GENI Global Energy Network Institute

Sustainable Energy Solutions for Rural Areas and Application for Groundwater Extraction

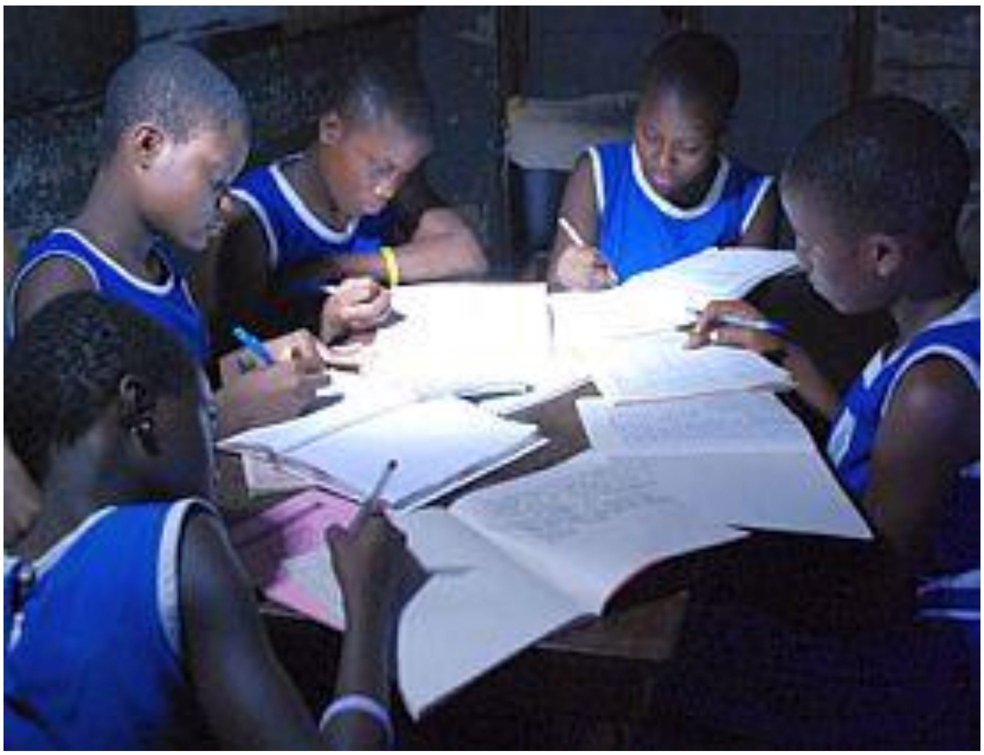

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Table of Contents

Table of Figures

Abstract

A reliable energy source is an essential component of any modern human society, yet roughly 23% of the world's population is currently experiencing energy poverty. According to a report issued by the United Nations, 1.6 billion of the 7.1 billion people in the world had no access to electricity as of 2010, the vast majority of who live in developing countries or regions.[1] According to the World Bank, 550 million people in Africa and 400 million people in India still live in the dark.[2] The organization claims that the current pace of electrification would have to double in order to achieve universal energy access by the year of 2030.[3] The goal of this paper is to discuss practical approaches to delivering energy in a sustainable way to rural populations that do not yet have access to it, so that their quality of life can be permanently enhanced to an acceptable level. Furthermore, gaining access to a reliable source of electricity is one of the most important milestones in modern community development because it can resolve many issues commonly faced by the population in rural area. Therefore this paper will also investigate how energy can make a difference in the extraction of clean water, which is a major challenge for rural communities in developing countries and regions.

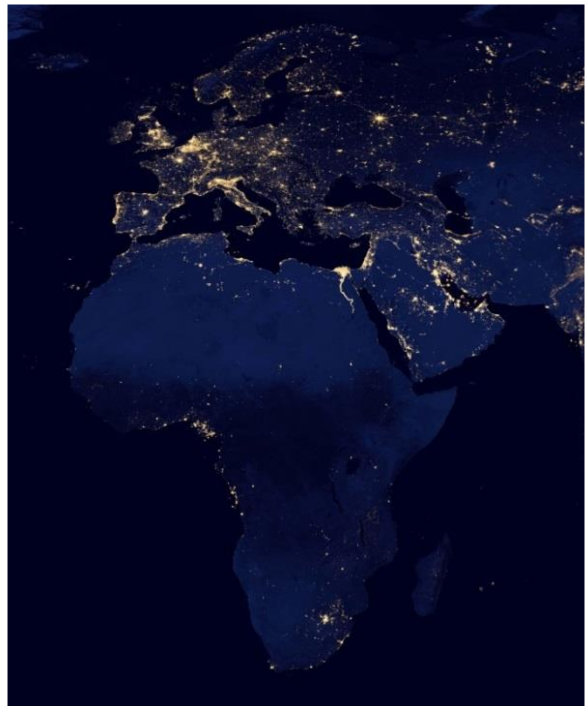

Figure 2: Image captured by NASA satellite revealing the enormous difference of light distributions during nighttime between continental Europe and Africa

1. Introduction

[1] Energy for a Sustainable Future, 2010; *World Population Data Sheet*, 2010.
[2] Energy - The Facts, 2013.
[3] Five Surprising Facts about Energy Poverty, 2013.

After World War II, the world entered a new era. Two super powers emerged, the United States and the Soviet Union, with the ambitious goal of spreading their respective political ideologies. In 1947, both the Americans and the Soviets created international aid programs – the Marshall Plan and the Molotov Plan, which mark the very first large-scale international aid programs in history. Putting their political intentions aside, this aid helped the post-war regions to rebuild their societies at a speed that was otherwise impossible.

Developing regions, however, have never received large-scale foreign aid through these plans. Slow economic growth has resulted in difficulty improving citizens' quality of life in developing regions such as many of the African countries. In addition, civil war continues in many of these regions, particularly in Africa. It is extremely difficult, if not impossible, for local governments to execute economic programs in an effective fashion in such unstable conditions and with insufficient manpower and resources.

Figure 3: Child soldiers in the African Great Lakes region serving the Uganda rebel group

Despite the lack of large-scale international effort, international Non-Governmental Organizations (NGOs) have been providing assistance to developing regions for humanitarian purposes. Many NGOs provide aid in terms of food, water and basic infrastructure. While these works are extremely valuable for those who receive the aid, they are insufficient to meet the great demand of the entire population living in poverty.

