.45 | 977  | 7.12 | 102  | 0.99 |
|           | September   | 24   | 0.27 | 1016 | 6.87   | 2557 | 15.64 | 3775 | 22.54 | 4333 | 26.36 | 4865 | 26.63 | 5002 | 28.33 | 4933 | 28.38 | 4526 | 25.64 | 3872 | 23.16 | 2908 | 17.77 | 1642 | 9.4   | 345  | 3.36 | 0    | n/a  |
|           | October     | 0    | n/a  | 618  | 4.01   | 2150 | 10.8  | 3409 | 18.52 | 4363 | 23.51 | 4879 | 25.95 | 5043 | 26.19 | 5015 | 25.63 | 4228 | 22.27 | 3368 | 17.7  | 2166 | 11.39 | 706  | 5.35  | 0    | n/a  | 0    | n/a  |
|           | November    | 0    | n/a  | 139  | 1.35   | 1260 | 8.42  | 2457 | 17.05 | 3305 | 23.67 | 4584 | 22.24 | 3786 | 29.38 | 3603 | 28.17 | 3690 | 19.85 | 2397 | 17.02 | 1333 | 8.73  | 183  | 1.58  | 0    | n/a  | 0    | n/a  |
|           | December    | 0    | n/a  | 0    | n/a    | 621  | 4.13  | 1730 | 11.93 | 3231 | 15.28 | 3119 | 24.32 | 3964 | 21.48 | 3820 | 20.43 | 2734 | 21.19 | 2049 | 14.42 | 1096 | 6.79  | 107  | 0.89  | 0    | n/a  | 0    | n/a  |
|           |             |      |      |      |        |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |       |      |      |      |      |
|           | Time        | 500  |      | 600  |        | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      |
|           |             | S.M. | C.I. | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
|           | Winter Mean | 0    | n/a  | 225  | 2.65   | 1217 | 7.98  | 2500 | 17.00 | 3498 | 23.56 | 4114 | 27.59 | 4290 | 29.20 | 4237 | 28.58 | 3796 | 25.51 | 2992 | 20.70 | 1883 | 12.63 | 660  | 4.77  | 74   | 1.69 | 0    | n/a  |
|           | Summer Mean | 408  | 2.59 | 1585 | 10.34  | 2903 | 19.07 | 4064 | 24.80 | 4779 | 27.56 | 5173 | 28.72 | 5322 | 29.87 | 5244 | 29.97 | 4894 | 28.70 | 4379 | 26.81 | 3379 | 22.88 | 2355 | 14.20 | 1028 | 6.84 | 149  | 1.71 |

