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Smart grid technology in the developing world

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SMART GRID TECHNOLOGY IN THE DEVELOPING WORLD

by

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Abstract

A smart grid is the integration of communication and information technologies with contemporary power infrastructure to enhance load service and to incorporate continually evolving end-use applications. It is the latest advancement in the areas of power generation, transmission and distribution. It has advanced beyond the traditional grid structure at every stage; a smart grid is capable of incorporating distributed generation (DG) renewable sources and has improved transmission capabilities through implementation of technologies such as Flexible AC Transmission Systems (FACTS). Through the addition of control technology in the distribution network a smart grid is able to implement "self-healing" and other methods to improve reliability of power supply. Enhanced interconnectivity also offers the option of microgrid development which can be accomplished more quickly and affordably than a large scale grid. The ultimate goal of this approach is to then connect various microgrids to establish a robust network. On the consumer's side, smart devices are being developed which can practice load shifting to reduce demand on the grid at peak hours. One facet of this technology network is the smart meter, an enhanced metering device used by the consumer to practice demand side management through control technology and informed decision making. All of these characteristics make the smart grid more reliable, efficient, versatile, cost effective, interactive and environmentally beneficial than other systems. The goal of this paper is to first explore the characteristics of a smart grid system and to report on current work that is being done implementing these systems, particularly in developing countries. The latter half of the paper will then present a test for smart grid compatibility on a national level based on the necessary and beneficial preconditions for smart grid development. That test will then be applied to nations that lack a significant or reliable power generation and transmission system. The results of this test will determine specific regions which meet the criteria for both a high compatibility for smart grid development and a high

demand for the solutions it offers. Those results will be synthesized into a proposal for future work, with the goal of broadening the global focus of smart grid development to include countries where millions of people still lack access to electricity in their cities and homes.

Preface

The sun shines brightly on a small village in Africa, no more than 200 people live here. There are children playing nearby, weaving through their mothers who are hanging clothes up to dry. In some houses the evening meal is being cooked over a kerosene fire. To the observer who may be a tourist on holiday they may not notice anything distinctly different about this village than those in their own country, even as the sun begins to descend beneath the horizon. Once darkness truly arrives, however, the observer will begin to wonder where all the lights are. This village, like many across the continent of Africa and in countries around the world, has no electricity. It does not even have power lines running above it that supply unreliable access to power a few hours of the day. The scattered homes are now completely dark, or else lit by the kerosene fires. These fires are the only source of light and heat they have access to. The poisonous carbon monoxide gas that is released from burning kerosene is a danger they cannot avoid. The children are now gathered around the dim fires in their homes with school books in their laps, while their mothers warn them to finish their studies soon so the family can conserve fuel. The children in the unlit homes are unable to study after the sun sets, many are doing worse than their peers as a result. This scenario describes the problem space for places around the world that lack electricity. These areas need reliable and efficient infrastructure, they need a smart grid.

1.0 Overview

There are more than 1.2 billion people in the world who don’t have access to electricity [5]. Those who lack this resource or who have unreliable electrical power often use open fires fueled by biomass to provide heat and light. This is the direct cause of death for over 4.3 million people per year who contract illnesses from household pollution [17]. There are also an estimated 1.6 billion people who rely on kerosene and oil for their source of light. Kerosene has a variety of adverse health effects. Long term exposure to kerosene fumes could result in neurological or kidney damage including blood clots that damage the brain, heart or other organs, and most commonly, carbon monoxide poisoning. Providing electrification to these people will greatly improve quality of life, as well as nearly eliminate the health issues brought about by these alternatives.

While there has been a growing need for electricity around the world, a solution has been developing alongside it. Smart grid technology offers the blueprint for a better power generation, transmission and distribution system. It is more easily implemented than a traditional grid in areas that lack any infrastructure because of its versatility. A smart grid can operate effectively on a microgrid level, which is a system that may be only the size of a small village yet contains power generation, distribution, energy storage, smart metering and more. A larger smart grid can then be synthesized by connecting various microgrids, thanks to smart grids’ enhanced capabilities to handle distributed generation (DG). Smart grids offer more reliability to consumers, a trait that is lacking in many infrastructures that have been built in developing countries. Smart grid implementation in the developing world has huge potential to address the need for electrification and many other needs, and is more feasible than any solution in the past.

This paper will describe the characteristics of smart grid technology and its current applications in the developing world before establishing a proposal for future work in the developing world.

1.1 Key players

It is important from a systems engineering perspective to recognize the key players surrounding any technology in order to gain a better understanding of it. These different groups for smart grid technology include: the designers who are responsible for innovative thinking about smart grid technologies, the workers who construct and implement these technologies, power providers who must integrate smart grid concepts into their own grid structure, consumers of electricity who are responsible for increased participation via demand side controls, and the governments of countries responsible for funding smart grid projects and passing legislation regarding them. These different groups and their contributions to smart grid development will now be examined in order to gain a systems perspective on this technology, the discussion is summarized in Table 1.1.

The primary way in which the developers of smart grid technology contribute is through innovation. This innovative design is needed to fit the variety of contexts in which a smart grid may be deployed. As will be discussed in section 2.5 there is a critical design decision about grid size and the development of either a “microgrid” system, or else a large centralized grid, or some middle ground between the two. This design choice is completely contextual and is affected by factors such as budget, power reliability and desired grid performance, as well as the desire for integrating renewable energy sources to supply power to the system. The designer of a smart grid technology must therefore have a contextual understanding of the project in order to design an appropriate solution.

The primary way that constructors of smart grid technologies contribute is through assessing and enacting its feasible implementation. This will involve an assessment of environmental factors to deployment of this technology which may not be obvious in the design phase. For example, a significant portion of smart grid design involves inclusion of renewable energy sources, which may include solar energy. However, if the construction plan involves adding a photovoltaic power generation system, yet the construction site is overshadowed by neighboring buildings and receives no direct sunlight, then that system is entirely ineffective. The contractor who is responsible for constructing the physical grid system will be the most responsible for observing these issues and making decisions to help solve problems.

The primary way that power producers contribute to smart grid technology is by integrating it with their own power grid network. Part of this process involves replacing old technology with new, such as the replacement of traditional electricity meters with "smart meters" that allow for demand side management of power supply. It also may involve the integration of renewable sources of energy to the power production system. These renewable sources however, as will be discussed, are often more effective with a small scale deployment scheme rather than large scale power production. The inclusion of various renewable DG will have an effect on the voltage level of the network due to their intermittency; therefore, the power supplier must be able to manage the multiple sources on their network. Lastly the integration of smart technology includes added responsibility on the supply side as well as the demand side to be managing load distribution. Power producers must employ control technology to measure and predict the load and to avoid excessive demand on the grid during peak consumption hours.

The primary way that consumers of electricity produced by a smart grid system contribute is through informed interaction. This makes them "prosumers," or an active member of the power supply system who makes decisions that affect the network. A prosumer interacts by using one characteristic of a smart grid which is the inclusion of various control technologies. One of the devices that is included in the control system is the smart meter, which gives the user a way to measure their power consumption in real time. An issue that arises in a non-smart grid system is the excessive demand on the grid's supply during peak usage times of day, which can cause reliability issues or necessitate the use of expensive, inefficient and polluting "backup" power supplies. With the introduction of user or "demand side" control, the consumer is given the ability to practice "load shifting," which is consuming power during non-peak hours. This informed participation of the consumer based on smart meter data allows for a more reliable and efficient grid supply system.

The primary way that governments, and also non-governmental organizations, contribute to smart grid technology is through funding and supporting through legislation the development and testing of these technologies. There are several examples of nations whose governments have chosen to invest a significant amount of funding and manpower in the development and testing of smart grids, the foremost of these include the United States, China, Brazil and India. The later three and their test projects will be discussed in detail as they represent a template for developing nations without existing infrastructure to implement this technology. Each of these governments have invested billions of dollars to support the development of smart grid technology.

Table 1.1 Summary of key players in smart grid technology development

Group/organization	How they are involved
Designer of smart grid	Considers design decisions including grid size and structure, available sources of power production, etc.
Implementer of smart grid	Has both an understanding of the intent of design and the feasibility of installation, and reconciles discrepancies between the two.
Power Producer	Integrates smart grid enabled distributed generation, practices enhanced control methods of power supply, implements smart metering.
Consumer	Uses available smart metering to practice load shifting and demand side response techniques.
Government/Private financing organization	Provides financing for smart grid development as well as regulation and legislation in the case of government.

2.0 Literature review

This section is comprised of a literature review on smart grid technology concerning its definition, characteristics, and design decisions regarding its implementation. Lastly a review of current applications of smart grid technology among nations considered developing is presented. This section predominately concerns the countries of China, Brazil and India, which are all forerunners in launching pilot projects and innovations of smart grid designs. These countries and their work in this field will provide information and background for section 3.0 which concerns compatibility analysis for smart grid development in other countries which lack substantial electrification.

2.1 Policies surrounding smart grid

In order to better understand the nature of smart grid technology as well as its capacity to be implemented, the policies and regulations that apply to smart grid development will now be examined. The foremost international authority on these regulations is the Institute of Electrical and Electronics Engineers (IEEE). Their policies on how to handle the transition from a traditional electric grid to a modern or smart grid have been cited in multiple legislative acts. Some of these legislations that were created for regulation of the United States' smart grid development shall be presented. In 2005 the United States Congress passed the Energy Policy Act, which cites the IEEE 1547 Standards and Best Practices for Interconnection as the national authority for interconnection of distributed energy resources (DER), which is a key innovation of the smart grid system [14]. Two years later the United States Congress passed the Energy Independence and Security Act (EISA), which officially charged IEEE along with other organizations to "coordinate framework and roadmap for smart grid Interoperability standards and protocols" [14]. This legislation expanded the IEEE 1547 standard, among others, to continue to define smart grid development and implementation. Later in 2009 the Federal American Recovery and Reinvestment Act (ARRA) was put into effect. This much more complex piece of legislation was an attempt to stimulate the U.S. economy on a massive scale, and $4.5 billion was allocated specifically for the "modernization" of the electric grid. This led to federal investment in the Smart Grid Investment Grant (SGIG) combined with other investors to a total of over $8 billion to help develop new smart grid and "high penetration" DER projects [14]. This was the first large step that the United States took to implementing smart grid technologies on a substantial level.

In order to better understand the basis for these key legislative acts, the underlying policies and standards will be examined. The previously mentioned IEEE 1547 Series is one of the foremost international standards for smart grid development. It deals with technical specifications and requirements for the interconnection of DERs and the traditional Area Electric Power System (EPS). It also covers testing of those specifications and requirements [14]. IEEE 1547 therefore presents the primary technical standard and functional requirements for these interconnections and their testing; it is also comprehensive enough to be sufficient for installation of most DER systems [14]. It does not include any information about the design, planning or operating of a smart grid system. The 1547 standard is effective when used as a reference during the design phase of smart grid development, because its specifications and requirements can be used as ultimate design parameters. It is also useful during and after installation to provide testing mechanisms in order to ensure that the installed grid is safe and functional.

Along with the pivotal 1547 standard IEEE also produced the 2030 Standard Series. While the 1547 series has a large focus on testing methods for smart grid applications, the 2030 standard provides definitions for terms associated with this technology. As a part of the revisions done due to the EISA the 2030 standard was written to document the IEEE standard definition of a smart grid, as well as an associated term called “interoperability.” The term interoperability is defined by Standard 2030 as “the capability of two or more networks, systems, devices, applications or components to externally exchange and readily use information securely and effectively” [14]. This is a key aspect of smart grids that make them unique, there is a continuous exchange of information between many components on the grid. The standard also gives a concise definition from IEEE for what a smart grid is: “the integration of power, communications, and information technologies for an improved electric power infrastructure serving loads while providing for an ongoing evolution of end-use applications” [14]. This definition highlights the different aspects of smart grid that make it unique. These include the integration of power and communication, which is done to increase control over distribution at both the supply and demand sides. The definition also includes the “evolution of end-use applications," which defines the smart grid as being highly receptive to innovation and improved technologies being added to it, including the addition of renewable sources as DERs.

2.2 Public opinion about smart grid

Because the effective operation of a smart grid system involves the active participation of many groups, it is important to understand the prevailing opinion about these technologies. A study was performed and published in the *Renewable and Sustainable Energy Reviews* journal which used a means of experimentally determining the mindset of consumers about smart grid technology. The research was performed using a tool called signal detection theory, which demonstrates a response under several input-signal conditions. The participants were presented with situations involving an actual smart grid design and its operation and asked to either confirm or deny claims about the usefulness and practicality of this technology. The questions that framed these scenarios are presented in table 2.1.

Table 2.1 List of questions used in end user perception study for smart grid operations and participation [11].

1	Have you adjusted your load-patterns to serve the utility supplier's wishes?
2	Have you adjusted your load-patterns to fit the patterns of power generated by renewable energy sources?
3	Do you adjust your micro-grid for the conditions of the utility supplier?
4	Do you know the values of power quality in real time for improving energy quality in the smart grid?
5	Do you know the fault conditions that affect the complete smart gird?
6	Do you want to monitor energy theft in the complete smart gird?
7	Do you desire to monitor the improvement of environmental conditions from reduced CO2 emissions in the entire smart grid?
8	Do you want to include your solar-energy production in your micro-grid or smart grid system?
9	Do you want to include your wind-energy production in your micro-grid or smart grid system?
10	Do you prefer to be involved in dynamic tariffs and load shift?
11	Does accurate meter reading change your decision about energy consumption?
12	Are you using community social capital to build a community micro-grid?
13	Are you willing to install your own generating capacity under the current government conditions?

14 Are you willing to accept smart metering in order to provide information that helps the smart grid?

15 Do you agree with the rules and infrastructure required for smart grid technology?

The participants who represented the end user population were assessing the smart grid scenarios based on the perceived usefulness and ease of use of that technology. It was found that most end users have a conservative criterion, or low level of confidence in the usefulness of smart grid technology, and that the root cause of this was that it was "not a well-known technology for end users" involved in the experiments [11]. This is evidenced by the fact that despite an observed interest in the general public about global environmental health, the sampled group of end users still had a lack of confidence in smart grid technology, which focuses on sustainable energy production integration. The sampled user population may also be unaware that smart grid technology is capable of reducing cost of power by enhancing system efficiency. A population of consumers that lack knowledge of and confidence in smart grid technology will reduce the effectiveness of the smart grid system. This is because the end user is intended to play an "active and efficient role" by detecting power information through a smart metering system and implementing practices such as load-shifting [11]. This research suggests that given proper knowledge and incentive, the end user population will adopt smart grid technology because it directly serves the desires of the majority of that population. It is only a matter of making that knowledge available and the technology accessible.

2.3 Communications technology

An important aspect to the management of a power system is the ability to predict the load of the system. This allows the operators to plan for variable load demand and to make adjustments based on this knowledge. According to an article written by Ioannis Panapakidis with the Department of Electrical Engineering at the Technological Education Institute of

Thessaly, there are a variety of load forecasting models, and no one model has a universal advantage but each are advantageous in specific situations [8]. It is therefore an objective of this paper to determine which model or models are most effective when applied to potential smart grid systems in the developing world.

Panapakidis does explain that an effective forecasting model always has a few basic properties: “low computation burden, capability of simulation of the human expertise, flexibility, interpretability and exploitation of the results” [8]. Furthermore, almost all existing models can be classified as fitting into one of two categories: trend methods and similar-day approaches. The first method is truly “forecasting” the load demand based on available historical load values and their trends. The second model type compares current and historical load values, and accounts for other exogenous factors other than the load itself to produce a “training set” that the model is then tested against until it performs well enough to be implemented. If the model is not forecasting with acceptable efficiency, the training set is adjusted and the model is retrained and then re-implemented. This category of models is often called “cluster based” [8]. According to the research that Panapakidis cites, a hybrid of the forecasting and clustering models is suggested for the purpose of lowering forecasting errors.

Panapakidis next introduces another method of categorizing forecasting models which is their predictive power. Most commonly models are either day-ahead or hour-ahead forecasts. Panapakidis states that “Hour-ahead forecasts are potentially essential in smart grid paradigms with prosumers that bid load reductions hourly, in distribution system lines congestion management and operational planning of distributed generation and storage technologies” [8]. Panapakidis suggests that a smart grid system hinges on load prediction on an hourly basis, because both the consumer and the power manufacturer will be making adjustments to the system multiple times daily, therefore smart grid load forecasting should be focused on hour-ahead models.

Panapakidis makes an observation of the current load-forecasting models: that they are most equipped to deal with large-load systems. “While the load level decreases, the deterministic character of the load sequence tends to limit” [8]. A large load system is typically considered to be on the scale of a country or a region, and there is a gradient between that and the smallest load variety which are micro grids. The nature of smart grid technology therefore makes it difficult to integrate with current load forecasting methods, because “the continuous evolution of smart grid and micro grid technologies provide the methods for the development of grid-independent small scale power communities” [8]. Smart grid technology, at least the beginning stages of it, lends itself well to a small scale or micro grid application, therefore there is a need for improving load forecasting models for small systems. This paper will continue to explore the consideration of grid size in developing a smart grid system.