1.1 Electricity in rural environments

Out of the six forms of energy (see Appendix B), electrical energy is the most desirable form of energy because it is very easy to transform into types of energy that are useful to our lives. The lack of electricity raises a list of negative effects that dramatically limit a community's potential rate of growth, as well as its residents' basic quality of life. Some of the most pressing effects are listed below:

Issues	Consequences
The inability to refrigerate	• Clinics that are unable to refrigerate medicines and vaccines greatly shorten their storage period. Considering that clinics near rural areas are most likely short in medical supply already, refrigeration can dramatically enhance the clinics' utility. • Most food (especially meats) cannot be stored without refrigeration for extended periods of time. As a result, either already scarce food is wasted or people are forced to consume it once it has expired.
The lack of lighting	• Particularly in developing countries and regions, education is a key to promoting social growth. However, in rural areas access to education is rare, which leads to a repetition of the poverty cycle. Lighting is a small investment that brings huge positive effects by allowing schools to operate under insufficient natural lighting conditions (rainy, cloudy, during night, etc.), dramatically extending the hours of operation and potentially allowing more people to receive education. • The lack of lighting limits a community's economic productivity due to the inability to work during the night or disruptive weather conditions.
Roadblock to modernization	• Residents of rural area are forced to rely on inefficient sources of animal or manpower to sustain their economy. • Devices like cell phones and computers cannot operate without an electricity source, the lack of which isolates the community from the rest of the world.

Emergency responsiveness	• Real-time communication is not possible without the use of a phone or radio, making emergency response extremely difficult. • The inability to respond to crimes increases the crime rate and can threaten citizens' property and security.

Table 1 - Consequences of the lack of electricity

Prior to implementing any electrical generation system, it is necessary to consider how much energy is expected to be consumed by the targeted community. A very rough estimation of energy demand can be computed by considering the power consumption of the appliances, as well as the expected time of operation.

Millions of residents who live in the rural areas in developing countries or regions have no access to electricity. Fortunately, it is often the case that a variety of energies are available to them that can be transformed into electricity.

2. Solar Energy

The sun emits enormous amount of energy that is sometimes hard for us to comprehend. In theory, the sun can easily provide a more than sufficient amount of energy to meet the worldwide energy demand, providing that we have the appropriate solar energy-capturing devices. In reality, though, solar power alone is not the answer to the world's energy challenge due to the technological limitations of solar power technology. That being said, it has been proven to be one of the best solutions for rural areas electrification.

Figure 4: Solar panels require minimal maintenance

A solar cell is a semiconductor, solid-state electronic device that converts radiant energy directly into electrical energy by employing the photovoltaic effect. A solar panel's power output depends on the load resistance, irradiance and temperature. Several techniques can be employed to create a reliable energy output by attempting to control these three parameters.[4]

Solar tracking devices can also be used to physically angle of solar penal toward the sun so the maximum amount of irradiance flux shines on the panel. However, solar tracking devices also need power to operate. Since mechanical parts are involved, the equipment requires constant maintenance. For a small solar energy system, it is often time and energy inefficient to implement a tracking system. However, for a solar array system in larger scale, or if space is a constraint, a tracking device may be very beneficial.

2.1 Advantages & Disadvantages of Solar Energy for Rural Area

With a basic understanding of solar energy systems, we are now ready to analyze the advantages and disadvantages of such systems in rural areas as a means of generating electricity.

Advantages of Solar Energy for Rural Area	
1.	**Low maintenance requirement** Traditional means of generating electricity involve mechanical parts and require regular maintenance. Solar cells, on the other hand, are solid-state electronic devices. No moving parts are involved in the entire process, which dramatically lowers the maintenance requirement. This is a huge advantage for rural area usage, because replacement parts are often difficult to obtain. In addition, it does not take as much time to train local residents to maintain a solar energy system.
2.	**Low operational cost** Solar power energy systems have the advantage of being able to operate with minimal cost. Unlike a traditional generator, no fuel is consumed in the generation process. In addition, the low maintenance requirement also helps to bring the operational cost down.
3.	**Long life expectancy** Over the years, the panel will experience decay, reducing the panel's efficiency. Yet compared with traditional electricity generator, the lifespan of solar panels is rather impressive. Most solar panels come with a warranty of 25 years or more. In general, a good panel can be expected to last for 40 years without major decay.

[4] One such method employs a device to adjust the load resistance in order to achieve a stable power output. A Maximum Power Point Tracking (MPPT) device automatically adjusts the load resistance to achieve maximum power output. A Pulse-Width Modulation (PWM) device (typically present as a battery-charging regulator) extracts roughly 20% less power than a MPPT device, but is cheaper.

4.	**Environmentally friendly** Since solar panel employs photovoltaic effect to generate electricity rather than burning fuel, no byproducts are generated throughout the process.
5.	**Highly portable** A typical solar panel is a flat device that can easily be transported. With a sturdy frame, the panel can be moved safety from one place to another. This is useful for rural areas because the system can be moved depending energy needs.
6.	**Ideal for LED lighting** LED lighting is becoming a very popular lighting solution. It is known for its long lifespan and low power consumption. Solar panels naturally generate DC power, and can therefore power an LED lighting system without the need of an inverter.
7.	**Easy integration with small appliances** Small, integrated DC systems can employ small solar panels as a power source. A solar lamp is a typical application of such system. In the example of a street light, two solar panels are integrated into the power system and are responsible for charging the internal battery during when light is presented. When sunlight is insufficient, the LED lights will automatically be switched on. LED lights are employed due to the high efficiency that can be achieved by the DC/DC usage, rather than DC/AC conversion. This type of self-contained system requires very little maintenance, which is a huge attraction in rural areas.