## v. Ndjili

|        | Time        | 600  |      | 700  |       | 800  |       | 900  |        | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      |
|--------|-------------|------|------|------|-------|------|-------|------|--------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|-------|------|------|------|------|
|        |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
| Ndjili | January     | 30   | 0.35 | 1247 | 6.95  | 2587 | 17.9  | 3797 | 25.674 | 4727 | 31.86 | 4984 | 33.32 | 5137 | 34.54 | 5947 | 36.41 | 5546 | 34.37 | 4736 | 30.18 | 3390 | 22.27 | 1568 | 9.3  | 240  | 1.26 |
|        | February    | 0    | n/a  | 1124 | 5.6   | 2687 | 15.62 | 3734 | 25.26  | 4797 | 32.8  | 5121 | 34.56 | 5435 | 35.89 | 5898 | 36.46 | 5618 | 34.24 | 5600 | 34.86 | 3465 | 22.78 | 1665 | 9.62 | 267  | 1.21 |
|        | March       | 0    | n/a  | 1157 | 6.1   | 2554 | 17.78 | 3977 | 24.96  | 5423 | 33.97 | 5898 | 36    | 6116 | 36.43 | 5931 | 35.86 | 5462 | 33.99 | 5034 | 23.29 | 3180 | 20.59 | 1474 | 8.61 | 137  | 1.19 |
|        | April       | 0    | n/a  | 1183 | 6     | 2473 | 16.73 | 3791 | 16.91  | 5257 | 33.37 | 5697 | 35.08 | 5841 | 35.72 | 5257 | 36.43 | 5526 | 27.53 | 4512 | 23.39 | 3132 | 14.56 | 1164 | 6.55 | 5    | 0.04 |
|        | May         | 0    | n/a  | 1161 | 6.66  | 2485 | 17.24 | 3575 | 24.97  | 4498 | 31.06 | 4816 | 33.16 | 5627 | 34.57 | 5414 | 33.67 | 4936 | 31.18 | 3570 | 25.9  | 2531 | 16.66 | 1014 | 5.44 | 0    | n/a  |
|        | June        | 0    | n/a  | 988  | 5.98  | 2307 | 16.21 | 3409 | 23.88  | 4147 | 29    | 4699 | 31.88 | 4708 | 33.22 | 5177 | 33.1  | 4677 | 30.25 | 3470 | 26.85 | 2349 | 16.96 | 987  | 6.42 | 0    | n/a  |
|        | July        | 0    | n/a  | 871  | 5.85  | 2331 | 16.6  | 3534 | 25.81  | 4377 | 31.31 | 4812 | 33.87 | 5476 | 35.26 | 5349 | 34.24 | 4459 | 33.94 | 3682 | 28.34 | 2456 | 18.83 | 1091 | 7.8  | 0    | n/a  |
|        | August      | 0    | n/a  | 1069 | 7.19  | 2666 | 19.12 | 3915 | 28.14  | 5249 | 33.45 | 5623 | 35.47 | 5717 | 35.93 | 5007 | 37.73 | 4597 | 34.62 | 3817 | 29.51 | 2583 | 20.23 | 1240 | 7.96 | 0    | n/a  |
|        | September   | 115  | 1.12 | 1463 | 9.34  | 2988 | 20.78 | 4148 | 29.29  | 4866 | 33.99 | 5437 | 37.03 | 5847 | 36.48 | 5622 | 35.39 | 5109 | 32.84 | 3901 | 28.63 | 2640 | 18.98 | 1198 | 7.15 | 0    | n/a  |
|        | October     | 300  | 1.63 | 1760 | 10.01 | 3091 | 21.16 | 4477 | 26.79  | 4847 | 32.85 | 5670 | 35.74 | 5409 | 36.2  | 5807 | 35.61 | 5132 | 32.84 | 4232 | 27.42 | 2951 | 13.41 | 936  | 4.79 | 0    | n/a  |
|        | November    | 369  | 1.8  | 1739 | 9.68  | 3246 | 17.77 | 4145 | 27.77  | 4936 | 33.14 | 5251 | 35.13 | 5896 | 36.66 | 5328 | 34.14 | 4995 | 30.85 | 4344 | 21.92 | 2568 | 15.56 | 934  | 4.4  | 0    | n/a  |
|        | December    | 198  | 1.37 | 1513 | 8.48  | 2929 | 15.38 | 3848 | 26.33  | 4767 | 32.05 | 5116 | 34.16 | 5262 | 35.01 | 5794 | 35.44 | 5318 | 33.44 | 4413 | 28.27 | 3008 | 19.11 | 1274 | 7.07 | 53   | 0.57 |
|        | Time        | 600  |      | 700  |       | 800  |       | 900  |        | 1000 |       | 1100 |       | 1200 |       | 1300 |       | 1400 |       | 1500 |       | 1600 |       | 1700 |      | 1800 |      |
|        |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
|        | Winter Mean | 150  | 1.29 | 1423 | 7.80  | 2849 | 17.60 | 3996 | 26.13  | 4916 | 32.78 | 5340 | 34.82 | 5543 | 35.79 | 5784 | 35.65 | 5345 | 33.29 | 4727 | 27.66 | 3094 | 18.95 | 1309 | 7.30 | 116  | 1.06 |
|        | Summer Mean | 19   | 1.12 | 1123 | 6.84  | 2542 | 17.78 | 3729 | 24.83  | 4732 | 32.03 | 5181 | 34.42 | 5536 | 35.20 | 5304 | 35.09 | 4884 | 31.73 | 3825 | 27.10 | 2615 | 17.70 | 1116 | 6.89 | 1    | 0.04 |

