BASIC DESIGN AND COST OPTIMIZATION OF A HYBRID POWER SYSTEM IN RURAL COMMUNITIES IN AFGHANISTAN

by

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Abstract

In Afghanistan, electricity is mostly generated by hydroelectric, diesel and natural gas generators. A significant amount of electricity also is imported from neighboring countries. Accessibility of electricity is mostly limited to the capital and main towns. The government of Afghanistan and other development organizations, such as The United States Agency for International Development (USAID) and Deutsche Gesellschaft für Internationale Zusammenarbeit (German Agency for International Cooperation "GIZ"), are striving to develop accessibility of electricity to remote communities by supporting the local population of people to enhance living conditions. Although some of these remote communities are served by local diesel fuel generators for just a couple of hours during the night, still most communities do not have access to electricity and they are using wood and kerosene as major sources of energy in cooking, heating and lighting. For those remote communities who are served by local diesel fuel generators, the cost of electricity is much higher than from the national grid. On the other hand, grid extensions are too expensive and, in some cases, impossible for such communities because of the geographical features of Afghanistan. Afghanistan is a mountainous country which receives a significant amount of snow during the winter and once it melts the water runs into rivers, lakes and streams. Therefore mostly it does not face any shortage of running water during the year. Also Afghanistan has plentiful wind and solar energy. Therefore, small hydro-power, wind turbine and solar energy are attractive renewable energy sources for remote communities. The development of such a hybrid power system is a complex process and technical expertise is essential in design and construction phases. The main challenges are the high cost of civil works and equipment, technical expertise for design and construction and encouragement of local people for the support of the project. This report will give an insight into design, cost-effectiveness and feasibility of the system using HOMER in order to encourage private investors and local community people to take advantage of this potential available in Afghanistan and be convinced of the sustainability for investments in micro-hydropower, wind and solar.

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I would like to express my special appreciation to my advisor, Professor Dr. Anil Pahwa for his support and kindness in assisting me in the completion of my project. I would like also to recognize my committee members, Professor Dr. Noel Schulz and Associate Professor Dr. Ruth Douglas Miller, for their assistance and guidance.

This project is designed to be implemented in Band-I-Amir district in Bamiyan, Afghanistan. Unfortunately, there are no reliable data of river and stream flow in Afghanistan; therefore I tried to find reasonably adequate data from reliable internet resources. After extensive research I finally found acceptable and practical wind, solar and flow of rivers data from National Renewable Energy Laboratory (NERL) and Afghan Energy Information Center (AEIC). Meanwhile, I contacted some friends in Afghanistan in order to find accurate data from reliable government sources, but they did not find much information. Therefore, I would like also to express my gratitude to Mustafa Amiryar and Abdul-Raouf Faqiree in searching for and providing data from Afghanistan.

DEDICATION

Dedicated to my Parents

CHAPTER I

Introduction

Energy is essential for society and economic growth of any country. Nowadays, it is really difficult to imagine life without electric energy. Electricity runs everything in our everyday life, for example lights, appliances, and cooling and heating for homes and businesses. As long as electricity is available, no one thinks much about it. The minute an outage happens in the power system, the importance of electricity is realized. However, still lots of people around the world do not have access to reliable electric energy.

Access to electricity in Afghanistan is very limited and only found in urban areas. More than 80% of Afghanistan's population does not have access to electricity [1]. However, to those who have access to electricity, electricity is served sporadically. For instance, electricity may be offered four to six hours per day or every other day. Electricity in Afghanistan is primarily used for lighting, communication and entertainment, such as TV and radio.

Afghanistan is becoming industrialized and, as the economy is growing, there is an increase in demand for electricity. Therefore, it is a significant challenge for the government to respond to the increasing demand and also provide accessibility to electricity to the rest of population who do not have access to electricity. Meanwhile, the government of Afghanistan is striving to decrease the imports of electric energy from neighboring countries and increase its own generation.

Although Afghanistan is becoming more urbanized, more than half of the population is living in rural communities. The primary source of energy in rural communities is diesel, kerosene and wood. Most of them do not have access to electricity. Extending the power grid connection is very expensive and the government does not have funds to invest in extending the power grid.

Afghanistan is rich in renewable energy resources such as hydro, wind and solar. Therefore, these resources provide great hope to urban, and particularly rural communities. In this report, a small hybrid power system with different sources such as micro-hydropower, photovoltaic, wind turbine, diesel generator and battery storage will be designed and optimized for cost effectiveness by using HOMER [6].

1.1 Overview of Current Energy Production & Power System in Afghanistan

1.1.1 Generation

Afghanistan is a developing nation with minimum generation of electricity energy. Historically, hydropower has been the most promising resource of generation in Afghanistan. In 2011 hydropower was 95% of the total energy generation inside of the country. The second leading resource comes from thermal sources, such as diesel and natural gas. Also, a significant amount of energy was imported from the neighboring countries. Although Afghanistan's energy production increased by 19% in 2011 from the previous year, the overall energy production is one of the lowest in the world and most of the Afghan people are not connected to the grid [1].

In 2011 Afghanistan had energy production of about 3,086 GWH, of which 27.5% was generated inside the country and 72.8% imported from the neighboring countries [1]. Energy generation from hydro and thermal in 2011 was 26% and 1.3% of total energy consumption in the country, which was 9 % and 2.6% less than 2010 respectively. The total energy imported from the neighboring countries was 60.9% in 2010 and this amount increased by 12% in 2011. The population of Afghanistan at the end of 2011 was estimated to be about 25 million [1]. According to these data, the electric power energy consumption per capita would be 117.2 kWh/year. This is notably small compared to the other developing countries. Therefore, it could be estimated that more than 80% of the population of Afghanistan do not have access to electricity.

Power generation facilities in the country have suffered from war damage, poor design quality, aging, poor management, and lack of sophisticated control systems and upgrades. Several factors contribute to the problems, such as lack of funds for regular maintenance and upgrades, and inadequate technical and management capacity. Moreover, private sectors are not encouraged to invest in solving the problems because of lack of security in the country. In the meantime, electricity demand is increasing day by day and the country continues to purchase power from the neighboring countries to satisfy the demand. In 2011, Afghanistan imported electricity from Uzbekistan, Turkmenistan, Tajikistan and Iran. The amount of imported electricity from each country is shown in Fig. 1.1.

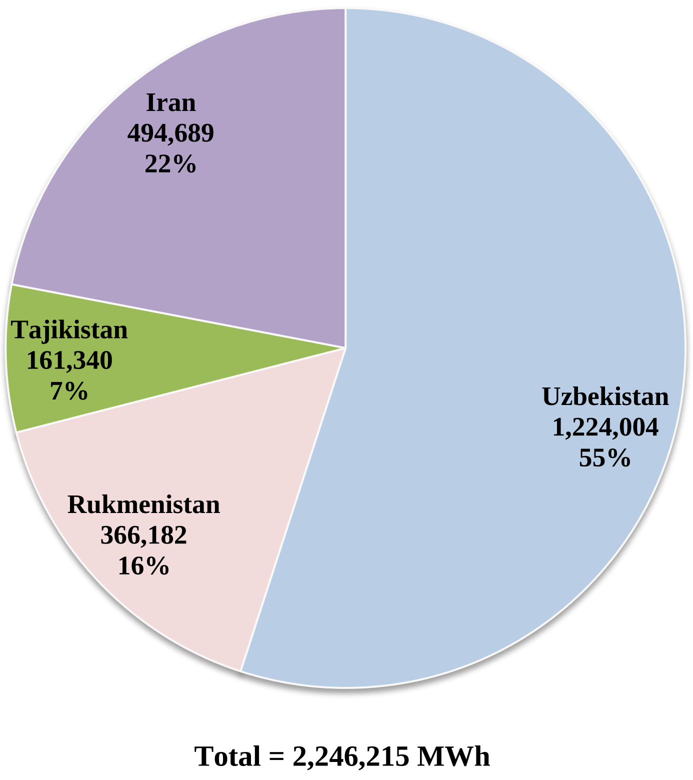

Figure 1.1 Afghanistan electricity imports by source (MWh) in 2011 [1]

1.1.2 Transmission

The electric transmission system is the backbone of the power system. It transmits electric energy from power plants to the electrical substations located near to demand centers. In most of the developed countries in the world, a transmission lines are not simply used to connect plants to the load centers; they also interconnect different power plants and transmission lines. They improve the reliability of the system and help to ensure the smooth flow of the power in the system. But in less developed countries, mostly transmission lines connect power generation plants with the load centers.

Initial efforts on transmission line design and construction focus on stabilizing the system, reducing the cost of operation and maintenance and power losses as much as possible. To facilitate the importing of power from neighboring countries, the transmission system in Afghanistan was improved and extended over the past five years. It is important to note that an adequate design and construction of the transmission system is crucial to achieve the objectives of a reliable power system in Afghanistan. However, there are seven different substation voltage levels being used in Afghanistan and these are 20, 35, 44, 110, 132, 220, and 500 kV. Although 20 and 35 kV are mostly used in medium voltage distribution systems, they also connects some small power plants located near the load centers. In the past, when there was no import of power from neighboring countries, 110 kV was the only high voltage for transmission lines in Afghanistan. Importing power from neighboring countries brought an opportunity to extend and build new transmission lines in the country.

Construction, rehabilitation and strengthening of the transmission system help to import low-cost power from neighboring countries. Currently, one 110 and two 220 kV transmission line circuits are installed between Tajikistan and Afghanistan; and also one 110 and one 220 kV transmission line circuits between Uzbekistan and Afghanistan. However, a 500 kV transmission line circuit with the total length of 450 km, 410 km in Turkmenistan and 40 km in Afghanistan, is under construction between Serdar substation in Turkmenistan and Andkhoy substation in the north of Afghanistan. There is also one 110 kV transmission line installed between Iran and Afghanistan border to the city of Farah [1].

1.1.3 Distribution

The distribution system is a complex part of a power system, which delivers electricity to the end users. Distribution networks are generally composed of medium-voltage (MV), low voltage (LV), substations, wires, poles, metering and other related system. Distribution systems around the world have different standards and applications. There are two main designs [4]

I. North American distribution design
II. European distribution design

Both systems are radial and have very similar hardware such as transformers, cables, poles, and insulators. However, the configuration, application and layouts are the main differences between these two systems. In the European system, the number of customers connected to the transformers is more than the number of customers connected in the North American system. Typically, North American systems have small single phase transformers of 15 to 50 kVA units where European systems have larger transformers that are typically are three-phase with capacity of 300 to 1000 kVA. Fig. 1.2 shows the comparison between the two systems.

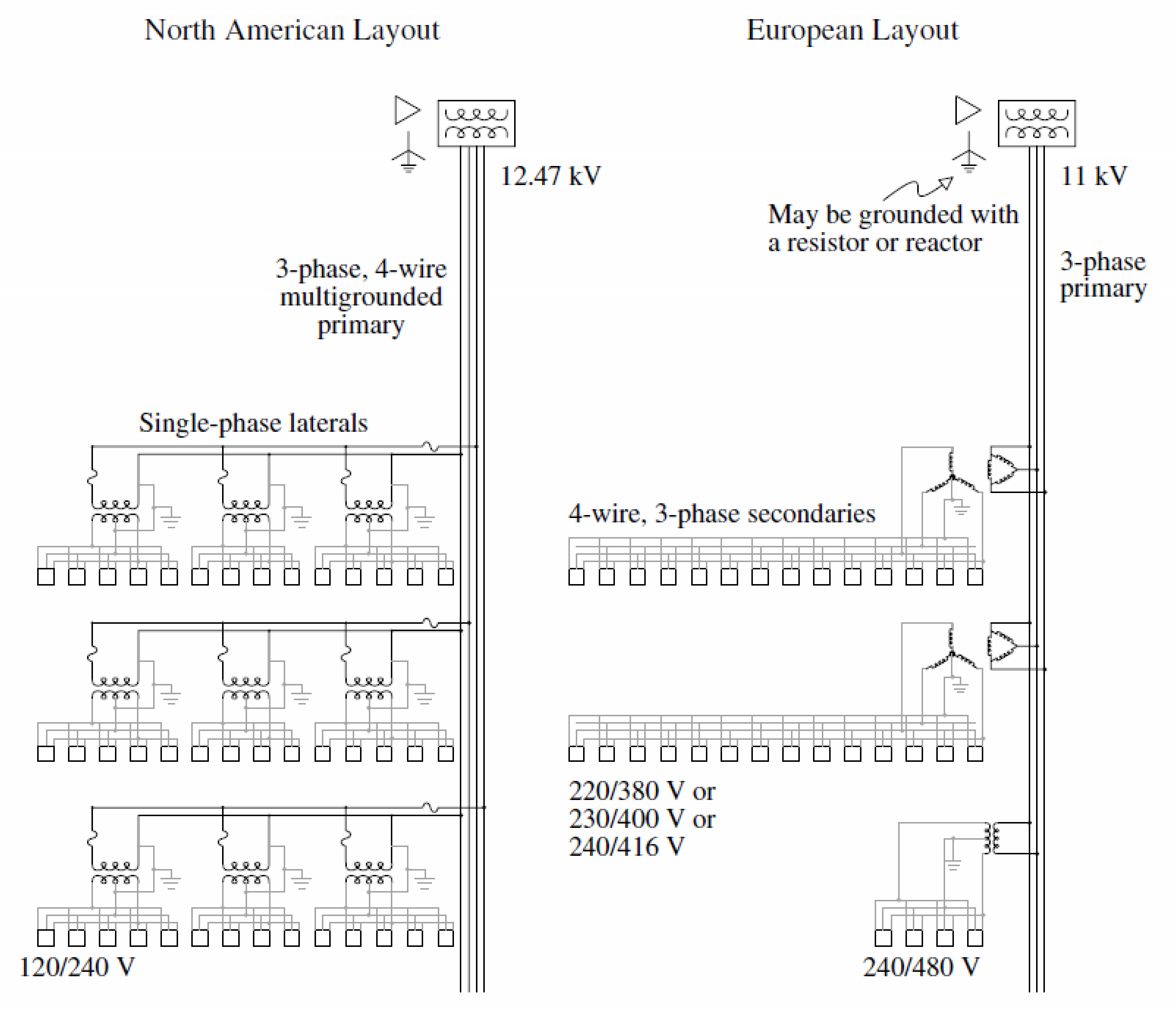

Figure 1.2 European versus North American distribution layouts [4]

The distribution system layout in Afghanistan is similar to the European distribution layout. Typically, primary distributions are overhead and secondary distributions are underground. In the city of Kabul, Afghanistan's capital, primary distribution voltage levels are 10, 15 and 20 kV. The secondary voltage standard in Afghanistan is 220/380Y. Higher secondary voltage allows the secondary cables to reach long distances and feed more customers; compared to the secondary North American distribution system, it can reach eight times further for same load and voltage drop [4].

Distribution systems in Afghanistan were destroyed extensively during the past war with the Soviet Union and continued to deteriorate. Although, the Afghanistan government is striving to expand and rehabilitate the distribution systems, still it is the least developed part of the power system. According to the power sector strategy of the Ministry of Energy & Water, upgrading of distribution system is very expensive and it is estimated that connecting each new customer to the system will cost $1,000 (US), according to Afghan Ministry of Water and Power [28].

One of the focuses of distribution systems design is to decrease power losses. Unfortunately, power loss in distribution systems in Afghanistan is too high due to poor design and ageing equipment. In addition, the voltage variation is also a big problem in Afghanistan. The voltage difference range in most parts of the Kabul city is between -20 % to +10 % of 220 V single-phase. Fig. 1.3 illustrates the distribution problem in Afghanistan with multiple wires connected to a pole in an unplanned design.

Figure 1.3 A lineman works on distribution lines in Kabul City [5]

1.1.4 Rural Electricity & Energy

Access to reliable and affordable electrical energy is vital for sustainable development in rural communities and it can play significant role in reducing poverty and deforestation and improve healthcare and living standards. More than 70% of Afghanistan's population is living in rural communities. However, access to electricity in rural communities in Afghanistan is very limited and an accurate estimation of rural population having access to electricity is not available. Extending the power grid to the rural communities is very expensive, yet crucial and remains unresolved.

Sources of power, except for the villages connected to the grid, are micro-hydropower plants (MHPs), diesel generators (mostly private), batteries, hurricane lamps for lighting, fuel, natural gas, and biomass for cooking. The Ministry of Energy & Water and Ministry of Rural Rehabilitation & Development are striving to promote rural energy/electrification in Afghanistan. Most MHPs and diesel generators are offered by donors, private sectors and sometimes with very limited government cost-sharing. In rural communities, electricity is mostly used for lighting, cell phone charging, and entertainment, such as television and radio.

1.2 Why Renewable Energy in Afghanistan?

Renewable energy sources are derived from natural resources such as water, biomass, wind, geothermal and solar. Renewable sources are the most promising energy resource in the world as they will never run out. Renewable resources are the key to a healthy environment and sustainable energy future. More than 80% of electricity generated in the world comes from traditional resources such as coal, natural gas and nuclear [24]. According to the Union of Concerned Scientists generating electricity from traditional resources significantly contributes to the carbon dioxide and sulfur dioxides emitted into the air [24]. Carbon dioxide and other heat emissions contribute to heating of the atmosphere and global warming. Additionally, people around the world are concerned about potential hazards associated with the conventional sources of energy, such as the oil spills or nuclear power meltdown such as the Chernobyl and Fukushima disasters.

Afghanistan has a significant amount of renewable energy sources such as hydro, wind and solar which offer the best solution and hope for Afghanistan in general, and particularly rural communities. Afghanistan is a mountainous country which has a significant amount of snow in the winter and when it melts it runs to rivers and streams and provides significant potential for hydro energy. Afghanistan also has excellent wind and solar potential in many areas as well. Particularly in rural communities, wind turbines and solar arrays along with micro-hydropower are the best option and cost effective electricity solution for Afghanistan.

1.2.1 Micro Hydropower

Micro-hydropower is derived from combination of head and flow of water. The energy of water turns the turbine, the turbine spins a generator and then electricity is generated. A micro-hydropower system is a small system in the range of 5 – 100 kW. The simplest micro-hydropower plant is based on a run-of-river design, which means it does not have water storage capability. It will produce power only when water is running or it might have relatively small water storage capability. Micro-hydropower is an interesting prospect for providing electricity for rural communities. Additionally, micro-hydropower plants have other benefits for the environment and the society such as

a. Drinking water supply systems
b. Irrigation channels
c. Recreation purposes
d. Flood protection

Micro-hydropower can also be substituted for fossil fuels and provide comprehensive economic benefits to society and maintain the ecosystem. Therefore, since Afghanistan is a mountainous country with lots of rivers, micro-hydropower is the best solution for communities, particularly remote communities. Furthermore, micro-hydropower can mitigate the financial cost of expanding power from the grid to the remote and mountainous areas.

1.2.2 Wind Energy

Wind power, another form of renewable energy, is one of the fastest growing energy sources in the world. It converts the kinetic energy of wind to a useful form of energy such as electricity and pumped water. Wind turbines operate on a simple principle. The kinetic energy of the wind converts to the mechanical energy through the blades around a rotor; and then the rotor is connected to the generator by a shaft and sometimes gearbox to generate electricity. Wind power has changed the face of industry in the world and it has brought more challenges in power system design, operation and installation. Integrating wind powering to traditional power grids needs more sophisticated design and technical support. Based on World Wind Energy Association (WWEA), the total capacity worldwide of wind turbines in 2011 reached 239 Gigawatts [3]. Fig. 1.4 shows the increase of wind power in the world.

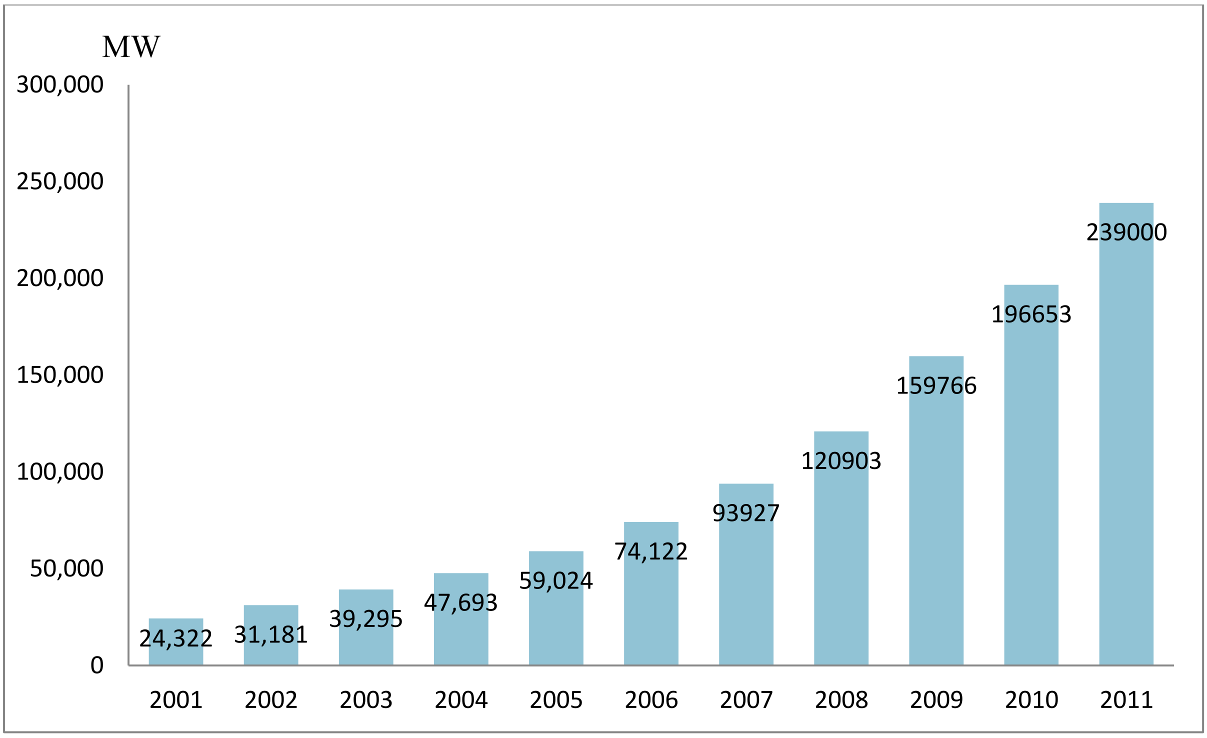

Figure 1.4 Worldwide total installed wind capacity [3]

Afghanistan has excellent wind potential in many areas. Major wind resource areas are in the western and northeastern parts of the country, elevated mountain summits and ridge crests in northern and eastern Afghanistan [2]. Wind energy is economical, especially for rural communities, compared to other fossil energy in long term. The wind electric potential in Afghanistan is summarized and shown in Table 1.1 [2]:

Wind Resource Utility Scale	**Wind Class**	**Wind Power W/m^2**	**Wind Speed m/s**	**Land Area km^2**	**Percent Windy Land**	**Total Capacity Installed MW**
Good	4	400 – 500	6.8 – 7.3	15,193	2.4	75,970
Excellent	5	500 – 600	7.3 – 7.7	6,633	1.0	33,160
Excellent	6	600 – 800	7.7 – 8.5	6,615	1.0	33,100
Excellent	7	> 800	> 8.5	3,169	0.5	15,800
Total				**31,611**	**4.9**	**158,100**

Table 1.1 Afghanistan's wind resource at 50 m [2]

Currently, wind pumps have been installed in several rural communities for drinking and irrigation purposes. Yet, wind power penetration is very limited to some small off-grid private houses in rural communities and there is no national or private utility-scale wind power plant.