Table 2 - Advantages of Solar Energy for Rural Area Usage

Disadvantages of Solar Energy for Rural Area	
1.	**High initial cost** The cost to produce a solar cell is high. Semiconductor devices like solar cells require a very specialized and precise industrial process to be made. Therefore, the dollar-per-watt ratio of solar energy is among the highest when compared with other alternative energy sources.
2.	**Limited power supply** A conventional silicon-based solar cell does not generate a lot of power. A solar array is often required to capture sufficient energy in order to power up the load.
3.	**Power availability depends on external conditions** Solar panels rarely produce their rated maximum power because all the external factors (mainly light irradiance, temperature, and load resistance) are not met. For example, during nighttime, no meaningful amount of electricity can be generated.
4.	**Energy storage devices are almost certainly necessary** Costly energy storage devices along with charge regulating systems have to be attached along with the solar panel if nighttime usage is required. In rural area where lighting solution is highly desired, a battery system is most certainly necessary.

5. **Integration with local electric grid**
Connecting solar energy system with local electric grid is a complex procedure that requires careful design. The local grid transmits power in the form of alternating current at high voltage. In order to integrate the solar energy system with the grid, the phases of the AC power for both ends need to be matched exactly. Catastrophic damage to the system may occur when the coupling is handled inappropriately.

Table 3 - Disadvantages of Solar Energy for Rural Area Usage

2.2 Pros & Cons Analysis

Although the solar energy solution is not perfect, its advantages arguably outweigh its disadvantages for rural area usage. Lighting is one of the main reasons of bringing electricity to the community in the first place, and LED lighting is highly applicable for DC solar power system. An independent system like the solar lamp (figure 4) can easily be installed in a rural community with minimal training of the local residents.

As for a general-purpose solar power system, as long as the local residents are trained to deal with the occasional maintenance, an independent (not connected to the grid) solar energy system is extremely reliable. On paper, the cost of solar energy is among the highest. However, if one targets rural areas that do not have access to cheap and reliable energy source through power grid, one can only look into independent power sources, like a solar power system.

Figure 5: A LED light run by solar panels

The fact that solar power systems do not release any greenhouse gases can ensure that the surrounding environment is not contaminated. In addition, many developing regions like central Africa and India are rich in solar irradiance resources, and they are available for free. Solar energy is therefore, widely considered as the top choice for rural electrification.

2.3 Case Study: Solar Electrification in Rural Area

The following documents a solar power implementation trip organized and carried out by a non-governmental organization. The targeted community is a small-scale village with no access to electricity. Before the introduction of electrical power, the local residents lived without access to a clean water source. Villagers were unable to extract water deep in the ground using only manpower. Residents used a single, contaminated water source near the surface for all their needs, which threatened the health of all residents. Prior to the introduction of electrical lighting, villagers used oil lamps. Without proper fire prevention knowledge and fire suppression equipment in place, these lamps can be dangerous. In addition, the local clinic was not able to refrigerate and store its medicines, meaning that it could not reach its full potential despite the concerns posed by the unsafe water source.

Figure 5: Unsafe fire lighting

Figure 6: Residents' unsafe water source

Electricity that the new solar system creates has brought enormous benefits to the local community. An electric water pump was installed, granting the villagers access to clean water 100 meters below ground level. Now, villagers can effortlessly extract clean, previously unreachable ground water without any physical effort. The oil lamps were replaced by an electric lighting system, which is a safer and brighter form of lighting. Proper lighting in the village enhances community safety, as well as the residents' productivity during nighttime. With access to electricity, the local clinic is now able to store medicines inside a refrigerator, and therefore greatly expand its effectiveness. Electricity has also brought information, education and entertainment to the community.

Figures 7a, 7b, 7c, 7d: The benefits the solar system has brought to the community

3. Wind Energy

Wind can be considered a form of kinetic energy and in order to take advantage of the energy carried by the wind, some form of energy conversion must be employed. The wind turbine is a device designed to capture the wind movement and turn the energy into rotational force. The rotational force is ultimately used to power a generator, which produces electricity. In rural areas, large-scale wind energy production is impractical. Therefore, a small wind turbine is usually used. A small wind turbine is not as complex as its commercial counterpart, but produces less energy and works less efficiently.

Wind speed is often higher at near surface levels due to the wind shear effect. Therefore, it is often beneficial to elevate the turbine to get greater rotational force out of the system. For this reason, the height of the tower is one of the determining factors for the maximum power generation of a wind power system.

Seacoasts are good places to install wind turbine systems. The temperature differential (most obvious after sunrise and sunset) produces wind, blowing from the cooler to the hotter area. Therefore, we can usually expect good power output from a wind turbine system if placed between land and sea. A similar effect takes place near mountaintops. Warm air rises to the mountaintop after sunrise, known as “mountain breezes” and cool air sinks down the hill after sunset, known as “mountain wind”.

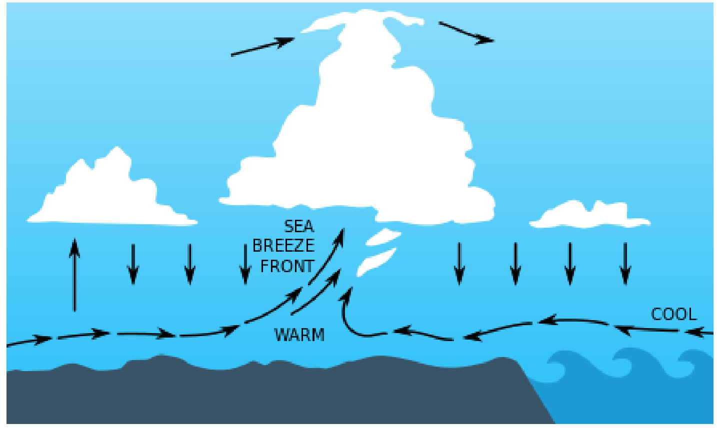

Figure 8: Wind flows from cooler to hotter areas

A wind turbine system is often quite heavy due to the required components involved. The need to elevate the system to capture more wind also poses an engineering challenge to achieve structural stability. Mounting a small-scale wind turbine system on a rooftop might not be a good solution due to the constant vibration of the system during operation, by which the structural integrity of the building might be compromised. In addition, the moving parts inside the system generate steady noise. Therefore, only a very light wind turbine system is applicable for mounting on a rooftop.

Figure 9: A roof-mounted wind turbine

3.1 Advantages & Disadvantages of Wind Energy for Rural Areas

With a basic understanding of wind turbine systems, we are in position to analyze the advantages and disadvantages of implementing such systems in rural areas.