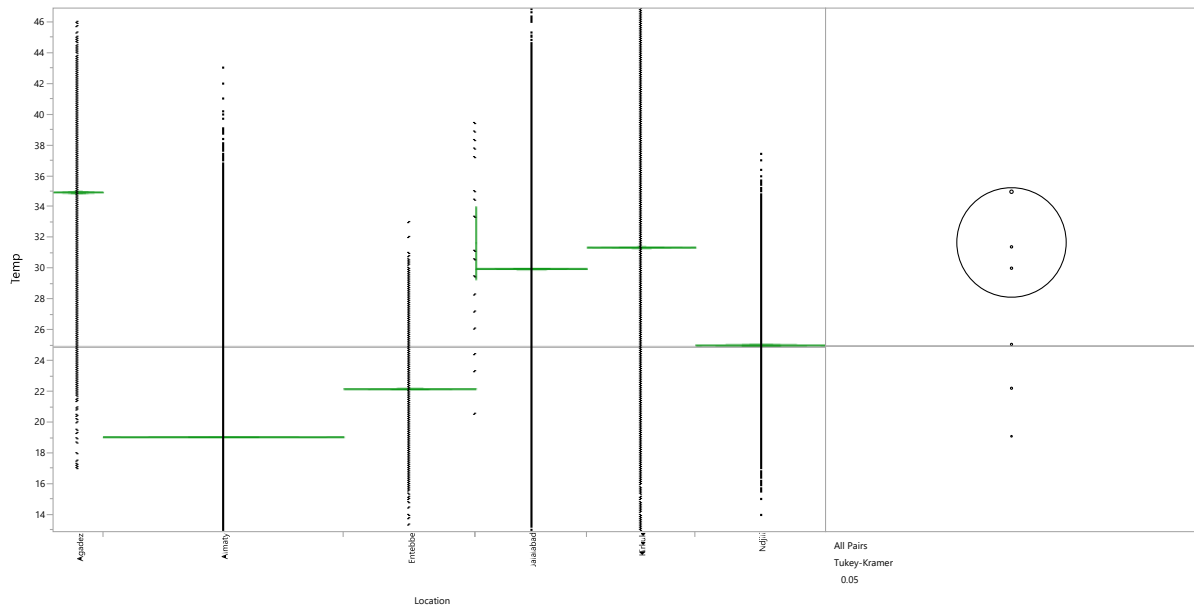
## vi. Almaty

|        | Time        | 600  |      | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |        | 1300 |        | 1400 |       | 1500 |       | 1600 |       | 1700 |       | 1800 |       | 1900 |      | 2000 |      |
|--------|-------------|------|------|------|-------|------|-------|------|-------|------|-------|------|-------|------|--------|------|--------|------|-------|------|-------|------|-------|------|-------|------|-------|------|------|------|------|
|        |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.   | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
| Almaty | January     | 0    | n/a  | 0    | n/a   | 0    | n/a   | 519  | 3.79  | 1320 | 9.39  | 2138 | 16.27 | 2721 | 20.93  | 3275 | 23.97  | 3125 | 22.51 | 2182 | 16.55 | 1426 | 10.55 | 556  | 4.27  | 0    | n/a   | 0    | n/a  | 0    | n/a  |
|        | February    | 0    | n/a  | 0    | n/a   | 123  | 1.38  | 1174 | 9.04  | 2111 | 16.13 | 2984 | 24.03 | 3583 | 28.47  | 4290 | 31.39  | 4099 | 30.22 | 3118 | 24.17 | 2688 | 19.34 | 1260 | 9.35  | 306  | 2.99  | 0    | n/a  | 0    | n/a  |
|        | March       | 0    | n/a  | 95   | 0.68  | 942  | 7.74  | 2126 | 16.66 | 3161 | 26.09 | 4288 | 32.7  | 4450 | 34.17  | 4755 | 36.99  | 4667 | 35.25 | 3883 | 29.18 | 3510 | 25.78 | 2004 | 15.38 | 857  | 6.7   | 59   | 0.69 | 0    | n/a  |
|        | April       | 30   | 0.4  | 719  | 5.68  | 1799 | 14.84 | 2963 | 23.9  | 4067 | 32.07 | 4587 | 35.86 | 5330 | 38.29  | 5007 | 38.06  | 5014 | 37.67 | 4344 | 33.05 | 3912 | 28.53 | 2610 | 20.56 | 1450 | 10.52 | 334  | 2.58 | 0    | n/a  |
|        | May         | 325  | 2.59 | 1492 | 10.13 | 2534 | 19.66 | 3846 | 26.91 | 4279 | 32.96 | 4851 | 35.59 | 5456 | 37.16  | 5136 | 37.17  | 5015 | 36.12 | 5178 | 34    | 4403 | 30.01 | 3420 | 23.53 | 1922 | 13.27 | 891  | 6.01 | 108  | 1.06 |
|        | June        | 1172 | 7.17 | 1592 | 10.21 | 2824 | 19.33 | 3647 | 26.6  | 4309 | 31.61 | 5386 | 31.5  | 5036 | 36.56  | 5719 | 33.01  | 4947 | 36.07 | 4769 | 33.85 | 4432 | 29.82 | 3600 | 24.14 | 2183 | 14.56 | 1153 | 7.17 | 269  | 1.79 |
|        | July        | 816  | 4.39 | 1455 | 9.34  | 2695 | 18.41 | 3489 | 25.89 | 4160 | 32.13 | 4660 | 34.12 | 4896 | 35.29  | 4980 | 35.818 | 4844 | 34.59 | 4728 | 32.31 | 4368 | 28.99 | 3484 | 23.68 | 2157 | 15.18 | 898  | 4.1  | 237  | 1.49 |
|        | August      | 82   | 0.79 | 851  | 5.92  | 2072 | 15.68 | 3091 | 24.05 | 4375 | 27.48 | 5027 | 29.82 | 5478 | 31.54  | 5463 | 31.13  | 5341 | 30.4  | 4381 | 32.48 | 3784 | 28.27 | 3100 | 21.81 | 1753 | 12.77 | 669  | 4.54 | 34   | 0.44 |