1.2.3 Solar Energy

Solar energy is another promising renewable energy. The sun provides enough energy needed to sustain life in the solar system. Approximately in one hour, the sun delivers enough energy to the earth to meet its energy needs for nearly a year. Photovoltaic (PV) technology converts the energy coming from the sun to electricity. Solar energy is used for multiple purposes including producing electricity, water heating, and cooking. Many developed countries in the world including USA are striving to develop and enhance solar power plants, but it still remains a high-cost energy resource for electricity.

Afghanistan on average has 300 sunny days per year which is an excellent solar potential. Solar energy is used in Afghanistan for various purposes such as water heating, cooking, cell phone charging and lighting. Currently, there are a few schools where solar panels are installed in different villages. As discussed previously, generated electricity is mostly served to the urban areas and the rural communities are suffering from lack of electricity since extending the power grid to rural communities is very expensive. Therefore, solar power offers a good opportunity for rural communities as well.

1.3 Aim of the Project

Afghanistan is a rich country in renewable and as well fossil energies, such as coal and natural gas. Constructing and developing a large hydro-power plant, wind farms or fossil power plants and transmission lines need a huge investment from the government or private investors. On the other hand, the security situation in Afghanistan is another reason that private investors and agencies do not have an interest in investing their money in developing a power plant and transmission lines. Afghanistan imports more power from its neighboring countries than it produces and the power is mostly served to the urban areas. More than 70% of population is living in rural communities and most rural communities and especially remote communities are suffering from lack of electricity.

Micro-hydropower is the most widely used and environmentally friendly renewable energy technology in Afghanistan. There are many for profit and non-profit organizations working to develop this technology in many areas, but they still face lots of challenges in the design, construction, and siting. Additional challenges to developing a micro-hydro include initial capital cost, operation and maintenance costs and lack of technical expertise.

Besides micro-hydropower, wind turbine and solar power are also attractive renewable energy sources for rural communities. The aim of the project is to introduce a hybrid power system which is comprised of micro-hydro, solar, and wind sources, plus diesel generator and battery storage. The development of a hybrid power system is a complicated process and needs technical expertise in the design and implantation. The project will give a simple design, cost optimization and feasibility study of the system using HOMER software [6] to encourage private investors and local communities to take the advantage of these technologies.

Chapter Two

2.1 Hydroelectric Power Plants

Hydroelectric power is the most widely-used renewable source of energy in the world. Hydropower plants use the potential energy of water stored in a reservoir to operate a turbine; and the turbine is connected to a large generator to produce electricity. It operates on varying volumes of water to adapt to changing demands in electricity. A hydroelectric power plant's capacity is related to the height and capacity of a reservoir, and other certain conditions such as local geography of the site. For certain locations small hydro is a more cost-effective renewable energy source than many other renewable sources such as photovoltaic and wind. Some of the advantages of hydroelectric power are [31]:

- Water is provided free by nature
- Fuel is not burned, therefore there is minimal pollution
- The technology is reliable and has been proven over time
- Hydropower plays a major role in reducing greenhouse gas emissions

Hydropower plants range in size from large power plants that supply many consumers including industrial and commercial load to small and micro plants that provide electricity for small numbers of houses or villages. Generally, there are three different sizes that hydropower plants are based upon [30]:

- Large hydropower plants: have more than 30 MW capacity.
- Small hydropower plants: have capacity between 100 kW to 30 MW.
- Micro-hydropower plants**:** have less than 100 kW capacity. A small or micro-hydroelectric plant can produce enough electricity for a home, farm or village.

2.2 Micro-Hydropower Plants

There are different micro-hydropower plant schemes based on site configuration. The power output from a scheme is proportional to the flow and head. Schemes are generally classified based on their height as follows [12]:

- High head: 100 m and above
- Medium head: 30 to 100 m
- Low head: 2 to 30 m

The schemes can also be classified based on a river type as follows:

- Run-of-river schemes
- Small dam schemes in which power house could be located at the base of the dam
- Schemes integrated on a canal or in a water supply pipe

The simplest micro-hydropower plant is the run-of-river scheme. Fig. 2.1 shows an example of run-of-river system.

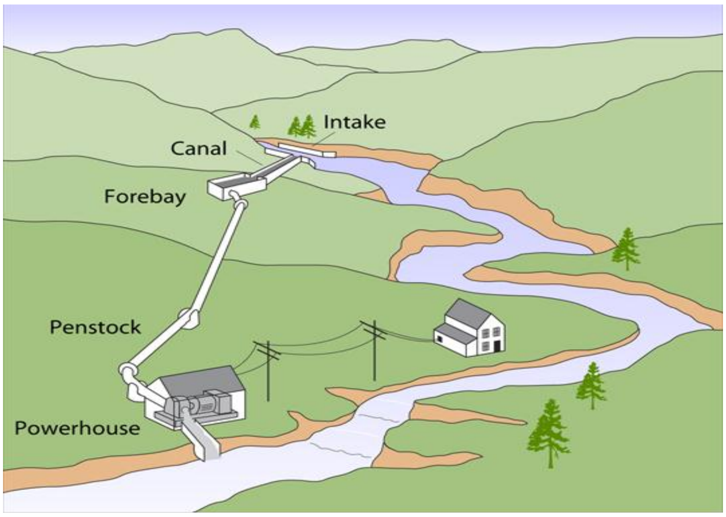

Figure 2.1 Run-of-river micro-hydropower system [25]

Run-of-the-river micro-hydropower systems consist of the following basic components:

- Water conveyance: is composed of intake, weir, canal, forebay and penstock.
    - Intake is a structure where the water to the power plant is either extracted or separated from the river flow. It prevents floating debris and trash from entering the water conveyance system.
    - Forebay is a drain valve or stop log gate, which flushes sediment, trash rack and disposal requirements of spilled water.

- Weir is a gate to control the volume of water for maintenance.
- Penstock: delivers the water to the turbine.

- Turbine: transforms the energy of flowing water into rotational energy.
- Alternator: transforms the rotational energy into electricity.
- Power house: a house for generator and all other electrical equipment.
- Regulator: controls the generator.

2.2.1 Micro-Hydropower Systems Planning

Planning a micro-hydropower project is a complex and iterative process, where consideration is given to; environmental impact, different technological options, economic evaluation of the project and other constraints. Although it is difficult to provide a detailed guide on how to evaluate a scheme, it is possible to provide a short feasibility study of a given site configuration in order to develop the project. The following diagram shows steps of developing and planning a micro-hydropower project.

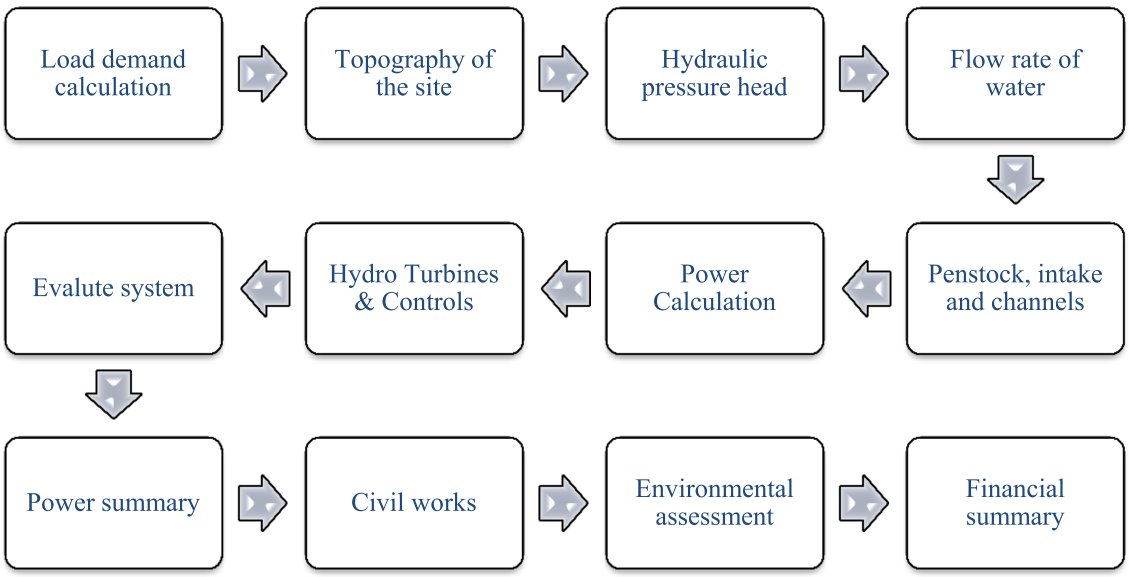

Figure 2.2 Planning and evaluation of a micro-hydropower plant [26]

2.2.2 Micro-Hydropower Systems Sizing

The hydraulic power or hydro potential available from a river is directly related to the flow rate, head and the force of gravity as given by [12]

$$Hydraulic\ power = \rho * Q * g * H_g \quad (1)$$

The electric power derived from hydraulic power at disposition of the turbine is given by

$$Electric\ Power\ (kW) = Hydraulic\ Power * e = \rho * Q * g * H_g * e \quad (2)$$

ρ	water specific density (1 kg/m^3 at C^o)
Q	flow rate, quantity of water flowing into turbine (m^3/second)
g	gravitational constant (9.81 m/s^2)
H_g	gross head in meters
e	system efficiency factor, turbine and generator efficiency (0.5 to 0.7)

The electric power output is directly proportional to river flow and the vertical distance that the water falls. Theoretically, a river with twice the amount of flowing water should produce twice as much energy, but in reality there is pipe loss due to the friction of pipes which decreases the output power.

2.2.3 Pipe Losses

Water flow in a pipe results in head loss due to friction and it is given by [12]

$$h_f = f * \left(\frac{L}{D}\right) * \frac{v^2}{2 * g} \quad (3)$$

f	friction factor, a dimensionless number
L	length of the pipe in meters
D	pipe diameter in meters
v	average velocity in m/s
g	gravitational constant (9.81 m/s^2)

Therefore, the net head available to the turbine is the difference between the gross head and friction loss head as given by

$$Net\ head\ (H_n) = Gross\ head - Friction\ loss\ head \quad (4)$$

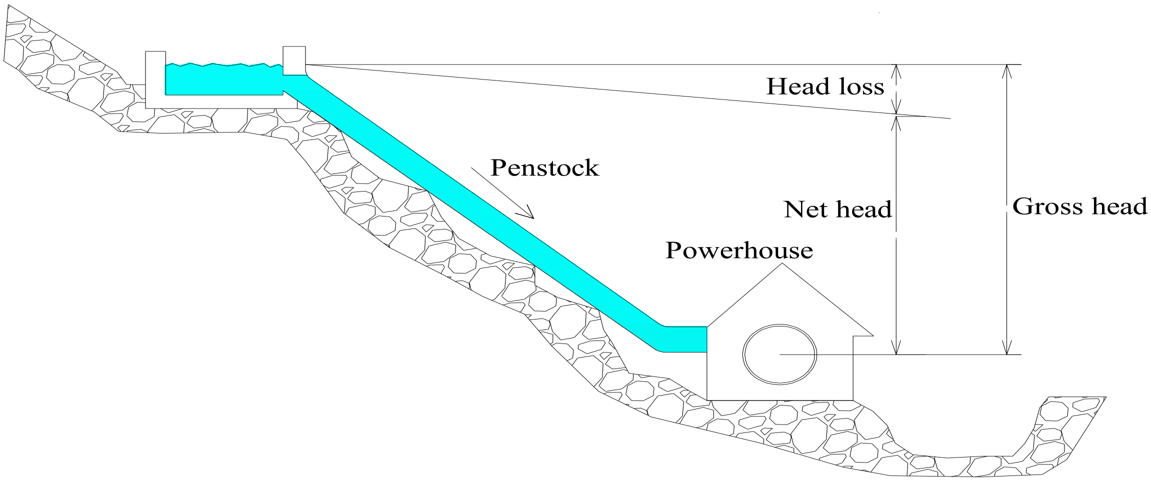

Figure 2.3 Net head remains after pipe loss[9]

Power output available after head loss is given by

$$Electric\ Power\ (kW) = H_n * Q * g * e \qquad (5)$$

Poly-vinyl chloride (PVC) and polyethylene (poly) pipes are the most typical pipes used in penstock. PVC and poly pipes are available with various diameters and lengths. The friction losses, expressed as feet of head per 100 feet of pipe, are shown in Fig. 2.4.

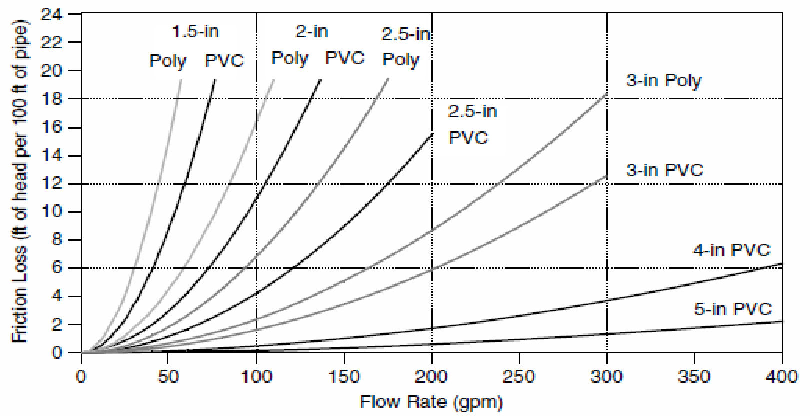

Figure 2.4 Friction head loss [9]

PVC pipes have lower friction loss than poly pipe and they are also less expensive. To get more power from the system, the friction loss should be minimized. Larger-diameter pipes will have less friction loss and result in more power delivery than small-diameter pipes. It should be noted that piping makes up a significant fraction of the total cost of a micro-hydropower plant. Therefore, in the design process the diameter of the pipe should be optimized in order to avoid increase in total cost. Furthermore, both types of piping should be protected from sunlight, as ultraviolet exposure makes these materials brittle and easier to crack [9].

2.2.4 Micro-Hydro Turbines

Energy stored in water will transfer to mechanical energy, which is needed to rotate the shaft of an electric generator. Generally there are three different types of turbines: impulse, reaction and waterwheel turbines.

- **Impulse Turbines:** In a system using an impulse turbine, water is diverted upstream to the turbine by a pipeline or penstock. Water then travels through this pipeline to a nozzle, which constricts the flow to a narrow high velocity jet of water, and squirts into buckets along the circumference of the turbine. The term 'impulse' means the force that turns the turbine and it comes from the impact of the water on the turbine runner. These kinds of turbines are used, when high head and low flow of water is available in a site.
- **Reaction Turbines:** Reaction turbines, which are highly efficient, depend on pressure rather than velocity to produce energy. All blades of the reaction turbine maintain a constant contact with water and usually they are used in large-scale hydropower plants. These kinds of turbines are not usually used for micro-hydropower projects.
- **Waterwheel Turbine:** A waterwheel turbine is a slow-moving turbine, but powerful and traditionally used in power mills. They are not used for electric generation because of slow rotational speed.

Impulse turbines are the most commonly used turbines in micro-hydropower systems. They are more efficient and have the least complex design. They rely on the velocity of water to move the turbine wheel, called the runner. The most common types of impulse turbines are the Pelton Wheel and the Turog Wheel.

2.2.5 Electric Aspects of Micro-Hydropower

As discussed above, the micro-hydropower systems are sized up to 100 kW. Larger micro-hydropower systems may be used as a source of AC power to provide electricity for a small village using conventional synchronous generators. However, a small size of micro-hydropower system usually uses a DC generator to supply electricity for a house. DC generators charge batteries and then an inverter is used to convert the DC voltage to AC voltage. A typical battery-based micro-hydropower plant with all the principal detailed components is shown in 2.5.

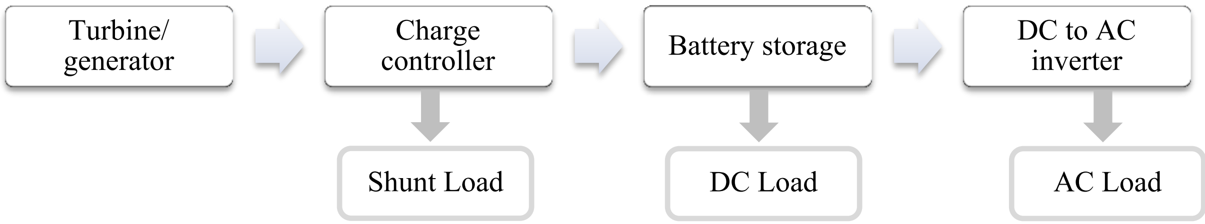

Figure 2.5 Basic principal components of a battery-based micro-hydropower system

2.3 Photovoltaic Power

Solar light is converted directly into electricity with modules consisting of many photovoltaic (PV) solar cells. A PV cell is a PN junction or Schottky barrier device which is often manufactured from fine films or wafers. They are semiconductor devices capable of converting incident solar energy into DC current, with efficiencies varying from 3 to 31% [20]. This depends on several factors such as: the technology, the light spectrum, temperature, design and the material of the solar cell. Typically, a PV cell produces less than 5 W at approximately 0.5V to 0.6V DC. However, cell illumination level is a key factor in determining the amount of current and voltage output from a PV cell. In order to obtain high currents and voltage (reaching up to kilovolts), PV cells are connected in series-parallel. The I-V characteristic equation of a PV cell is given by [10]

$$I \quad = I_l - I_s(e^{\frac{q*v}{k*T}} - 1) \tag{6}$$

k	Boltzmann constant (1.38047×10^{-23} J/K)
q	electronic charge (1.60210×10^{-19} C)
v	voltage across the PV cell
T	$273.2 + t_c$ is absolute temperature given as function of the temperature in ^{o}C
I_s	reverse saturated current of the diode, typically 100 pA for silicon cell
I_l	cell current due to photons

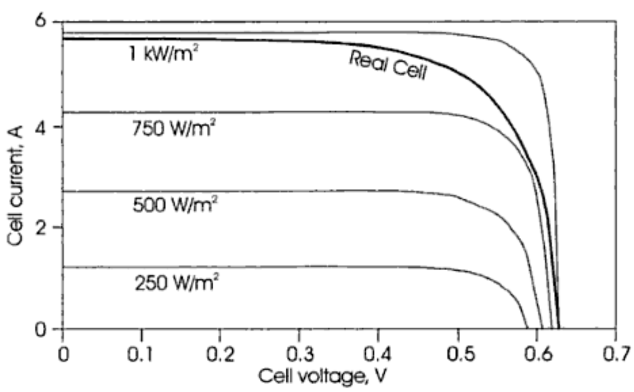

Figure 2.6 I-V characteristics of real and ideal PV cells [10]

As shown in Fig 2.6 it can be seen that a PV cell has a limiting voltage and a limiting current. The maximum power provided by an ideal PV cell (rectangular cell I-V) characteristic can be expressed as [10]:

$$P_{max} = I_{sc} * V_{oc} \tag{7}$$

Open-circuit voltage of a PV cell is determined by setting I = 0 in the I-V characteristics equation and it is given by:

$$V_{oc} = k * \frac{T}{q} * \ln\left(1 + \frac{I_l}{I_s}\right) \cong k * \frac{T}{q} * \ln\left(\frac{I_l}{I_s}\right) \tag{8}$$

And the short-circuit current of a PV cell is determined by setting V = 0 in the I-V characteristic equation, so that $I_{sc} = I_l$.

Yet, real PV cells are not ideal and have both voltage and current limitations. Therefore, a fill factor, which is a measure of the quality of the cell, should be multiplied by P_{max}. Hence the maximum power from a cell expresses as [10]:

$$P_{max} = FF * I_{sc} * V_{oc} \tag{9}$$

"Typical fill factors for real PV cells, depending on the technology and quality of the cells, may vary from 0.5 to 0.82" [10]. The technique to maximizing the fill factor is to minimize series resistance and maximize shunt resistance and the ratio of photocurrent to reverse saturation current.