Advantages of Wind Energy for Rural Area	
1.	**Cost effective in a good location** Wind turbine systems use electrical induction to generate electricity, which has a potential of generating multiple times more power that what can be generated by a solar energy system of the same price.
2.	**Can expect power output throughout the day** Unlike a solar energy system, which only generates power during daytime, wind power works throughout the day cycle as long as there are sufficient winds blowing in the area.

Table 4 - Advantages of Wind Energy for Rural Area Usage

Disadvantages of Wind Energy for Rural Area	
1.	**High maintenance requirement** Wind turbine systems consist of many mechanical parts. Systems that employ generators may reduce maintenance needs, but the fact that constant maintenance is required for maintaining the system remains unchanged.
2.	**Unavailability of parts to rural area** Moving parts such as the gears are going to wear down at some point. In rural areas with limited logistical capabilities, getting the right parts can be a big challenge. The cost of the parts as well as the associated transportation can pose a financial challenge for the community.
3.	**Limited location choice for installation** Wind turbine systems are only cost efficient when they are placed at a location with strong winds, such as an offshore or mountainous area. For wind turbine systems on a larger scale, mounting on rooftops is not recommended due to noise and vibration. Therefore, only very limited locations are appropriate for wind turbine installations that makes economic sense.

4.	**Energy storage system is necessary for off grid usage** Since wind resources are not constantly available, an energy storage system like a battery bank is necessary to maintain a steady power supply at times when there is no sufficient wind blowing through the area.	

Table 5 - Advantages of Wind Energy for Rural Area Usage

3.2 Pros & Cons Analysis

In order for a wind turbine power system to be effective, it is essential to select a place with moderate to strong wind speeds, like an offshore area, mountainous pass or high hill. Unless these requirements are met, a wind turbine system would not be very effective at generating enough electricity to meet a village's energy demand, as compared to a solar array.

Even if the village is located at a high wind speed area, a wind turbine system is a complex system with many moving mechanical components. Constant maintenance and regular part replacement are necessary for the system to function properly. Gaining access to and affording the parts can be a challenge for rural villages. By comparison, solar power systems employ the photovoltaic effect to generate electricity. The cells are solid-state device with no moving parts; therefore a minimal amount of maintenance is required, which makes it stand out in comparison with wind energy.

Figure 10: A rural wind turbine

That being said, a wind turbine system is a very good choice for complementing a solar array system. This is because solar cell can only generate a meaningful amount of electricity during daytime with good solar irradiance, while a wind turbine is completely independent of solar irradiance. Wind turbine systems become very good candidates when a village has grown to a level at which the energy demand can no longer be met with the pre-existing solar array system. Otherwise, it is generally not a first choice to implement a wind turbine system for electrification of rural villages.

3.3 Case Study: Wind Turbine in Rural Area

Sri Lanka is an island country off the southern coast of India. Since the national grid generally does not extend beyond major cities, people living in poor rural areas often need to travel miles in order to purchase kerosene for heating and lighting needs.

Practical Action South Asia is a non-governmental organization that aims to improve the quality of life of people living in poverty. The group did an assessment on a remote village in Sri Lanka and implemented a wind turbine system to provide access to electricity for local residents.

Figure 11: A villager standing next to a newly installed turbine

Practical Action believes that community ownership plays a critical role in local residents' ability to sustain the system. For this reason, a group called the "Electricity Consumer Association" was formed to help with the planning, construction and operation of the system. To order to make sure the local residents understood how to operate and control the system, a training plan was created so that a fully self-sufficient system could be achieved.

Figure 12: A child reading in a well-lit room

Due to the implementation of the wind energy system, the village now enjoys the benefit of having access to electricity. Getting kerosene from miles away is no longer necessary for lighting, and other appliances can also be powered using wind power.

4. Hydropower

Figure 13: A small hydropower station

By taking advantage of the downward water flow from higher to lower elevations, it is possible to generate mechanical force to propel a turbine and create electricity through electromagnetic induction, similarly to a wind turbine. The only difference is that a wind power system takes advantage of the movement of air, whereas a hydropower system takes advantage of the movement of water.

Generating power from rivers is a less expensive investment that serves as an appealing alternative to solar and wind energy. By intercepting the water flow with hydropower generator, one may convert kinetic energy into mechanical energy by spinning a turbine and, eventually, into electrical energy by electromagnetic induction.

Only the turbine is submerged and the main generator is outside of the water, reducing both initial installation and operational costs. Moderate amounts of power can be generated when river current is strong. The disadvantage is that rivers with strong currents have to be close by in order to use the hydropower generating method.

4.1 Advantages & Disadvantages of Hydropower for Rural Areas

Listed below is a summary of why one may want to implement a hydropower station in rural area.

Advantages of Hydropower for Rural Area	
1.	**Cost effective at good location** Hydropower, like wind turbine systems, uses electrical induction to generate electricity, which has the potential to generate multiple times more power that what can be generated by solar energy system of the same price.

2.	**Power output is often predictable** Unlike solar energy, which only generates power when light is present, hydropower works throughout the day as long as there is sufficient water movement through the turbine. Since the volume of water flow tends to be periodic, it is possible to estimate future output to a reasonable degree of precision.[5]	
3.	**Good complement with solar energy** Since the water flow of river is independent of the time of the day, hydropower can be a good complement to a solar panel array for providing an undisrupted power source to villages.	

Table 6 - Advantages of Hydropower for Rural Areas

	Disadvantages of Hydropower for Rural Area
1.	**Relatively high maintenance requirement** The half-submerged design can reduce maintenance procedures and cost. However, since underwater and mechanical parts are still involved, the maintenance requirement is considerably higher than solar power.
2.	**Narrow location choice** River and water resources might not be accessible to many rural areas. In fact, such resources are often scarce.
3.	**Secondary energy source can be considered a requirement** Water might not flow all year around. In a dry season, the hydropower plant won't be able to produce any energy at all.

Table 7 - Disadvantages of Hydropower for Rural Areas

4.2 Pros & Cons Analysis

Hydropower is very similar to wind power, in the sense that both require some form of propulsion to drive a turbine connected to a generator, where mechanical energy is transferred into electrical energy through electrometric induction. In addition, they both have a very similar advantage/disadvantage profile.

[5] Y. Al-Zu`bi, A. S.-Z., 2010.