|        | September   | 0    | n/a  | 365  | 3.02  | 1598 | 11.16 | 2653 | 20.75 | 3507 | 27.49 | 4533 | 31.37 | 4454 | 34.156 | 5063 | 30.92  | 4272 | 32.88 | 4087 | 30.48 | 3272 | 24.89 | 2013 | 15.8  | 975  | 7.82  | 152  | 1.46 | 0    | n/a  |
|        | October     | 0    | n/a  | 43   | 0.41  | 771  | 5.91  | 1770 | 15.01 | 3013 | 23.76 | 3608 | 28.39 | 4258 | 32.61  | 3977 | 31.39  | 3830 | 30.15 | 2909 | 23.68 | 2046 | 16.64 | 1049 | 8.17  | 234  | 2.28  | 0    | n/a  | 0    | n/a  |
|        | November    | 0    | n/a  | 0    | n/a   | 210  | 2.02  | 1030 | 8.01  | 1863 | 14.99 | 2577 | 20.48 | 2950 | 23.61  | 2954 | 24.2   | 2652 | 21.25 | 1989 | 15.58 | 1184 | 8.78  | 343  | 2.86  | 0    | n/a   | 0    | n/a  | 0    | n/a  |
|        | December    | 0    | n/a  | 0    | n/a   | 0    | n/a   | 510  | 3.84  | 1241 | 8.68  | 1966 | 14.35 | 2385 | 18.37  | 2775 | 19.1   | 2495 | 16.66 | 1640 | 11.9  | 906  | 6.02  | 158  | 1.1   | 0    | n/a   | 0    | n/a  | 0    | n/a  |
|        |             |      |      |      |       |      |       |      |       |      |       |      |       |      |        |      |        |      |       |      |       |      |       |      |       |      |       |      |      |      |      |
|        | Time        | 600  |      | 700  |       | 800  |       | 900  |       | 1000 |       | 1100 |       | 1200 |        | 1300 |        | 1400 |       | 1500 |       | 1600 |       | 1700 |       | 1800 |       | 1900 |      | 2000 |      |
|        |             | S.M. | C.I. | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.   | S.M. | C.I.   | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I.  | S.M. | C.I. | S.M. | C.I. |
|        | Winter Mean | 0    | n/a  | 23   | 0.55  | 341  | 4.26  | 1188 | 9.39  | 2118 | 16.51 | 2927 | 22.70 | 3391 | 26.36  | 3671 | 27.84  | 3478 | 26.01 | 2620 | 20.18 | 1960 | 14.52 | 895  | 6.86  | 233  | 3.99  | 10   | 0.69 | 0    | n/a  |
|        | Summer Mean | 404  | 3.07 | 1079 | 7.38  | 2254 | 16.51 | 3282 | 24.68 | 4116 | 30.62 | 4841 | 33.04 | 5108 | 35.50  | 5228 | 34.35  | 4906 | 34.62 | 4581 | 32.70 | 4029 | 28.42 | 3038 | 21.59 | 1740 | 12.35 | 683  | 4.31 | 108  | 1.20 |

## Appendix C

### i. Temperature Comparison (Agadez, Almaty, Entebbe, Jalalabad, Kirkuk, & Ndjili)

#### Oneway Analysis of Temp By Location



#### Oneway Anova Summary of Fit

|                            |          |
|----------------------------|----------|
| Rsquare                    | 0.444422 |
| Adj Rsquare                | 0.444413 |
| Root Mean Square Error     | 5.910346 |
| Mean of Response           | 24.93862 |
| Observations (or Sum Wgts) | 385128   |