2.3.1 Series-Parallel Configuration of PV Cells

Usually PV cells inside the PV module are manufactured with very similar characteristics to avoid circulation of internal currents among the cells. Therefore, it can be assumed that the PV cells are identical when they are connected in series or parallel. Connecting PV cells in series results in increase of the voltage across PV panels, whereas connecting PV cells in parallel results in the increase of the output current from PV panels. The efficiency of a solar panel is given by [20]:

$$\eta = \frac{P_{electrical}}{P_{illumination}} * 100\% \tag{10}$$

$P_{electrical} = I * V$ or PV output power

$P_{illumination} = effective\ illuminating\ area * radiation\ intensity$

"As an example, suppose that a manufacturer's data sheet provides effective illuminating area = 0.16m^2, V_p =20.6V, and I_p = 1.8A for the standard test conditions (100 W/m^2, 25 ^{o}C, air mass 1.5)" [20]. Then efficiency of the solar panel will be equal to

$$\eta = \frac{20.6 * 1.8}{1000 * 0.16} * 100\% = 23.175\ \%$$

2.3.2 Photovoltaic Systems

A photovoltaic electric system is implemented as a stand-alone system with battery bank or a grid-connected system. A photovoltaic electric system consists of: photovoltaic modules, an electronic inverter, a charge controller, and battery storage. For a stand-alone system battery storage usually is necessary in order to accumulate the electric power generated during the day, and supply it back whenever it is needed. For grid-connected systems it is not necessary or cost effective to include battery storage. The modern charge controllers and inverters are designed and integrated with maximum power point tracking (MPPT) circuitry to provide maximum power from arrays [9].

To design a stand-alone system, one should consider the following important steps:

- Site evaluation, with proper design to avoid shadows
- Load Analysis
- PV sizing
- Battery storage sizing with considering days of storage
- Charge controller and inverter sizing
- Structures of the system
- Grounding and other wiring system
- Cost evaluation

2.4 Wind Power

Wind energy is derived from solar energy, due to uneven distribution of temperatures in different areas of the earth. The resulting movement of air mass is the source of mechanical energy that drives wind turbines and generators. To select the ideal site for wind power plants, it is necessary to study and observe the existence of adequate amounts of wind. Some basic observations of a candidate site are listed

- Wind intensities in the area
- Topography of the area
- Proximity to transmission and distribution networks

Although flat plains may have steady strong winds, for small-scale wind power the best choice is usually along dividing lines of waters, the crests of mountains and hills. It is imperative to evaluate the historical wind power intensity (W/m^2) of the site in order to access the economic feasibility of the site, taking into account seasonal, as well as year-to-year variations in the local climate. The energy captured by the rotor of a wind turbine is proportional to the cubic power of the wind speed and it is given by [20]:

$$P = \frac{1}{2} * \rho * C_p * A * {v_1}^3 \tag{11}$$

$$C_p = \frac{(1-\frac{{v_2}^2}{{v_1}^2})*(1+\frac{v_2}{v_1})}{2} \tag{12}$$

ρ	air density (1.2929 kg/m^3 at 0^oC and at sea level)
A	surface area swept by the rotor or blades in m2
C_p	power coefficient, power output from wind machine per power available in wind or rotor efficiency
v_1	wind speed derived from airflow just reaching the turbine
v_2	wind speed leaving the turbine

If C_p is considered as a function of v_2/v_1, the maximum of such a function can be obtained for $v_2/v_1=1/3$ as $C_p = 16/27 = 0.5926$. This value is known as the Betz limit [20]. In practice, the collective efficiency of a rotor is not as high as 59%, more typical efficiencies are between 35 and 45%. The maximum wind power can be obtained from the above equation without taking into account the aerodynamic losses in the rotor, the wind speed variations in the blade sweeping area, the rotor type and other losses [20]:

$$\frac{P}{A} = \frac{1.2929}{2} * 0.5926 * v^3 = 0.3831 * v^3$$

The coefficient in the equation is usually quite small because of losses and uneven distribution of the wind on the blades, and it may be approximated by

$$\frac{P}{A} = 0.25 * v^3 \tag{13}$$

For industrial-scale C_p is more than 25% and is some cases it reaches to 45%.

2.4.1 Types of Wind Turbines

One way to classify wind turbines is in terms of the axis around which the turbine blades rotate. The two major categories are horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT). The most common wind turbines are HAWT. Examples of each type are shown in Fig. 2.7.

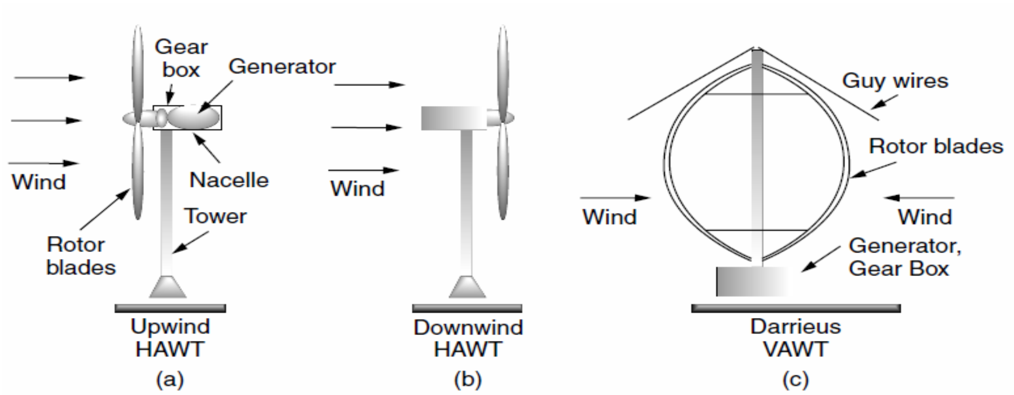

Figure 2.7 Examples of horizontal and vertical axis wind turbines [9]

Both types have several advantages and disadvantages. The principle advantage of vertical axis machines, such as the Darrieus VAWT, is that they do not need any kind of yaw control to keep them facing into the wind or in other words they can accept the wind from any direction. The second advantage is that the heavy machinery contained in the nacelle (the housing around the generator, gear box, and other mechanical components) can be located down on the ground, where it can be serviced easily. A disadvantage of the vertical axis turbine is that the blades are relatively close to the ground where wind speeds are lower. Another disadvantage of a vertical axis is that winds near the surface of the earth are not only slower but also more turbulent, which increases stresses on VAWTs. "Darrieus rotors have very little starting torque, which is good at low wind speed. But in higher wind speeds, Darrieus rotors cannot control the input power to the generator to protect the generator" [9].

They cannot be made to spill wind as easily as pitch-controlled blades do in HAWT configuration.

Another fundamental design decision for wind turbines relates to the number of rotating blades. The choice depends on the size of the wind turbines and purpose. In general, large size wind turbines (in terms of output power) have fewer blades (usually 3) than small size turbines since more blades will decrease the rotational speed [9].

2.4.2 Impact of Tower Height

Since power in the wind is proportional to the cube of the wind speed, the economic impact can be significant even with a modest increase in wind speed. Wind turbines with a higher tower can capture more wind power, resulting in more electric power output. Wind speeds are greatly affected by the friction that the air experiences as it moves across the earth's surface and the height from the ground level. One expression for impact of the roughness of the earth's surface and height from a reference point is given by [9]

$$\left(\frac{v}{v_o}\right) = \left(\frac{H}{H_o}\right)^{\alpha} \quad (14)$$

v	wind speed at height H
v_o	wind speed at height H_o
α	friction coefficient

The friction coefficient is a function of the terrain over which the wind blows. Table 2.1 shows some representative values for some defined terrain types.

Terrain Characteristics	**Friction Coefficient α**
Smooth hard ground, calm water	0.1
Tall grass on level ground	0.15
High crops, hedges and shrubs	0.2
Wooded countryside, many trees	0.25
Small town with trees and shrubs	0.3
Large city with tall buildings	0.4

Table 2.1 Friction coefficient for various terrain characteristics[9]

Another approach to get wind speed in different heights is the log law. The log law is often used to extrapolate wind speed from a reference height H_o to another height H using the following relationship [22]

$$\left(\frac{v}{v_o}\right) = \frac{\ln(\frac{H}{z_0})}{\ln(\frac{H_o}{z_0})} \tag{15}$$

where z_0 is the roughness length as specified in Table 2.2.

Terrain description	**Z_o (mm)**
Very smooth, ice or mud	0.01
Water surface	0.2
Lawn grass	8.00
Rough pasture	10.00
Few trees	50.00
Many trees, hedges, few buildings	250.00
Suburbs	1500.00
Centers of cities with tall buildings	3000.00

Table 2.2 Roughness classifications and roughness length [22]

Both equations (14) and (15) provide a first approximation to the variation of wind speed with elevation. In reality, nothing is better than actual site measurements.

2.4.3 Wind Turbine Generators

Kinetic energy of the wind is converted by blades into rotating shaft power that spins a generator to produce electricity. Generally, wind turbines in small sizes use asynchronous generators with battery-banks, while wind turbines in large-size grid-connected systems use synchronous generators.

Synchronous generators are occasionally used in large-size wind turbines. They are forced to spin at a precise rotational speed determined by the number of poles and the frequency needed for the power lines. Small synchronous generators can create the needed magnetic field with a permanent magnet rotor, while large synchronous generators create the field by running direct current through windings around the rotor core. Fig 2.8 shows the basic components of a wind turbine with a synchronous generator.

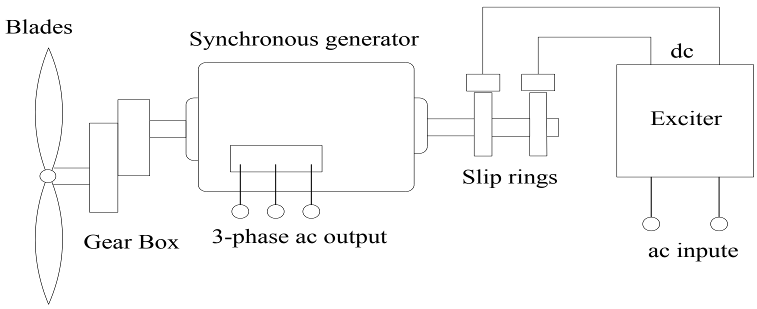

Figure 2.8 A three phase synchronous generator wind turbine [9]

Blades are connected through a gearbox to a generator. A gearbox is used to match the speeds required by synchronous generator in order to have a fixed AC frequency.

Most of the small wind turbines use permanent magnet generators rather than synchronous machines. In contrast to a synchronous generator, permanent magnet machines do not require a fixed speed from the shaft of the blades. Permanent magnet machines can act as generators or motors and it depends on the shaft power. Similarly Induction machines can act as generator or motor and it depends to the power applied to the shaft. If power is put into the shaft it is a generator and if the power is taken from the shaft it is a motor. Fig 2.9 shows basic components of an asynchronous permanent magnet generator.

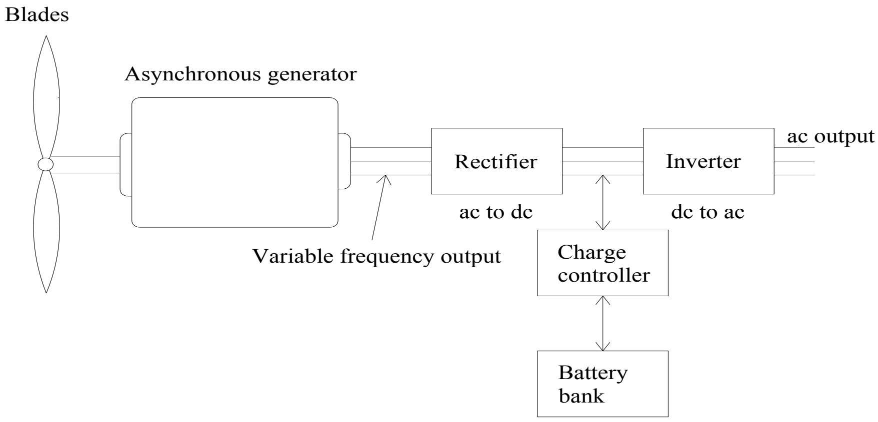

Figure 2.9 A synchronous generator wind turbine [9]

The advantage of an asynchronous permanent magnet generator is that their rotors do not need exciters and gearboxes which are mostly required by synchronous generators. They create a magnetic field in the stator, rather than the rotor which makes them less complicated and less expensive.

2.4.4 Wind Turbine Applications

Wind energy historically has been used for a wide range of special applications, such as grinding and sawing wood, and more recently water pumping and desalination. Wind turbines in small sizes are used to produce electric power for an off-grid home, usually with battery storage. A group of wind turbines in the same location, called a wind farm, is placed to produce large amount of electric power. A large wind farm connected to a grid may consist of several hundred individual wind turbines. To design an off-grid home wind turbine system, one should follow the following important steps [9]:

- Site evaluation
- Historical data of the selected site
- Load Analysis
- Wind turbine selection
- Battery storage sizing with consideration of the days of storage
- Charge controller and inverter sizing
- Civil works and wiring system
- Cost evaluation

2.5 Hybrid Power Systems

Electrical energy requirements for rural communities are slightly large and it may not be cost effective or not enough renewable energy to implement a stand-alone PV system, wind turbine or any other power sources. In this case, it is recommended to combine different types of available power sources to form what is known as a “hybrid-power” system. For example, small hydro turbine, solar and wind can be combined with other power sources such as power grid or diesel generator to provide enough electrical energy for a city or rural villages. Hybrid power systems combine many different technologies to provide reliable power. Hybrid power systems are a new favorable system, especially for rural areas, to provide enough electrical energy using different available renewable energies.

Traditionally, diesel generators are used in remote communities and villages; and they will grow to be a barrier due to the operating, maintenance and gradually increasing fuel cost and other factors, such as impact on the environment and the geographical difficulties in delivering fuel to remote areas. Therefore, hybrid power systems will turn out to be a more suitable candidate solution for remote areas. Hybrid power systems can provide a steady service to remote communities. Furthermore, these systems can also be used as an effective backup solution to the public grid, in case of blackouts or peak demand time due to their high levels of efficiency, reliability and long-term performance.

For more reliability and responsiveness to a system's load demand, hybrid systems can be designed with a backup generator that has minimal diesel consumption. The generator would come online only when a high load is required or low renewable power is available. Hybrid systems can be designed in three different configurations according to their voltages, in order to effectively use the local available renewable energy sources [29].

- DC voltage bus
- AC voltage bus
- DC and AC voltage buses

2.5.1 Hybrid Systems, DC Voltage bus Coupled

In this configuration, all electricity-generating components are connected to a DC bus. If there is an AC generating source, then an AC/DC converter is needed to convert the ac voltage to DC voltage. The system also needs a battery controller charger to protect battery storage from overcharges and discharges. If there are AC loads, then they can be optionally supplied by an inverter. Fig 2.8 shows an example of a hybrid system coupled with DC voltage bus [29].

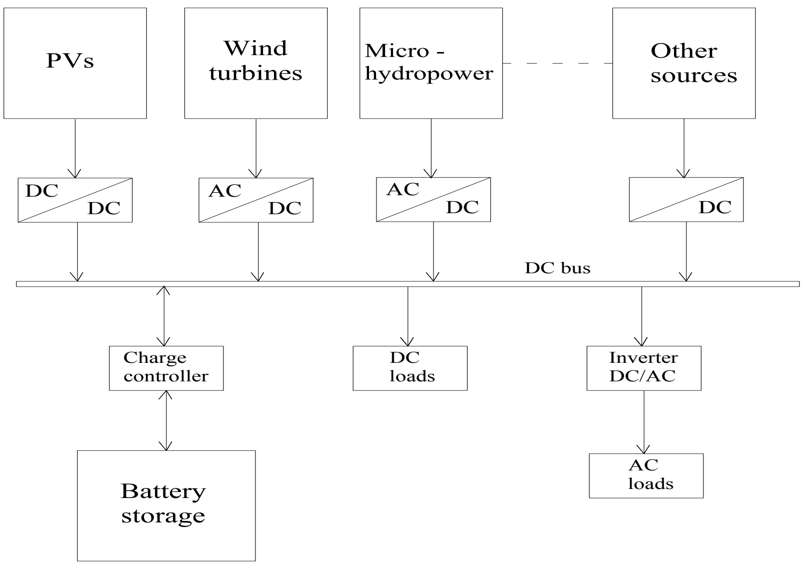

Figure 2.10 Hybrid system, DC voltage bus coupled

2.5.2 Hybrid Systems, AC Voltage bus Coupled

In this configuration, all electricity-generating components are connected to an AC bus. If there is a DC generating source, then a DC/AC inverter is needed to convert the DC voltage to ac voltage. AC generating systems may be directly connected to AC bus line or may need an AC/AC converter to enable stable coupling of the components. Battery storage is optional to store energy for demanded time when there is not enough renewable energy available [29].

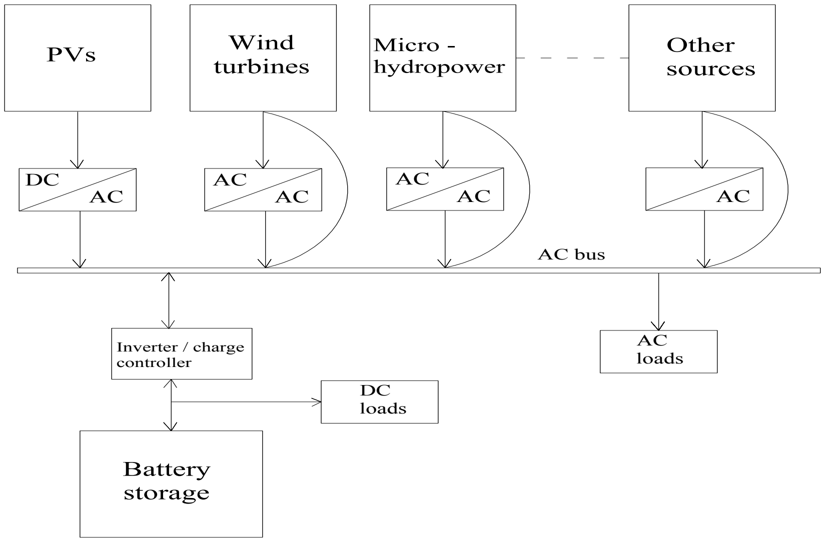

Figure 2.11 Hybrid system, AC voltage bus coupled

2.5.3 Hybrid Systems, AC & DC Voltage buses Coupled

In this configuration, all electricity-generating components which supply AC are connected to AC bus and DC components are connected to a DC bus. There will be need of an AC/DC inverter and DC/AC converter between these two buses and they depend on the design and system requirements. Again battery storage is optional to meet demand time [29].

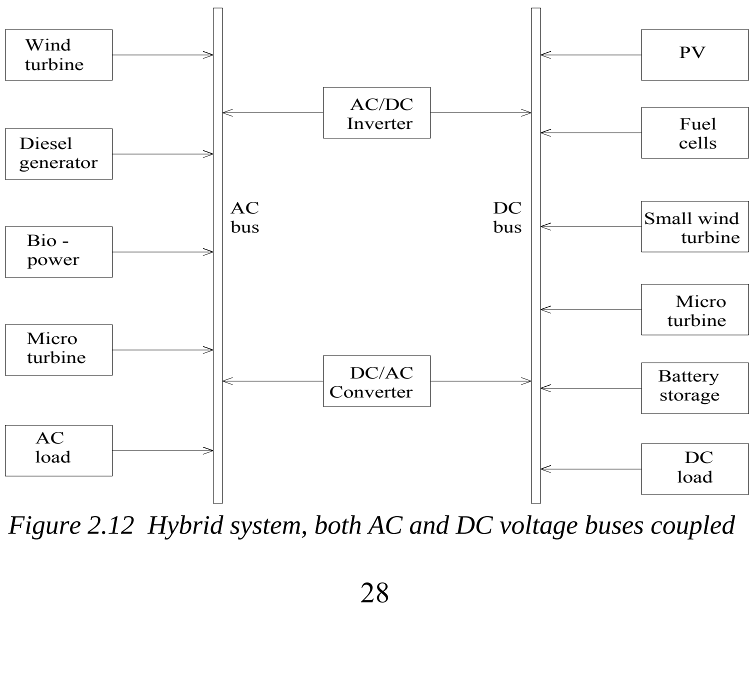

Figure 2.12 Hybrid system, both AC and DC voltage buses coupled

2.6 HOMER Introduction

HOMER [6] is a computer model developed by the U.S. National Renewable Energy Laboratory (NREL) to assist in the design of micro-hybrid power systems and to facilitate the comparison of power generation technologies across a wide range of applications. HOMER models a hybrid power system's physical behavior and life-cycle cost, which is the total cost of installing and operating the system over its lifetime. HOMER also allows the designers to compare many different design options based on their technical and economic approach. More specifically, HOMER is a program that simulates a power system design including renewable sources. It provides optimized solutions of the power system's problem based on cost-effectiveness. HOMER helps the user to analyze the results of the optimization process in tables and graphs, after entering the information about components, loads and other important data.

HOMER can model grid-connected and off-grid micro hybrid power systems serving electric (AC and DC) and thermal loads. The micro-hybrid systems can be a combination of photovoltaic (PV) modules, wind turbines, small hydro, biomass power, reciprocating engine generators, micro-turbines, fuel cells, batteries, and hydrogen storage. Design, analysis and comparison of such hybrid power systems with different combinations of sources, due to the large number of design options and uncertainty in some key parameters such as diesel price and availability of different renewable resources is a long and challenging process. HOMER was designed to overcome these challenges.

Basically, HOMER performs three different principle tasks:

- Simulation
- Optimization and
- Sensitivity analysis

In the simulation process, HOMER determines the performance of a particular hybrid system configuration, a combination of system components of specific sizes, and an operating strategy that defines how those components work together in its life-cycle cost. HOMER can simulate a wide variety of hybrid system configurations and compare all different combinations of sources. The simulation process has two purposes. First, it determines the feasibility of the system due to different loads and sources combinations. Secondly, it estimates the life-cycle cost of the system, which is the total cost of installing and operating the system over its lifetime.