Panapakidis believes that the solution may be in the innovative use of hybridized forecasting with an hour-ahead load model. The trend of smaller smart grid systems is that they are composed of “a large number of buses; their consumption patterns differ significantly and characterized by stochasticity and presence of outliers” [8]. The research conducted by Panapakidis demonstrates that this hybridized hour-ahead load forecasting model is able to “effectively stimulate the nonlinearity and the special attributes of bus loads,” which makes it a good candidate for the current stage of smart grid technology development.

2.4 Renewable and alternative energy integration

In regards to renewable energy concepts being pursued in the developing world there is a great deal of effort put into innovation. There are some countries that are becoming developed at a rapid rate which results in the unique combination of high electricity demand as well as a capacity to invest in new technology development. Countries such as Brazil, China, India, Mexico, Russia and South Africa fall into this category. According to data gathered by the International Energy Agency (IEA), in 2008 these countries spent more on research, development, demonstration and deployment of renewable energy technology than IEA member countries did [9].

India is in a unique situation in that it was one of few countries with the capacity to develop nuclear power generation technology that was excluded from the Nuclear Non-Proliferation Treaty, which means that it has spent decades developing a “largely indigenous” nuclear power program [9]. India also holds 25% of the world’s known reserves of thorium, which can be used in a pressurized heavy-water reactor (PHWR) to absorb additional neutrons and become fissile and useful for nuclear reaction. This innovation with thorium based reactors will allow India to make use of its large supply of the element and develop more infrastructure for this type of alternative energy. As of April 2015 the Indian government stated that a 300 MW advanced heavy water reactor (AHWR) for the processing of thorium has been developed and will be implemented as a new standard.

Elsewhere in the world, where even less capacity for large infrastructure exists, innovation still occurs. In 2014 a startup company in Tunisia called Saphon Energy demonstrated their design of a bladeless wind turbine [9]. This design replaces the rotating blades and hub with a sail shaped body. It not only minimizes materials and environmental impact, but allegedly is able to capture “twice as much wind energy as a conventional bladed wind turbine for the same swept area” [9].

In a partnership of ideas between the University of Nottingham and local universities in Bangladesh, Nepal and Kenya, the researchers in these developing countries have been able to test and improve upon the design of a thermo-acoustic stove. This device uses an ambient heat exchanger (AHX) to remove heat from the stove which is generated by fuel burning. The air within the stove then undergoes "repetitive thermal expansion and rarefaction to produce acoustic energy" [9]. Between the heat source and the AHX there is a porous regenerator whose purpose is to sustain a resonant acoustic wave from the acoustic energy being produced. Then a closed loop linear alternator converts that resonant wave into electrical energy. This technology, while still requiring more development in order to make it perform as well as a conventional oven, serves another distinct purpose for the areas it is being tested and implemented in. This stove was developed as "a means to reduce health problems that occur from chronic exposure to smoke and other pollutants emitted by rudimentary wood-fired cook stoves and open fires" [9]. This type of innovation is important, because it solves more than just the immediate energy need of people in the developing world, but also recognizes that there are other related issues that are not always obvious.

While current models of renewable energy are important to discuss, it also must be evaluated how these renewable generation sources integrate with smart grid technology. The common model for smart grid development shares an important characteristic with most renewable energy generation, which is that both involve distributed generation. Most smart grid models are characterized by "small rating electrical sources, typically decentralized and located close to the end-user locations" [13]. One primary reason for this is that it provides enhanced grid security; having distributed generation means that the failure of one power source will not cause a global failure, and power can therefore be rerouted to ensure grid integrity [13]. The reason that renewable energy generation is typically distributed is because of its limited power production capabilities. Currently the power production capabilities of most renewable sources are much less than that of oil, coal and natural gas facilities, and therefore it becomes less feasible to build a centralized renewable energy facility as it would need to be built on a very large scale. Building multiple, decentralized and smaller scale renewable energy systems is the most cost effective way to use the technology.

It is promising that smart grids are capable of operating on a microgrid level which can make better use of small and distributed renewable energy production than a larger system could. It is also noteworthy that smart grid innovations can alleviate issues related to renewable energy production such as intermittent power production and voltage variation. An article published by the Renewable and Sustainable Energy Reviews journal states that “renewable generations cause new challenges to the distribution system over centralized, predictable, and dispatchable production due to their intermittency and fluctuating characteristics” [10]. The article states that the most prominent renewable generation sources such as wind energy and solar photovoltaic inherently involve significant fluctuation, due to changing wind speeds or changing solar collection. These fluctuations of power production cause a variation of voltage from the source, which can result in “degraded protection, two-way power flow, and increased fault level” [10]. These issues are common and can be crippling when renewable energy sources are implemented in the current centralized grid model. The smart grid is able to employ control technology to mitigate negative effects of renewable integration thereby making it more feasible [10].

The smart grid differs from a standard grid system by employing control technologies for the purposes of monitoring and analyzing power flow, and for sending communication and control signals throughout the system [10]. Through these enhanced levels of information about the grid and control over it a smart grid system can enable a more complex system of loads and DG, including renewable sources of power. The primary issue in renewable energy production is that the lack of control over the energy source results in a lack of control over voltage and power output. Smart grid technology offers three primary methods to address the power production issues of renewable sources. These are inclusion of standby conventional power sources, demand response, and the addition of energy storage [10].

Employing standby power sources involves the most automated control of the grid. The conventional power sources would be on standby mode until production from the renewable sources stops, at which point the standby would rapidly be turned on in an effort to maintain constant production. In theory this works, but “it is difficult to achieve in practice the required level of power tracking capability” [10]. More than lack of precision, it is also costly to build and maintain these standby power sources when they are not being used to their full capacity. Overall this approach to solving the issues in renewable power production is the most costly and also not very effective.

Smart grid technology also allows for the use of demand side integration, of which demand response is an integral part. This method involves “active participation of both producers and consumers of electrical energy in network operation.” Producers might participate in demand response through employing a “time of use rate, real time pricing and direct load control” in order to minimize energy usage and add incentive for consumers to do so [10]. Consumer participation includes “energy consumption reduction through load curtailment strategies and load shifting to off-peak period” [10]. Consumers and producers must therefore be informed about overall grid power production and consumption, in order to make decisions to mitigate stress on the grid during “peak periods.” This is made much more feasible with the development of smart metering infrastructure, which provides “real time data” to these groups and allows for “demand side voltage control” [10]. Demand side integration has been shown to be an effective way to “mitigate voltage variations with minimum network reinforcement and constant output of the renewable generation sources” [10]. Demand response allows for the ability to control the load demand in response to variations in power production and overall load consumption, which is an effective way to handle a variable production source.

Smart grids may also resolve distributed power production issues by the inclusion of energy storage. Energy storage can be used to normalize a variable production source, by storing excess production when it is greater than the demand, and then utilizing that stored power when the demand exceeds production. Smart grids integrate this technology by installing small energy storage units near the end user, such as on the feeders in a residential distribution network [10]. Having a local or community energy storage system means less line loss in power distribution when the stored energy is released. Also in keeping with the demand response paradigm, it allows for the local consumer side to be responsible for the distribution of their own locally stored power. This method has been shown to reduce voltage variation problems in grid systems that have significant renewable generation sources included [10].

It is therefore evident that a smart grid model is more adept at utilizing renewable energy production than a standard centralized grid scheme. By employing a distributed, interconnected structure and by using methods such as integration with conventional power production, demand response and energy storage to manage the load and the power quality smart grids can make renewable energy production efficient and useful [10].

2.5 Grid size and structure

As will be discussed in section 2.6, it is worthy of note that the majority of successful smart grid applications have so far been implemented with small, decentralized infrastructures, such as a microgrid. This is partially due to smart grid development being in its early stages, but it has also been shown that smart grid technology works well in smaller systems which employ DG [10]. In planning for the future of smart grid it is important to consider whether this technology should be applied large grid structures, such as the United States system, as well as to microgrid schemes. Researcher Paul Hines of the University of Vermont and his colleagues have attempted to model the "optimal planning of networks that deliver services or otherwise provide connectivity over physical space" [4]. The goal of their efforts is to "describe the conditions under which it is optimal to build decentralized network infrastructures, such as a microgrid, rather than centralized ones, such as a large high voltage power system" [4]. They have chosen to perform this analysis by selecting the simplest set of conditions for decision-making in grid design. Using the two conditions of cost and network reliability they generated spatial models for optimal grid size based on these variables.

The first stage of the grid size model which considers capital cost of building the infrastructure and interconnections within the network is relatively straightforward. The analysis performed suggested that "as capital costs increase network sizes decrease gradually, according to a power law" [4]. It makes sense that as the cost of building a grid increases building a larger and more interconnected grid becomes less feasible due to the total cost becoming excessive. Therefore if the cost of building infrastructure and interconnections is high there is a strong argument for smaller, decentralized systems which can be installed individually and represent much less cost upfront. When interconnection cost is low then highly connected centralized systems become more optimal because these have the advantage of increased reliability.

Reliability is the other parameter used in this modeling system, it is observed that "as the value of reliability increases network sizes increase abruptly – there is a threshold in the value of reliability at which large, highly interconnected networks are economically justified" [4]. A large and centralized grid offers increased reliability due to its larger amount of redundant connections. Those redundancies help prevent failure in power supply and as reliability becomes more significant of a factor having a large, redundant system becomes advantageous. When the importance of reliability is much greater than the cost of building interconnections, "the extent of interconnection redundancy increases even in a highly connected network" [4], meaning that affordable, highly reliable networks are optimized by a large centralized network. It is only when the cost of interconnection and network reliability are both high that it is "sensible to build redundancy through additional local supply rather than through interconnection" [4]. This means that if the cost of building interconnections exceeds the cost of building DG sources by a certain amount, then decentralized systems again become more optimal. It is even observed that the cost of interconnection must be "orders of magnitude smaller than the value of reliability" for a centralized network to be justified. Therefore a situation where it is costly to build interconnections and where the network reliability is high is most optimally implemented by the decentralized network.

In order to test this modeling program on a real geographical region, the country of Senegal was selected. This region represents a low electrification area, "About half of the countries' population still has no access to electricity" with electrification rates in rural areas as low as 28% [4]. Despite the low levels of infrastructure for electricity, there is a large amount of infrastructure for mobile communications, with 1666 mobile phone towers distributed across Senegal and a mobile phone penetration rate of practically 100%. Because the mobile communication system is so well developed, the concentration of mobile towers can be used as an estimation to predict the concentration of electricity needs. The optimal grid modeling was done without any constraints on reliability, and it produced "tree-like networks that are similar in structure to what we found with randomly distributed vertices…the network realization resembles the spatial topology of the existing electricity grid in Senegal" [4]. This test using a real geographic region with non-random load centers confirmed that a modeling system based on the simple parameter set was accurate.

The Senegal test also confirmed what Dr. Hines refers to as the "power law." Using the optimally placed distribution of grid components, the model also tested various costs of infrastructure construction to see how varying this parameter affected resulting grid size. It was found that the optimal grid size and structure obeyed the power law, which theoretically calculates how the cost parameter affects optimal grid size. This power law is given by the relation $\omega^{-2/3}$, where ω is the cost of one unit length-capacity used in building interconnections for a given network [4]. The power law shows that, while it can logically be surmised that as network infrastructure costs increase the optimal grid size decreases, in actuality the optimal grid size decreases very gradually. The Senegal analysis results demonstrated that ω had to increase several orders of magnitude before optimal grid size decreased appreciably due to the increased cost [4].

The power law has implications on the ultimate goal of this modeling system, which is to determine the optimal size of grid infrastructure for any given situation. However what the power law means is that if cost is the most important factor involved then an optimal grid structure cannot be determined. The information necessary is the distribution of demand for electricity, and because of this "there is no single optimal size for infrastructure networks, but rather that different sizes are likely to be optimal for different locations." [4]. This modeling system therefore suggests that "a highly connected power grid" is only optimal if the cost of transmitting power is very small relative to the cost of producing power locally in a decentralized system, and also as the value of reliability increases so does the optimal grid size. Future analysis that is applied to specific regions should include the geographic distribution of load centers as a third important parameter that has a significant effect on grid structure.

2.6 Applications in the developing world

The benefits of smart grid technology have already been discussed, and it has been demonstrated that this system design can be more cost effective and power efficient than traditional grids, is very compatible with inclusion of renewable energy sources, helps eliminate failures in power supply, and in general gives more control to both those involved in power generation and distribution and to the end user. However, despite the universal advantages to utilizing this technology, its development and application have been very imbalanced based on a region's economic status. It has been observed that the "application of smart grid in developing countries is still lagging behind as compared to the developed ones" [3]. The remainder of this paper is concerned with presenting a description of the status of smart grid technology in the developing world and assessing the future work that needs to be pursued in order to most effectively provide this technology to these regions.

According to an article published in the Renewable and Sustainable Energy Reviews journal in 2013, there are a few countries that are considered "developing economies" which stand out in the area of smart grid development. As mentioned in section 2.4 these are China, India and Brazil. These few countries among many in the developing world have demonstrated "proper planning and developing in this technology…therefore, according to the developing progress for smart grid in China, India and Brazil, a pattern of reference for other developing countries is suggested” [3].

The development of smart grid technology in the country of Brazil will now be examined. Unlike many other nations that are considered developing, Brazil has a large and centralized power production and transmission grid in place similar to those found in developed countries. However the Brazilian grid system is problematic in many ways, including “obsolete assets” in its distribution network, an average of 8.7% commercial power lost in transmission, and issues with blackouts and loss of power provided [2]. A literature review produced by researchers at the University of Sao Paulo identifies the main incentives for smart grid technologies to be developed in Brazil as “the reduction of cost [of power production and transmission], increase of reliability and quality of energy services, reduction of technical and commercial losses; grid preparation for the future, and environmental sustainability” [2].

Because of the issues of the Brazilian grid, the national government has funded multiple large scale projects to test and demonstrate different aspects of smart grid technologies. The action plan to raise this funding is named Inova Energia, and it involves the “joint effort of the Brazilian Development Bank (BNDES), Brazilian Electricity Regulatory Agency (ANEEL) and Brazilian Financer of Studies and Projects (FINEP)” to provide US $920 million for projects” [2].

The first of these projects is the “Smart City” of Buzios. The goal of this project was to build the “first smart city” in Latin America, which would “implement clean technologies…align with the current societal problems…and acquire experiences on new smart technologies” [2]. The scope of this project was 10,000 consumers ranging from “homes, industries, businesses and public services,” with an overall grid system rated at 36MVA and a power consumption rate of

55GWh/year for a three year period [2]. The Buzios project had many focuses including "energy management, generation and storage, electric mobility, public lighting and smart buildings, telecommunications, grid automation, broadband internet, and consumer awareness" [2].

The management of energy consumption is an important aspect to all smart grid projects, and like many others the Buzios project accomplished this with smart meters. These meters had a communication network of their own; each consumer unit had its own smart meter located inside it monitoring energy consumption, and each transformer station had a data concentrator which compiles regional data to be sent to the central system, which processes all of the data and manages grid activity [2]. This system allows for automated reading of electricity consumption, automated billing and quality of service control.

In the category of power generation and energy storage, the Buzios project chose to have each consumer producing local power by using solar panels and small wind turbines, as a way to supplement centralized production [2]. The power produced by centralized systems also incorporated renewable energy sources, and also involved a 200kW battery bank for energy storage. This storage system was then use to help reduce strain on the grid during peak demand, when energy consumption was reaching the same level as energy production, the stored energy would then be used so that energy production systems could have reduced usage [2].

The Smart City was lit using 150 LED grid integrated lamps, whose brightness was remotely regulated based on the time of day and the level of people flow [2]. Finally, the consumer awareness program focused on "disseminating information about sustainability and rational use of energy and natural resources, together with the local identity of the population, raising awareness to support the project and to incorporate it in the people's daily life" [2]. This aspect of the Buizos project is a sometimes overlooked asset to smart grid development. Because the demand side regulation of power involves the active participation of the consumer, not just the producer of power, it may be worthwhile to invest more time and energy into consumer education than some projects choose to do.

The application of smart grid technology in China is also a key example for developing countries. China represents a unique case as it is a very rapidly developing economy with massive energy demands, much larger than most other countries. China’s electricity demand is predicted to increase by 233% over the period of 2007 to 2050, up to an estimated 9500 TWh [3]. Smart grid development can help alleviate the problems that this extreme growth rate creates by utilizing a more robust and efficient generation, transmission and distribution system. In addition to the need for a greater power supply capacity, the Chinese power grid is under internal and external pressures to integrate more renewable energy sources and thereby reduce its carbon footprint. A primary issue that China currently faces in harnessing these sources such as wind and solar is an uneven distribution of these sources and in particular a lack of overlap between regions of high production potential and high demand [1]. Therefore the smart grid solution will also be useful for its more advanced distribution and transmission capabilities including distributed generation integration as previously discussed in this paper.