Figure 14: The peripherals of a small-scale hydropower system

Location consideration plays the key role in the decision making process, as it is the main factor in determining the impact of the system. To establish a hydropower station in a rural area, one must perform extensive studies on the river's water flow profile to determine average flow speed in each month in the past couple of decades. Unfortunately, for smaller rivers, data like this is not always available due to the lack of organized official documentation. In such cases, decision-makers should seek alternatives. While hydropower has the potential to generate more energy than wind power in the long run, the establishment of a hydropower station is a complex engineering task. Water management, channel routing and dam construction all need to be designed carefully by professional engineers to ensure the safe and efficient operation of the power station. This introduces an extra layer of implantation time and cost to the project, which might not be a practical choice. By contrast, solar and wind power are based on pre-made modular components. Both the implementation time and cost can be much less than building a hydroelectric station.

4.3 Case Study: Hydropower in Rural Area

Practical Action East Africa and Kenyan Ministry of Energy have constructed a hydropower station in a rural village in Kenya, called Mbuiru. In Kenya, 96% of its citizens have no access to the national electric grid, which results in the negative effects previously discussed. The village of Mbuiru has a population of 1000

Figure 15: A small dam was built to divert water

Figure 16 – The main power generator

people, with around 200 households. The community is located next to a small river, which allowed engineers to implement a small-scale hydroelectric station to harness the kinetic energy of the nearby river.

To ensure that a steady supply of electricity can be produced by the system, the team studied the flow history of the river extensively, and determined that the location was suitable for a hydropower source. On average, the water flow speed into the generator is about 200L/s, capable of generating 14kW of electricity per hour.

Ever since the village has had a steady supply of electricity, the villagers' quality of life has improved greatly. For instance, people no longer need to travel 17 miles to get their batteries charged. New businesses like hair salons and welding workshops are now possible. The electricity bills that villagers share are used to pay for the maintenance of the system. Electricity has undoubtedly brought positive economic impacts to the community.

5. Application: Groundwater Extraction

Aside from energy poverty, the lack of access to water is yet another global issue that requires a lot of attention. According to the United Nations, roughly 11% of the global population, or 783 million people, still live without access to potable water as of 2012.[6] Each year, contaminated water claims the lives of more than 3.4 million people, 99% of who live in the developing world.[7] In remote villages located in poor regions, it is quite common to see villagers travel miles to transport water back to their homes. Since men usually work during the day, women and children often carry out such tasks.

Figure 16: A hand-dug well

Groundwater is the most logical and accessible place to obtain water in mainland areas. In general, the deeper one drills into an underground water channel, the more water

[6] United Nations Water Statistics, 2012.
[7] World Health Organization, 2008.

one may be able to extract. The Water Project is a non-profit organization aims to introduce sustainable water to Sub-Saharan Africa. According to the organization, wells for extracting groundwater can generally be divided into three categories: hand dug wells, shallow wells and deep wells. As the name suggests, they are classified by the depth of the well. Given the right location, the amount of water available is directly proportional to the well's depth and becomes more drinkable at deeper levels.

The depth of hand-dug wells is usually only 50 feet. Water can be extracted from the well through simple pulley driven mechanics. Such an extraction method is slow and inefficient. The water may run dry or be contaminated due to the unsealed opening. This method is obviously not recommended.

Figure 17: A hand pump

Shallow wells are drilled by machinery and extend 150-200 feet into the ground. Pulley systems cannot effectively transport the water to ground level. Therefore, a mechanical pump is usually installed. The purpose of the pump is to inject air into a sealed well, forcing the water to ground level through a water tube. Such a system works fairly well with a manual pump, and can be found across Africa. Since the well is sealed, contamination to the water source is less likely to occur.

Figure 18: A deep well with an automatic pumping system

The true value of having access to electricity is that an electric water pump may be installed to achieve greater efficiency. Deep wells are the most desirable type of well, where vast amounts of clean water can potentially be extracted. The issue is that a manual pump takes too much time and effort. This is where electric water pump comes into play, with which people can effortlessly extract clean, uncontaminated water from deep underground, fulfilling the water needs of the nearby area. This in turn promotes community growth by freeing up villagers’ time for productive work, ensuring water resources are available for future population growth and suppressing water-transmitted diseases.

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7. Appendix A: Resources for Humanitarian Aid Interventions

7.1 The 3-Step Planning Process

In the early stages of planning a humanitarian aid operation, it is essential to communicate with the targeted community and to consider the following:

The 3-Steps Planning Process	
1	**Prioritize the community's needs:** - Are they lacking elements that are essential for survival (food/water)? - Do they have access to one or more energy sources (fire/fuel/electricity)? - Do they have reliable and convenient access to the above materials?
2	**Solution effectiveness:** - Given limited resources in manpower, capital, time and expertise, what are the most effective materials that you can deliver to the community to achieve the greatest impact on its residents' quality of life?
3	**Sustainability consideration:** - Your system(s) need to be reliable, easy to maintain, and inexpensive to operate - You must create an effective educational plan for the local community residents so they know how to operate and maintain the system(s) in the long run. - Ensure that your solution is financially sustainable considering operational, maintenance, repair and labor costs.

Table 8 - The 3-Step Planning Process

This paper is an attempt to create a reference manual for those planning on carrying out an aid effort in the developing world by providing all the necessary details of the 3-Step Planning Process, with the goal of informing decisions and accelerating operations.

7.2 Energy Demand Estimation

Prior to implementing any electrical generation system, it is necessary to consider how much energy is expected to be consumed by the targeted community. A very rough estimation of energy demand can be computed by considering the power consumption of the appliances, as well as the expected time of operation. For example, a clinic may use a small refrigerator to store medicines 24 hours a day, as well as two 60-watt equivalent CFL light bulbs to provide proper lighting during nighttime from 6pm to 12pm. The refrigerator operates at 300 watts when its compressor is running, but it only runs one quarter of the time, each time activates for 5 minutes.