In the optimization process, HOMER simulates numerous system configurations in order to determine the best optimal system configuration. In HOMER, the best optimal configuration is the one that satisfies the user-specified constraints, at the lowest total net present cost. A designer may determine the optimal sizes and numbers of each component in order for HOMER to consider multiple sizes and numbers in its optimization process.

HOMER allows designers to enter a range of values for a single input variable. A variable for which the user has entered multiple values is called a sensitivity variable. Then in the sensitivity process, HOMER performs multiple optimizations within the specified range of variables to gauge the effects of changes in the model inputs. Diesel price, interest rate, grid power price, life time of components, load and renewable generation variables are examples of variables for which sensitivity analysis can be performed.

Chapter Summary

Total power provided by a micro-hydropower is given by equation (5) and the total power provided by a PV cell and wind turbine are given by equation (9) and (11). The most common turbine for micro-hydropower is an impulse turbine. This turbine is used when high head and low flow of water is available at a site. Photovoltaic systems and wind turbines are implemented either as stand-alone system or grid connected system. A photovoltaic electric system consists of photovoltaic modules, an electronic inverter, a charge controller, and battery storage. Wind turbines in small sizes are used to produce DC electric power for an off-grid home, usually with battery storage. Hybrid power system is a technology which combines different types of available power sources. In the next chapter a hybrid power system with different available power sources will be modeled in HOMER to obtain the most optimal combination of available power sources for a given location.

Chapter Three

3.1 Project Background

This is a brief design and cost estimation of the proposed Darya-ye-Band-e-Amir hybrid power system project. The information in this study includes cost estimation with available wind, solar and water flow data. It does not include construction drawings or electric systems drawings in sufficient detail. Detailed construction and electric system drawings need to be designed by an engineering consultant service. However, this is a bulk hybrid power system design, with different combinations of power sources to evaluate the cost of each configuration. The project's site is shown in Fig 3.1 and Fig 3.2.

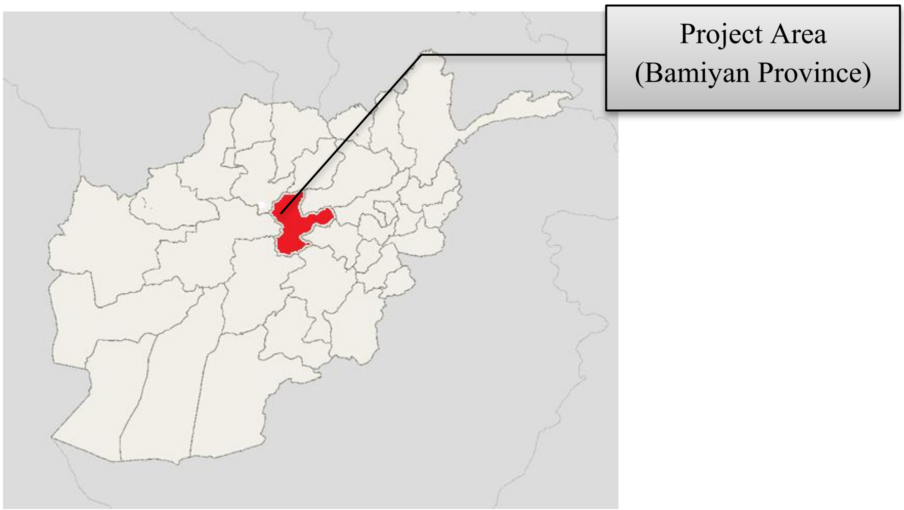

Figure 3.1 Political map of Afghanistan showing project area province [16] "Geospatial Toolkit"

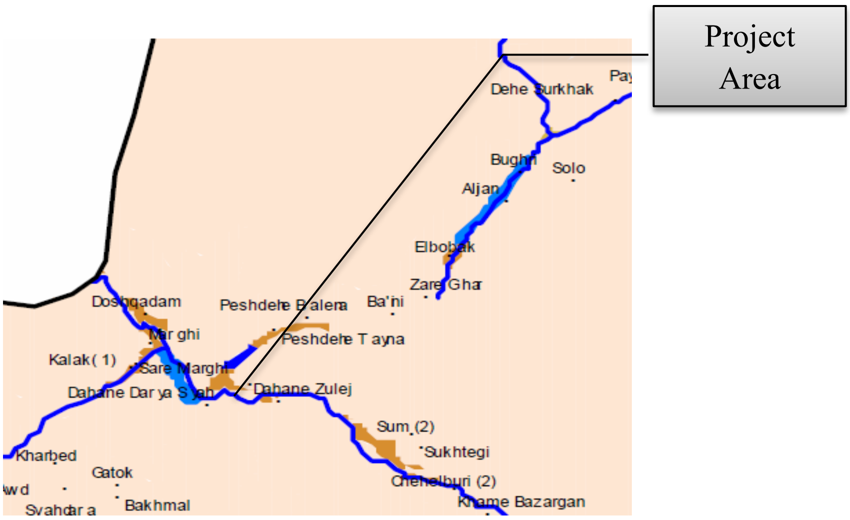

Figure 3.2 Part of provincial map of Bamiyan [27]

3.2 Rural Communities Area Description

Bamiyan is one of the 34 provinces in Afghanistan which is located in northern part of the country. Bamiyan is the largest province of Hazarajat region in Afghanistan. The Bamiyan province is historically and touristically famous because of the heritage site of the tallest Buddha statues in the world. Unfortunately, the Buddha statues were completely destroyed by the Taliban regime. Bamiyan is also known for its beautiful nature, historic caves and local culture. Bamiyan is divided into seven minor civil divisions. Table 3.1 shows each division and its populations.

No	Minor civil Division	Total Population Urban and Rural			Urban			Rural		
		Both sexes	Male	Female	Both sexes	Male	Female	Both sexes	Male	Female
1	Bamiyan Center	75.5	37.7	37.8	11	5.5	5.5	64.5	32.2	32.3
2	Shebar	26.8	13.9	12.9	0.0			26.8	13.9	12.9
3	Saighan	21.8	11.1	10.7	0.0			21.8	11.1	10.7
4	Kahmard	33.1	16.9	16.2	0.0			33.1	16.9	16.2
5	Yakawolang	79.5	40.4	39.1	0.0			79.5	40.4	39.1
6	Panjab	62.0	31.3	30.7	0.0			62.0	31.3	30.7
7	Waras	99.3	50.4	48.9	0.0			99.3	50.4	48.9
	Total	**398.0**	201.7	196.3	11.0	5.5	5.5	387.0	196.2	190.8

Table 3.1 Bamiyan's minor division and its population [1] (numbers are in 1000)

The project is located in the northwestern region of the Yakawolang division. The topography of the area is characterized by deep valleys and snow fed rivers with poor wind but good solar energies. Site altitude is approximately 3,000 meters. The villages which will be electrified are Sukhtagi, Sum, Dahan-e-Zulej and Chasht. Natives in these villages are mostly farmers. These villages do not have access to electricity, and extending the grid to these villages is very expensive. On the other hand, the government does not have plans in the near future to extend the grid connection. Therefore, the best solution to provide electricity to these rural and valley villages is to integrate renewable energies together to provide electricity.

3.3 Load Estimation and Demand

Electric power is the most adaptable energy source that can be used to meet any kind of energy demand. However, based on the availability of renewable energy resources a small hybrid power system is the most appropriate system to be implemented. The electrical energy supplied by the hybrid power system is assumed to be used by small household appliances, lighting and entertainment in each village.

The primary load is residential with some load for stores, and schools. There is no industrial or commercial load demand. The load is composed of the household devices such as lights, fans, TVs and radios. Note that refrigerators, ironing devices and other heavy electric equipment are not included in the calculation for houses and schools. It is assumed that the houses are divided into two categories i.e. small/medium and large houses. The estimated energy consumed by each of the categories is shown in Table 3.2. The table shows estimation of each appliance's rated power, its quantity and the hours of use by each house, store and school in a single day. The miscellaneous load is for unknown loads in each category.

	Load Types	Rated power (Watt)	Quantity	Hours	Energy (Wh/day)	Total energy (kWh/day)
Small/ Medium Houses	Radio	15	1	7	105	1.91
	TV	80	1	9	720	
	Light	20	3	4	240	
	Fan	50	1	5	300	
	Miscellaneous load	20	1	24	480	
Large Houses	Radio	15	1	7	120	2.38
	TV	80	1	9	640	
	Light	20	5	4	400	
	Fan	50	2	5	600	
	Miscellaneous load	20	1	24	480	
Stores	Refrigerator	100	1	8	1200	2.4
	Light	20	4	5	640	
	TV	80	1	9	800	
	Miscellaneous load	20	1	24	480	
School	Light	20	10	7	1400	4.24
	Fan	50	10	7	3500	
	Miscellaneous load	20	1	24	480	

Table 3.2 Load types and estimation

It is assumed that there are 430 houses in total in the four villages: 80 large houses and 350 small/medium houses, 10 stores and two schools. It is important to note that the fans are not used during the winter and parts of spring and fall seasons. Since fans contribute significant loads in the system, the total estimated energy consumed is separated into two different six month periods for more accuracy. The estimated hourly loads of the warmer and cooler parts of the year, based on the information given in Table 3.2, are given by Fig 3.3 and Fig 3.4. Details of calculation are given in appendix B.

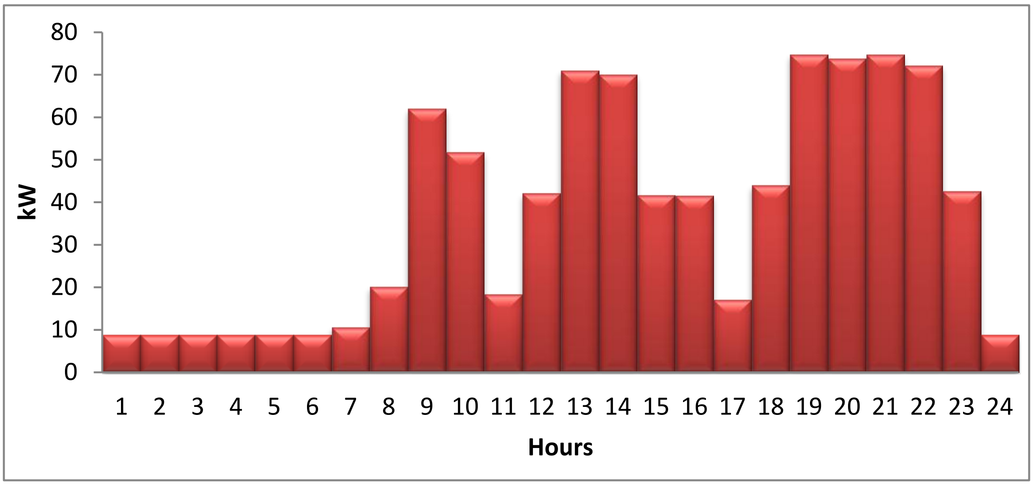

Figure 3.3 Approximate Average load demand for a day in the warmer period (Apr - Sep)

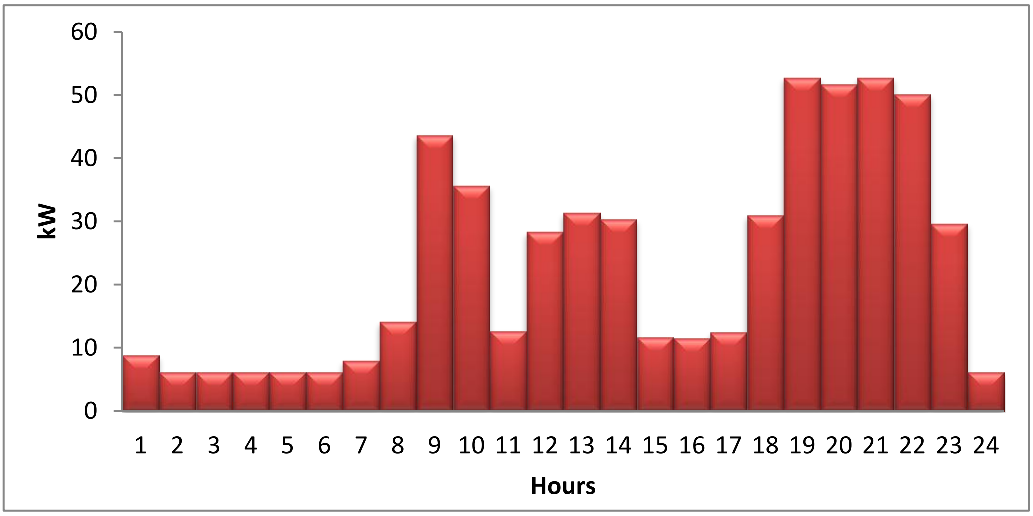

Figure 3.4 Approximate Average load demand for a day in the cooler period (January – Feb and Nov-Dec)

The total estimated peak load is not the actual peak load that will be seen by the system, because all the loads allocated for a certain time period might not be switched on at the same time. Therefore, a coincident factor is applied to the load data. Based on experience and engineering judgment, the coincidence factor is assumed to be 0.8. Additionally a 10% spinning reserve is assumed in the system as well. To import the load data into HOMER hourly load profile for the whole year is required. A load profile of 8,760 hours was thus created for a year based on hourly estimated load for different months.

3.4 Renewable Resources Assessment of the Project

3.4.1 Wind and Solar: Estimated high-resolution annual wind power potential for Afghanistan is developed by NREL's empirical validation methodology using a numerical modeling approach. The high resolution annual and seasonal solar resource maps were also developed by NREL using weather satellite data incorporated into a site-time by State University of New York at Albany in the United States [16].

Data of wind and solar were developed in the Geographic Information Systems (GIS) format and incorporated into a Geospatial Toolkit (GsT). GsT provides monthly average wind and solar data of every province in Afghanistan and helps engineers use these data to develop a renewable project [16].

HOMER simulates the system with either hourly wind speed and solar radiation data in a period of a year, or monthly average wind speed and solar radiation data. Since the hourly wind speed and solar radiation data do not available, the system is designed with monthly average wind speed and solar data provided by NREL [16]. The Table 3.3 and 3.4 show the average solar radiation and wind speed data for the selected site.

Month	Clearness Index	Average Radiation ($kWh/m^2/day$)
Jan	0.450	2.293
Feb	0.457	2.936
Mar	0.490	4.028
Apr	0.601	5.987
May	0.642	7.131
Jun	0.698	8.050
Jul	0.712	8.044
Aug	0.732	7.582
Sep	0.750	6.594
Oct	0.738	5.119
Nov	0.557	2.997
Dec	0.334	1.565
Scaled annual Ave		**5.194**

Table 3.3 Solar data, provided by NREL in Geospatial Toolkit format [16]

Month	Wind Speed (m/s)
Jan	4.655
Feb	5.064
Mar	5.054
Apr	4.655
May	5.395
Jun	5.375
Jul	4.966
Aug	4.733
Sep	4.723
Oct	4.460
Nov	4.450
Dec	4.528
Scaled annual Ave	**4.97**

Table 3.4 Wind data, provided by NREL in Geospatial Toolkit format [16]

Wind power density (W/m^2) at 50-m above ground level and high resolution seasonal latitude solar radiation maps are shown in appendix C.

3.4.2 Hydro: Unfortunately, there is no accurate data of stream flow in Afghanistan. Data on stream flow is financially difficult for the government to survey and obtain over all across Afghanistan. Most of the rivers are due to snow and precipitation. Therefore, flow volume varies by season. However, the flow of water is higher during warm seasons, because of snow-melting. On average, April to August have higher water flow than other months and August and September have lower volume.

Band-e-Amir, which is located in Bamiyan province, has a minimum flow of approximately 200 l/s during the dry season, based on a survey in 2003 [8]. Geographically the two rivers, Band-e-Amir and Darya-ye-Band-e-Amir are located in the same province and the weather is similar. Because of the lack of survey and flow data of the proposed river, the flow of the Darya-ye Band-e-Amir is assumed to be half of the Band-e-Amir in worst case scenario. A stream flow profile was created for the proposed river based on the seasonal weather of the site and is shown in Fig 3.5. The available head of the river is assumed to be 20 meters.

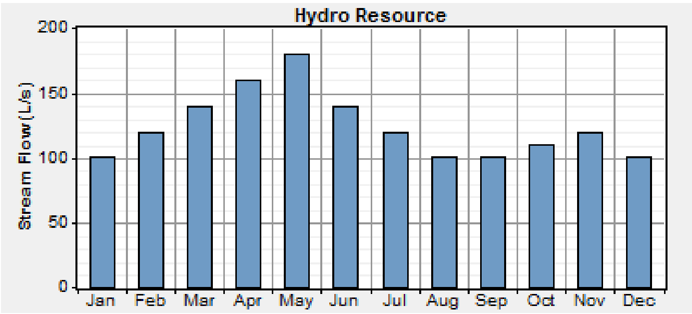

Figure 3.5 Stream flow profile

3.5 Simulation Data

In order to estimate the cost of a hybrid power system, it is required to provide availability of renewable energy over a period of one year and details of each component. The available renewable resources are already discussed for the selected site. The details of each component include capital cost, replacement cost, operation and maintenance cost, diesel cost and some other constraints which will be introduced in the following discussion. HOMER simulates the system with different combinations of the available sources. The output includes the capital cost, net present worth, energy per kWh cost, component size and other electrical characteristics.

In this project, available power sources are expected to be micro-hydropower, PV, wind turbine, diesel generator, and battery storage. HOMER simulates the different combinations of these power sources and provides the best optimal combination. The characteristics of each source and component are explained in the following sections.

3.5.1 Micro-hydropower:

The specific cost of micro-hydroelectric stations varies from $400 to $800 per kW of established capacity. The transportation and civil work add another $600 to $1,200 per kW. In general, expenses are determined by the condition and cost of transportation, civil work, and technology offered in the topographic area. For this project, different micro-hydroelectric generators and civil work costs were investigated and finally capital, replacement, operation and maintenance costs estimated to be $43,000, $10,000, and $500/year respectively [8].

Type	**Permanent magnet alternator**
Power output	30 kW
Voltage	380V AC, 3 phase
Frequency	50 Hz
Water Head Range	30 – 40 meters
Water Flow	90 – 120 liter/second
Inlet Pipe Diameter	250 - 300 mm
Cost	$16,000

Table 3.5 Generator Characteristics [17]

$$Capital\ Cost = Generator + Installation\ cost$$

$$Capital\ Cost = \$16000 \ \ + 30\ kW * \frac{\$900}{kW} = \$43000$$

The capital cost includes the electrical parts as well as engineering. HOMER can only consider a single size of hydro system. For this reason, the Hydro Inputs Window does not contain tables of different costs or sizes to be considered. Thus, the cost and properties of the size of hydro system should be specified. The characteristics of the considered generator are given in Table 3.5. The detailed summary inputs required by HOMER are shown in Table 3.6.

Hydroelectric Generator		Properties of the hydro	
Size	30 kW	Available head (m)	20
Capital ($)	43,000	Design flow rate (L/s)	100
Replacement ($)	16,000	Min flow ratio (%)	90
O&M ($/year)	500	Max flow ratio (%)	120
Lifetime (year)	30	Efficiency (%)	80
Generator type	AC	Pipe head loss (%)	0.968

Table 3.6 Cost specifications and properties of the hydro system

3.5.2 Photovoltaic System:

In general, the PV costs $1.60/W, but may be more depending on the technology used by PV arrays. The capital costs of a PV system include: the PV array cost and other costs such as labor, installation and structure costs. Different PV arrays costs were investigated and finally a 1kW PV array cost was assumed to be $1600 [18]. Civil work also contributes a significant portion of the capital cost and based on labor wages and materials in Afghanistan, it is assumed to be $600/kW.

$$Capital\ Cost\ (1kW) = PVs + Installation(worker\ wages\ and\ civil\ materials)\ cost$$

$$Capital\ Cost\ (1kW) = \frac{\$1600}{kW} + \frac{\$600}{kW} = \$2200$$

The replacement cost is almost equivalent to the capital cost. Operating and maintenance costs are not high for a PV system. The detailed summary inputs required by HOMER are shown Table 3.7.

Size (kW)	1	Derating factor	90%
Capital ($)	2200	Slope	35 deg
Replacement ($)	2200	Azimoth	0 deg
O&M ($/year)	100	Ground reflection	20%
Lifetime (year)	25	Tracking System	No tracking
Size to consider	0,1,2,…, 100		

Table 3.7 PV's cost specifications and installation characteristics

3.5.3 Wind Turbine:

Wind turbine cost varies based on the technology used and tower heights. Costs of civil work and installation of wind turbines also vary based on site condition and turbine size. The wind turbine that was chosen to be installed in the system is 10 kW BWC Excel-S w/ Powersync and fortunately it also exists in the HOMER database. The power output curve of the turbine is shown in Fig 3.6.

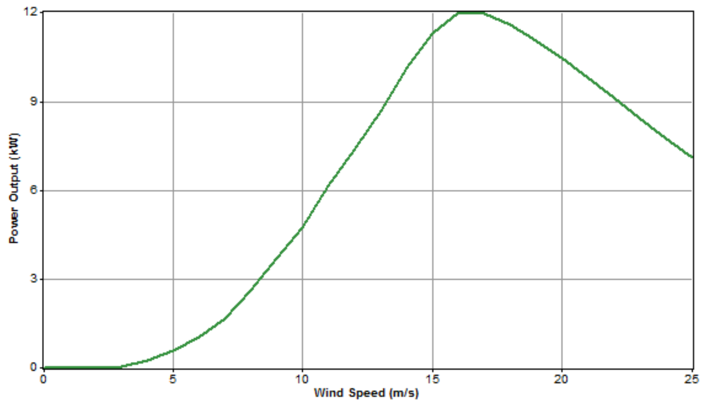

Figure 3.6 Power output of wind turbine

The turbine costs about $50,000 [19] and it includes 100-ft. guyed lattice tower kit, inverter and tower wiring kit. Installation costs of the turbine range between $10,000 and $15,000 in the selected site including the civil materials and worker wages. Therefore, capital cost associated with the turbine is calculated as follows:

$$Capital\ Cost\ (1\ unit) = Turbine\ cost + Installation(worker\ wages\ and\ civil\ materials)\ cost$$

$$Capital\ Cost\ (1\ unit) = \$50{,}000\ + \$15{,}000\ = \$65{,}000$$

The detailed summary inputs to HOMER are shown in Table 3.8.