China’s case is a useful one to examine particularly because it is under the process of rapid development and is in a sense in transition out of the class of nations in the “developing world” and towards those that have strong economies and infrastructure. In fact there is a direct correlation between the rapid development of China and its environmental issues [1], as it has been forced to rely on coal as an expedient source of energy. The ways in which the Chinese smart grid system is tailored towards addressing the consequences of its transition out of an undeveloped state will be useful in the design of smart grid systems for nations with little to no development.

The concept of smart grid technology was first introduced in China around 2006 and was immediately adopted as a popular direction for the future of the Chinese power system. Since then the Chinese literature on this development has also rapidly grown, one article published in the Asian-Pacific Power and Energy Engineering Conference (APPEEC) describes the plan for development in China for a "strong smart grid." This design is made possible with China's unique current grid structure that operates at "ultra-high voltage" of roughly 1000kV AC and 800kV DC [6]. The planned "strong smart grid" is still intended to maintain the characteristics of lower voltage systems, and will integrate information based control over transmission, as well as higher levels of interaction on the parts of both consumer and producer [6].

China has successfully invested in some key technologies of smart grid development, such as DG. Because of China's unique situation of rapid growth of infrastructure as well as areas of high production potential but lower demand, DG has been used for more than as a supplemental power supply, which is its common use in well-developed grid structures. The growing Chinese grid in some cases uses DG as the only means of providing in remote areas where the larger grid structure does not service [1]. The bulk of China's DG systems that were built before smart grid plans were made need to be overhauled, as many of them contained small thermal plants which were cheap but highly polluting. However other DG systems that were powered by small hydropower can be readily integrated into smart grid development, and in either case the existing distribution network is a valuable base for further infrastructure [1]. Additionally as a part of the Chinese government's initiative to build upon its DG resources, further investment will be made in its vast untapped wind energy sources, particularly those located offshore near eastern cities and demand centers. Solar powered systems have likewise been installed and used as DG sources powering regions of China where the grid does not service, and further plans to install an additional 20,000 PV rooftop systems by 2020 are being enacted [1].

Aside from the construction and design of better DG systems, China is in the development phase of other key smart grid technologies. The next level of complexity and organization is connecting DG sources to loads and distribution networks in an interconnected microgrid. One of the purposes of a microgrid is increased interconnection, including connecting an “islanded” network to a larger grid or allowing it to operate independently. The multiple modes of operation make a microgrid system much more reliable than the larger grid which is prone to more frequent failures, as well as increased power potential over a simple DG source. The Chinese government is again a major instigator in the development of this technology, with plans to install 30 different microgrid projects for testing and refinement [1]. Research is also being conducted on the bi-directional communication channel and smart metering system which will enable demand side management (DSM), a key innovation discussed previously in this paper [1].

Thus far the most robust and successful implementations of smart grid innovation by developing countries have been presented in the cases of Brazil, India and China. However it is important to note also that these countries represent significant economies, and despite their classification as developing they are in a much different state than countless other nations in regards to infrastructure and economic wellness. These countries therefore represent a transitory stage, not only are they the forerunners of smart grid development among developing nations but they also are at the forefront of other areas of development. I believe that this enforces their usefulness as cases to be examined for the benefit of other nations attempting to transition towards establishing economic and physical infrastructure. The remainder of this paper will be dedicated to the task of determining factors that aid or hinder the development of smart grid technology and apply these to the generation of a national compatibility test for smart grid development. Through the application of this test will be determined some of the best candidates for nations with high smart grid potential as well as high need for it, and finally a proposal of future work for smart grid applications in the developing world based on the results of these tests will be presented.

3.0 Analysis of smart grid potential in the developing world

3.1 National compatibility analysis described

Smart grid technology has many advantages over the typical grid system that allow it to address specific needs that are experienced to different degrees in different regions. The needs of a nation or region vary significantly based on economic and development status. Smart grid applications in areas such as the European Union and the United States are focused on optimization and customer satisfaction. They accomplish tasks such as replacing aged infrastructure, improving reliability, integrating existing and future DG, strengthening the distribution network using more advanced communication technology, and microgrid development. The applications in developing regions such as China are focused on establishing new infrastructure including the development of new renewable DG sources to replace more polluting generation methods, and also to handle the rapidly growing energy demands of the developing nation [1]. In general, smart grid applications in the developing world will look to address similar problems to these, and will address areas of need through the development of new infrastructure that is DG compatible, implements microgrid technology, improves network reliability and also implements demand side management to give the consumer more control of their power consumption.

Through examination of the characteristics of a smart grid earlier in this report it has become clear that there are certain criteria that if met make a nation much more compatible for this technology. I will examine these factors and compile them into a test for compatibility of a nation for smart grid development. The factors that appear to have the greatest effect on compatibility are: access to appropriate education and training, proximity of demand centers to renewable energy production areas, available government spending, and political climate and stability. As a precondition to be considered before assessing the factors of the compatibility test, nations will be filtered based on the percent of their population that has access to electricity. This means that the test will only consider nations in which 50% or less of their population has reliable access to electricity. In this way the test will be considering developing nations who have the greatest need for electrical power infrastructure to be developed. All percentages were obtained via the World Bank database which has collected data as recently as 2012. The nations to be considered for this compatibility test are presented in table 3.3.

3.1.1 Education and training accessibility:

Firstly, as a means of determining a nation's compatibility for smart grid implementation its rate of enrollment in tertiary education will be assessed. In order for a nation to provide its citizens with the proper training to operate a smart grid system they must have higher education institutions, including trade schools and universities. The specialized knowledge provided by these institutions is a necessity for being able to properly construct, operate and maintain a smart grid system. All information regarding tertiary enrollment was obtained from the World Bank database and its information regarding global education, which was collected between 1960 and 2016 [16]. The percentages given by World Bank pertain to groups of individuals who were surveyed during and after their secondary education. Many groups have been assessed since 1960, and the percent of each year's group that enrolled in a tertiary education institution was reported. The compatibility test will consider the most recent percentage for each nation, and because data is not available for every nation for each year, only percentages since 2008 will be considered. If the most recent percentage is greater than a 5% enrollment in tertiary education then that nation will be considered more able to educate its population than other nations being tested. Table 3.4 presents each of the 42 nations that have an enrollment percentage of greater than 5%.

3.1.2 Available resources vs. proximity to urban centers:

Secondly, in order to assess the potential for renewable energy sources to be adopted in a nation the proximity of sources of renewable energy to the large demand centers such as cities must be examined. China will again demonstrate this consideration, with the example of its potential wind energy as one type of renewable source. China has a huge potential for wind energy to be harnessed, an estimated 2548 GW of power production capacity in 2006 [1]. However the majority of wind energy potential lies in western China which is much less populous and lacks the large urban centers of east China. Therefore in order to make use of this renewable source effective integration and long-distance transmission technologies must be utilized [1]. As previously discussed, smart grid systems are much more adept at transmission of power over distance and minimizing power loss. An example of smart grid transmission technologies are Flexible AC Transmission Systems (FACTS), which are located along the transmission route and increase quality of power supplied, reduce transmission losses and improve network stability [1]. These and other control devices that are added to the transmission system are essential for long distance transmission as well as the intermittent power supplied by distributed renewable generation sources. The compatibility test therefore will select for nations or regions whose sources of renewable energy production are located a significant distance from the largest centers of demand. This is a positive indication of smart grid compatibility because only through smart grid transmission technologies can those renewable energy sources be effectively utilized.

3.1.3 Development cost:

The third aspect of smart grid compatibility is the ability of a nation to afford the initial cost of developing smart grid infrastructure. There is a significant cost associated with developing new transmission systems, new distributed generation centers, smart meter infrastructure, and other technologies. In order to estimate the cost of developing these infrastructures from little to no starting infrastructure, the previously mentioned smart grid projects in the nation of Brazil will be examined below. The article by Di Santo [2] lists several Brazilian projects and their annual budget, as well as their relative scale based on number of consumers (homes, industries, businesses, and the total power consumption of each project in GWh/year. Those projects and their cost information are summarized in the table below.

The duration of each of these projects ranged from 2 to 7 years; therefore, they offer information about the upfront costs associated with developing smart grid infrastructure in situations that are lacking any substantial or efficient power system currently. Five of the seven projects were performed in urban centers where population density is high, and two were performed in communities that are not connected to a grid because of their remote location. Both of these projects (Parintins and Fernando de Noronha) previously relied on small thermal generation plants, and had the beginnings of a microgrid distribution system.

Each of the seven projects had specific focuses, some of which were shared by the majority of the projects. Every project focused on smart metering which is the communication infrastructure for demand side management as well as grid automation which encompasses distribution capacities such as self-healing. Six of the seven projects included distributed generation renewable sources, and five had focuses on public lighting, electric-powered public transportation, or both.

Table 3.1 Smart grid cost estimation

Project Name	# of consumers	Annual budget (Million USD)	Budget/consumer (USD/consumer)	Project Focuses
Smart City	10,000	4.2	420	Urban: smart metering, distributed generation, energy storage, transportation, public lighting, grid automation, consumer awareness.
Smart Grid Program	84,000	5.925	70	Urban: transportation, distributed generation, smart metering, grid automation.
InovCity	15,000	3.100	206	Urban: smart metering, public lighting, transportation, grid automation, consumer awareness, distributed generation, energy efficient home devices.
Cities of the Future	95,000	3.55	37	Urban: smart metering, grid automation, distributed generation, smart home development.
Parintins project	145,000	1.80	12	Off grid thermal system: grid automation, smart metering.
Fernando de Noronha project	885	.883	998	Off grid thermal and renewable-sourced system: smart metering, distributed generation, energy storage, grid automation, transportation, public lighting.
Parana smart grid	10,000	7.85	785	Urban: grid automation, distributed generation, transportation, smart metering.

From the information provided by [2] about the budgeting for each of the seven smart grid projects in Brazil, a number of conclusions can be made about the cost of smart grid development. Firstly it must be noted that from the sample set, no evidence suggests that there is a cost per consumer difference in developing infrastructure in urban centers vs. rural areas. It may be noted that the two off-grid rural projects represented both the least and most expensive projects. This would suggest that it is unlikely that cost per consumer is most related to consumer population density, however a larger data set would be needed to draw conclusions from. Two projects stand out as being significantly cheaper in cost per consumer than the rest, those are the

Cities of the Future and Parintins projects. When examining the different focuses of every project it may be noted that neither of these projects included public lighting or public electric-powered transportation focuses; therefore, these two project focuses may contribute to a high cost per consumer value.

Overall these seven projects represent both urban and off-grid situations and a wide variety of smart grid characteristics in their project focuses. Therefore the calculated average cost per consumer value (in USD) of $361.14 may be used as an approximation for the initial cost of smart grid development.

3.1.4 Political Stability:

The last consideration of this compatibility test is the political climate of the remaining nations. As a means of quantifying the political stability of each nation the 2016 Fragile States Index (FSI) will be utilized. This source is the culmination of research performed and presented by the Fund for Peace in an attempt to quantify the risk that each nation is in due to political instability and poor government structure. The FSI categorizes each nation based on its assessed level of risk into various alert stages, which will correlate to different utility scores assigned to each nation in this compatibility test.

3.1.5 Kepner-Tregoe analysis and test summary:

The final stage of the compatibility test will apply Kepner-Tregoe analysis [15] as a means of assessing multi-criteria decision making. This method of analysis will yield the most compatible nations for smart grid development by applying weighting factors to each criteria and assessing the utility score of each nation for each criteria. This analysis will be presented in section 3.2.5. Table 3.2 summarizes the four portions of the compatibility test and the specific means of testing for each criterion, as already discussed in this section.

Table 3.2 Summary of smart grid compatibility test

Criteria	Description
1. Education and training accessibility	**This nation's most recent tertiary enrollment rate is greater than 5%, considering rates as early as 2008.**
2. Available resources vs. proximity to urban centers	**This nation has high potential for renewable energy generation that doesn't overlap with demand centers. The region of high potential must be a minimum of 240km from a demand center and must itself be 50 square km in area to be considered significant.**
3. Development cost	**Assesses the ratio of this nation's GDP to the estimated cost of developing smart grid infrastructure (Population to be serviced * $361.14).**
4. Political climate/stability	**Reference the 2016 Fragile State Index ratings of each nation to determine its political stability.**

3.2 Compatibility test results

The precondition for this compatibility test is that less than 50% of the population of a nation has reliable access to electricity. The information regarding electrification rates was collected from the World Bank database whose most recent survey dates back to 2012. There are 43 nations who have less than a 50% accessibility to electricity; however, the nation of North Korea will for the purpose of this paper will not be included, due to various impracticalities of development there. The remaining 42 nations and the percent of their populations with access to electricity are summarized in table 3.3 below.

Table 3.3 Summary of 42 nations to be considered and their percentages of electrification

Nation	% of population with access to electricity in 2012	Nation	% of population with access to electricity in 2012
Afghanistan	43	Mauritania	21.8
Angola	37	Mozambique	20.2
Benin	38.4	Namibia	47.3
Burkina Faso	13.1	Niger	14.4
Burundi	6.5	Papua New Guinea	18.1
Cambodia	31.1	Rwanda	18
Central African Republic	10.8	Sierra Leone	14.2
Chad	6.4	Solomon Islands	22.8
Congo, Dem. Rep.	16.4	Somalia	32.7
Congo, Rep.	41.6	South Sudan	5.1
Eritrea	36.1	Sudan	32.6
Ethiopia	26.6	Swaziland	42
Rep. of the Gambia	34.5	Tanzania	15.3
Guinea	26.2	Timor-Leste	41.6
Haiti	37.9	Togo	31.5
Kenya	23	Tuvalu	44.6
Lesotho	20.6	Uganda	18.2
Liberia	9.8	Vanuatu	27.1
Madagascar	15.4	Rep. of Yemen	48.4
Malawi	9.8	Zambia	22.1
Mali	25.6	Zimbabwe	40.5

3.2.1 Education and training accessibility:

This portion of the compatibility test will focus on the ability of each nation to educate its citizens so that they will be capable of operating a complex smart grid system. The parameter that this test utilizes is the tertiary enrollment rate of a sample population of secondary education graduates, using that nation’s most recent annual data since 2008. The results of this portion of the test are summarized in table 3.4.

Table 3.4 Summary of national tertiary enrollment rates

Country	Year of Most Recent Data	Tertiary Enrollment %
Afghanistan	2014	8.66%
Angola	2013	9.92%
Benin	2013	15.36%
Cambodia	2015	13.09%
Congo, Dem. Rep.	2013	6.64%
Congo, Rep.	2013	9.72%
Ethiopia	2014	8.13%
Guinea	2014	10.84%
Lesotho	2014	9.84%
Liberia	2012	11.63%
Mali	2012	6.87%
Mauritania	2015	5.62%
Mozambique	2014	5.97%
Namibia	2008	9.33%
Rwanda	2013	7.53%
Sudan	2014	16.32%
Swaziland	2013	5.33%
Timor-Leste	2010	18.15%
Togo	2015	10.63%
Yemen, Rep.	2011	9.97%
Zimbabwe	2015	8.43%

This test selected for nations that in recent years have shown tertiary enrollment rates of at least 5%. Of the 42 nations tested and listed in table 3.3 only the 21 in table 3.4 met this criteria. The lowest tertiary enrollment rate that was still considered by this test was 5.33% for Swaziland, and the highest of all nations considered was 18.15% for Timor-Leste.

3.2.2 Available resources vs. proximity to urban centers:

This portion of the test will focus on the advanced transmission capabilities of smart grid technology and its consequent ability to make use of resources that otherwise would be less accessible. The test will look for DER that are a minimum of 240km away from any major load center, and will be looking for areas of high potential that are at least 50 square km in area to be considered significant. Because smart grid transmission networks are able to transmit power over larger distances with less power loss more natural resources become available for use in distributed power production. Most of the primary renewable sources of energy are geographically constrained, for example different areas of the world experience greater exposure to sunlight or higher average wind speed. If high potential for those resources are located away from the areas of demand (such as cities) then they are of little use within a traditional transmission paradigm. A smart grid system will enhance the range at which large load centers like cities can draw on renewable sources of power generation, therefore this portion of the test takes the remaining countries and examines which have high potential for renewable energy production located a standard distance away from a large population. When considering solar irradiance an area will be considered “high potential” if its average annual GHI measurement is at least 2200 kWh/square meter. The 240km distance is derived from the fact that “long” transmission lines are those which are 240km in length and above. A long transmission line in a standard grid network would need to be operated at a higher voltage so that power loss over that distance does not become unacceptably high. Therefore, this test will select for DERs that would require the implementation of higher voltage, higher cost infrastructure to make use of them in a traditional network paradigm. Appendix A contains all solar irradiance maps that were used for this test and were downloaded from Solargis [12]. The table below summarizes how many significant regions of energy potential located more than 240km that each country has. It is worth noting that some nations did not have available maps detailing their solar irradiance levels. While this is undesirable it is also noteworthy that the DER proximity criterion was assigned the smallest weighting factor. This is because it does not describe a necessity for smart grid development so much as a greater incentive for it. Because of this the compatibility test results are still deemed to be acceptable.