Constant Load		$5watts$
Variable Load	**6:00pm – 12:00am (6 hours)**	$2 \times 18 = 36watts$
	5 minutes every 15 minutes	$300 - 5 = 295watts$
Power Consumption @ Min		$5watts$
Power Consumption @ Peak		$5 + 36 + 295 = 336watts$
Average Power Consumption		$5 + \frac{6}{24}(36) + \frac{1}{4}(295) = 87.75watts$

Table 9 - Energy demand estimation of a clinic

8. Appendix B: The Engineering of Renewable Technologies

8.1The Classification of Energy

The Law of Conservation of Energy states that energy cannot be created nor destroyed. However, they can be transferred into other form of energy without any loss of total energy. Scientists have defined six possible forms of energy in the universe, each of which can be converted into another form for extraction. They are:

Energy	Description	Examples
1) Electrical 	Electrical energy refers to the power dissipation in a resistive material, where there exists a voltage differential across its terminals, resulting in the flow of electrons (otherwise known as current). $Power(W) = Voltage(V)\ x\ Current(A)$	• Direct current powering up a phone • Alternating current powering up a lamp

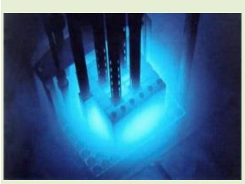
2) Mechanical 	Mechanical energy refers to the sum of potential energy and kinetic energy that is stored in any physical object with mass. $E_{mec\hbar anical}(J) = PE(J) + KE(J)$	• Sea water moving underwater turbine • Automated machines
3) Chemical 	Chemical energy refers to the potential contained in any chemical substance. The energy can only be extracted through chemical reaction.	• Chemical reaction inside a battery • Burning fuel produce heat and rapid expansion
4) Radiant 	Radiant energy is the energy carried by photons in the form of electromagnetic waves. The sun, as well as any light sources emits radiant energy.	• Sunlight • LED lights • Incandescent light blub
5) Thermal 	Thermal energy refers to the intensity of vibration of individual atoms inside a matter. Higher vibrational activity results in a higher thermal energy and vice versa.	• Movement of wind due to temperature differential
6) Nuclear 	Nuclear energy refers to the energy emitted during the process of nuclear fission, where particle is split into smaller particle through the absorption of neutron.	• U-235 + neutron → U-236 (unstable) → Kr + Ba + 3 free neutrons + gamma rays

Table 10 - The six types of energy

8.2 Terminology

Terminology	**Definition**
Joule ($\boldsymbol{J}$)	Joule is the fundamental unit of energy(E), which can be exist in either one of the six forms of energy *(Table 2)*.
Wattage ($\boldsymbol{W}$)	Watt is the fundamental unit of power(P), which is defined as

	the rate of energy consumption (or reception) over time, or the product of voltage(V) and current(A). $Power\ (P) = \frac{Energy}{Time} = \frac{1\ Joule}{1\ second} = Voltage \times Current$
Kilowatt-hour ($\boldsymbol{kWh}$)	Kilowatt-hour is the amount of power (in kilo-watt, or $1W \times 1000$) consumed (or received) in one hour. $1(kW\hbar) = 1(W) \times 1000 \times 3600(s)$
Average Power	The amount of energy consumption during a period of time. $Average\ Power\ (P_{avg}) = \frac{\Delta Energy}{\Delta Time}$
Instantaneous Power	The amount of power at any given instant of time. $Instantaneous\ Power\ (P_{ins}) = \lim_{\Delta t \to 0} P_{avg} = \frac{d}{dt}E$

Table 11 - Useful terminologies

8.3 Solar Energy

The Photovoltaic Effect

It is important to make sense of the physics behind solar cells in order to understand its advantages and disadvantages.

Modern solar cells vastly available commercially use silicon as its base material. Silicon is a semiconductor with 4 valence electrons *(the amount of negatively charged particle at the most outer shell)*, which is why it is also known as a "type-IV material". When multiple silicon atoms are put together, covalent bonding is formed between the 4 outer-most valence electrons of each individual atom. However, such structure is undesirable for the photovoltaic effect to take place, because the material is neutrally charged. Therefore, two types of atoms are intentionally introduced into the silicon lattice by the process of "doping".

The first type of atoms comes from the family of type-III material, meaning that they carry only 3 valence electrons. Imagine the middle silicon atom on figure 5 is replaced by a type-III atom. In such case, one electron is missing from the covalent bond (the empty space is known as a "hole"), which results in a naturally positively charged material, known as "P-type material".

Likewise, when the middle silicon atom in figure 5 is replaced by a type-V atom, an extra electron is going to exist on top of the structure, effectively making the material a naturally negatively charged material, or "N-type material".

A solar cell typically consists of an N-type material stacked on top of a P-type material. A “PN junction” naturally forms between the two materials. The junction is made up of the free electrons from the N-type, as well as the holes from the P-type. Together, a non-conductive layer is sandwiched between the two types of material, and this is where the photovoltaic effect takes place.

Inside the PN junction, there is what’s known as a “build-in potential” barrier. When light with sufficient energy is shined upon the junction, the build-in potential is overcome and the bond is disintegrated, creating an “electron-hole pair”. The creation of electron-hole pair is known as “carrier generation”. Once an electron-hole pair is created, the device is no longer operating under equilibrium and a voltage differential develops across the solar cell. When a load is attached to the terminal of the solar cell, electrical current is passed through the load. Ultimately, the hole and electron that travel through the load will be combined once they reached the N-type and P-type material, respectively. This process is known is “carrier re-combination”. The continuous process of carrier generation and re-combination is how solar cells generate electricity.

Device Characteristic of Solar Cells

The current-voltage characteristic curve, or IV-curve, is a powerful yet simple way to study that characteristic of an electronic device, like the solar cell. It is a curve formed by plotting the voltage generated by the cell against the current that goes through the load attached to the cell by the variation of load resistance, according to the Ohm’s Law:

$$Resistance(Ohms) = \frac{Voltage(V)}{Current(A)}$$

A solar cell is not a linear electronic device, in the sense that it does not exhibit a linear IV-curve. That is, even if we maintain the irradiance and the temperature at a constant level, there exists a point where the device is going to generate maximum amount of power that is associated with a specific amount of load resistance.

To better understand the device characteristic of a solar cell, a small solar panel shown at the right was used to demonstrate the idea of IV-curve. The panel is connected to a variable load resistor, while the voltage and current is monitored and recorded.

Irradiance and temperature were maintained at a constant level throughout the experiment.