Capital ($)	65000
Replacement ($)	50000
O & M ($/year)	500
Quantity Considered	0,1,2,3,4,5,6,7,8,9,10
Life Time	25
Hub height	30 m
Power Rated	10 kW

Table 3.8 Wind turbine inputs

3.5.4 Diesel Generator:

The cost of generators varies based on size and brand. A list of generator sizes by different manufacturers is shown in Table 3.9 [14].

Type	Diesel Engine	Rated PowerKW	Unit Price in S with different Generator			
			Chinese	Stamford	Siemens	Marathon
7KW	403C-11G	9.4/8.5	5,074.63	NA	NA	NA
10KW	403C-15G	13.3/12	5,552.24	NA	NA	NA
15KW	404C-22G	20.4/18.5	6,567.16	NA	NA	NA
24KW	1103A-33G	30.4/27.7	7,014.93	NA	NA	NA
50KW	1104A-44TG1	59/53	11,343.28	12,029.85	11,686.57	11,791.04
75KW	1104C-44TAG2	98/89	13,880.60	15,074.63	14,776.12	14,686.57
120KW	1006TAG2	143/129.5	19,253.73	20,835.82	20,626.87	20,447.76
150KW	1106D-E66TAG4	174/156.7	23,582.09	25,268.66	24,925.37	24,820.90
200KW	1306C-E87TAG6	239/218	33,134.33	35,000.00	34,328.36	34,626.87
250KW	2306C-E14TAG1	304/261	35,223.88	37,611.94	36,567.16	37,059.70
300KW	2306C-E14TAG2	344/304	36,567.16	39,253.73	37,313.43	38,686.57
320KW	2306C-E14TAG3	387/344	40,597.01	43,134.33	41,194.03	42,552.24
350KW	2506C-E15TAG1	435/396	49,850.75	52,238.81	51,194.03	52,089.55
400KW	2506C-E15TAG2	478/435	52,537.31	55,671.64	54,328.36	55,537.31
500KW	2806A-E18TAG1	556/482	73,731.34	77,358.21	74,776.12	76,895.52
520KW	2806A-E18TAG2	611/556	80,746.27	84,776.12	82,089.55	84,328.36
800KW	4008TAG2A	947/861	138,059.70	145,373.13	139,402.99	145,074.63
1000KW	4012-46TWG2A	1154/1044	202,985.07	210,597.01	204,328.36	209,402.99

Table 3.9 Perkins Diesel Generator Price List (in USD)

The operating and maintenance costs of diesel generators are high due to the consumption of diesel and lubricant. Different sizes of generators are selected so to allow HOMER to simulate the system with these sizes and determine the optimal size of the generator. The installation cost is assumed $4000 per generator. The operation and maintenance cost varies based on each generator size and it is typically higher for higher size of generator. Diesel prices in Afghanistan were last reported at $1.50/liter, and the lubrication price reported was also $1.50/liter. The emission penalty is fixed to $2.25/l as per international standard. The selected generator sizes, capital, replacement, operation and maintenance and diesel cost are shown in Table 3.10.

Size (kW)	Capital ($)	Replacement ($)	O & M ($/hr)	Life time (hr)	diesel ($/l)
7	9074	6074	0.600	17520	1.5
10	9552	6552	0.800		
15	10657	7357	0.800		
20	11014	8014	1.000		
50	15343	12343	1.200		

Table 3.10 Diesel generator sizes and their cost characteristics

Due to the different diesel prices in the market, a sensitivity analysis for the diesel cost was considered as well at $1.50/l, and $1.60/l.

3.5.5 Inverters and Control Charger:

Costs of inverters and control chargers vary based on their sizes. Often they decrease per kW when the size is increased. Different sizes of inverters and control chargers were considered in order for HOMER to simulate the system with different sizes and determine the optimal size and cost. The inverters and control charger sizes and their costs are shown in Table 3.11 [18].

Size (kW)	Capital ($)	Replacement ($)	O & M ($/hr)	Life time (year)
3.000	2300	2300	0	25
3.800	3400	3400	0	
5.000	4500	4500	0	
6.000	5000	5000	0	
10.00	6500	6500	0	

Table 3.11 Inverter and control charger cost characteristics [18]

3.5.6 Battery Storage:

Battery storage is considered in the system so that when the load demand is less than the available renewable energy, the excess energy can be stored in battery storage. Battery will supply stored energy when the load demand increases in the system. Although battery storage needs regular maintenance, it is less expensive than running a generator in the long term. However, HOMER will analyze the system with different combinations, both with diesel generator and battery storage separately and will provide the optimal solution. Trojan L16P battery type was selected and the capital, replacement and operation and maintenance costs associated with it are $360, $300 and $15 respectively [18].

3.5.7 Other Constraints:

Since the diesel price varies during the life-cycle of the system, sensitivity variables are introduced on diesel prices and they are $1.50/l and $1.60/l in order to investigate the total cost of the system with each diesel price. Additionally, sensitivity variables were added also on the height of the wind turbine and they are 30-m and 50-m to inspect the impact of wind turbine height in the system. Moreover, a 10% spinning reserve was considered for an incident increase in load demand.

Two scenarios were introduced to be simulated. The first scenario is taking in to consideration that there will not be any energy shortage in the system or in other word customers will not have an outage due to the energy shortage in the system. the second scenario a 14.3% annual energy shortage is considered based on the number of houses. Total houses are 430 and 14.3% is a total of 62 houses that will meet an outage once a week.

3.6 Results and Discussions

The schematic diagram of the project is shown in Fig. 3.7.

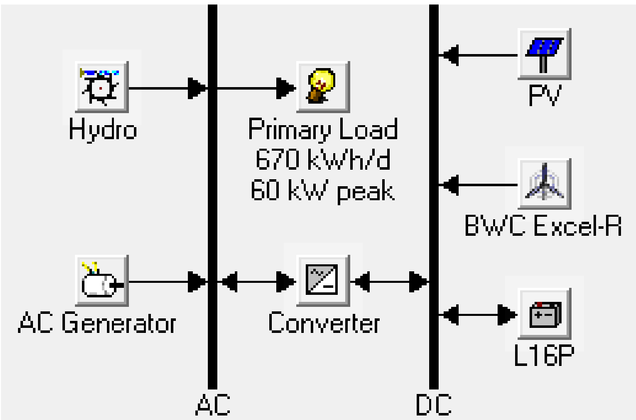

Figure 3.7 Schematic diagram of the project

The inputted data treated by the software described the renewable energy availability, load demand, hybrid system component costs (PV array, hydro turbine, converter and diesel generator) and sizes as mentioned in previous sections. The system's simulations are performed by HOMER for each of the 8,760 hours in a year. The output consists of different combinations of each source, with net present and initial cost of each of them. The simulation took two scenarios into consideration: fist no annual shortage of energy in the system and second a 14.3% annual shortage of energy in the system. It should be noted that for each scenario 10% of spinning reserve is taken into consideration for an unexpected increase in load demand.

3.6.1 First Scenario:

In this scenario, there is no annual shortage of energy in the system, which means that the electricity will be available without an outage. After simulation, HOMER provides several combinations of available power sources with their total net present worth, initial capital cost, energy per kWh cost, and the total system configuration and component sizes that meet the load requirement. Simulation results which include each component size, each system configuration's costs and total net present worth are shown in Fig. 3.8 with selected diesel price of $1.50/liter and wind turbine height of 30-m.

PV (kW)	G10	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20		27.5		300	40	$ 248,948	18,701	$ 512,516	0.149	1.00	
21		27.5	7	300	40	$ 260,222	18,442	$ 520,142	0.151	1.00	
29	1	27.5		250	40	$ 303,748	16,901	$ 541,947	0.157	1.00	
29	1	27.5	7	250	40	$ 312,822	16,777	$ 549,272	0.159	1.00	
		27.5	40	350	35	$ 228,457	29,681	$ 646,776	0.188	0.95	5,880
	1	27.5	40	300	35	$ 263,457	27,705	$ 653,935	0.190	0.96	5,165
30		27.5	40		15	$ 134,890	45,801	$ 780,406	0.226	0.83	27,027
29	1	27.5	40		15	$ 185,690	45,498	$ 826,936	0.240	0.84	26,506
		27.5	40			$ 56,900	59,162	$ 890,721	0.258	0.76	35,123
	1	27.5	40		10	$ 115,313	58,715	$ 942,846	0.274	0.77	34,495
30	1		60	150	18	$ 206,811	120,600	$ 1,906,548	0.553	0.25	69,299
30			60	200	18	$ 171,811	124,397	$ 1,925,056	0.559	0.22	71,339
	3		60	150	17	$ 245,133	139,416	$ 2,210,061	0.641	0.11	81,041
			60	150	15	$ 82,776	153,759	$ 2,249,853	0.653	0.00	90,488
30			70		20	$ 104,611	185,326	$ 2,716,583	0.788	0.18	112,868
30	1		70		20	$ 157,611	184,271	$ 2,754,712	0.799	0.20	111,853
			70			$ 18,229	200,239	$ 2,840,387	0.824	0.00	122,689
	1		70		10	$ 76,642	198,978	$ 2,881,028	0.836	0.03	121,520

Figure 3.8 HOMER simulation results for the first scenario

The first optimal system configuration, in terms of total net present worth, is the combination of the solar arrays, micro-hydropower, battery storage and inverter as shown in the first row of Fig. 3.8. The second optimum system configuration is the combination of solar arrays, micro-hydropower, diesel generator, battery storage, and inverter. The diesel generator in this combination is utilized only during peak time. The third optimum system configuration is the combination of PVs, wind turbine, micro-hydropower, battery storage, and inverter. In this combination the available energy by each renewable sources, during which the peak demand is low, will be stored in battery storage. Then all renewable sources including battery storage will contribute together to respond to the peak demand. The fourth system configuration is the combination of all sources, such as PVs, wind turbine, micro-hydropower, diesel generator, battery storage, and inverter. The most expensive system configuration is the last row, which is a combination of diesel generator and wind turbine.

The solar source is available only during day time. Since the maximum output of PVs is during the mid-day the solar power can take care of the peak load in the mid-day where micro-hydropower alone would not be able to respond to the total demand. During the time where the demand is low, the excess energy produced by micro-hydro and PVs is used to charge the batteries. The highest load demand is during evenings. Since PVs do not produce power, the battery storage will produce enough power to meet load requirement during peak time. Micro-hydropower will run all the year and supply power to the base load.

Furthermore, since the price of diesel varies during the lifetime of the system, sensitivity variables were added to simulate and obtain the costs of each system with different average diesel prices during the lifetime of each system. Additionally, sensitivity variables were introduced on the height of the wind turbine as well to check the impact of turbine height on the system. After simulation of each scenario by HOMER, the results of the two best optimal and the two most expensive combinations, based on the selected diesel price and wind turbine height, are shown in the following Tables.

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best combination	20	0	27.5	0	300	40	248,948	512,516	0.149
Second best combination	21	0	27.5	7	300	40	260,222	520,142	0.151
Second most expensive combination	0	0	0	70	0	0	18,229	2,840,387	0.824
The most expensive combination	0	1	0	70	0	10	76,642	2,881,028	0.836

Table 3.12 Results of the system configuration with diesel price of $1.50/liter, turbine height 30-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best combination	20	0	27.5	0	300	40	248,948	512,516	0.149
Second best combination	21	0	27.5	7	300	40	260,222	520,142	0.151
Second most expensive combination	0	0	0	70	0	0	18,229	2,840,387	0.824
The most expensive combination	0	1	0	70	0	10	76,642	2,875,434	0.834

Table 3.13 Results of the system configuration with diesel price of $1.50/liter, turbine height 50-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best combination	20	0	27.5	0	300	40	248,948	512,516	0.149
Second best combination	21	0	27.5	7	300	40	260,222	520,142	0.151
Second most expensive combination	0	0	0	70	0	0	18,229	3,013,304	0.874
The most expensive combination	0	1	0	70	0	10	76,642	3,052,297	0.886

Table 3.14 Results of the system configuration with diesel price of $1.60/liter, turbine height 30-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best combination	20	0	27.5	0	300	40	248,948	512,516	0.149
Second best combination	21	0	27.5	7	300	40	260,222	520,142	0.151
Second most expensive combination	0	0	0	70	0	0	18,229	3,013,304	0.874
The most expensive combination	0	1	0	70	0	10	76,642	3,046,332	0.884

Table 3.15 Results of the system configuration with diesel price of $1.60/liter, turbine height 50-m

The most optimum combination is the first row of each of the previous tables and it consists of PVs, micro-hydro, battery storage and inverter. Since wind turbine and diesel generator are not included in this combination, the total net present worth of the system and energy cost per kWh are not changed with different diesel prices and different wind turbine heights as shown in Table 3.12, 3.13, 3.14, and 3.15.

The second best combination is given in the second row of all the previous tables and it comprises PVs, micro-hydropower, diesel generator, battery storage, and inverter. Wind turbine is not included in this combination; therefore there is no change on the costs due to the turbine heights. Since the diesel generator only gets online during peak time and it has a small size, the total net present worth and energy cost per kWh for each diesel price is similar. The first and second combinations are very similar due to the total net price cost and energy cost per kWh. The differences between total net present worth and energy cost per kWh are about $8,000 and 0.2 cents, which is very insignificant. But since the second combination has a diesel generator, it is recommended that the first combination should be implemented.

The two last rows in each of the previous tables are the most expensive combinations. The second most expensive combination comprises only a 70 kW diesel generator and the impact of diesel price increase from $1.50/l to $1.60/l results in increase of $172,917 in the total net present worth. The energy cost per kWh has also increased by $0.05/kWh in this combination. The most expensive combination, which is the last row of all the previous tables, includes wind turbine and diesel generator. This combination is sensitive to different diesel prices and turbine heights, therefore it has different total net present worth for any combination of turbine heights and diesel prices.

Since the most optimal combination does not have diesel generator and wind turbines, it is insensitive to variation in diesel prices and wind turbine heights. Therefore, the total net present worth and energy cost per kWh will not be changed. Graphs for the total net present worth and energy cost per kWh for all possible combinations, based on diesel price of $1.50/l and turbine height 30-m, are drawn to compare the cost of each combination. In the following graphs, WT, HY, GN, BT, IN are abbreviations for wind turbine, micro-hydropower, diesel generator, battery and inverter respectively. Figs 3.9 and 3.10 show the total net present worth and energy cost per kWh for all possible combinations respectively. The detailed summary of each component of the optimal combination is shown in appendix A.

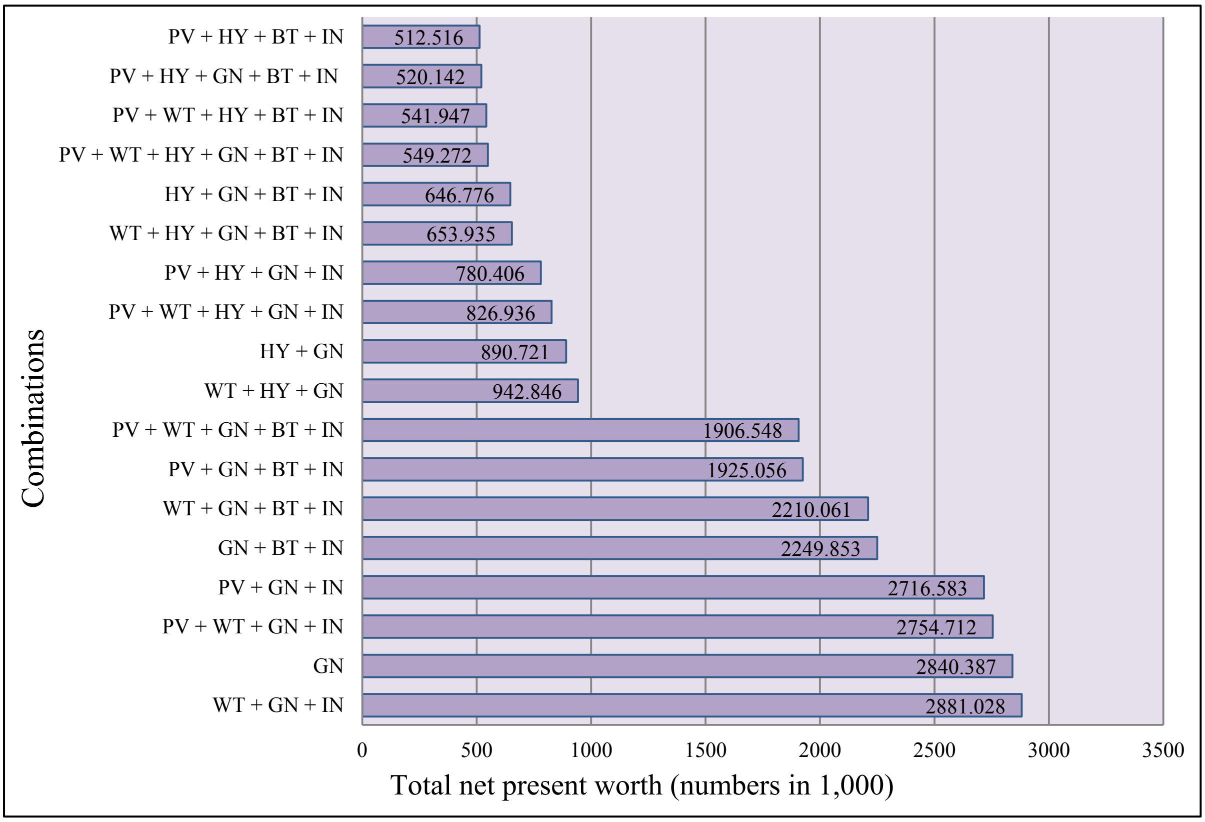

Figure 3.9 Total net present worth of each combination based on system configuration with diesel price of $1.50/l and turbine height 30-m

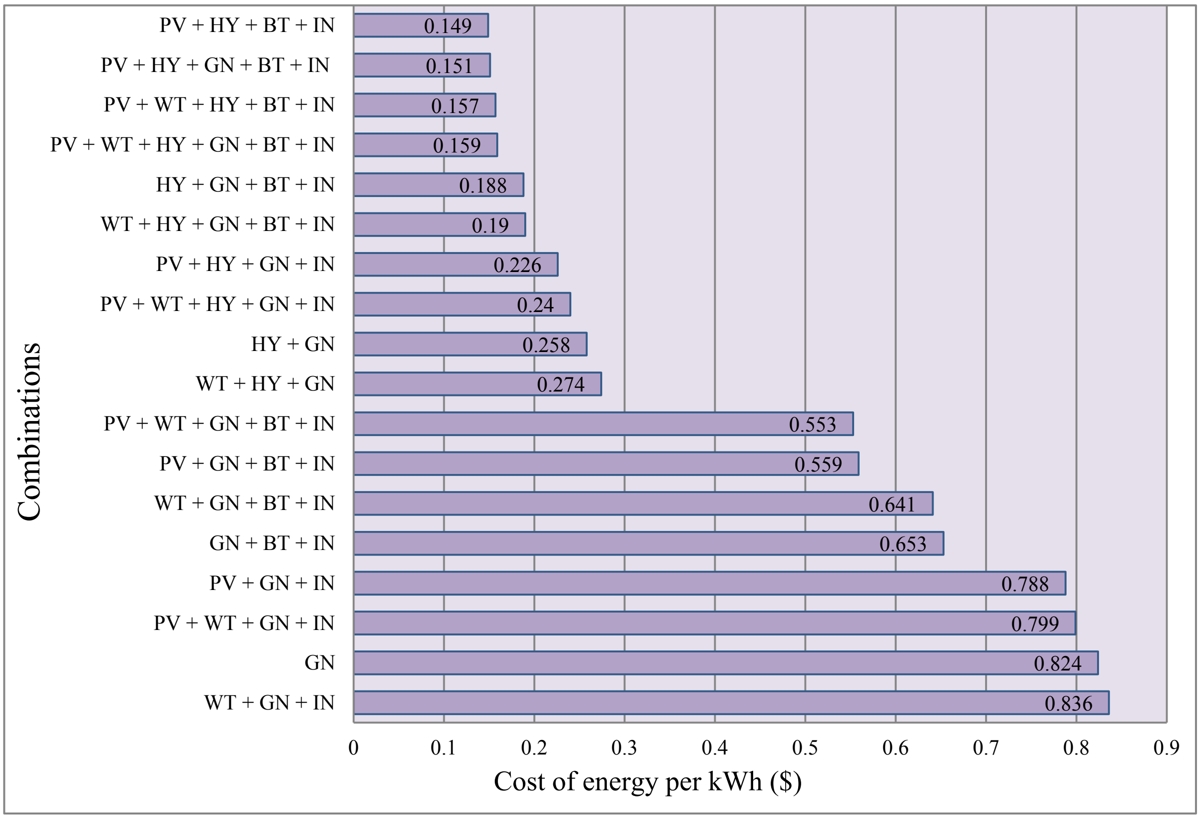

Figure 3.10 The energy cost per kWh of each combination based on system configuration with diesel price of $1.50/l and turbine height 30-m

3.6.2 Second Scenario:

This scenario is designed with a 14.3% annual shortage of energy in the system. It is based on the assumption that the communities do not have more funds to invest in the project and pay less for energy per kWh by introducing certain load and outage management rules. The overall system cost and energy cost per kWh will decrease by having annual energy shortage. An annual energy shortage requires a load management in the system, meaning that certain rules for the communities have to be put in place to manage their energy consumption during peak load hours. If for some reason, the communities do not want to manage their energy consumption during peak time, another solution is that each of the 65 houses will have an outage of power once a week. The simulation results of each combination of power sources, with a 14.3% annual energy shortage, is shown in Fig 3.11 with diesel price of $1.50/l and wind turbine height of 30-m.