Table 3.5 Summary of number of DER locations greater than 240km away from load centers

Nation	Number of solar irradiance regions > 2200kWh/m^2 and > 50 sq. km.	Nation	Number of solar irradiance regions > 2200kWh/m^2 and > 50 sq. km.
Afghanistan	*Data not found	Mauritania	>1
Angola	>1	Mozambique	0
Benin	0	Namibia	>1
Burkina Faso	0	Niger	>1
Burundi	0	Papua New Guinea	*Data not found
Cambodia	*Data not found	Rwanda	0
Central African Republic	0	Sierra Leone	0
Chad	>1	Solomon Islands	0
Congo, Dem. Rep.	0	Somalia	0
Congo, Rep.	*Data not found	South Sudan	0
Eritrea	0	Sudan	>1
Ethiopia	>1	Swaziland	0
Rep. of the Gambia	0	Tanzania	0
Guinea	*Data not found	Timor-Leste	0
Haiti	0	Togo	0
Kenya	>1	Tuvalu	0
Lesotho	0	Uganda	0
Liberia	0	Vanuatu	*Data not found
Madagascar	>1	Rep. of Yemen	>1
Malawi	0	Zambia	0
Mali	>1	Zimbabwe	0

This test showed that of the 42 nations to be considered only 11 had one or more significant area of solar energy production potential that was located at least 240km away from any urban center. GHI data was not found for 6 of the countries tested. Future work in this section of the compatibility test would include gathering GHI data for all 42 nations and determining results for these 6 inconclusive cases. This portion of the test should also include other types of renewable energy production potential, such as wind energy distribution across these 42 nations and how this DER and its proximity to load centers would affect each nation's smart grid compatibility.

3.2.3 Development cost:

This portion of the test will consider a nation's capacity to pay for the estimated initial cost of development of smart grid infrastructure and technology, using the previously calculated metric of $361.14 per consumer to be serviced. This test will calculate the estimated cost of servicing the urban population of each nation under the assumption that urban centers will have the most significant demand for electricity. The test will provide a ratio of that nation's GDP to the cost of development for smart grid. All GDP values were obtained from the World Banks's most recent report regarding 2015 gross domestic products of 217 nations, and all population estimates were also provided by World Bank's most recent information based on data collected in 2015. The results of this portion of the test are summarized in table 3.6 on the following page. The range of ratios varies significantly between countries, with the lowest ratio of GDP to estimated smart grid development cost being only 2 for several nations, while the highest is 47 for Papua New Guinea. Other notably high ratios included Swaziland with a ratio of 42, Vanuatu with a ratio of 29, Namibia with a ratio of 27, Angola with a ratio of 25, and the Solomon Islands with a ratio of 24.

Table 3.6 Ratio of national GDP to estimated SG cost

Nation	Population to be serviced	Initial smart grid cost	Nation's GDP	Ratio of GDP to smart grid cost
Afghanistan	8,686,000	3,136,862,040	19,331,000,000	6
Angola	11,022,000	3,980,485,080	102,627,000,000	25
Benin	4,782,000	1,726,971,480	8,291,000,000	4
Burkina Faso	5,406,000	1,952,322,840	10,678,000,000	5
Burundi	1,348,000	486,816,720	3,097,000,000	6
Cambodia	3,228,000	1,165,759,920	18,050,000,000	15
Central African Republic	1,962,000	708,556,680	1,584,000,000	2
Chad	3,154,000	1,139,035,560	10,889,000,000	9
Congo, Dem. Rep.	32,834,000	11,857,670,760	35,238,000,000	2
Congo, Rep.	3,021,000	1,091,003,940	8,553,000,000	7
Eritrea	1,000,000	361,140,000	2,600,000,000	7
Ethiopia	19,353,000	6,989,142,420	61,540,000,000	8
Gambia, The	1,187,000	428,673,180	939,000,000	2
Guinea	4,685,000	1,691,940,900	6,699,000,000	3
Haiti	6,282,000	2,268,681,480	8,765,000,000	3
Kenya	11,799,000	4,261,090,860	63,398,000,000	14
Lesotho	583,000	210,544,620	2,278,000,000	10
Liberia	2,238,000	808,231,320	2,053,000,000	2
Madagascar	8,508,000	3,072,579,120	9,739,000,000	3
Malawi	2,801,000	1,011,553,140	6,404,000,000	6
Mali	7,025,000	2,537,008,500	12,747,000,000	5
Mauritania	2,435,000	879,375,900	5,442,000,000	6
Mozambique	9,013,000	3,254,954,820	14,807,000,000	4
Namibia	1,147,000	414,227,580	11,492,000,000	27
Niger	3,728,000	1,346,329,920	7,714,000,000	5
Papua New Guinea	991,000	357,889,740	16,929,000,000	47
Rwanda	3,345,000	1,208,013,300	8,096,000,000	6
Sierra Leone	2,578,000	931,018,920	4,215,000,000	4
Solomon Islands	130,000	46,948,200	1,129,000,000	24
Somalia	4,266,000	1,540,623,240	5,925,000,000	3
South Sudan	2,320,000	837,844,800	9,015,000,000	10
Sudan	13,602,000	4,912,226,280	97,156,000,000	19
Swaziland	274,000	98,952,360	4,188,000,000	42
Tanzania	16,901,000	6,103,627,140	45,628,000,000	7
Timor-Leste	408,000	147,345,120	1,422,000,000	9
Togo	2,919,000	1,054,167,660	4,088,000,000	3
Tuvalu	6,000	2,166,840	33,000,000	15
Uganda	6,285,000	2,269,764,900	27,529,000,000	12
Vanuatu	69,000	24,918,660	742,000,000	29
Yemen, Rep.	9,286,000	3,353,546,040	37,734,000,000	11
Zambia	6,634,000	2,395,802,760	21,154,000,000	8
Zimbabwe	5,052,000	1,824,479,280	14,419,000,000	7

3.2.4 Political Stability

This portion of the compatibility test will consider the political stability of each nation in order to assess their capacity to invest in such a complex infrastructure development as a smart grid. The information presented in table 3.7 below was gathered from the Fund for Peace organization which assigns to every nation a Fragile State Index (FSI) value annually. The numerical FSI value assigned to each nation correlates to a particular category of severity that described the nation's political stability. Those categories include, in descending order of severity: Very High Alert, High Alert, Alert, High Warning, Elevated Warning, and Warning. Additionally nations that scored better FSI values than the Warning category are considered Stable. The results of applying this portion of the compatibility test are summarized in table 3.7.

Table 3.7 Summary of 2016 FSI alert levels

Nation	2016 FSI Level	Nation	2016 FSI Level
Afghanistan	High Alert	Mauritania	Alert
Angola	Alert	Mozambique	High Warning
Benin	Elevated Warning	Namibia	Elevated Warning
Burkina Faso	High Warning	Niger	Alert
Burundi	High Alert	Papua New Guinea	High Warning
Cambodia	High Warning	Rwanda	Alert
Central African Republic	Very High Alert	Sierra Leone	Alert
Chad	Very High Alert	Solomon Islands	High Warning
Congo, Dem. Rep.	Very High Alert	Somalia	Very High Alert
Congo, Rep.	Alert	South Sudan	Very High Alert
Eritrea	Alert	Sudan	Very High Alert
Ethiopia	Alert	Swaziland	High Warning
Gambia, The	High Warning	Tanzania	High Warning
Guinea	High Alert	Timor-Leste	Alert
Haiti	High Alert	Togo	High Warning
Kenya	Alert	Tuvalu	Stable
Lesotho	High Warning	Uganda	Alert
Liberia	Alert	Vanuatu	Warning
Madagascar	High Warning	Yemen, Rep.	Very High Alert
Malawi	High Warning	Zambia	High Warning
Mali	Alert	Zimbabwe	High Alert

Of the 42 nations considered in this test only Tuvalu received an FSI evaluation of Stable and only Vanuatu received the next lowest risk category of Warning. Two more nations, Benin and Namibia received the next lowest risk category of Elevated Warning, while 13 nations received an evaluation of High Warning, the next lowest risk category. This portion of the test distinguishes a small percentage of the 42 nations considered that have comparatively more stable political climates than the majority of the other 42 nations. This distinction has significant effect on the final result of the compatibility test due to the large weighting factor for the political stability criteria, this impact will be explored in section 3.3.

3.2.5 Kepner-Tregoe analysis

In the final stage of the compatibility test I took the information gathered about each country and applied a manner of multi-criteria decision making called Kepner-Tregoe analysis [15]. The first step in Kepner-Tregoe analysis is to determine the relative weighting factors for each of the criteria used. The manner in which this is done is called the Analytical Hierarchy Process (AHP), which was developed by Thomas L. Saaty in the 1970's. This process considers the most significant criteria to be used in a particular decision and evaluates them via pairwise comparison. This means that each criteria is compared to every other criteria, and a value is assigned to how much more significant one criteria is than the other. Once this process is complete, the AHP algorithm provides weighting factors based on how each criteria compared to all of the others [7]. Additionally a consistency ratio is also calculated based on whether or not the individual performing the pairwise comparisons assigned values consistently between various criteria. A consistency ratio of .01 or less is considered acceptable in most trade studies [7]. The results of the AHP that I applied to smart grid compatibility criteria are summarized in the table below, as well as the corresponding consistency ratio of my comparisons.

Table 3.8 AHP results and consistency ratio

	Evaluation Criteria	Weighting Factor
1	Has tertiary enrollment of > 5%	0.411
2	Has DER > 200km away from any major load center	0.055
3	GDP/cost estimate ratio	0.162
4	Has stable political climate	0.372

Reference Data - Consistency Ratio (measure of grading consistency):	0.01

Based on the results of the AHP, the most significant criteria in determining smart grid compatibility are the tertiary enrollment rate of that country, which is an indicator of its capacity to educate operators of smart grid infrastructure, and the political stability of that nation. Additionally the criteria used in the AHP were assessed with a consistency ratio of .01.

Once the weighting factors have been determined each criterion can be applied to every alternative decision choice, in this case the 42 nations to be considered for smart grid compatibility. This is done by assigning a value to each of the criteria, for example the tertiary enrollment criterion has a value of 5% enrollment. This means that if a nation has less than 5% enrollment in tertiary education it will receive a 0 utility score because it did not meet the minimum value. However, in order to account for the wide range of enrollment percentages, the utility scores are assigned in this way; if a nation has an enrollment rate of 5-10% it receives a .33 utility score, if the enrollment rate is between 10-15% it receives a .66 utility score, and an enrollment rate of greater than 15% receives a full utility score of 1. In this way every nation considered is assigned a utility score for their tertiary enrollment percentage that correlates to their capacity to provide the necessary education for smart grid development.

The next criterion is the distance between DER and load centers. The value assigned to this criterion is greater than or equal to 1, meaning that nation must have at least one DER defined as significant size that is greater than 240km from any major load center. The utility scores for this criteria are assigned in this way: if a nation has no DER that are greater than 240km from a major load center it receives a utility score of 0. If a nation has 1 DER greater than 240km from any major load center it receives a utility score of .5. If a nation has more than one DER that is greater than 240km from any major load center it receives the full utility score of 1.

The next criterion is the ratio of a nations GDP to its estimated cost for smart grid development. The ratios determined in this portion of the test ranged from 2 to 47. If a nation has a GDP to cost ratio of less than 5, it receives a utility score of 0. If a nation has a ratio between 5 and 10 it receives a utility score of .2. If a nation has a ratio between 10 and 15 it receives a utility score of .4. If a nation has a ratio between 15 and 20 it receives a utility score of .6. If a nation has a ratio between 20 and 30 it receives a utility score of .8. If a nation has a ratio greater than 30 it receives the full utility score of 1.

The last criterion is the political stability of a nation, the measurement used is the alert level assigned to that nation by the 2016 FSI. An alert level of Very High translates to a utility score of 0 for that nation. An alert level of High translates to a utility score of .2 for that nation. An "Alert" designation translates to a utility score of .4 for that nation. An alert level of High Warning translates to a utility score of .6 for that nation. An alert level of Elevated Warning translates to a utility score of .8 for that nation. An alert level of Warning or better translates to a utility score of 1 for that nation.

The results of the Kepner-Tregoe Analysis are presented in the table below. Each nation receives a total score ranging from 0 to 1 based on the sum of each product of the utility score and the weighting factor for all four criteria. The nations are presented in descending order based on their score from the Kepner-Tregoe Analysis. All of the raw data from the Kepner-Tregoe Analysis is included in Appendix B.

Table 3.9 Results of Kepner-Tregoe Analysis

Rank based on Score	Nation	Kepner Tregoe Score	Rank based on Score	Nation	Kepner Tregoe Score
1	Benin	.71	16	Madagascar	.28
2	Namibia	.62	17	Kenya	.27
3	Timor-Leste	.59	18	Malawi	.26
4	Cambodia	.56		Tanzania	.26
	Sudan	.56		Republic of Yemen	.26
5	Swaziland	.52		Zambia	.26
6	Togo	.49	19	Zimbabwe	.24
7	Angola	.47		Afghanistan	.24
8	Tuvalu	.44	20	Burkina Faso	.22
9	Vanuatu	.43		Republic of the Gambia	.22
10	Liberia	.42	21	Uganda	.21
11	Lesotho	.39	22	Niger	.20
	Papua New Guinea	.39	23	Eritrea	.18
12	Ethiopia	.37	24	Sierra Leone	.15
	Mauritania	.37	25	Democratic Republic of the Congo	.14
13	Mozambique	.36	26	Burundi	.11
	Guinea	.35	27	Chad	.09
	Solomon Islands	.35	28	Haiti	.07
14	Mali	.34	29	South Sudan	.03
15	Rwanda	.32	30	Somalia	0.00
	Republic of the Congo	.32		Central African Republic	0.00

The Kepner-Tregoe method of multi-criteria decision making is a way to quantify how much each alternative choice matches the given criteria in order to provide a ranking of compatibility. Combined with AHP to provide weighting factors for each criteria this becomes a powerful tool for synthesizing a large amount of data and alternative options in order to make an optimized decision. The result of this test yielded a score ranging from 0 to 1 for each nation's compatibility for smart grid development. I chose the top five scores, those greater than .50 as the nations selected by this compatibility test. The top scores were Benin with .71, Namibia with .62, Timor-Leste with .59, Cambodia and Sudan both with .56 and Swaziland with .52. However, of these six nations the nation of Sudan is notably the most politically unstable with an FSI categorization of Very High Alert. For this reason Sudan will not be included in the future work analysis section of this paper. The other five nations will be further analyzed in section 3.3, the proposal for future work.

3.3 Proposal for future work

The results of the compatibility test will be examined in order to provide a baseline for future work in the area of smart grid implementation in the developing world. This compatibility test considered only nations that have the greatest need for infrastructure that can supply electrical power, as all of them have less than 50% accessibility to reliable electricity. As stated in section 3.2.5 the results of the Kepner-Tregoe Analysis, the nations of Benin, Namibia, Timor-Leste, Cambodia and Swaziland were selected as most compatible for immediate investment in large-scale smart grid technology. I therefore recommend that proponents of and investors in smart grid development should focus on applications in these nations. Projects in these nations will be the most likely to succeed compared to all other nations with the greatest need for smart grid technology, for the reasons described in this section below.

The nation of Benin had the highest Kepner-Tregoe score of .71. The criteria that Benin matched well with were its tertiary enrollment rate and its political stability. Benin had a tertiary enrollment percentage of 15.36% in 2013, which put it in the top three of all nations considered in terms of education accessibility. It also scored very well in political stability based on a FSI rating of Elevated Warning, one of the few nations considered that scored so well. Benin noticeably scored very poorly in terms of the other two criteria, as it has a GDP to smart grid cost ratio of only 4, and does not have any DER greater than 240km from its load centers. However in regards to funding there is always the opportunity for outside organizations and governments to invest in the development in Benin, and they may be especially willing to based on Benin's tertiary enrollment rates and its relative stability.

The nation of Namibia had the second highest Kepner-Tregoe score of .62. Namibia scored well against all four criteria, as opposed to Benin which only matched two of the four well. Namibia had a tertiary enrollment rate of 9.33% 2008, which means it is just below the median value for nations considered. Namibia additionally has multiple DER regions that are located farther than 240km from its load centers, meaning it could make better use of smart grid's advanced transmission technology. Namibia additionally scored very well against the GDP to cost ratio criterion, it has a ratio of 27 making it one of the top three nations considered in this analysis. It also was given a FSI rating of Elevated Warning, the same as Benin, making it also one of the most politically stable nations among those considered. It is worth noting that Namibia scored the same or better than Benin in three out of the four criteria used in this analysis, but is placed second overall due to Benin being superior in tertiary enrollment. It is also of significance that Namibia was at the top of its utility score bracket, it received a .33 due to being between 5-10% with a value of 9.33%. Benin was also at bottom of its bracket, receiving a utility score of 1 for being above 15% with a value of %15.36. Recognizing the small margins of difference in scoring for the tertiary enrollment criterion, this test will consider Benin and Namibia to be equally the most compatible nation for smart grid development.