Resistance	**Voltage**	**Current**	**Power**
4000	3.61	0.0007	0.002527
3000	3.61	0.0009	0.003249
2000	3.6	0.0012	0.00432
1000	3.6	0.0018	0.00648
324	3.59	0.0036	0.012924
180	3.52	0.0108	0.038016
123	3.39	0.019	0.06441
90	3.19	0.026	0.08294
73	2.86	0.0314	0.089804
60	2.85	0.0315	0.089775
55	2.84	0.0319	0.090596
52	2.13	0.0345	0.073911
40	2.01	0.0351	0.070551

Table 12 - Experimental data

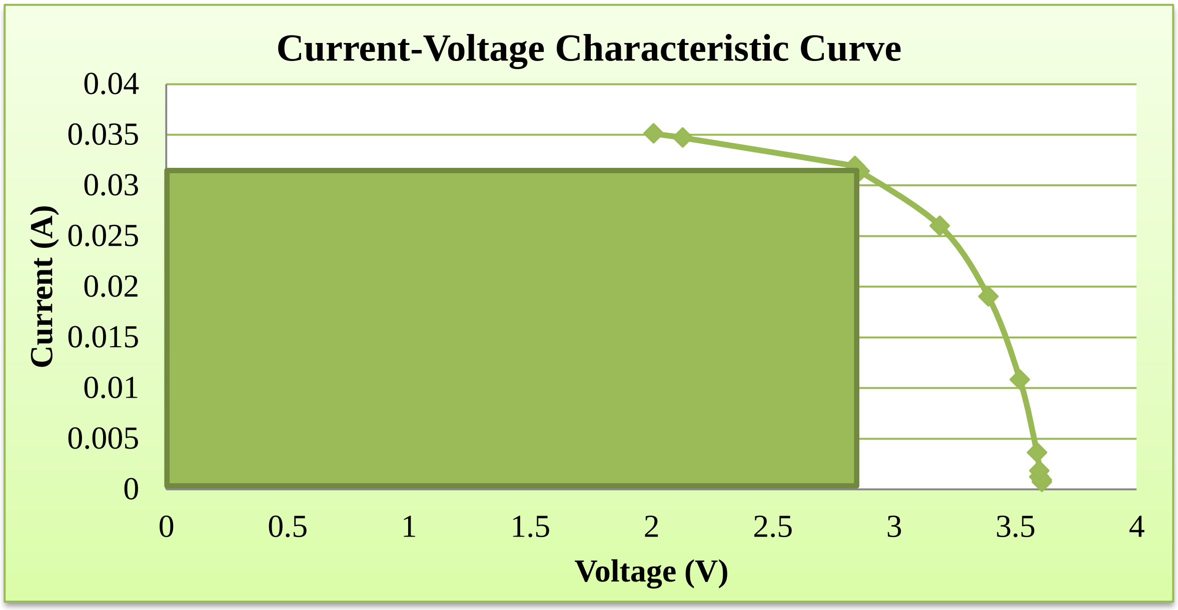


Table 13: maximum power output is determined by plotting the current-voltage characteristic curve

Solar Energy System References

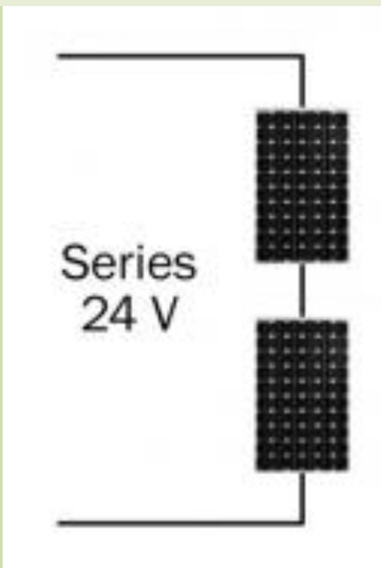
A solar energy system typically consists of the following components:

Common Component	Description
Charge Controller 	A charge controller regulates the current flow from the solar panel system to the battery bank. The device is primarily used for preventing the batteries from over-charging or over-discharging. Nowadays, charge controllers may divide into two categories – Pulse Width Modulation (PWM) and Maximum Power Point Tracking (MPPT). Both technologies are designed to ensure that the battery charging process is as efficient as possible. *(PWM and MPPT were briefly discussed in page 15)*
Battery Bank	As discussed, the amount of power produces by a solar panel depends on light irradiance, temperature and the load resistance. Since power generation of the solar panel varies greatly throughout the day, it is often necessary to have the ability to store the energy generated by the panel system. A battery charging process converts electrical

	energy into chemical (and thermal energy), and may convert back into electrical energy when needed.
Inverter 	Solar panel generates direct current (DC), as opposed to alternating current (AC). Since most of the household appliances use AC as their only power source, an inverter is necessary to convert DC power from the solar panel into AC. Note that the energy conversion process is not 100% efficient. Some electrical energy will be lost in the form of thermal energy.
Circuit Breaker 	Circuit breaker is a protection device designed to protect the entire system in an event of overcurrent. Circuit breakers are often resettable. Once the issue is resolved, one may simply reset the device and the system will resume operation.
Combiner Box 	For a solar array system that consists of two panels or more, a combiner box is often used to combine the wires.
Electric Meter	An electric meter is a device to measure the amount of power transmitted from the solar panel system to the load.

Table 14 - Solar energy system components

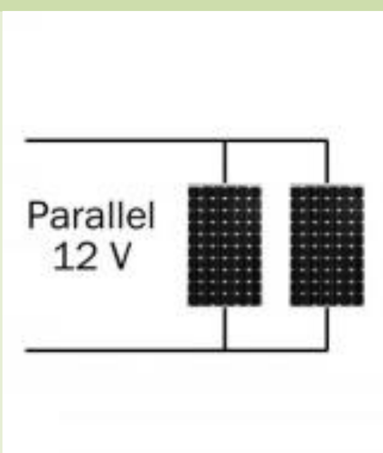
Solar Array Configuration



For the system to the left, two panels are connected in series. As a result, the voltage is increased and the current remains the same.