Sensitivity variables

Diesel Price ($/L) 1.5 XLR Hub Height (m) 30

Double click on a system below for simulation results.

PV (kW)	XLR	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
19		27.5		180	17	$ 164,947	11,848	$ 331,928	0.105	1.00	0.14	
20	1	27.5		160	17	$ 212,947	11,157	$ 370,193	0.117	1.00	0.14	
13		27.5	7	110	10	$ 125,687	19,076	$ 394,546	0.125	0.94	0.14	6,241
26		27.5	13		15	$ 122,405	21,407	$ 424,110	0.136	0.91	0.14	11,598
11	1	27.5	7	110	10	$ 174,287	18,625	$ 436,788	0.139	0.94	0.14	6,135
		27.5	7	180	10	$ 122,287	23,754	$ 457,080	0.145	0.93	0.14	6,904
27	1	27.5	12		18	$ 182,419	20,040	$ 464,866	0.149	0.92	0.14	10,402
	1	27.5	7	140	10	$ 160,887	22,132	$ 472,808	0.150	0.94	0.14	6,524
		27.5	17			$ 53,800	33,276	$ 522,784	0.166	0.84	0.14	18,843
	5	27.5		180	17	$ 388,147	11,753	$ 553,787	0.176	1.00	0.14	
	1	27.5	16		10	$ 112,141	31,861	$ 561,182	0.178	0.85	0.14	17,643
30	4		30	180	17	$ 370,604	95,947	$ 1,722,872	0.550	0.38	0.14	51,211
30			60	160	18	$ 157,411	124,290	$ 1,909,147	0.554	0.22	0.00	71,327
30	5		40		25	$ 373,673	116,892	$ 2,021,145	0.638	0.37	0.14	69,610
	3		40	150	10	$ 232,313	129,730	$ 2,060,717	0.639	0.12	0.11	74,016
30			50		20	$ 101,725	146,741	$ 2,169,886	0.666	0.20	0.09	88,680
			40	170	10	$ 80,513	148,423	$ 2,172,376	0.674	0.00	0.11	84,644
			50			$ 15,343	161,235	$ 2,287,782	0.709	0.00	0.11	98,263
	1		50		10	$ 73,756	160,698	$ 2,338,624	0.718	0.04	0.11	97,574

Figure 3.11 HOMER simulation results for the second scenario

In this scenario, the total net present worth and costs of energy per kWh are significantly lower than the first scenario, i.e. without any annual energy shortage. The results in Fig. 3.11 show that the optimum system combination is the first row, which consists of PVs, micro-hydropower, battery storage, and inverter. The initial capital and total net present worth, and energy cost per kWh are much lower than the first scenario. The second best optimum system combination is comprised of PVs, micro-hydropower, wind turbine, and battery storage with inverter. The most expensive system combination is shown in the last row of the simulation results and includes diesel generator and wind turbine.

Since the price of diesel varies during the life-cycle of the system, sensitivity variables were introduced in diesel price during the lifetime of the project in order to simulate and obtain the costs of the system with different diesel prices. Additionally, sensitivity analysis was conducted for the height of the wind turbine. The cost of the first two and last two combinations based on the selected diesel cost and wind turbine height are shown in the following Tables.

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best Combination	19	0	27.5	0	180	17	164,947	331,928	0.105
Second best Combination	20	1	27.5	0	160	17	212,947	370,193	0.117
Second most expensive Combination	0	0	0	50	0	0	15,343	2,287,782	0.709
The most expensive Combination	0	1	0	50	0	10	73,756	2,338,624	0.718

Table 3.16 Results of the system configuration with diesel price of $1.5/liter, turbine height 30-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best Combination	19	0	27.5	0	180	17	164,947	331,928	0.105
Second best Combination	19	1	27.5	0	160	17	210,747	367,116	0.116
Second most expensive Combination	0	0	0	50	0	0	15,343	2,287,782	0.709
The most expensive Combination	0	1	0	50	0	10	73,756	2,336,014	0.716

Table 3.17 Results of the system configuration with diesel price of $1.5/liter, turbine height 50-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best Combination	19	0	27.5	0	180	17	164,947	331,928	0.105
Second best Combination	20	1	27.5	0	160	17	212,947	370,193	0.117
Second most expensive Combination	0	0	0	50	0	0	15,343	2,426,274	0.752
The most expensive Combination	0	1	0	50		10	73,756	2,476,144	0.761

Table 3.18 Results of the system configuration with diesel price of $1.6/liter, turbine height 30-m

System Optimality	PV (kW)	Wind (Quantity)	Hydro (kW)	Generator (kW)	Battery (Quantity)	Inverter (kW)	Initial Cost ($)	Total NPW ($)	Energy cost ($/kWh)
The best Combination	19	0	27.5	0	180	17	164,947	331,928	0.105
Second best Combination	20	1	27.5	0	160	17	210,747	367,116	0.116
Second most expensive Combination	0	0	0	50	0	0	15,343	2,426,274	0.752
The most expensive Combination	0	1	0	50	0	10	73,756	2,473,361	0.758

Table 3.19 Results of the system configuration with diesel price of $1.6/liter, turbine height 50-m

The most optimum combination is the first row of each of the previous tables and includes PVs, micro-hydro, battery storage and inverter. Since wind turbine and diesel generator are not included in this combination, the total net present worth of the system and energy cost per kWh are insensitive to different diesel prices and wind turbine's heights as shown in Table 3.16, 3.17, 3.18, and 3.19.

The second best combination is the second row in all the previous tables and is comprised of PVs, wind turbine, micro-hydropower, battery storage, and inverter. The impact of changing turbine heights from 30-m to 50-m has an increase of $3077 in the total net present worth. The energy cost per kWh has also increased by $0.001/kWh. Since a diesel generator is not included in this combination, different diesel prices do not have any impact in the system's costs. Similarly, changing turbine height from 30-m to 50-m does not have any significant effect in decreasing the overall total costs and cost of energy, because of the weak wind source in the selected site. Therefore, if the second best combination is going to be implemented, a turbine of 30-m height is recommended, since turbine with 50-m height will cost more than the money which will be saved by the higher turbine height.

The two most expensive combinations are the two last rows in the previous tables. The second most expensive combination comprises only a 50 kW diesel generator and the impact of increasing diesel prices from $1.50/l to $1.60/l has an increase of $138,492 in the total net present worth. The energy cost per kWh is also increased by $0.043/kWh in this combination. The most expensive combination, which is the last row of all previous tables, includes wind turbine and diesel generator and therefore it has different total cost for each diesel price and turbine height.

In general, raising turbine height from 30-m to 50-m has insignificant impact on the overall system costs and energy cost per kWh whereas raising diesel prices have more impact in the overall system costs and energy cost per kWh. Since the most optimum combination is insensitive to changes in diesel prices and turbine heights, the total net present worth and energy cost per kWh will not be affected.

Graphs for the total net present worth and energy cost per kWh for all possible combinations, based on diesel price of $1.50/l and turbine height 30-m, are drawn to compare the cost of each combination. In the following graphs, WT, HY, GN, BT, IN are abbreviations for wind turbine, micro-hydropower, diesel generator, battery and inverter respectively. Figs 3.12 and 3.13 show the total net present worth and energy cost per kWh for all possible combinations respectively. The detailed summary of each component of the optimal combination is shown in Appendix A.

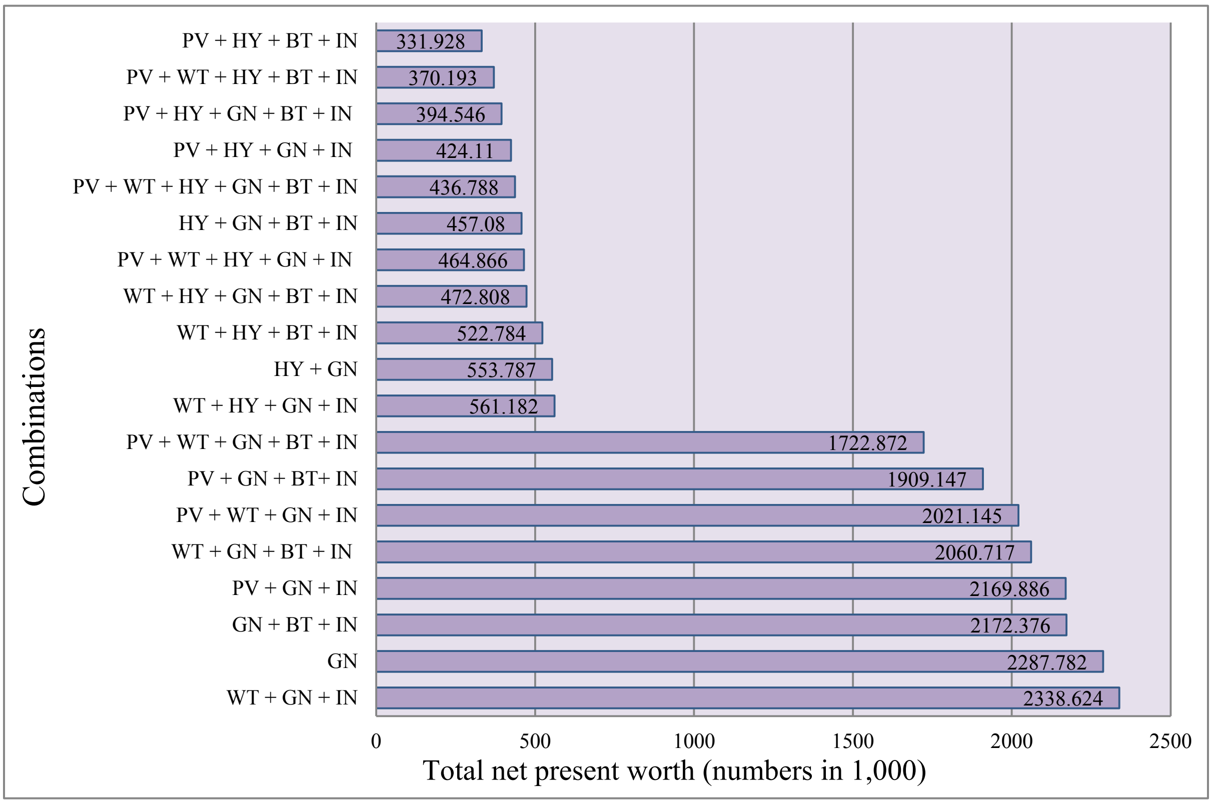

Figure 3.12 Total net present worth of each combination based on system configuration with diesel price of $1.50/l and turbine height 30-m

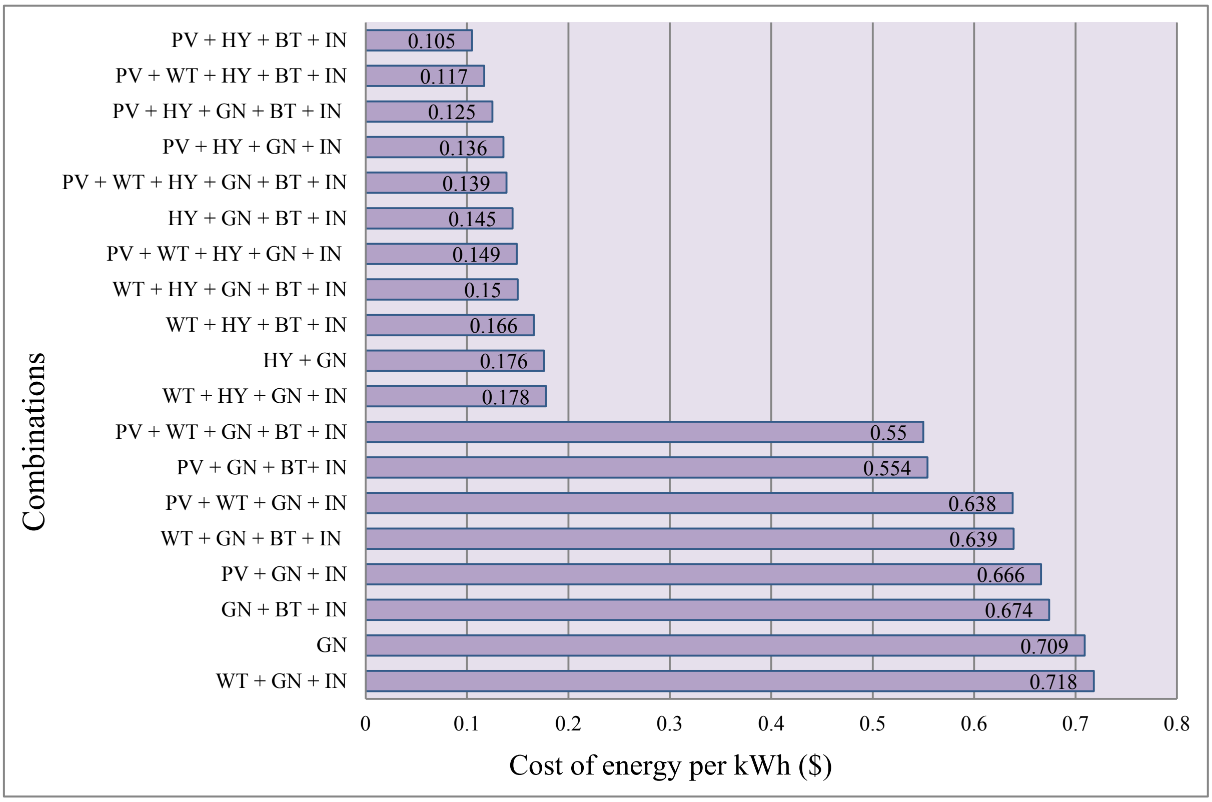

Figure 3.13 The energy cost per kWh of each combination based on system configuration with diesel price of $1.50/l and turbine height 30-m

From results in the first scenario (without annual energy shortage in the system) and the second scenario (with 14.3% annual energy shortage in the system), it could be observed that the second scenario is more optimal and cost effective. The second scenario can be implemented with certain load management rules in the system.

3.6 Recommendations and Conclusion

The main goal of this project is to show that renewable energy can play a satisfactory role in providing electricity to rural communities. Integrating available renewable energy and implementing as a hybrid power system mitigates the cost of the system and energy per kWh in the long term rather than investing in diesel generators.

Distribution of the load in 24 hours within a community varies, and often the peak demand is during the evening and mid-day. If there is not enough renewable energy to meet the demand during the peak time, there are two solutions that are recommended to meet the load demand during the peak time. First, the system should be designed with a battery storage bank. The battery storage bank will be charged by renewable sources such as micro-hydropower, PVs and wind turbines, when the energy output from these sources is larger than load demand. Usually, load demand is low during nights and energy provided by micro-hydro and wind turbines will be saved in battery storage bank. The second solution is to run a diesel generator during the peak demand time. The proposed project was designed with back-up sources, battery storage and diesel generator. Yet, the results shown in previous sections state that for long term plans, battery storage is more suitable and cost-effective than a diesel generator.

The proposed project was designed and simulated for two different scenarios based on annual energy shortage in the system. Two scenarios were completed in order to discover the optimum results, by having the choice to compare the results against each other. In the first scenario, the system was designed without any annual shortage energy in the system. The resulted costs of the system are

$Initial\ Cost = \$\ 248{,}948 \quad Net\ Present\ Cost = \$512{,}516 \quad Cost\ of energy = \$0.149/kWh$

In the second scenario, the system was designed to have a 14.3% annual energy shortage in the system. The resulted costs of the system are

$Initial\ Cost = \$\ 164{,}947 \quad Net\ Present\ Cost = \$331{,}928 \quad Cost\ of energy = \$0.105/kWh$

By comparing both scenarios, it appears that the costs of the system in the second scenario are much lower than in the first scenario.

The second scenario is recommended to be implemented, because it requires much less financial investment in the long term and the cost of energy per kWh is low. Additionally, the communities can easily provide financially to implement the project by some restrictions on the use of the electricity. The annual shortage of energy will be compensated by putting into place some restrictions of use for the customers during peak time to decrease their energy consumption. Another way to take care of the annual shortage of energy is for approximately 15% of the total houses to have an outage once a week. Note that both scenarios have a 10% spinning reserve for an immediate increase of load in the system.

It should be noted that, wind speed data, which is provided by NREL, is an estimation and it looks poor for the selected site. Generally larger wind turbine size provides more power than small ones. Therefore, to determine an effective size of turbine, wind speed should be measured at the given site. When size of a wind turbine increased, it will become more cost-effective compare to small sizes. As an example, a 2 kW wind turbine costs about $16,000 and 5 of this turbine will cost $80,000, where a 10 kW wind turbine costs about $48,000 [19].

In conclusion, this study shows that developing a stand-alone hybrid power system is more cost effective and suitable for rural communities, while renewable energies are available, than running diesel generators. The result of this study encourages private investors and local community members, especially in Afghanistan, to take advantage of renewable energy and be convinced that there is sustainability in investing in stand-alone hybrid power systems.

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Appendix A

The detailed summary of each component for the first configuration and each scenario are shown:

I. **First Scenario**:

PV (kW)	G10	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20		27.5		300	40	$ 248,948	18,701	$ 512,516	0.149	1.00	
21		27.5	7	300	40	$ 260,222	18,442	$ 520,142	0.151	1.00	
29	1	27.5		250	40	$ 303,748	16,901	$ 541,947	0.157	1.00	
29	1	27.5	7	250	40	$ 312,822	16,777	$ 549,272	0.159	1.00	
		27.5	40	350	35	$ 228,457	29,681	$ 646,776	0.188	0.95	5,880
	1	27.5	40	300	35	$ 263,457	27,705	$ 653,935	0.190	0.96	5,165
30		27.5	40		15	$ 134,890	45,801	$ 780,406	0.226	0.83	27,027
29	1	27.5	40		15	$ 185,690	45,498	$ 826,936	0.240	0.84	26,506
		27.5	40			$ 56,900	59,162	$ 890,721	0.258	0.76	35,123
	1	27.5	40		10	$ 115,313	58,715	$ 942,846	0.274	0.77	34,495
30	1		60	150	18	$ 206,811	120,600	$ 1,906,548	0.553	0.25	69,299
30			60	200	18	$ 171,811	124,397	$ 1,925,056	0.559	0.22	71,339
	3		60	150	17	$ 245,133	139,416	$ 2,210,061	0.641	0.11	81,041
			60	150	15	$ 82,776	153,759	$ 2,249,853	0.653	0.00	90,488
30			70		20	$ 104,611	185,326	$ 2,716,583	0.788	0.18	112,868
30	1		70		20	$ 157,611	184,271	$ 2,754,712	0.799	0.20	111,853
			70			$ 18,229	200,239	$ 2,840,387	0.824	0.00	122,689
	1		70		10	$ 76,642	198,978	$ 2,881,028	0.836	0.03	121,520

Figure A1 System configuration with diesel price of $1.50/liter, turbine height 30-m

PV (kW)	G10	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20		27.5		300	40	$ 248,948	18,701	$ 512,516	0.149	1.00	
21		27.5	7	300	40	$ 260,222	18,442	$ 520,142	0.151	1.00	
27	1	27.5		250	40	$ 299,348	16,917	$ 537,775	0.156	1.00	
27	1	27.5	7	250	40	$ 308,422	16,793	$ 545,101	0.158	1.00	
		27.5	40	350	35	$ 228,457	29,681	$ 646,776	0.188	0.95	5,880
	1	27.5	40	300	35	$ 263,457	27,375	$ 649,284	0.188	0.96	5,095
30		27.5	40		15	$ 134,890	45,801	$ 780,406	0.226	0.83	27,027
30	1	27.5	40		15	$ 187,890	45,113	$ 823,711	0.239	0.84	26,264
		27.5	40			$ 56,900	59,162	$ 890,721	0.258	0.76	35,123
	1	27.5	40		10	$ 115,313	58,475	$ 939,453	0.273	0.77	34,338
30	2		60	200	40	$ 314,734	111,132	$ 1,881,023	0.546	0.30	61,987
30			60	200	18	$ 171,811	124,397	$ 1,925,056	0.559	0.22	71,339
	3		60	150	17	$ 245,133	137,128	$ 2,177,807	0.632	0.13	79,789
			60	150	15	$ 82,776	153,759	$ 2,249,853	0.653	0.00	90,488
30			70		20	$ 104,611	185,326	$ 2,716,583	0.788	0.18	112,868
30	1		70		20	$ 157,611	183,969	$ 2,750,463	0.798	0.21	111,654
			70			$ 18,229	200,239	$ 2,840,387	0.824	0.00	122,689
	1		70		10	$ 76,642	198,581	$ 2,875,434	0.834	0.04	121,256

Figure A2 System configuration with diesel price of $1.50/liter, turbine height 50-m

PV (kW)	G10	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20		27.5		300	40	$ 248,948	18,701	$ 512,516	0.149	1.00	
21		27.5	7	300	40	$ 260,222	18,442	$ 520,142	0.151	1.00	
29	1	27.5		250	40	$ 303,748	16,901	$ 541,947	0.157	1.00	
29	1	27.5	7	250	40	$ 312,822	16,777	$ 549,272	0.159	1.00	
		27.5	40	350	35	$ 228,457	30,269	$ 655,063	0.190	0.95	5,880
	1	27.5	40	300	35	$ 263,457	28,222	$ 661,214	0.192	0.96	5,165
30		27.5	40		15	$ 134,890	48,504	$ 818,498	0.237	0.83	27,027
29	1	27.5	40		15	$ 185,690	48,149	$ 864,294	0.251	0.84	26,506
		27.5	40			$ 56,900	62,674	$ 940,223	0.273	0.76	35,123
	1	27.5	40		10	$ 115,313	62,165	$ 991,464	0.288	0.77	34,495
30	2		50	200	18	$ 276,368	122,192	$ 1,998,533	0.580	0.29	64,661
30			60	200	18	$ 171,811	131,531	$ 2,025,600	0.588	0.22	71,339
	3		60	150	17	$ 245,133	147,521	$ 2,324,280	0.674	0.11	81,041
			60	200	17	$ 104,133	161,076	$ 2,374,333	0.689	0.00	88,129
30			70		20	$ 104,611	196,613	$ 2,875,659	0.834	0.18	112,868
30	1		70		20	$ 157,611	195,456	$ 2,912,357	0.845	0.20	111,853
			70			$ 18,229	212,508	$ 3,013,304	0.874	0.00	122,689
	1		70		10	$ 76,642	211,130	$ 3,052,297	0.886	0.03	121,520

Figure A3 System configuration with diesel price of $1.60/liter, turbine height 30-m

PV (kW)	G10	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Diesel (L)
20		27.5		300	40	$ 248,948	18,701	$ 512,516	0.149	1.00	
21		27.5	7	300	40	$ 260,222	18,442	$ 520,142	0.151	1.00	
27	1	27.5		250	40	$ 299,348	16,917	$ 537,775	0.156	1.00	
27	1	27.5	7	250	40	$ 308,422	16,793	$ 545,101	0.158	1.00	
		27.5	40	350	35	$ 228,457	30,269	$ 655,063	0.190	0.95	5,880
	1	27.5	40	300	35	$ 263,457	27,885	$ 656,465	0.190	0.96	5,095
30		27.5	40		15	$ 134,890	48,504	$ 818,498	0.237	0.83	27,027
30	1	27.5	40		15	$ 187,890	47,739	$ 860,727	0.250	0.84	26,264
		27.5	40			$ 56,900	62,674	$ 940,223	0.273	0.76	35,123
	1	27.5	40		10	$ 115,313	61,909	$ 987,849	0.287	0.77	34,338
30	2		60	200	40	$ 314,734	117,515	$ 1,970,987	0.572	0.30	61,968
30			60	200	18	$ 171,811	131,531	$ 2,025,600	0.588	0.22	71,339
	4		50	200	18	$ 316,368	139,670	$ 2,284,872	0.663	0.17	74,924
			60	200	17	$ 104,133	161,076	$ 2,374,333	0.689	0.00	88,129
30			70		20	$ 104,611	196,613	$ 2,875,659	0.834	0.18	112,868
30	3		70		25	$ 272,002	186,514	$ 2,900,727	0.842	0.27	106,597
			70			$ 18,229	212,508	$ 3,013,304	0.874	0.00	122,689
	1		70		10	$ 76,642	210,707	$ 3,046,332	0.884	0.04	121,256

Figure A4   System configuration with diesel price of $1.60/liter, turbine height 50-m

The following tables show the detail of each component of the first optimum configuration with diesel price $1.50/liter and turbine height 30-m.