Timor-Leste received the third highest score from the Kepner-Tregoe analysis with a value of .59. The primary criterion that Timor-Leste matched well was the tertiary enrollment percentage, it had the highest percentage with a value of %18.15 recorded in 2010. While Timor-

Leste does not have any DER located more than 240km from its load centers, it does have a GDP to cost ratio of 9, which earned it a score just below the average for the cost criterion. Timor-Leste was given a FSI rating of Alert which was just below the median value for the political stability criterion. It is worth noting that Timor-Leste was given the third highest score overall mostly because of its very high tertiary enrollment percentage, which is a good indicator of its ability to educate its civilians to build and operate a smart grid system. Similar to the nation of Benin, Timor-Leste may need to depend somewhat on the investment of other nations and of organizations in order to afford large scale smart grid projects, however it does have more than twice the capacity of Benin to invest on its own.

Cambodia received the fourth highest Kepner-Tregoe score of .56. Cambodia was able to match two criteria decently well, its scores for tertiary enrollment percentage and FSI stability rating were both above average. Cambodia had a tertiary enrollment percentage of 13.09% in 2015 which was the fourth highest score of all 42 nations considered. In regards to political stability it was given an FSI rating of High Warning which means its political stability is in the top 50% of all of the nations tested. Cambodia also has a ratio of GDP to estimated smart grid cost of 15. This value is at the very top of its utility score bracket, meaning Cambodia was very close to scoring higher in this category as well. Overall the nation of Cambodia is ranked highly for smart grid compatibility due to its above average scores for nearly every criteria of this test. This nation has significant ability to provide necessary education and training for smart implementation, to provide its own capitol investment for developing smart grid infrastructure and to provide a more stable political climate to develop this technology in.

The nation of Swaziland received the fifth highest score from the Kepner-Tregoe analysis after the exclusion of Sudan for its severe political instability. Swaziland received a score of .52, one of six nations to score above a .50. Swaziland was able to score so highly on the Kepner-Tregoe analysis due to its above average scores matching the cost estimate and political stability criteria. Swaziland has a ratio of GDP to smart grid cost estimate of 42, this is second among all nations tested only to Papua New Guinea. Swaziland also received a FSI stability rating of High Warning, which like Cambodia means it is in the top 50% for nations tested in regards to political stability. Swaziland notably had a tertiary enrollment percentage of 5.33% in 2013. This means it is essentially the median value for education rates for all 42 nations considered, since 21 nations including Swaziland had tertiary enrollment rates above 5% which was the cutoff to receive a utility score greater than 0. Swaziland therefore has more capacity than nearly all of the other 42 nations to provide funding for smart grid development, and also has an above average stability rating. Its education rate is very average however and it therefore does not have the same capacity to provide necessary training for smart grid development and operation as the four nations that scored higher than it in this test.

The discussion above has described the specific reasons why each of the five nations selected by the compatibility test are the most likely candidates for implementing smart grid technology. Through the use of communications technology integrated with traditional power supply infrastructure the smart grid offers the best solution to the widespread problem of access to electricity in these nations. Smart grid solutions are more versatile in terms of size than traditional grid schemes which must be large and centralized. Therefore, these countries may be capable of successfully implementing smart microgrids with their resources which would have been too limited to construct a functioning traditional grid. Smart grids also include technology that helps correct power loss in distribution to make the grid more efficient. This is critical because developing nations when building power infrastructure initially often face issues of efficiency. Because of this compatibility test and analysis I recommend that each of the five nations selected be considered for immediate smart grid pilot projects, so that this superior solution may ensure that their citizens have reliable access to electricity.

It is important to note that this test cannot encompass every factor that would make smart grid implementation feasible or not feasible. It is also important to note that the compatibility test was concerned with large scale implementation of smart grid technology, assuming that the entire urban population of each nation was the target consumer population. It would be much more practical and feasible for many of these nations to begin with smaller projects that target only a small percentage of their consumer population as the basis for future infrastructure development. This test does select, based on the factors considered, the nations that are most compatible for immediate investment and implementation of smart grid technology. The nations selected by this test will likely be more capable of implementing this technology on a large scale than those not identified.

4.0 Conclusion

This paper has been concerned with the smart grid, its relevant technologies and the benefits that these provide over a standard grid infrastructure. The smart grid incorporates two way communication and control devices with power distribution networks so that loads can be served more efficiently, outages can be resolved quickly and automatically, and renewable energy sources can be integrated. Smart meters allow for demand side management to be practiced, giving more control and influence to the consumer. The smart grid is the solution for issues in power efficiency, loss of power on the grid and incorporating sustainable energy sources. All of these issues can be crippling to grid systems in developing nations where power infrastructure may be nonexistent, or very inefficient systems may be in place. Any developing nation could benefit from smart grid applications; however, many nations lack the necessary factors to make good use of this technology. After completing a literature review on smart grid technology I chose four factors that seemed to be most significant in determining national compatibility for smart grid projects. These are: access to education and training, proximity of renewable resources to load centers, ability to afford cost of development, and political stability. After assigning weighting factors to each of these criteria and applying Kepner-Tregoe analysis I was able to determine five nations which are most compatible for immediate investment in this technology. The compatibility test has limitations and should be improved upon and expanded in the future. For example, additional criteria could be added if deemed necessary, and the weighting factors could also be adjusted so that the test could be rewritten and replicated for an even more effective result. It is the goal of this paper to encourage investment in the selected nations due to likelihood of successful application, and also to describe the compatibility test so that it may revised and reapplied.

5.0 Glossary

Analytical Hierarchy Process (AHP): Method of determining weighting factors for multiple criteria to be used in a decision making process.
Area Electric Power System (EPS): Term that describes the generation, transmission and distribution of electrical power.
Bi-directional communication channel: Describes how smart grid control technology is design not only to send control signals to devices on the grid but also to monitor and receive data from grid components and loads.
Bus loads: Describes the various components all powered by an electrical bus which is not connected to any power generators.
Closed loop linear alternator: An electromechanical device used to covert acoustic energy from resonance into electricity.
Demand side controls: Describes the devices, namely the smart meter, which allows consumers to actively participate in managing the energy consumption.
Demand-side management (DSM): The process by which a consumer uses metering and control technologies to manage their energy consumption and/or production.
Demand-side response: A method of demand side management in which a consumer adjusts their electrical consumption or production in response to changing conditions on the distribution system.
Developing world: Describes nations that have underdeveloped physical, economical and/or political infrastructure.
Distributed energy resources (DER): Describes a decentralized natural resource that can be used for energy production in a power generation network.
Distributed generation (DG): The use of distributed energy resources to generate power at a decentralized location, meaning not in a large production plant.
Flexible Alternating Current Transmission (FACTS): The addition of power electronic based technologies to the transmission network to help reduce power loss and therefore increase transmission efficiency and range.
Fragile States Index (FSI): A rating produced by the Fund for Peace organization which categorizes every nation based on a large amount of criteria that contribute to political stability.
Forecasting: The ability to predict the load or demand on a power distribution network hours or even days in advance.
Global Horizontal Irradiance (GHI): The total amount of shortwave radiation that a surface horizontal to the ground will receive, value typically used to calculate the energy input to photovoltaic systems.
Input-signal conditions: The various inputs to a system that yield measurable and corresponding outputs.
International Energy Agency (IEA): An international organization focused on monitoring global energy production and consumption and the effects of these and on promoting the use of renewable energies.
Kepner-Tregoe Analysis: Method of comparing two or more options based on weighted criteria in order to make quantitative multi-criteria decisions.
Load center: In power grid a load center is a concentration of high power demand, typically a city or something that represents a large concentration of consumers.
Load distribution: The arrangement and concentration of loads in a distribution network.

Load forecasting models: Different algorithms used to predict the load on an electrical distribution network.
Load shifting: The practice of recognizing times of peak demand on an electrical distribution system and choosing to consume electricity at a different time other than that of peak demand.
Microgrid: A small and decentralized collection of electrical power producers and loads that is capable of functioning autonomously while separated from the larger centralized grid.
Nuclear Non-Proliferation Treaty: An international treaty originating in 1968 that indefinitely prohibits the production of nuclear weapons for those countries that choose to sign.
Nonlinearity: Describes a trend that changes at a rate of a higher degree than 1.
Prosumers: A term used to describe electrical consumers that have an active role in the process of generating and distributing power.
Photovoltaic power system: A means of generating electrical power using photovoltaic cells to convert solar irradiance to electricity.
Rarefaction: The reduction of an item's density, the opposite of compression, can propagate in the form of waves.
Renewable energy: Describes an energy resource that does not have a finite quantity.
Smart meter: An enhanced metering system that enables two way communication between it and the power utility for data collection as well as control signals.
Standard: An IEEE standard is a document stipulating mandatory requirements.
Supply-side management (SSM): Traditional manner of control on a power grid in which the flow of signals is one way, from power generator to the load.
Sustainable energy: Describes an energy resource that can be replenished at a rate equal to or greater than its consumption.
Systems Engineering: A field of engineering that is focused on integration and holistic design.