For example, each individual penal can generate a voltage of 12V and a current of 1A.

$$V_{system} = V_1 + V_2 = 12 + 12 = 24(V P_{system} = I_{system} V_{system} = 1 \times 24 = 24(W)$$



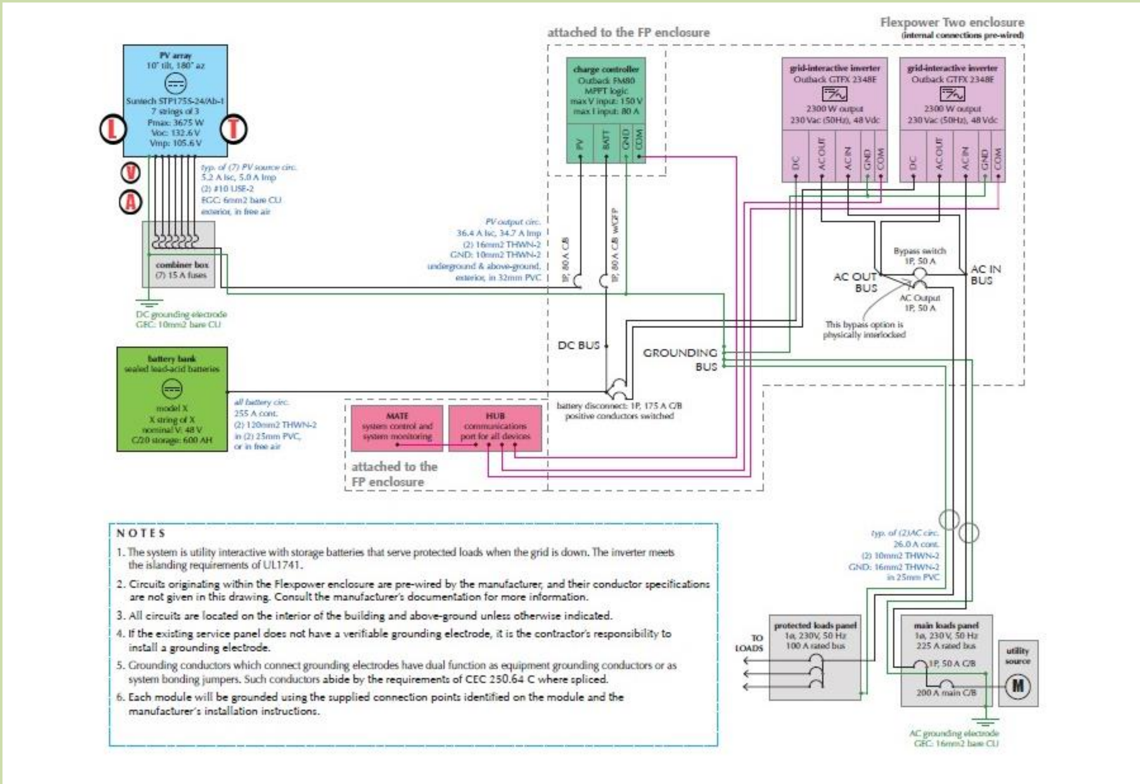
For the system to the left, two panels are connected in parallel. As a result, the current is increased and the voltage remains the same.

For example, each individual penal can generate a voltage of 12V and a current of 1A.

$$I_{system} = I_1 + I_2 = 1 + 1 = P_{system} = I_{system} V_{system} = 2 \times 12 = 24(W)$$

Table 15 - Typical solar energy system configuration

Solar Energy System Reference Design



The above diagram is a reference design of a complete solar energy system. The design was drafted by the Engineers Without Boarders, San Diego Chapter. The system was originally intended be implemented in a village in Kenya. In the design, a total of 21 solar panels are employed. The wires are combined inside the combiner box with a built in circuit breaker and go into a charge controller. A battery bank, system monitor and inverter (with electric meter) are also connected to the charge controller. A grid inverter is in place for interfacing the system to the local electric grid.

Table 16 - Reference design by the Engineers without Boarders. Product of the Power Up Kenya project.

8.4 Wind Energy

On earth, there exists a gravitational field that exerts a force on any object with mass and pulls the object toward the center of the earth. Since air is composed of particles with mass, they too experience gravitational force and constantly being driven toward the ground. The fact that the air is being pulled to the ground creates air pressure, which explains why high altitude areas (example: mountain tops) have a relatively thin layer of air.

Air pressure is the accumulation of air particles presented in an area. Air pressure is not unified across the surface of the earth due to the difference in temperatures. At elevated temperatures, air particles become less dense, which results in a rise of air due to its reduced mass. The sun is the prime factor affecting the temperature of air. Since the earth is constantly rotating, the air pressure changes accordingly. Wind is the by-product of the pressure differential of air, and it moves from a high-pressure to low-pressure areas.

Wind turbines can generally be divided into two types—Fixed Speed and Variable Speed. In both types of systems, a speed control unit keeps the rotational speed within the desired operational range. In addition, any wind turbine is rated at a maximum allowable wind speed, known as the survival speed. Going above this rated speed will result in permanent damage to the electronic components of the system.

A variety of methods can be used to control the speed. For example, an automatic control system may apply a break on the rotator to convert the excess mechanical force into heat. A resistance block may also be employed to convert the excess electrical energy directly into heat in order to prevent it damaging the rest of the electronic system. A gearbox system can be implemented to slow down or speed up the rotational speed. It is also possible to adjust the pitch of the blades using motors to achieve the ideal rotational speed.

Generators

A generator is the device responsible for converting mechanical energy into electrical energy. There are a couple types of generators that are commonly used in wind turbine systems, two of which are briefly discussed below:

The SCIG is an energy conversion technology commonly seen in older wind turbines with fixed speed or smaller systems. Electricity is usually transmitted in three phase AC power to enhance efficiency. A SCIG provides a simple solution for interfacing a wind turbine system directly to the grid. A drawback of SCIG system is that it must be operated at a constant rotational speed. Therefore, speed control systems must be in place to control the speed.

The PMSG energy conversion technique is commonly seen in today's commercial wind turbine system that runs at variable speed. A permanent magnet is used for the electrical energy generation process through induction. The fact that there is no brush contact or gearless option reduces the need of maintenance for the generator. The diagram[8] below shows how the entire conversion steps of a wind turbine system are connected to the utility grid.

[8] Molina and Alvarez, 2011.