Micro-hydropower					
Nominal capacity	27.5	kW	Minimum output	27.2	kW
Mean output	30.6	kW	Maximum output	32.6	kW
Capacity factor	111	%	Hydro penetration	109	%
Total production	267,677	kWh/yr	Hours of operation	8,760	hr/yr
			Levelized cost	0.0131	$/kWh

PV Arrays					
Rated capacity	20.0	kW	Minimum output	0.0	kW
Mean output	4.3	kW	Maximum output	23.1	kW
Mean output	102	kWh/d	PV penetration	15.3	%
Capacity factor	21.3	%	Hours of operation	4,386	hr/yr
Total production	37,346	kWh/yr	Levelized cost	0.0889	$/kWh

Battery							
Nominal capacity	648	kWh	Energy in	66,042	kWh/yr	String size	1
Usable nominal capacity	454	kWh	Energy out	56,580	kWh/yr	Strings in parallel	300
Autonomy	16.2	hr	Expected life	419	kWh/yr	Batteries	300
Lifetime throughput	322,500	kWh	Losses	9,043	kWh/yr	Bus voltage (V)	6

Inverter & Controller							
Capacity	40.0	40.0	kW	Hours of operation	4,374	3,589	hrs/yr
Mean output	7.8	6.2	kW	Energy in	72,215	63,491	kWh/yr
Minimum output	0.0	0.0	kW	Energy out	68,605	53,966	kWh/yr
Maximum output	32.7	21.7	kW	Losses	3,610	9,525	kWh/yr
Capacity factor	19.6	15.4	%	Hours of operation	4,374	3,589	hrs/yr

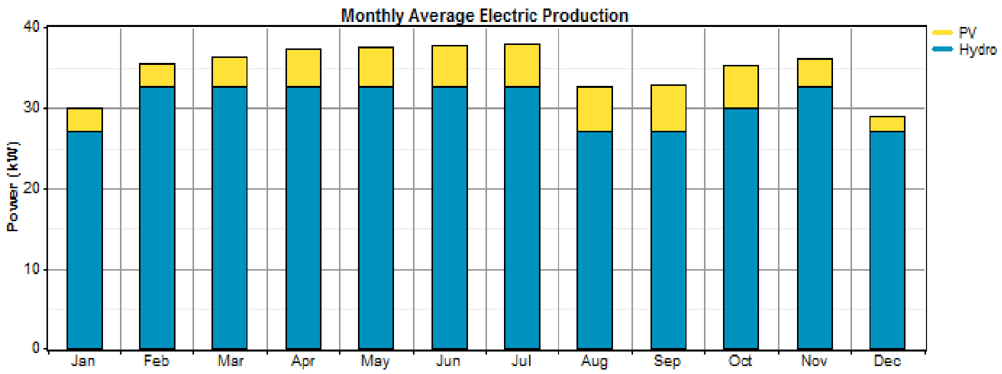


Figure A5 Average monthly electric production

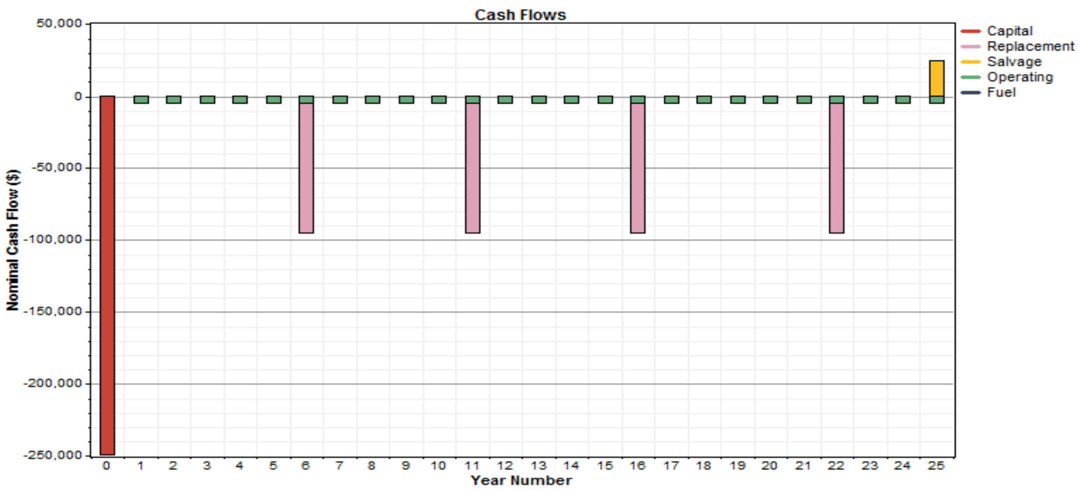


Figure 6   Cash flows of the system based on costs type

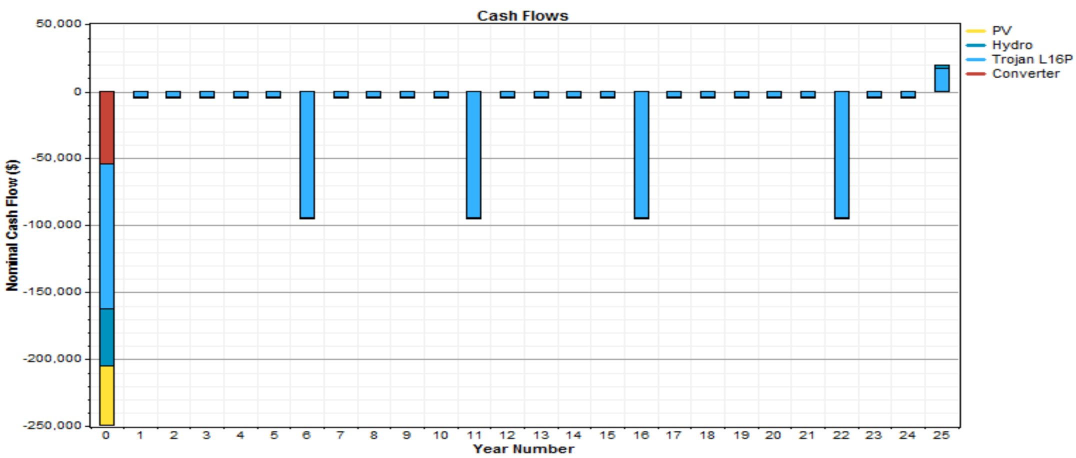


Figure 7 Cash flows of the system based on component type

II. Second Scenario:

Sensitivity variables

Diesel Price ($/L) 1.5 XLR Hub Height (m) 30

Double click on a system below for simulation results.

PV (kW)	XLR	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
19		27.5		180	17	$ 164,947	11,848	$ 331,928	0.105	1.00	0.14	
20	1	27.5		160	17	$ 212,947	11,157	$ 370,193	0.117	1.00	0.14	
13		27.5	7	110	10	$ 125,687	19,076	$ 394,546	0.125	0.94	0.14	6,241
26		27.5	13		15	$ 122,405	21,407	$ 424,110	0.136	0.91	0.14	11,598
11	1	27.5	7	110	10	$ 174,287	18,625	$ 436,788	0.139	0.94	0.14	6,135
		27.5	7	180	10	$ 122,287	23,754	$ 457,080	0.145	0.93	0.14	6,904
27	1	27.5	12		18	$ 182,419	20,040	$ 464,866	0.149	0.92	0.14	10,402
	1	27.5	7	140	10	$ 160,887	22,132	$ 472,808	0.150	0.94	0.14	6,524
		27.5	17			$ 53,800	33,276	$ 522,784	0.166	0.84	0.14	18,843
	5	27.5		180	17	$ 388,147	11,753	$ 553,787	0.176	1.00	0.14	
	1	27.5	16		10	$ 112,141	31,861	$ 561,182	0.178	0.85	0.14	17,643
30	4		30	180	17	$ 370,604	95,947	$ 1,722,872	0.550	0.38	0.14	51,211
30			60	160	18	$ 157,411	124,290	$ 1,909,147	0.554	0.22	0.00	71,327
30	5		40		25	$ 373,673	116,892	$ 2,021,145	0.638	0.37	0.14	69,610
	3		40	150	10	$ 232,313	129,730	$ 2,060,717	0.639	0.12	0.11	74,016
30			50		20	$ 101,725	146,741	$ 2,169,886	0.666	0.20	0.09	88,680
			40	170	10	$ 80,513	148,423	$ 2,172,376	0.674	0.00	0.11	84,644
			50			$ 15,343	161,235	$ 2,287,782	0.709	0.00	0.11	98,263
	1		50		10	$ 73,756	160,698	$ 2,338,624	0.718	0.04	0.11	97,574

Figure A8 System configuration with diesel price of $1.50/liter, turbine height 30-m

Sensitivity variables

Diesel Price ($/L) 1.5 XLR Hub Height (m) 50

Double click on a system below for simulation results.

PV (kW)	XLR	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
19		27.5		180	17	$ 164,947	11,848	$ 331,928	0.105	1.00	0.14	
19	1	27.5		160	17	$ 210,747	11,095	$ 367,116	0.116	1.00	0.14	
13		27.5	7	110	10	$ 125,687	19,076	$ 394,546	0.125	0.94	0.14	6,241
26		27.5	13		15	$ 122,405	21,407	$ 424,110	0.136	0.91	0.14	11,598
10	1	27.5	7	110	10	$ 172,087	18,574	$ 433,868	0.138	0.94	0.14	6,131
		27.5	7	180	10	$ 122,287	23,754	$ 457,080	0.145	0.93	0.14	6,904
27	1	27.5	12		16	$ 179,062	20,175	$ 463,413	0.148	0.92	0.14	10,496
	1	27.5	7	140	10	$ 160,887	21,780	$ 467,859	0.148	0.94	0.14	6,452
	4	27.5		180	17	$ 335,147	11,820	$ 501,736	0.159	1.00	0.14	
		27.5	17			$ 53,800	33,276	$ 522,784	0.166	0.84	0.14	18,843
	1	27.5	16		10	$ 112,141	31,809	$ 560,457	0.177	0.85	0.14	17,609
30	4		30	170	17	$ 367,004	93,677	$ 1,687,288	0.538	0.40	0.14	50,181
30			60	160	18	$ 157,411	124,290	$ 1,909,147	0.554	0.22	0.00	71,327
30	5		40		30	$ 382,065	114,549	$ 1,996,514	0.627	0.40	0.14	68,161
	3		40	140	10	$ 228,713	127,339	$ 2,023,419	0.627	0.14	0.11	72,786
30			50		20	$ 101,725	146,741	$ 2,169,886	0.666	0.20	0.09	88,680
			40	170	10	$ 80,513	148,423	$ 2,172,376	0.674	0.00	0.11	84,644
			50			$ 15,343	161,235	$ 2,287,782	0.709	0.00	0.11	98,263
	1		50		10	$ 73,756	160,513	$ 2,336,014	0.716	0.04	0.11	97,451

Figure A9 System configuration with diesel price of $1.50/liter, turbine height 50-m

Sensitivity variables

Diesel Price ($/L) 1.6 XLR Hub Height (m) 30

Double click on a system below for simulation results.

PV (kW)	XLR	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
19		27.5		180	17	$ 164,947	11,848	$ 331,928	0.105	1.00	0.14	
20	1	27.5		160	17	$ 212,947	11,157	$ 370,193	0.117	1.00	0.14	
13		27.5	7	110	10	$ 125,687	19,700	$ 403,342	0.128	0.94	0.14	6,241
27		27.5	13		15	$ 124,605	22,409	$ 440,436	0.141	0.91	0.14	11,512
11	1	27.5	7	110	10	$ 174,287	19,239	$ 445,435	0.141	0.94	0.14	6,135
		27.5	7	180	10	$ 122,287	24,445	$ 466,811	0.148	0.93	0.14	6,904
27	1	27.5	12		19	$ 184,097	20,959	$ 479,496	0.153	0.92	0.14	10,327
	1	27.5	7	140	10	$ 160,887	22,784	$ 482,003	0.153	0.94	0.14	6,524
		27.5	17			$ 53,800	35,160	$ 549,342	0.174	0.84	0.14	18,843
	5	27.5		180	17	$ 388,147	11,753	$ 553,787	0.176	1.00	0.14	
	1	27.5	16		10	$ 112,141	33,625	$ 586,048	0.186	0.85	0.14	17,643
30	4		30	180	17	$ 370,604	101,068	$ 1,795,048	0.573	0.38	0.14	51,211
30			60	160	18	$ 157,411	131,423	$ 2,009,675	0.583	0.22	0.00	71,327
30	5		40		25	$ 373,673	123,853	$ 2,119,253	0.669	0.37	0.14	69,610
	4		40	140	10	$ 281,713	133,477	$ 2,162,933	0.671	0.15	0.11	72,191
			40	170	10	$ 80,513	156,887	$ 2,291,674	0.711	0.00	0.11	84,644
30			50		20	$ 101,725	155,609	$ 2,294,871	0.704	0.20	0.09	88,680
			50			$ 15,343	171,061	$ 2,426,274	0.752	0.00	0.11	98,263
	1		50		10	$ 73,756	170,455	$ 2,476,144	0.761	0.04	0.11	97,574

Figure A10 System configuration with diesel price of $1.60/liter, turbine height 30-m

Sensitivity variables

Diesel Price ($/L) 1.6 XLR Hub Height (m) 50

Double click on a system below for simulation results.

PV (kW)	XLR	Hydro (kW)	AC GE (kW)	L16P	Conv. (kW)	Initial Capital	Operating Cost ($/yr)	Total NPC	COE ($/kWh)	Ren. Frac.	Capacity Shortage	Diesel (L)
19		27.5		180	17	$ 164,947	11,848	$ 331,928	0.105	1.00	0.14	
19	1	27.5		160	17	$ 210,747	11,095	$ 367,116	0.116	1.00	0.14	
13		27.5	7	110	10	$ 125,687	19,700	$ 403,342	0.128	0.94	0.14	6,241
27		27.5	13		15	$ 124,605	22,409	$ 440,436	0.141	0.91	0.14	11,512
11	1	27.5	7	110	10	$ 174,287	19,031	$ 442,510	0.140	0.94	0.14	6,119
		27.5	7	180	10	$ 122,287	24,445	$ 466,811	0.148	0.93	0.14	6,904
	1	27.5	7	140	10	$ 160,887	22,424	$ 476,934	0.151	0.94	0.14	6,449
27	1	27.5	12		16	$ 179,062	21,225	$ 478,205	0.153	0.92	0.14	10,496
	4	27.5		180	17	$ 335,147	11,820	$ 501,736	0.159	1.00	0.14	
		27.5	17			$ 53,800	35,160	$ 549,342	0.174	0.84	0.14	18,843
	1	27.5	16		10	$ 112,141	33,570	$ 585,275	0.185	0.85	0.14	17,609
30	4		30	170	17	$ 367,004	98,695	$ 1,758,012	0.561	0.40	0.14	50,181
30			60	160	18	$ 157,411	131,423	$ 2,009,675	0.583	0.22	0.00	71,327
30	5		40		30	$ 382,065	121,365	$ 2,092,579	0.657	0.40	0.14	68,161
	4		40	130	10	$ 278,113	131,055	$ 2,125,199	0.659	0.18	0.11	71,030
			40	170	10	$ 80,513	156,887	$ 2,291,674	0.711	0.00	0.11	84,644
30			50		20	$ 101,725	155,609	$ 2,294,871	0.704	0.20	0.09	88,680
			50			$ 15,343	171,061	$ 2,426,274	0.752	0.00	0.11	98,263
	1		50		10	$ 73,756	170,258	$ 2,473,361	0.758	0.04	0.11	97,451

Figure A11 System configuration with diesel price of $1.60/liter, turbine height 50-m

The following tables show the detail of each component of the first optimum configuration with diesel price $1.50/liter and turbine height 30-m.