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6.0 Appendices

6.1 Appendix A – Solargis global horizontal irradiation (GHI) maps

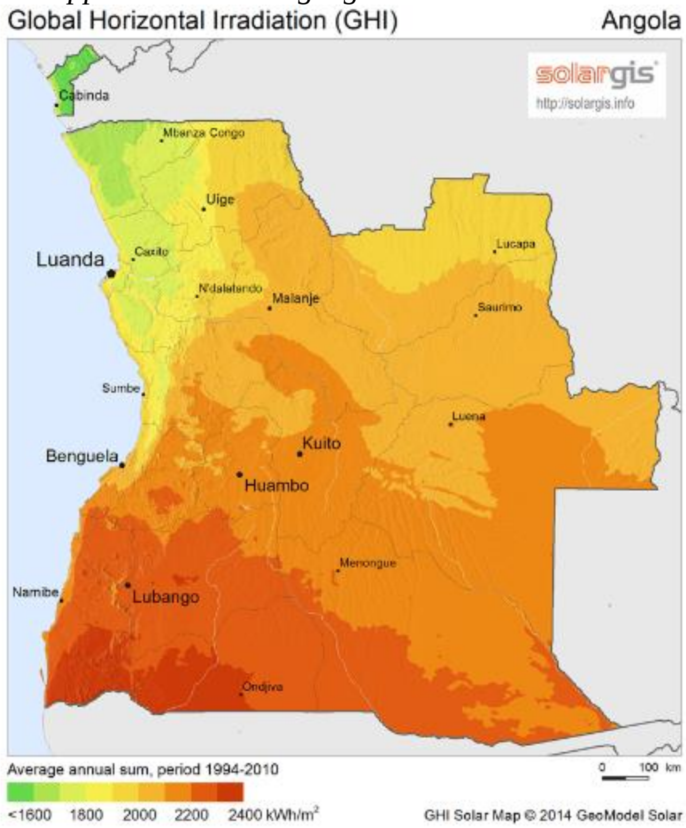

Diagram 5.1 GHI in Angola

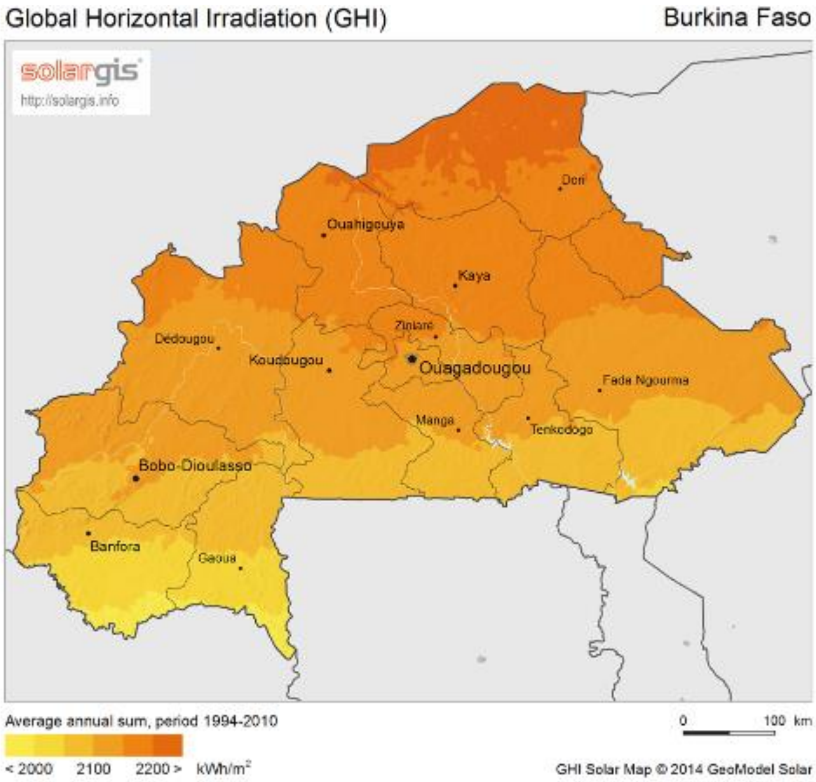

Diagram 5.2 GHI in Burkina Faso

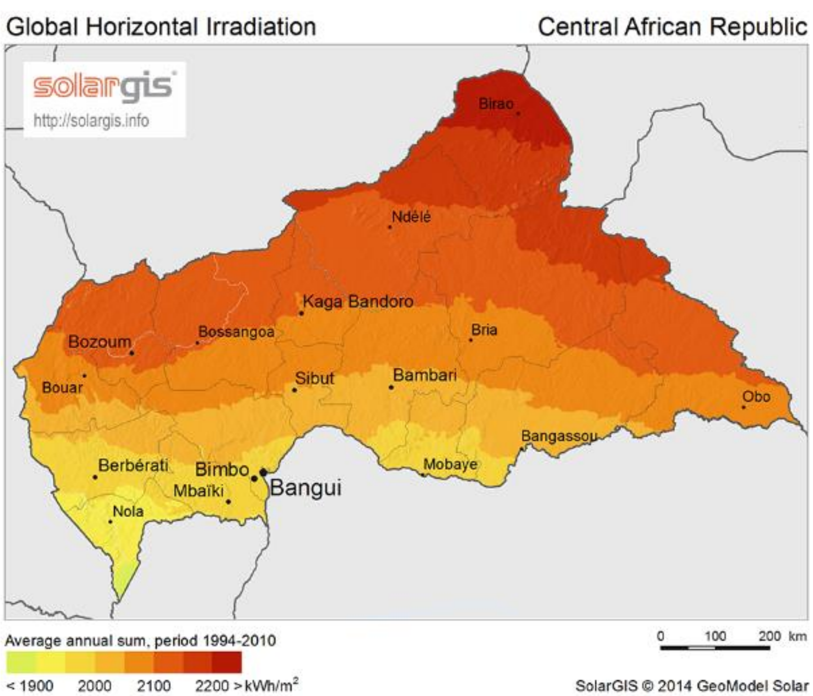

Diagram 5.3 GHI in Central African Republic

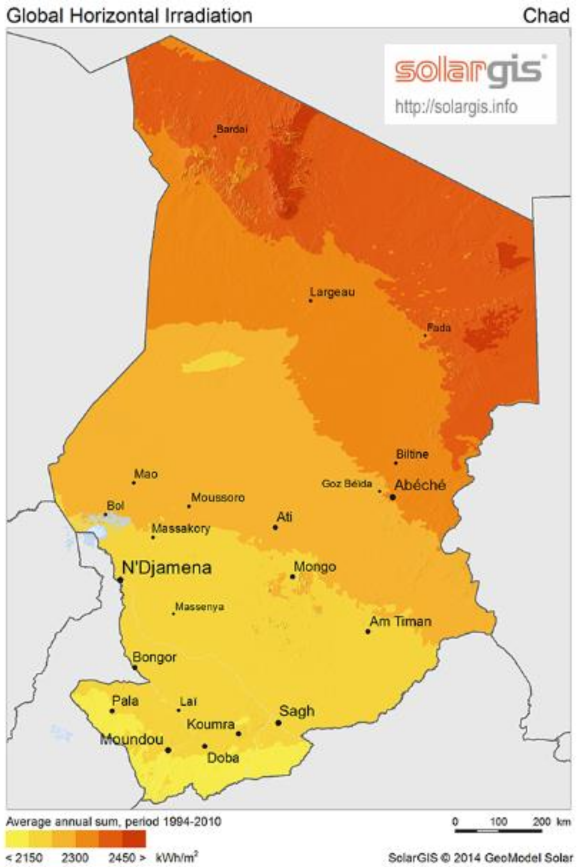

Diagram 5.4 GHI in Chad

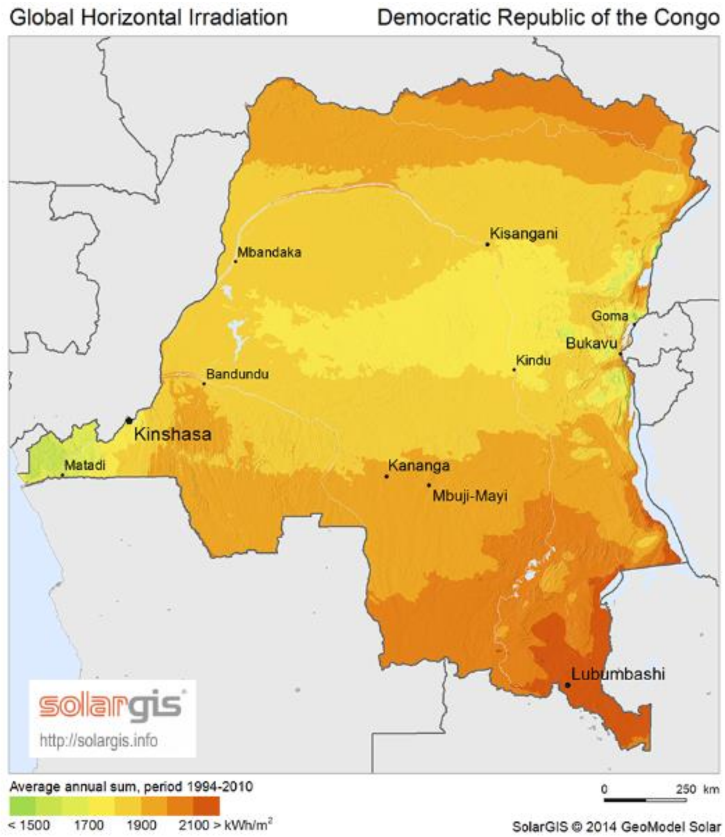

Diagram 5.5 GHI in Democratic Republic of the Congo

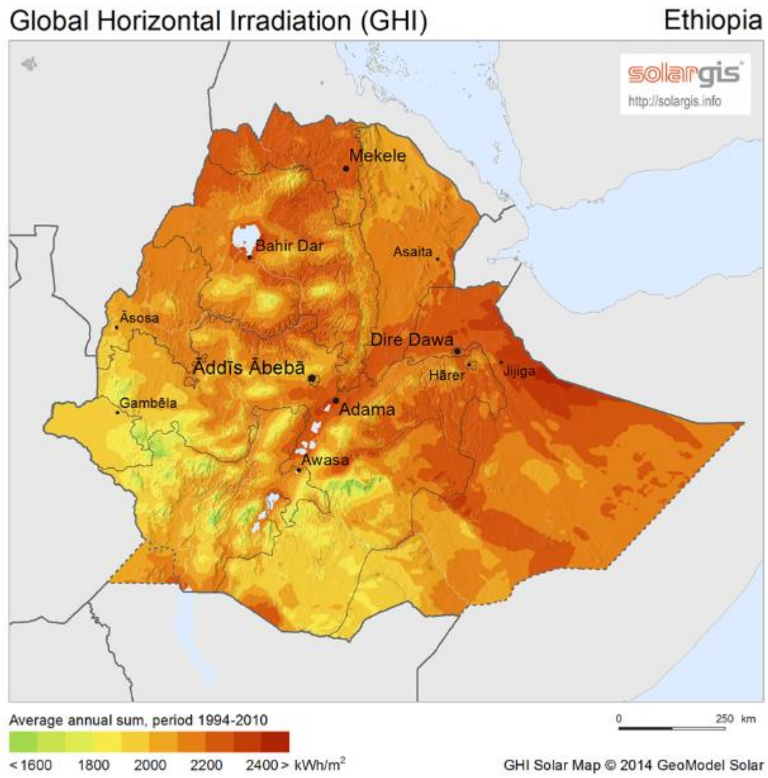

Diagram 5.6 GHI in Ethiopia

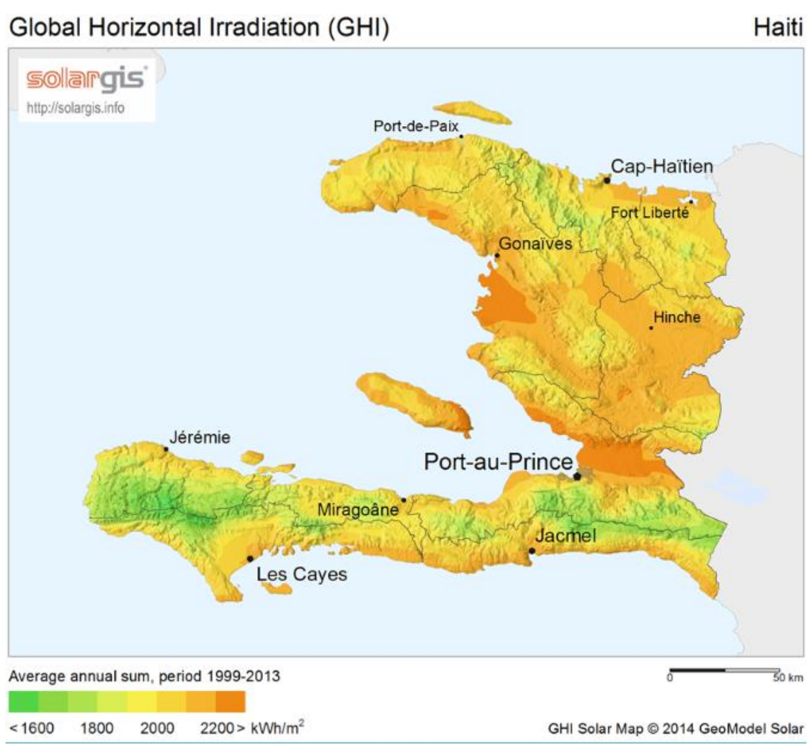

Diagram 5.7 GHI in Haiti

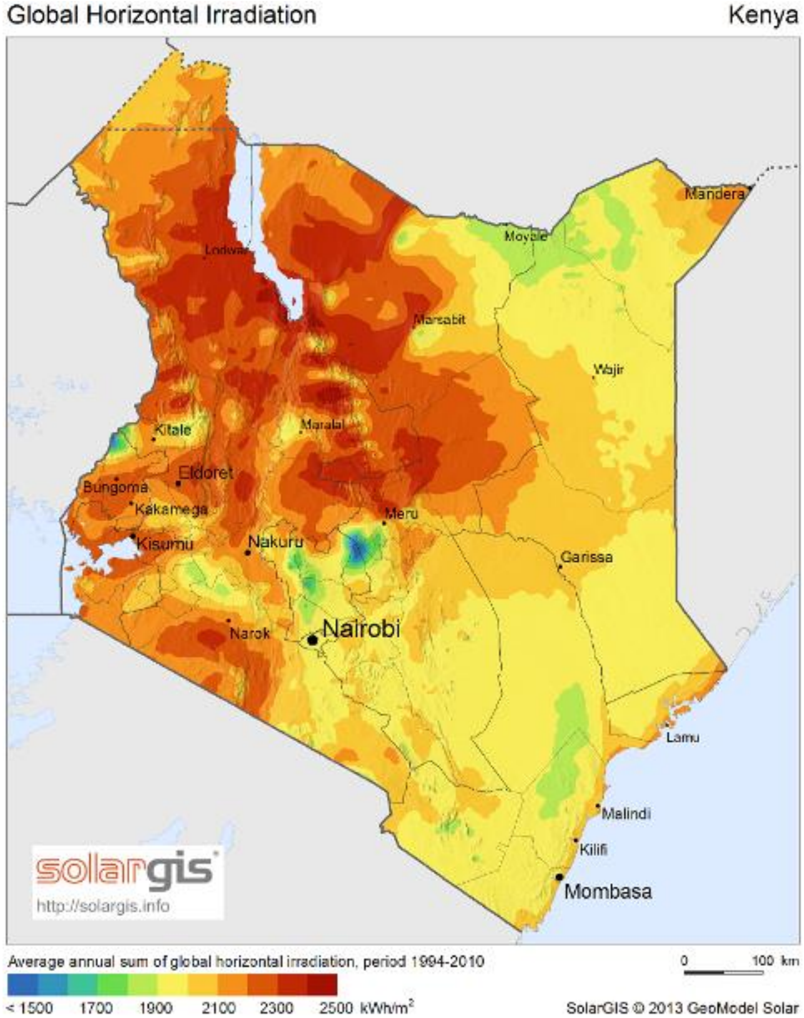

Diagram 5.8 GHI in Kenya

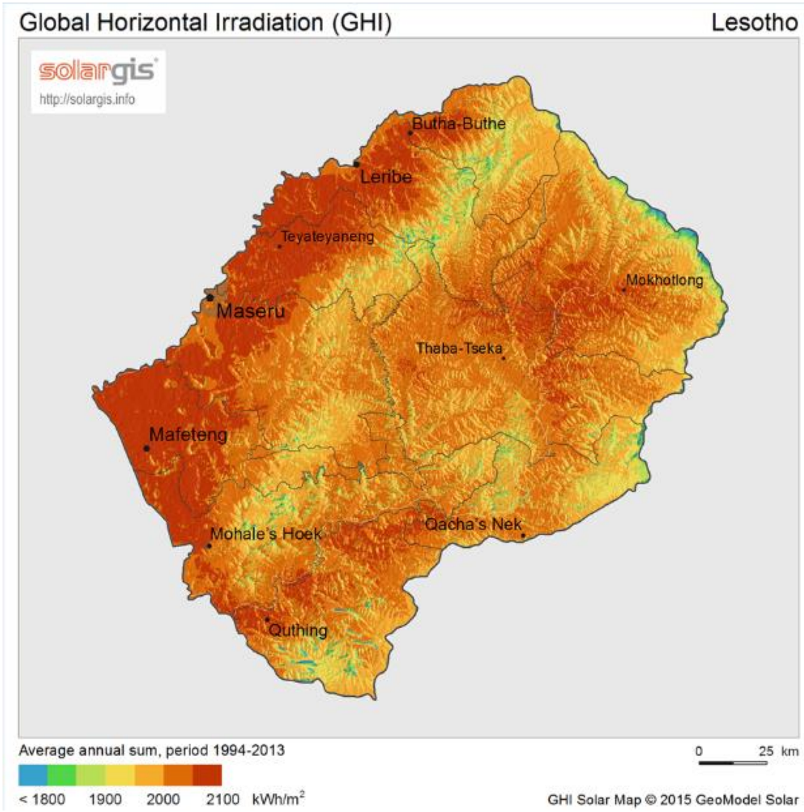

Diagram 5.9 GHI in Lesotho

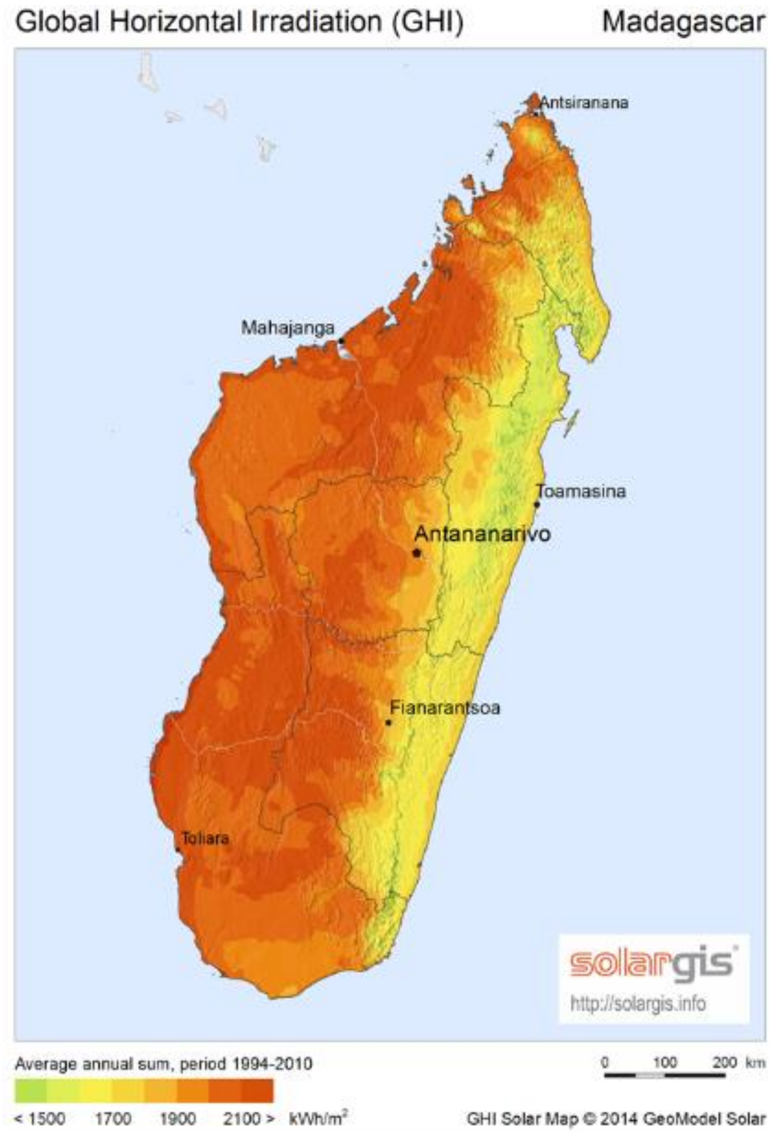

Diagram 5.10 GHI in Madagascar

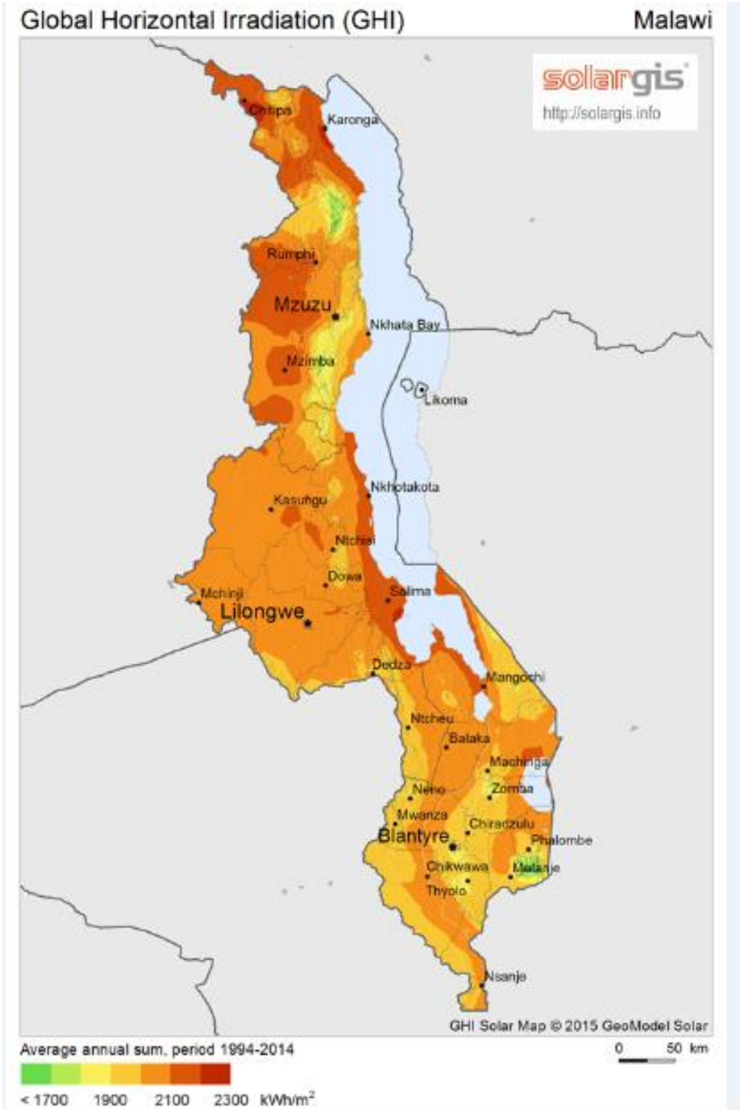

Diagram 5.11 GHI in Malawi

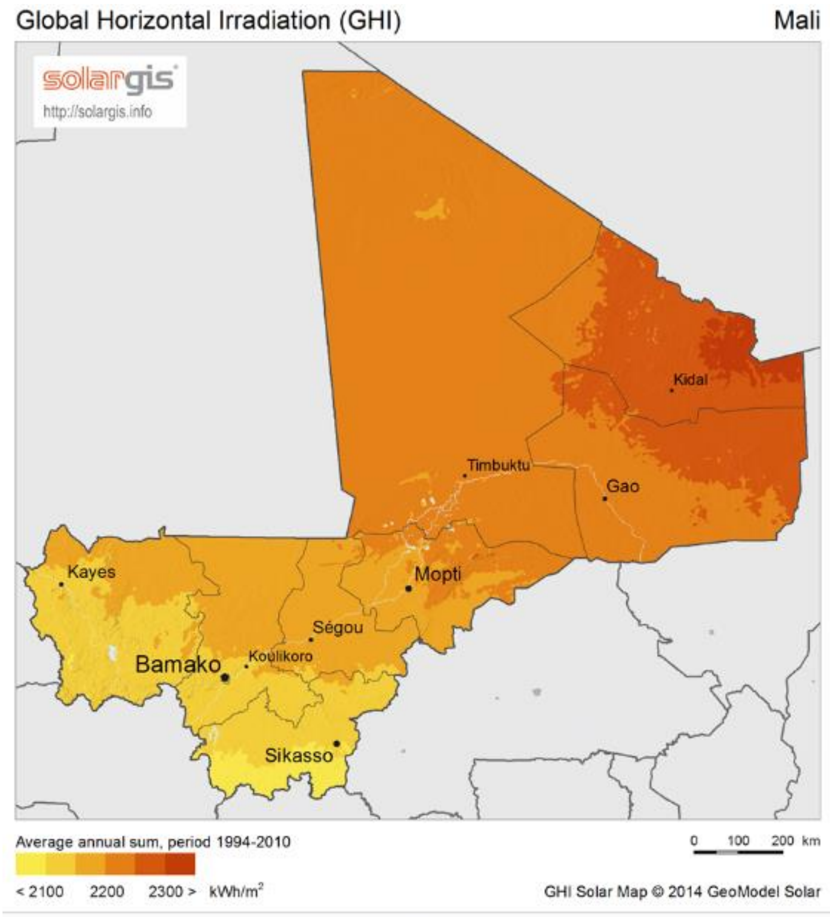

Diagram 5.12 GHI in Mali

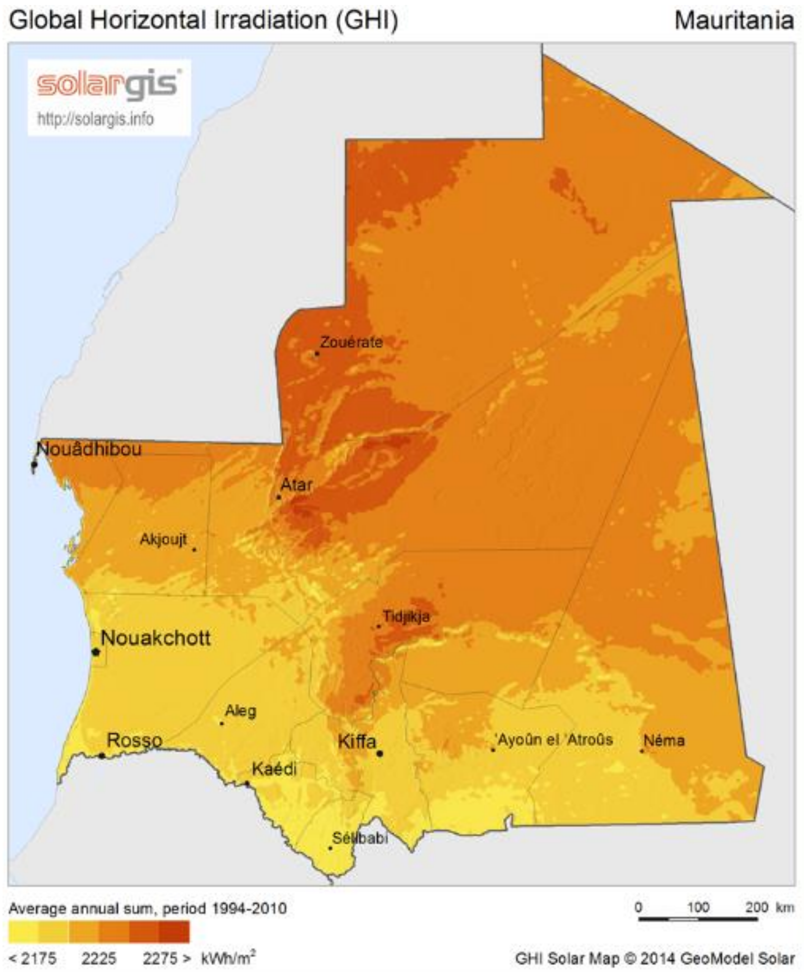

Diagram 5.13 GHI in Mauritania

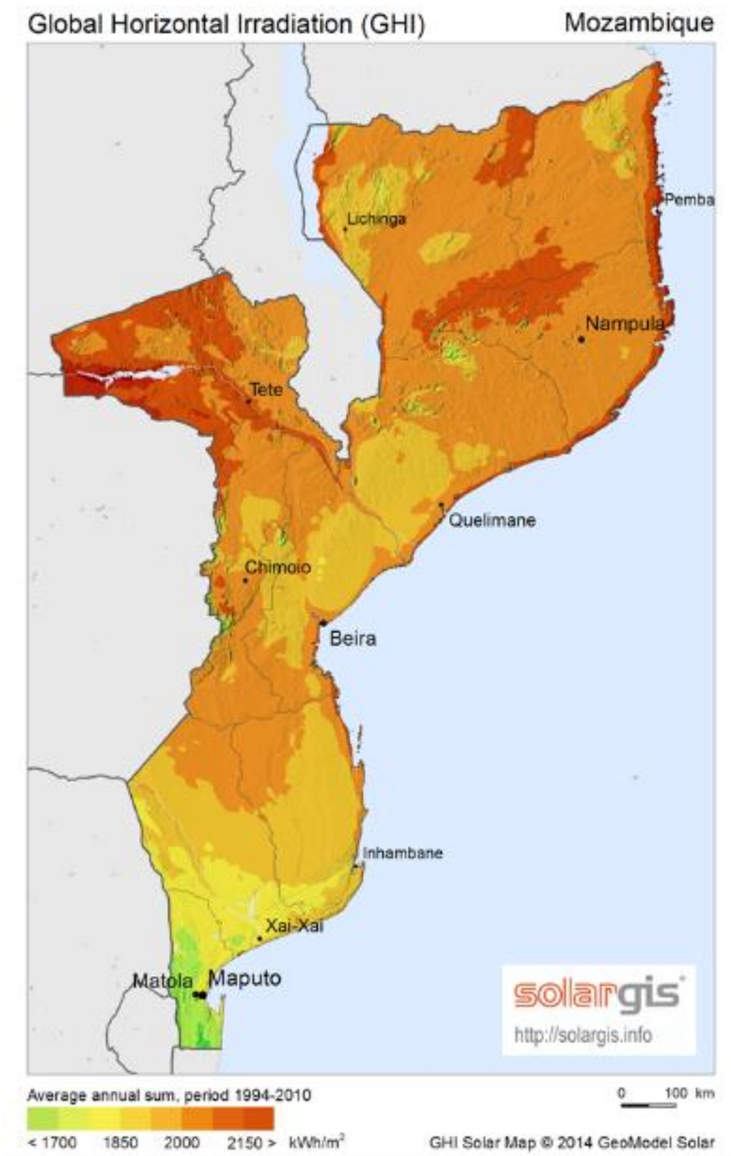

Diagram 5.14 GHI in Mozambique

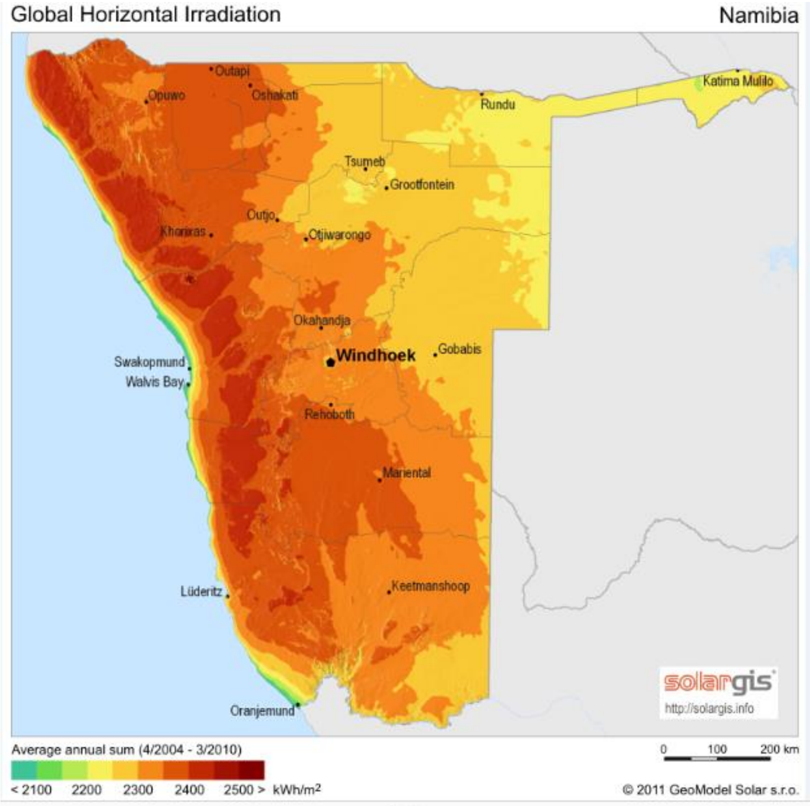

Diagram 5.15 GHI in Namibia

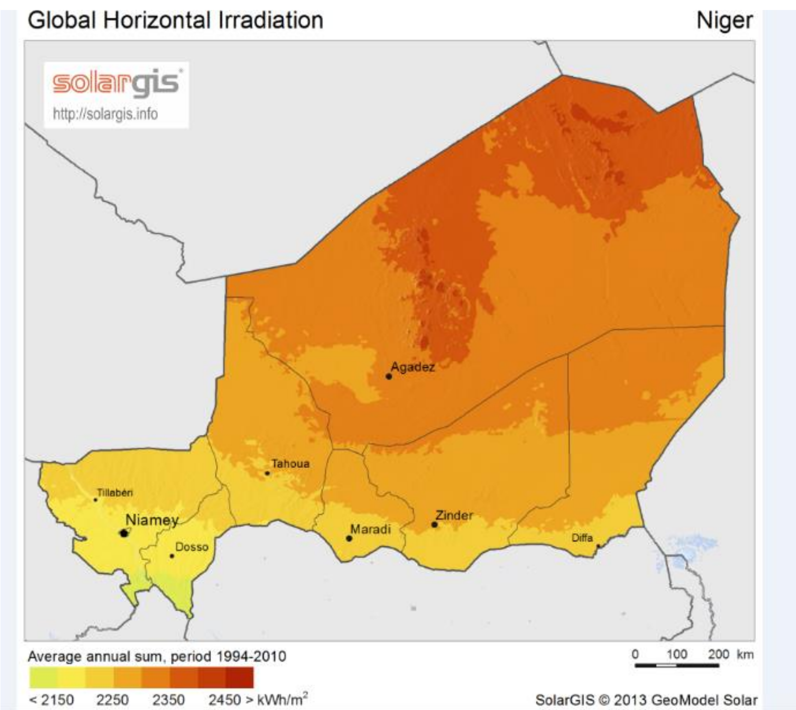

Diagram 5.16 GHI in Niger

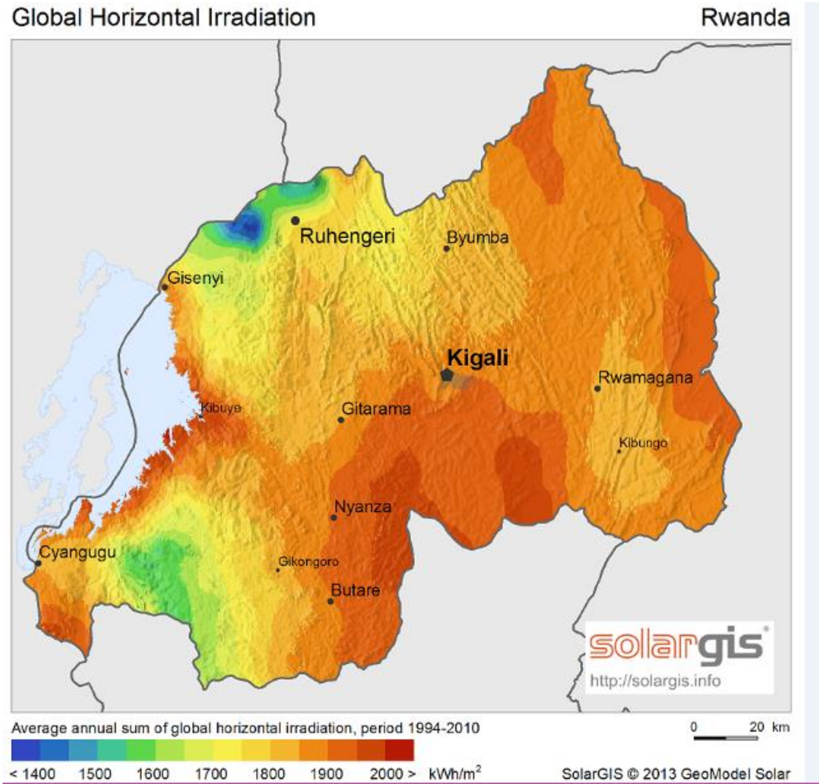

Diagram 5.17 GHI in Rwanda

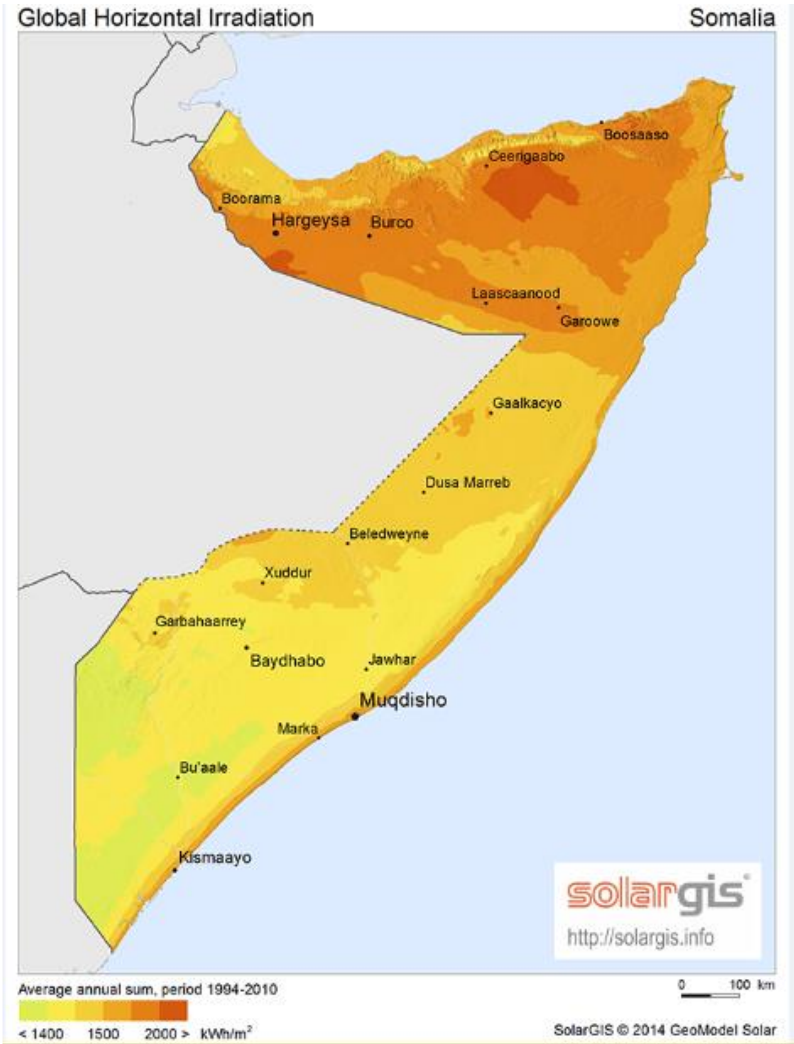

Diagram 5.18 GHI in Somalia

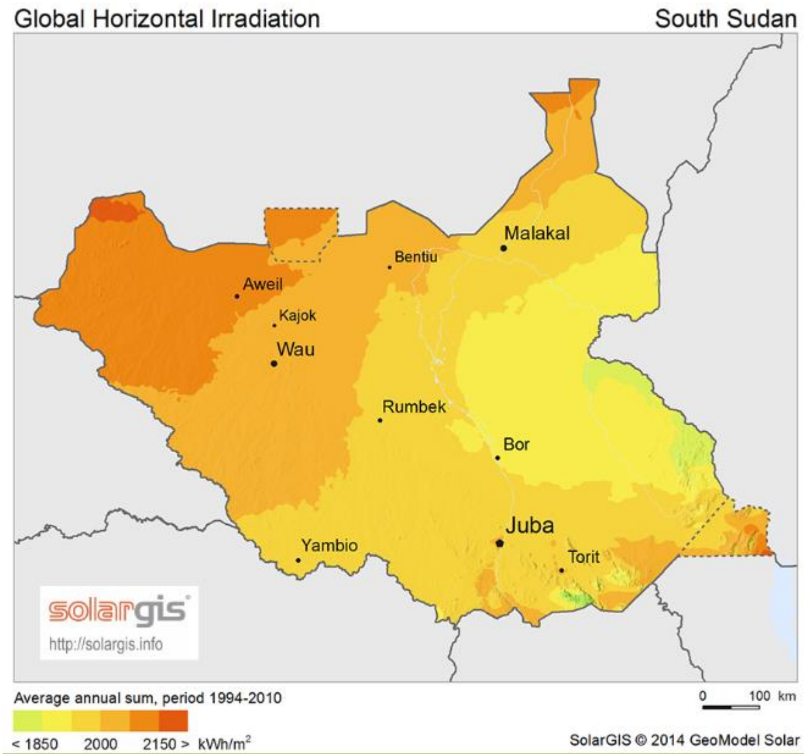

Diagram 5.19 GHI in South Sudan

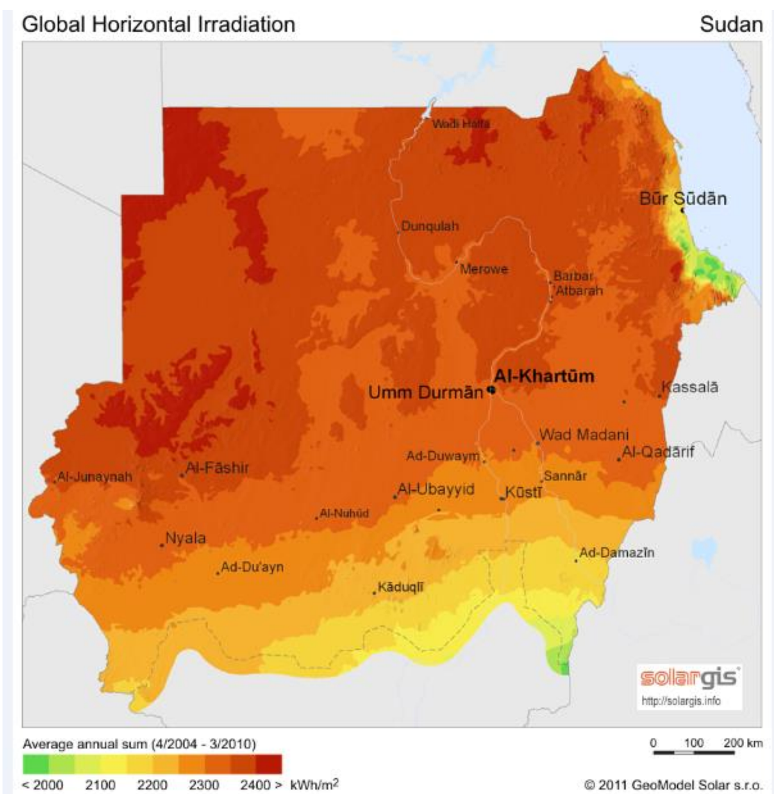

Diagram 5.20 GHI in Sudan

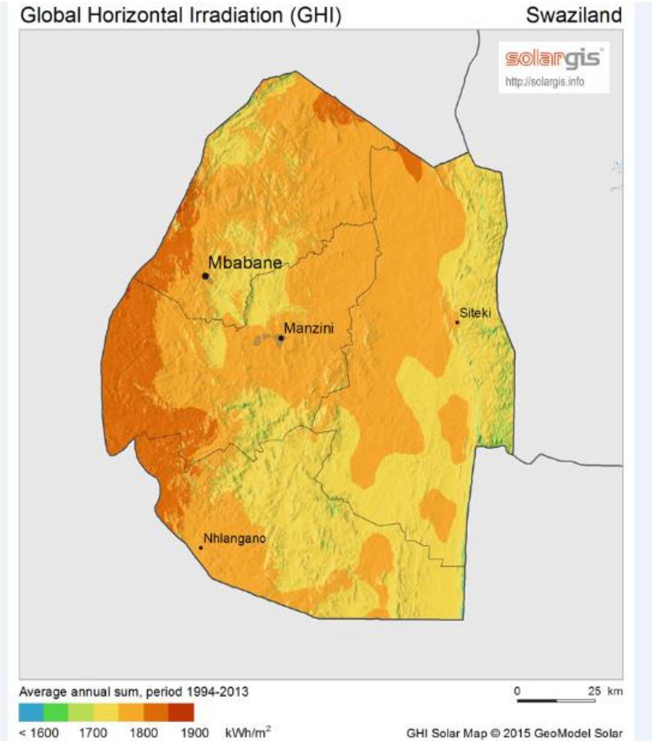

Diagram 5.21 GHI in Swaziland

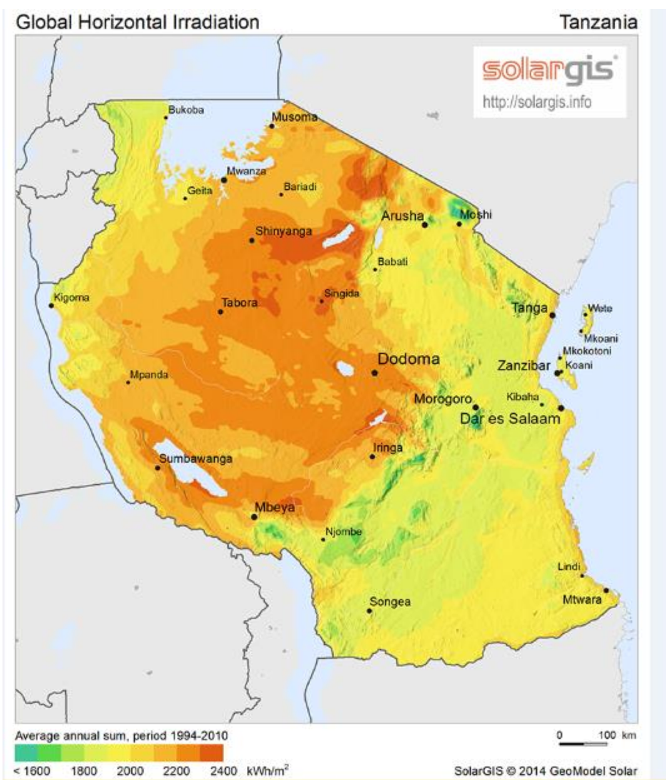

Diagram 5.22 GHI in Tanzania

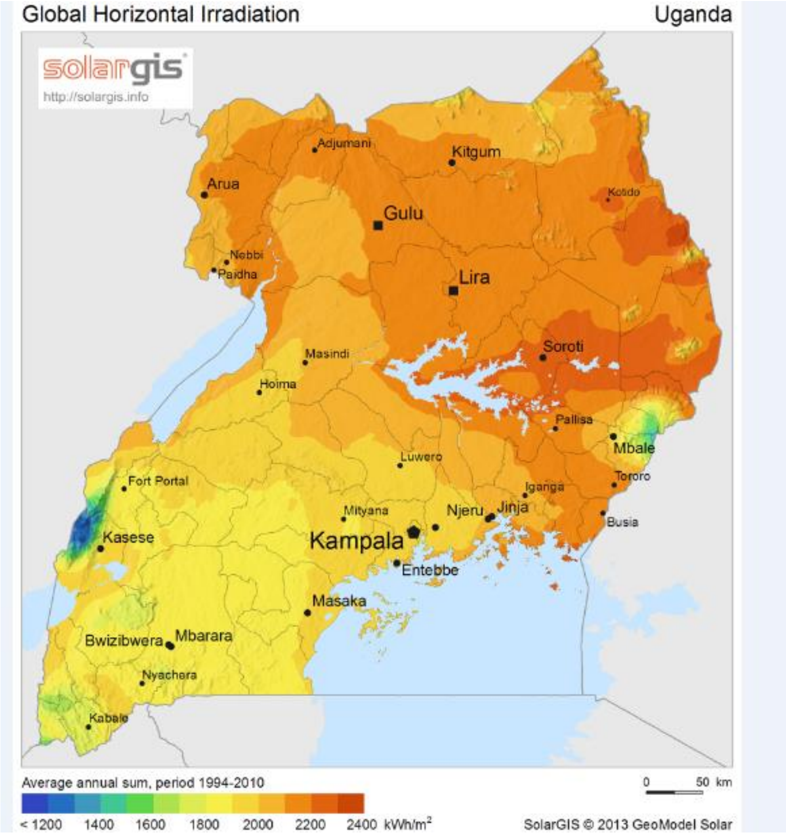

Diagram 5.23 GHI in Uganda

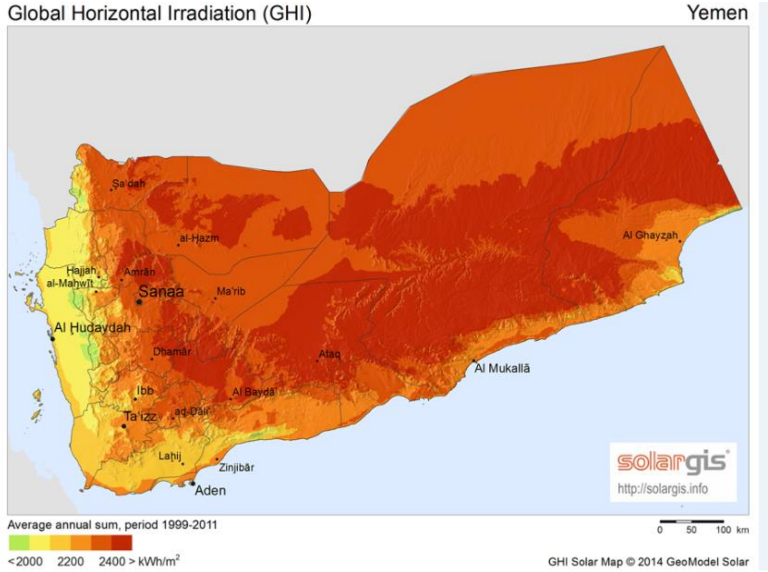

Diagram 5.24 GHI in Yemen

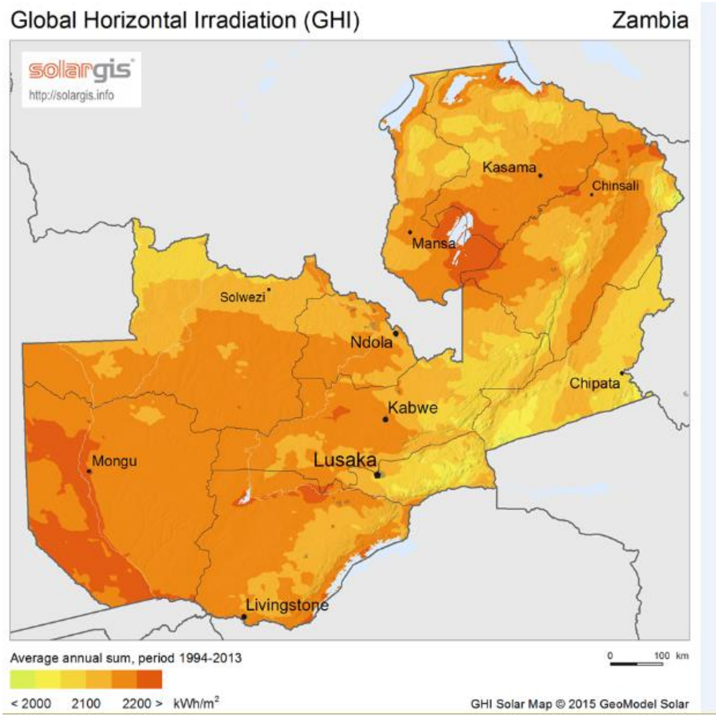

Diagram 5.25 GHI in Zambia

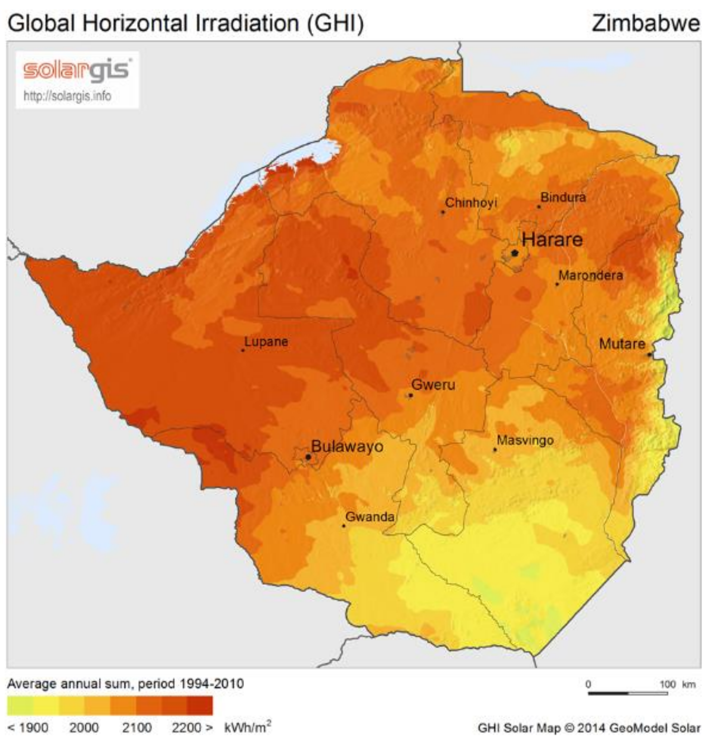