#### Analysis of Variance

| Source   | DF     | Sum of Squares | Mean Square | F Ratio  | Prob > F |
|----------|--------|----------------|-------------|----------|----------|
| Location | 6      | 10761515       | 1793586     | 51344.78 | <.0001*  |
| Error    | 385121 | 13453122       | 35          |          |          |
| C. Total | 385127 | 24214637       |             |          |          |

#### Means for Oneway Anova

| Level     | Number | Mean    | Std Error | Lower 95% | Upper 95% |
|-----------|--------|---------|-----------|-----------|-----------|
| Agadez    | 24761  | 34.9588 | 0.0376    | 34.885    | 35.032    |
| Almaty    | 119985 | 19.0779 | 0.0171    | 19.044    | 19.111    |
| Entebbe   | 65785  | 22.1975 | 0.0230    | 22.152    | 22.243    |
| Holloman  | 24     | 31.6650 | 1.2064    | 29.300    | 34.030    |
| Jalalabad | 55372  | 29.9929 | 0.0251    | 29.944    | 30.042    |
| Kirkuk    | 54080  | 31.3796 | 0.0254    | 31.330    | 31.429    |
| Ndjili    | 65121  | 25.0470 | 0.0232    | 25.002    | 25.092    |

Std Error uses a pooled estimate of error variance

## Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

### Confidence Quantile

| q*      | Alpha |
|---------|-------|
| 2.94834 | 0.05  |

### HSD Threshold Matrix

Abs(Dif)-HSD

|           | Agadez | Holloman | Kirkuk | Jalalabad | Ndjili | Entebbe | Almaty |
|-----------|--------|----------|--------|-----------|--------|---------|--------|
| Agadez    | -0.157 | -0.265   | 3.446  | 4.833     | 9.782  | 12.631  | 15.759 |
| Holloman  | -0.265 | -5.030   | -3.272 | -1.886    | 3.060  | 5.910   | 9.030  |
| Kirkuk    | 3.446  | -3.272   | -0.106 | 1.281     | 6.231  | 9.081   | 12.211 |
| Jalalabad | 4.833  | -1.886   | 1.281  | -0.105    | 4.845  | 7.695   | 10.825 |
| Ndjili    | 9.782  | 3.060    | 6.231  | 4.845     | -0.097 | 2.753   | 5.884  |
| Entebbe   | 12.631 | 5.910    | 9.081  | 7.695     | 2.753  | -0.096  | 3.035  |
| Almaty    | 15.759 | 9.030    | 12.211 | 10.825    | 5.884  | 3.035   | -0.071 |

Positive values show pairs of means that are significantly different.

### Connecting Letters Report

| Level     | Mean            |
|-----------|-----------------|
| Agadez    | A 34.958847     |
| Holloman  | A B C 31.665000 |
| Kirkuk    | B 31.379553     |
| Jalalabad | C 29.992854     |
| Ndjili    | D 25.047012     |
| Entebbe   | E 22.197513     |
| Almaty    | F 19.077924     |

Levels not connected by same letter are significantly different.