Micro-hydropower					
Nominal capacity	27.5	kW	Minimum output	27.2	kW
Mean output	30.6	kW	Maximum output	32.6	kW
Capacity factor	111	%	Hydro penetration	109	%
Total production	267,677	kWh/yr	Hours of operation	8,760	hr/yr
			Levelized cost	0.0131	$/kWh

PV Arrays					
Rated capacity	19.0	kW	Minimum output	0.0	kW
Mean output	4.1	kW	Maximum output	21.9	kW
Mean output	97.2	kWh/d	PV penetration	14.5	%
Capacity factor	21.3	%	Hours of operation	4,386	hr/yr
Total production	35,479	kWh/yr	Levelized cost	0.0889	$/kWh

Battery							
Nominal capacity	389	kWh	Energy in	41,356	kWh/yr	String size	1
Usable nominal capacity	272	kWh	Energy out	35,238	kWh/yr	Strings in parallel	180
Autonomy	9.75	hr	Expected life	5.06	yr	Batteries	180
Lifetime throughput	193,500	kWh	Losses	6,032	kWh/yr	Bus voltage (V)	6

Inverter							
Capacity	17.0	17.0	kW	Hours of operation	4,375	3,247	hrs/yr
Mean output	5.5	4.0	kW	Energy in	50,308	40,713	kWh/yr
Minimum output	0.0	0.0	kW	Energy out	47,794	34,606	kWh/yr
Maximum output	17.0	17.0	kW	Losses	2,515	6,107	kWh/yr
Capacity factor	32.1	23.2	%	Hours of operation	4,375	3,247	hrs/yr

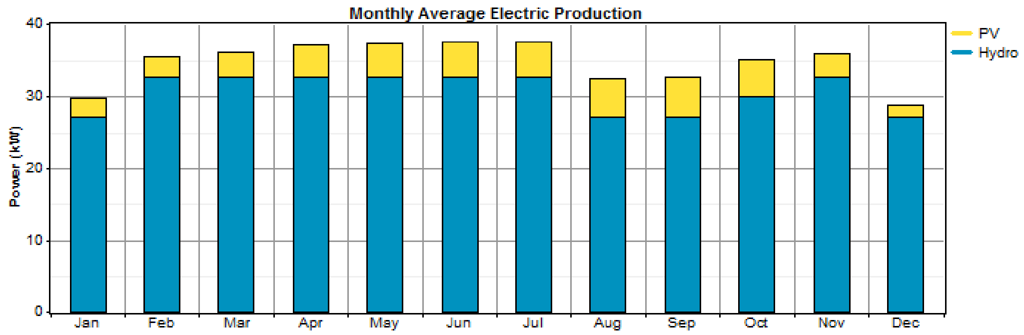


Figure A12 Average monthly electric production

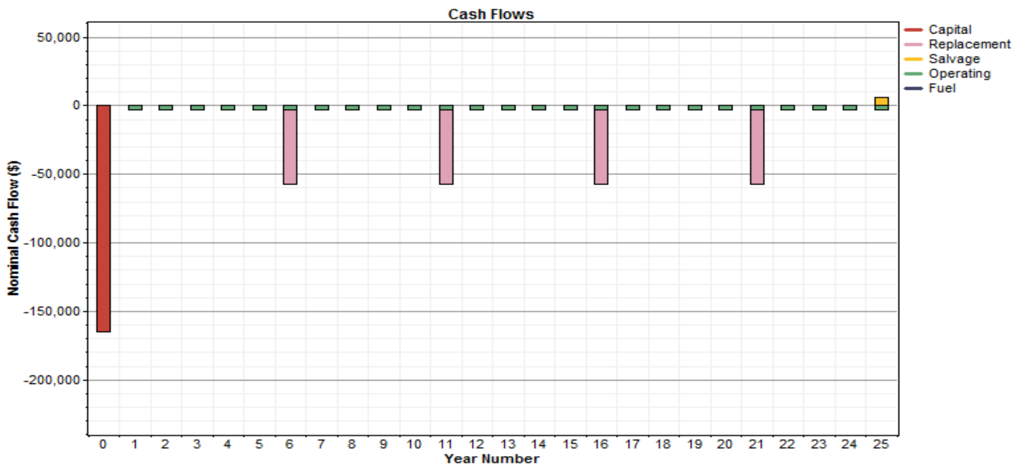


Figure A13 Cash flows of the system based on cost type

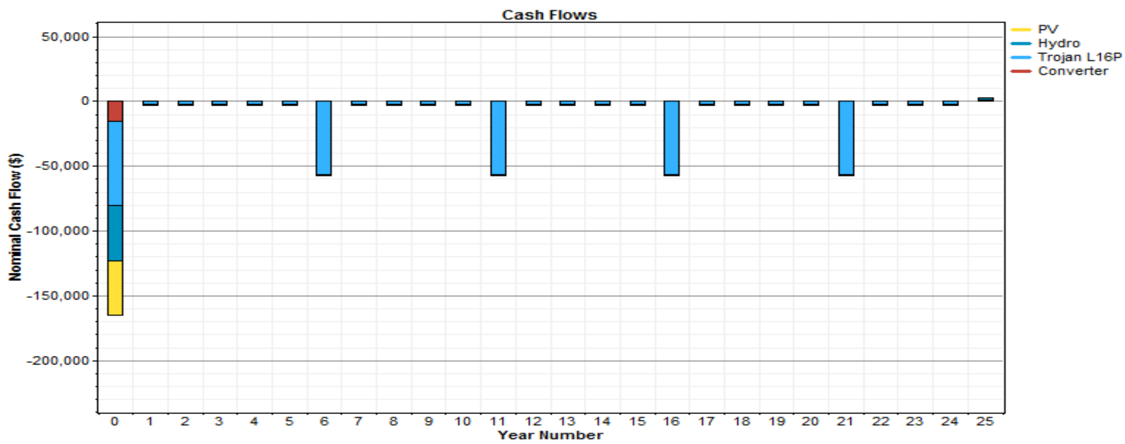


Figure A14 Cash flows of the system based on component type

Appendix B

Load Estimation:

Load Estimation (Apr, May, Jun, Jul, Aug, Sep)									
Hours	**Small House (Wh)**	**Types**	**Large House (Wh)**	**Store (Wh)**	**Types**	**School (Wh)**	**Types**	**Total Load**	**Total Load (0.8 DF)**
0	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
1	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
2	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
3	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
4	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
5	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
6	20	Miscellaneous	20	200	Miscellaneous + Light + Refrigerator	20	Miscellaneous	10.64	8.512
7	40	Miscellaneous + Light	60	100	Miscellaneous + Light	200	Light	20.2	16.16
8	135	Miscellaneous + Light + TV + Radio	155	200	Miscellaneous + Refrigerator + TV	200	Light	62.05	49.64
9	115	Miscellaneous + Light + TV	115	100	Miscellaneous + TV	700	Light + Fan	51.85	41.48
10	35	Miscellaneous + Radio	35	200	Miscellaneous + Refrigerator + TV	700	Light + Fan	18.45	14.76
11	85	Miscellaneous + Radio + Fan	135	20	Miscellaneous	700	Light + Fan	42.15	33.72
12	150	Miscellaneous + TV + Fan	200	120	Miscellaneous + Refrigerator	700	Light + Fan	71.1	56.88
13	150	Miscellaneous + TV + Fan	200	20	Miscellaneous	700	Light + Fan	70.1	56.08
14	85	Miscellaneous + Fan + Radio	135	120	Miscellaneous + Refrigerator	20	Miscellaneous	41.79	33.432
15	85	Miscellaneous + Fan + Radio	135	100	Miscellaneous + TV	20	Miscellaneous	41.59	33.272
16	35	Miscellaneous + Radio	35	200	Miscellaneous + Refrigerator +TV	20	Miscellaneous	17.09	13.672
17	100	Miscellaneous + TV	100	100	Miscellaneous + TV	20	Miscellaneous	44.04	35.232
18	160	Miscellaneous + TV + Light	200	280	Miscellaneous + Light + Refrigerator +TV	20	Miscellaneous	74.84	59.872
19	160	Miscellaneous + TV + Light	200	180	Miscellaneous + Light +TV	20	Miscellaneous	73.84	59.072
20	160	Miscellaneous + TV + Light	200	280	Miscellaneous + Light + Refrigerator +TV	20	Miscellaneous	74.84	59.872
21	160	Miscellaneous + TV + Light	200	20	Miscellaneous	20	Miscellaneous	72.24	57.792
22	95	Miscellaneous + Radio + Light	115	20	Miscellaneous	20	Miscellaneous	42.69	34.152
23	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
Total estimated energy consumed per day is 713 kWh									

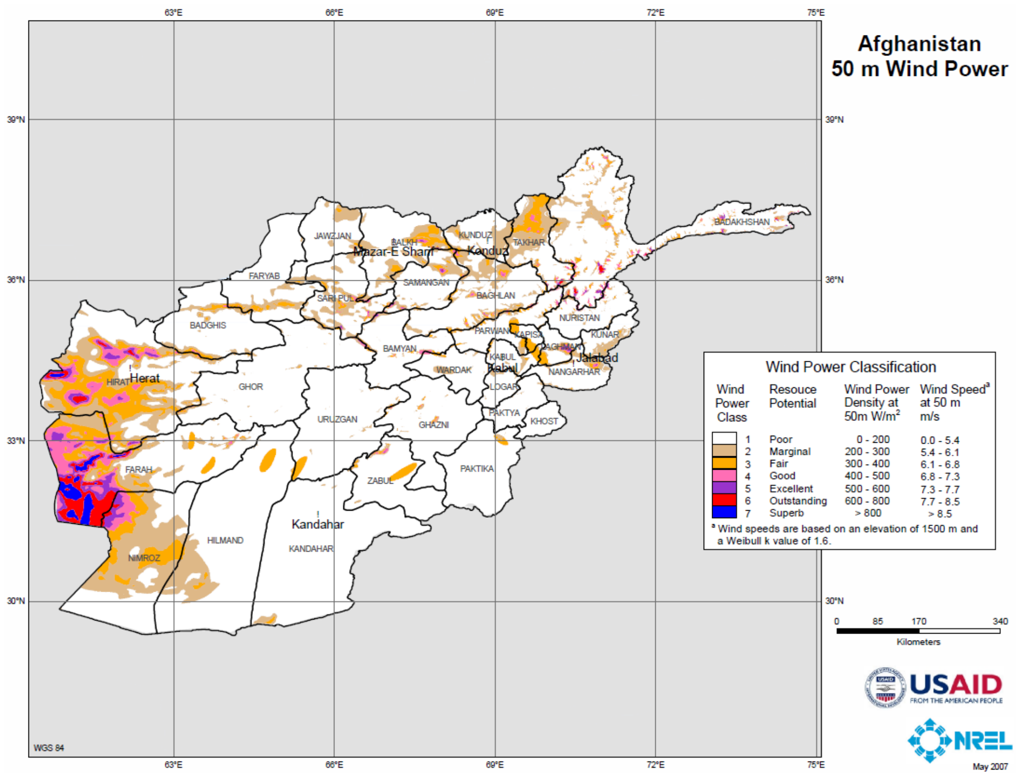
Load Estimation (Jan, Feb, Mar, Oct, Nov, Dec)

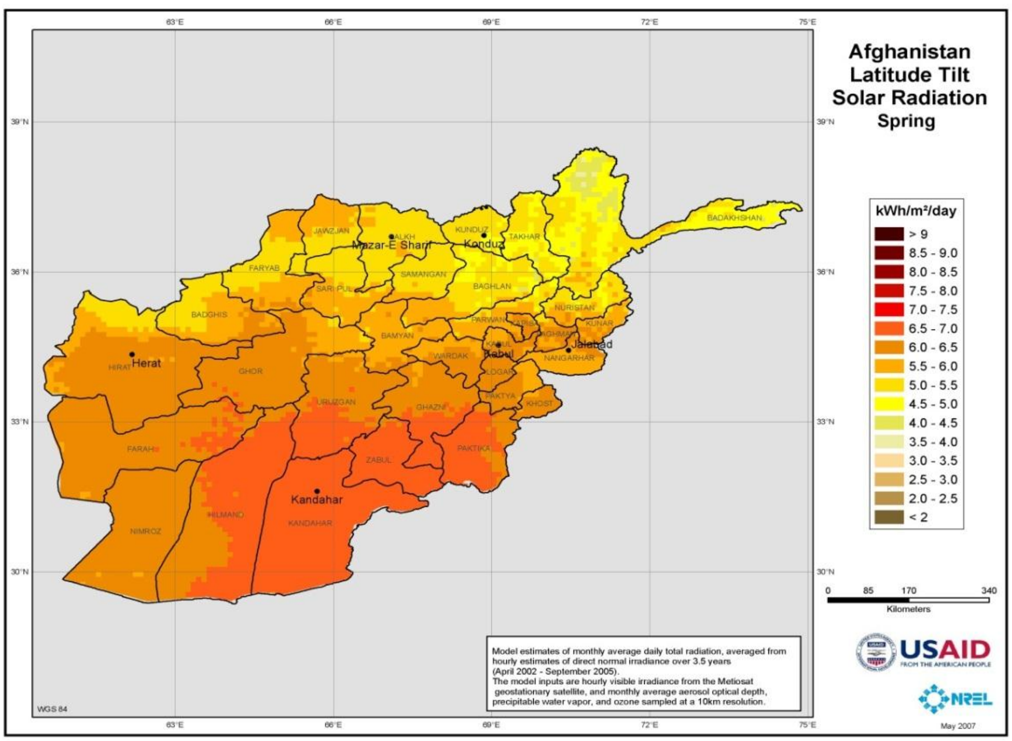
Hours	Small House (Wh)	Types	Large House (Wh)	Store (Wh)	Types	School (Wh)	Types	Total Load	Total Load (0.8 DF)
0	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
1	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
2	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
3	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
4	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
5	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072
6	20	Miscellaneous	20	200	Miscellaneous + Light + Refrigerator	20	Miscellaneous	10.64	8.512
7	40	Miscellaneous + Light	60	100	Miscellaneous + Light	200	Light	20.2	16.16
8	135	Miscellaneous + Light + TV + Radio	155	200	Miscellaneous + Refrigerator + TV	200	Light	62.05	49.64
9	115	Miscellaneous + Light + TV	115	100	Miscellaneous + TV	200	Light	50.85	40.68
10	35	Miscellaneous + Radio	35	200	Miscellaneous + Refrigerator + TV	200	Light	17.45	13.96
11	85	Miscellaneous + Radio + Fan	135	20	Miscellaneous	200	Light	41.15	32.92
12	100	Miscellaneous + TV	100	120	Miscellaneous + Refrigerator	200	Light	44.6	35.68
13	100	Miscellaneous + TV	100	20	Miscellaneous	200	Light	43.6	34.88
14	35	Miscellaneous + Radio	35	120	Miscellaneous + Refrigerator	20	Miscellaneous	16.29	13.032
15	35	Miscellaneous + Radio	35	100	Miscellaneous + TV	20	Miscellaneous	16.09	12.872
16	35	Miscellaneous + Radio	35	200	Miscellaneous + Refrigerator +TV	20	Miscellaneous	17.09	13.672
17	100	Miscellaneous + TV	100	100	Miscellaneous + TV	20	Miscellaneous	44.04	35.232
18	160	Miscellaneous + TV + Light	200	280	Miscellaneous + Light + Refrigerator +TV	20	Miscellaneous	74.84	59.872
19	160	Miscellaneous + TV + Light	200	180	Miscellaneous + Light +TV	20	Miscellaneous	73.84	59.072
20	160	Miscellaneous + TV + Light	200	280	Miscellaneous + Light + Refrigerator +TV	20	Miscellaneous	74.84	59.872
21	160	Miscellaneous + TV + Light	200	20	Miscellaneous	20	Miscellaneous	72.24	57.792
22	95	Miscellaneous + Radio + Light	115	20	Miscellaneous	20	Miscellaneous	42.69	34.152
23	20	Miscellaneous	20	20	Miscellaneous	20	Miscellaneous	8.84	7.072

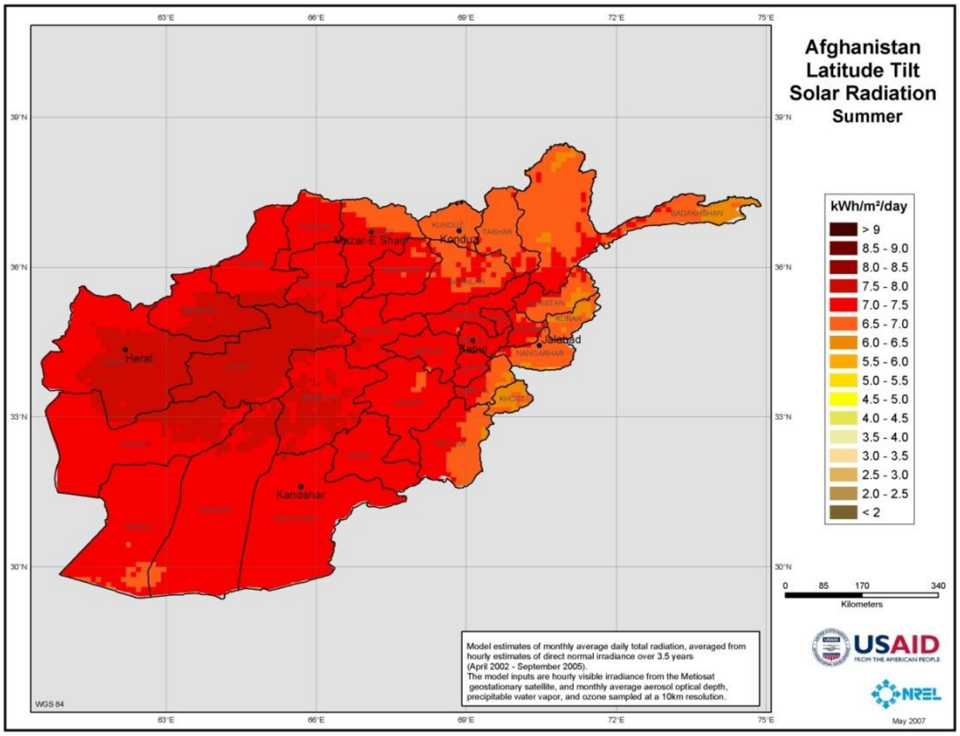
Total energy consumed per day is 627.5 kWh

Appendix C

Afghanistan's wind and solar seasonal maps:






Afghanistan
Latitude Tilt
Solar Radiation
Summer
kWh/m²/day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Herat
Mazar-E Sharif
Kondus
Kabul
Jalabad
Kandahar
0 85 170 340
Kilometers
Model estimates of monthly average daily total radiation, averaged from hourly estimates of direct normal irradiance over 3.5 years (April 2002 - September 2005).
The model inputs are hourly visible irradiance from the Metiosat geostationary satellite, and monthly average aerosol optical depth, precipitable water vapor, and ozone sampled at a 10km resolution.
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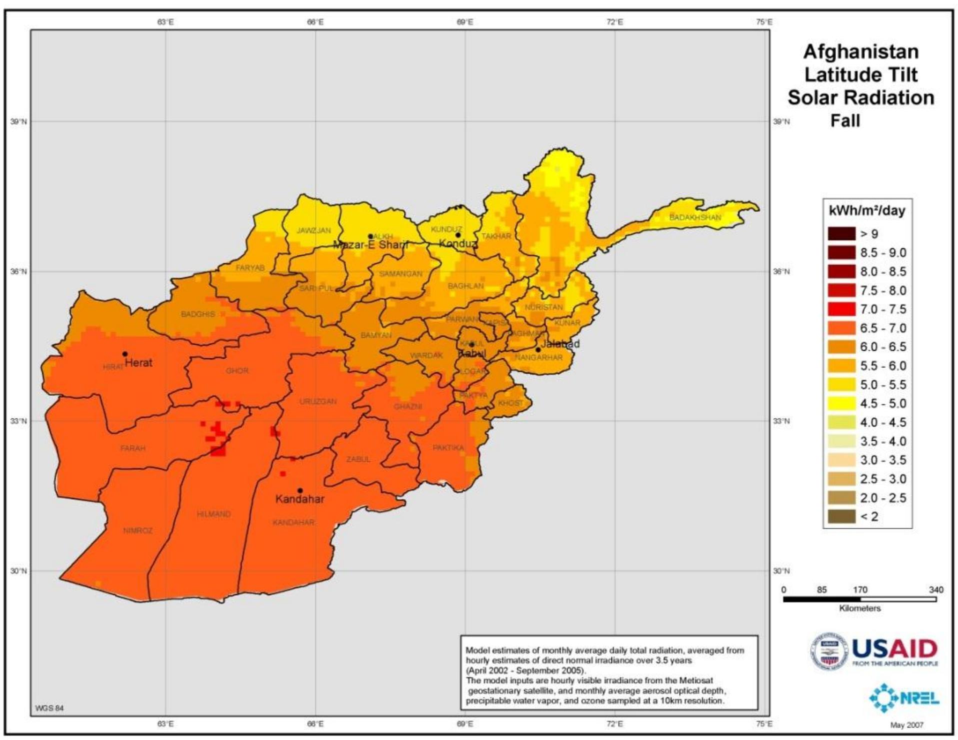
Afghanistan
Latitude Tilt
Solar Radiation
Fall
kWh/m²/day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Herat
Mazar-E Sharif
Kondus
Kabul
Jalabad
Kandahar
0 85 170 340
Kilometers
Model estimates of monthly average daily total radiation, averaged from hourly estimates of direct normal irradiance over 3.5 years (April 2002 - September 2005).
The model inputs are hourly visible irradiance from the Metiosat geostationary satellite, and monthly average aerosol optical depth, precipitable water vapor, and ozone sampled at a 10km resolution.
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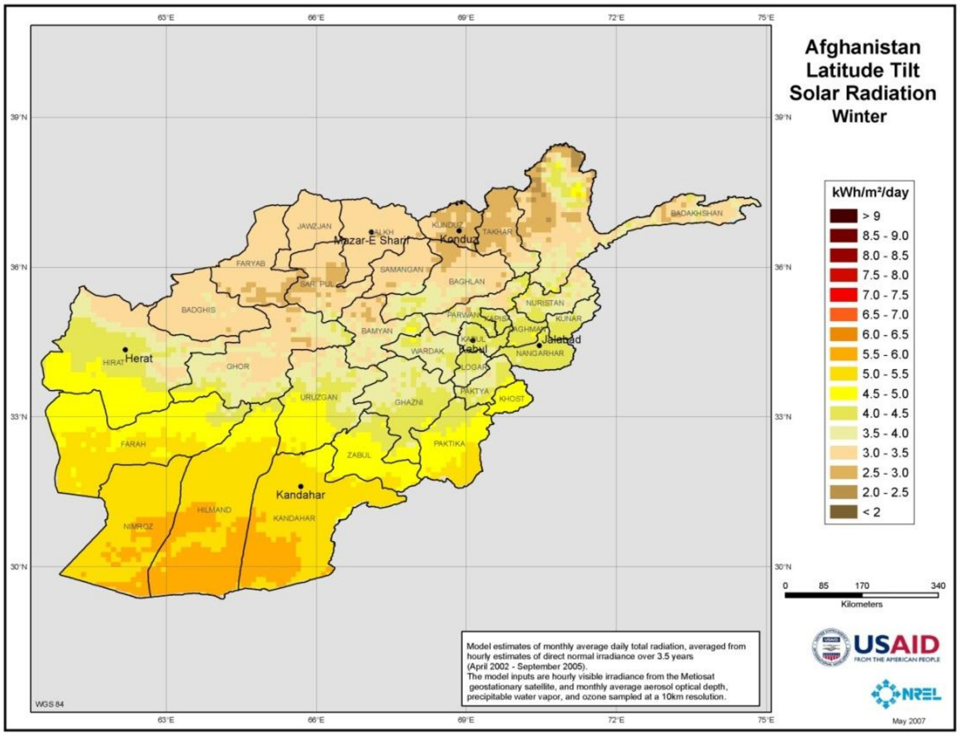
Afghanistan
Latitude Tilt
Solar Radiation
Winter
kWh/m²/day
> 9
8.5 - 9.0
8.0 - 8.5
7.5 - 8.0
7.0 - 7.5
6.5 - 7.0
6.0 - 6.5
5.5 - 6.0
5.0 - 5.5
4.5 - 5.0
4.0 - 4.5
3.5 - 4.0
3.0 - 3.5
2.5 - 3.0
2.0 - 2.5
< 2
Herat
Kandahar
Kabul
Jalalabad
Konduz
Mazar-E Sharif
0 85 170 340
Kilometers
Model estimates of monthly average daily total radiation, averaged from hourly estimates of direct normal irradiance over 3.5 years (April 2002 - September 2005).
The model inputs are hourly visible irradiance from the Metiosat geostationary satellite, and monthly average aerosol optical depth, precipitable water vapor, and ozone sampled at a 10km resolution.
WGS 84
May 2007