Diagram 5.26 GHI in Zimbabwe

6.2 Appendix B - Kepner-Tregoe Spreadsheets

Kepner-Tregoe Decision Analysis		Afghanistan				Angola				Benin			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0.33	0.14	%	5	0.33	0.14	%	5	1	0.41
Has DER > 200km away from any major load center	0.055	#	1<=		0.00	#	1<=	1	0.06	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.20	0.03	#	5<	0.80	0.13	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.2	0.07	y/n	Y	0.4	0.15	y/n	Y	0.8	0.30
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.24				0.47				0.71

		Burkina Faso				Burundi				Cambodia			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5	0.66	0.27
Has DER > 200km away from any major load center	0.055	#	1<=	0	0.00	#	1<=	0	0.00	#	1<=		0.00
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	0.20	0.03	#	5<	0.40	0.06
Political stability	0.372	y/n	Y	0.6	0.22	y/n	Y	0.2	0.07	y/n	Y	0.6	0.22
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.22				0.11				0.56

		Central African Republic				Chad				Democratic Republic of the Congo			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=		0.00	#	1<=	1	0.06	#	1<=		0.00
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	0.20	0.03	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0	0.00	y/n	Y	0	0.00	y/n	Y	0	0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.00				0.09				0.14

		Republic of the Congo				Eritrea				Ethiopia			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0.33	0.14	%	5	0	0.00	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=		0.00	#	1<=	0	0.00	#	1<=	1	0.06
GDP/cost estimate ratio	0.162	#	5<	0.20	0.03	#	5<	0.20	0.03	#	5<	0.20	0.03
Political stability	0.372	y/n	Y	0.4	0.15	y/n	Y	0.4	0.15	y/n	Y	0.4	0.15
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.32				0.18				0.37

		Republic of the Gambia				Guinea				Haiti			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0.66	0.27	%	5	0	0.00