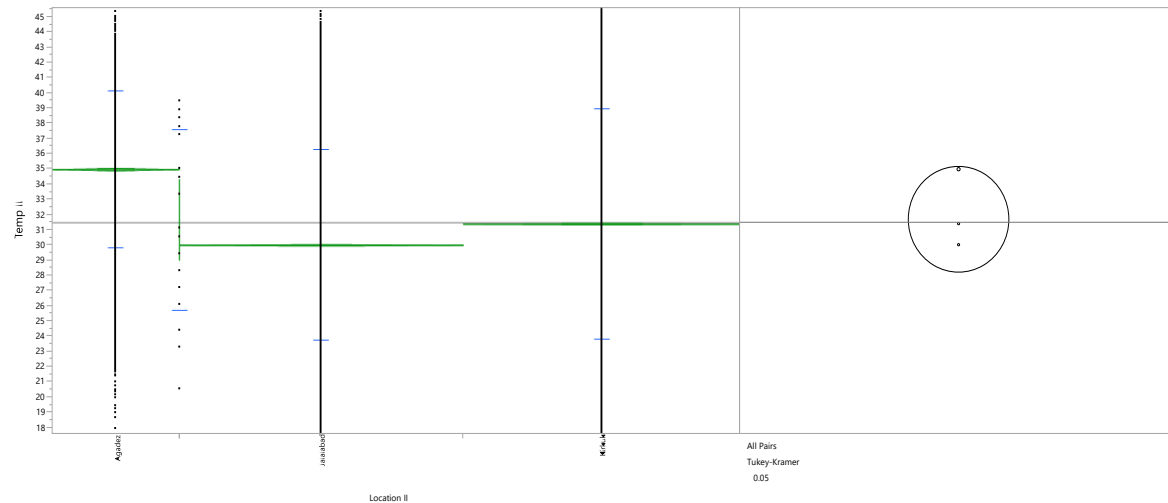
### Ordered Differences Report

| Level     | - Level   | Difference | Std Err Dif | Lower CL | Upper CL | p-Value |
|-----------|-----------|------------|-------------|----------|----------|---------|
| Agadez    | Almaty    | 15.88092   | 0.041254    | 15.7593  | 16.00255 | <.0001* |
| Agadez    | Entebbe   | 12.76133   | 0.044066    | 12.6314  | 12.89125 | <.0001* |
| Holloman  | Almaty    | 12.58708   | 1.206565    | 9.0297   | 16.14444 | <.0001* |
| Kirkuk    | Almaty    | 12.30163   | 0.030612    | 12.2114  | 12.39188 | <.0001* |
| Jalalabad | Almaty    | 10.91493   | 0.030364    | 10.8254  | 11.00445 | <.0001* |
| Agadez    | Ndjili    | 9.91183    | 0.044127    | 9.7817   | 10.04194 | <.0001* |
| Holloman  | Entebbe   | 9.46749    | 1.206664    | 5.9098   | 13.02514 | <.0001* |
| Kirkuk    | Entebbe   | 9.18204    | 0.034307    | 9.0809   | 9.28319  | <.0001* |
| Jalalabad | Entebbe   | 7.79534    | 0.034086    | 7.6948   | 7.89584  | <.0001* |
| Holloman  | Ndjili    | 6.61799    | 1.206667    | 3.0603   | 10.17565 | <.0001* |
| Kirkuk    | Ndjili    | 6.33254    | 0.034385    | 6.2312   | 6.43392  | <.0001* |
| Ndjili    | Almaty    | 5.96909    | 0.028767    | 5.8843   | 6.05390  | <.0001* |
| Agadez    | Jalalabad | 4.96599    | 0.045184    | 4.8328   | 5.09921  | <.0001* |
| Jalalabad | Ndjili    | 4.94584    | 0.034166    | 4.8451   | 5.04657  | <.0001* |
| Agadez    | Kirkuk    | 3.57929    | 0.045351    | 3.4456   | 3.71300  | <.0001* |
| Agadez    | Holloman  | 3.29385    | 1.207029    | -0.2649  | 6.85257  | 0.0911  |
| Entebbe   | Almaty    | 3.11959    | 0.028673    | 3.0351   | 3.20413  | <.0001* |

| Level    | - Level   | Difference | Std Err Dif | Lower CL | Upper CL | p-Value |  |
|----------|-----------|------------|-------------|----------|----------|---------|--|
| Ndjili   | Entebbe   | 2.84950    | 0.032671    | 2.7532   | 2.94583  | <.0001* |  |
| Holloman | Jalalabad | 1.67215    | 1.206706    | -1.8856  | 5.22992  | 0.8097  |  |
| Kirkuk   | Jalalabad | 1.38670    | 0.035732    | 1.2813   | 1.49205  | <.0001* |  |
| Holloman | Kirkuk    | 0.28545    | 1.206712    | -3.2723  | 3.84324  | 1.0000  |  |

## ii. Temperature Comparison (Agadez, Jalalabad, & Kirkuk)

### Oneway Analysis of Temp II By Location II



Missing Rows 250891

### Oneway Anova

#### Summary of Fit

|                            |          |
|----------------------------|----------|
| Rsquare                    | 0.066834 |
| Adj Rsquare                | 0.066813 |
| Root Mean Square Error     | 6.630483 |
| Mean of Response           | 31.46783 |
| Observations (or Sum Wgts) | 134237   |

### Analysis of Variance

| Source      | DF     | Sum of Squares | Mean Square | F Ratio  | Prob > F |
|-------------|--------|----------------|-------------|----------|----------|
| Location II | 3      | 422654.4       | 140885      | 3204.600 | <.0001*  |
| Error       | 134233 | 5901326.3      | 44          |          |          |
| C. Total    | 134236 | 6323980.7      |             |          |          |

### Means for Oneway Anova

| Level     | Number | Mean    | Std Error | Lower 95% | Upper 95% |
|-----------|--------|---------|-----------|-----------|-----------|
| Agadez    | 24761  | 34.9588 | 0.0421    | 34.876    | 35.041    |
| Holloman  | 24     | 31.6650 | 1.3534    | 29.012    | 34.318    |
| Jalalabad | 55372  | 29.9929 | 0.0282    | 29.938    | 30.048    |
| Kirkuk    | 54080  | 31.3796 | 0.0285    | 31.324    | 31.435    |

Std Error uses a pooled estimate of error variance

## Means Comparisons

Comparisons for all pairs using Tukey-Kramer HSD

Confidence Quantile

| q*      | Alpha |
|---------|-------|
| 2.56906 | 0.05  |

## HSD Threshold Matrix

Abs(Dif)-HSD

|           | Agadez  | Holloman | Kirkuk  | Jalalabad |
|-----------|---------|----------|---------|-----------|
| Agadez    | -0.1531 | -0.1849  | 3.4486  | 4.8358    |
| Holloman  | -0.1849 | -4.9173  | -3.1924 | -1.8057   |
| Kirkuk    | 3.4486  | -3.1924  | -0.1036 | 1.2837    |
| Jalalabad | 4.8358  | -1.8057  | 1.2837  | -0.1024   |

Positive values show pairs of means that are significantly different.

## Connecting Letters Report

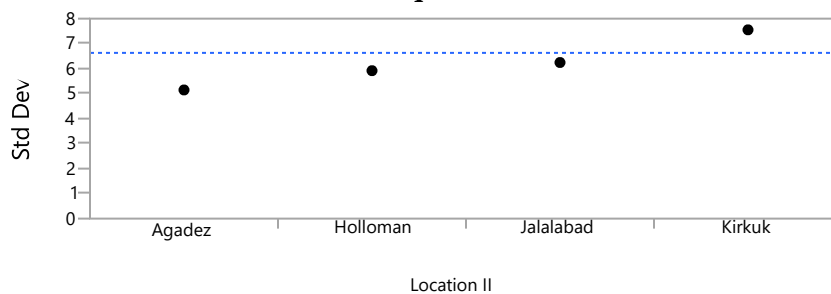
| Level          | Mean      |
|----------------|-----------|
| Agadez A       | 34.958847 |
| Holloman A B C | 31.665000 |
| Kirkuk B       | 31.379553 |
| Jalalabad C    | 29.992854 |

Levels not connected by same letter are significantly different.

## Ordered Differences Report

| Level   | - Level   | Difference | Std Err  | Lower CL | Upper CL | p-Value |
|---------|-----------|------------|----------|----------|----------|---------|
| Dif     |           |            |          |          |          |         |
| Agadez  | Jalalabad | 4.965993   | 0.050690 | 4.83577  | 5.096218 | <.0001* |
| Agadez  | Kirkuk    | 3.579294   | 0.050877 | 3.44859  | 3.710000 | <.0001* |
| Agadez  | Holloman  | 3.293847   | 1.354097 | -0.18492 | 6.772610 | 0.0711  |
| Holloma | Jalalabad | 1.672146   | 1.353735 | -1.80569 | 5.149978 | 0.6044  |
| Kirkuk  | Jalalabad | 1.386699   | 0.040086 | 1.28372  | 1.489682 | <.0001* |
| Holloma | Kirkuk    | 0.285447   | 1.353742 | -3.19240 | 3.763298 | 0.9967  |

## Tests that the Variances are Equal



| Level     | Count | Std Dev  | MeanAbsDif to Mean | MeanAbsDif to Median |
|-----------|-------|----------|--------------------|----------------------|
| Agadez    | 24761 | 5.147168 | 4.380500           | 4.349857             |
| Holloman  | 24    | 5.918366 | 5.185417           | 5.139167             |
| Jalalabad | 55372 | 6.245266 | 5.012104           | 5.010722             |
| Kirkuk    | 54080 | 7.552759 | 6.117505           | 6.106150             |

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## **Vita**

Captain Anthony D. Williams graduated from North Carolina Agricultural and Technical State University with a Bachelor of Science degree in Architectural Engineering. He was commissioned through the Air force Reserve Officers' Training Corps Detachment 605. His first assignment was at Davis-Monthan Air Force Base, Arizona, where he held the positions of Asset Optimization Chief, Asset Management Support Deputy, Project Manager, Portfolio Optimization Officer in Charge, and Operations Deputy for the 355th Civil Engineer Squadron. In January 2015, he deployed to Ali Al Salem Air Base, Kuwait for six months as the Operations Commander for the 386th Civil Engineer Squadron. In August 2015, he entered the Graduate School of Engineering and Management, Air Force Institute of Technology, where he earned a Master of Science degree in Engineering Management. Upon graduation, he will be assigned to the 820th RED HORSE Squadron, Nellis Air Force Base, Nevada.

| REPORT DOCUMENTATION PAGE                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  |                                   |                                      | Form Approved<br>OMB No. 0704-0188                                   |                                                                                                  |
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| 1. REPORT DATE (DD-MM-YYYY)<br>23-03-2017                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                             |                  | 2. REPORT TYPE<br>Master's Thesis |                                      | 3. DATES COVERED (From - To)<br>August 2015 – March 2017             |                                                                                                  |
| 4. TITLE AND SUBTITLE<br><br>Predicting Solar Performance in a Contingency Environment to Meet Net-Zero Facility Power                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                |                  |                                   |                                      | 5a. CONTRACT NUMBER                                                  |                                                                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   |                                      | 5b. GRANT NUMBER                                                     |                                                                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   |                                      | 5c. PROGRAM ELEMENT NUMBER                                           |                                                                                                  |
| 6. AUTHOR(S)<br><br>Williams, Anthony D., Captain, USAF                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                               |                  |                                   |                                      | 5d. PROJECT NUMBER                                                   |                                                                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   |                                      | 5e. TASK NUMBER                                                      |                                                                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   |                                      | 5f. WORK UNIT NUMBER                                                 |                                                                                                  |
| 7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)<br>Air Force Institute of Technology<br>Graduate School of Engineering and Management (AFIT/EN)<br>2950 Hobson Way<br>WPAFB, OH 45433-7765                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |                                   |                                      | 8. PERFORMING ORGANIZATION REPORT NUMBER<br><br>AFIT-ENV-MS-17-M-237 |                                                                                                  |
| 9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)<br>Air Force Civil Engineer Center<br>Attn: Mr. Rodney A. Fisher<br>139 Barnes Dr., Suite 1 Tyndall AFB, FL 32403-5319<br>DSN: 523-6701; COMM: (850) 283-6701 (rodney.fisher.1@us.af.mil)                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                   |                  |                                   |                                      | 10. SPONSOR/MONITOR'S ACRONYM(S)<br><br>AFCEC/CXX                    |                                                                                                  |
|                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   |                                      | 11. SPONSOR/MONITOR'S REPORT NUMBER(S)                               |                                                                                                  |
| 12. DISTRIBUTION / AVAILABILITY STATEMENT<br>DISTRIBUTION STATEMENT A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION UNLIMITED                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                            |                  |                                   |                                      |                                                                      |                                                                                                  |
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| 14. ABSTRACT<br>The U.S. government is involved in contingency operations all over the world and these operations require operational support and sustainment in these locations; this includes the reliable delivery of power to base infrastructure. The traditional means of delivering this support requirement in austere environments has been the use of diesel-power generation that has an extensive logistical and economic tail. The research sought out contingency solar applications that may be implemented and operated to offset the facility demand loads in the location to achieve net-zero power. This research explores the technical feasibility of a deployable photovoltaic microgrid to deliver power to a contingency location. The research evaluates the system's potential power performance in six locations throughout the U.S. Central Command (CENTCOM) and U.S. Africa Command (AFRICOM) using probabilistic simulation modeling techniques. The results showed that there is a potential for photovoltaic microgrids to drastically reduce the demand of contingency shelter systems. The research established recommendations for extensive field testing based on the feasibility of said systems to drastically reduce the demand of shelter systems in contingency locations. |                  |                                   |                                      |                                                                      |                                                                                                  |
| 15. SUBJECT TERMS<br>Photovoltaic microgrid, contingency, net-zero, Air Force                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                         |                  |                                   |                                      |                                                                      |                                                                                                  |
| 16. SECURITY CLASSIFICATION OF:                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                       |                  |                                   | 17. LIMITATION OF ABSTRACT<br><br>UU | 18. NUMBER OF PAGES<br><br>138                                       | 19a. NAME OF RESPONSIBLE PERSON<br>Stoppel, Christopher M., Lt Col, PhD, USAF                    |
| a. REPORT<br>U                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                                        | b. ABSTRACT<br>U | c. THIS PAGE<br>U                 |                                      |                                                                      | 19b. TELEPHONE NUMBER (include area code)<br>(937) 255-3636 x4645 (Christopher.Stoppel@afit.edu) |

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