Has DER > 200km away from any major load center	0.055	#	1<=	0	0.00	#	1<=	0	0.00	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	0.00	0.00	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.6	0.22	y/n	Y	0.2	0.07	y/n	Y	0.2	0.07
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.22				0.35				0.07

		Kenya				Lesotho				Liberia			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0.33	0.14	%	5	0.66	0.27
Has DER > 200km away from any major load center	0.055	#	1<=	1	0.06	#	1<=	0	0.00	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.40	0.06	#	5<	0.20	0.03	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.4	0.15	y/n	Y	0.6	0.22	y/n	Y	0.4	0.15
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.27				0.39				0.42

Criteria	Weights	Madagascar				Malawi				Mali			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=	1	0.06	#	1<=	0	0.00	#	1<=	1	0.06
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	0.20	0.03	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.6	0.22	y/n	Y	0.6	0.22	y/n	Y	0.4	0.15
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.28				0.26				0.34

Criteria	Weights	Mauritania				Mozambique				Namibia			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0.33	0.14	%	5	0.33	0.14	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=	1	0.06	#	1<=		0.00	#	1<=	1	0.06
GDP/cost estimate ratio	0.162	#	5<	0.20	0.03	#	5<	0.00	0.00	#	5<	0.80	0.13
Political stability	0.372	y/n	Y	0.4	0.15	y/n	Y	0.6	0.22	y/n	Y	0.8	0.30
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.37				0.36				0.62

Criteria	Weights	Niger				Papua New Guinea				Rwanda			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=	1	0.06	#	1<=		0.00	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	1.00	0.16	#	5<	0.20	0.03
Political stability	0.372	y/n	Y	0.4	0.15	y/n	Y	0.6	0.22	y/n	Y	0.4	0.15
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.20				0.39				0.32

Criteria	Weights	Sierra Leone				Solomon Islands				Somalia			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5		0.00
Has DER > 200km away from any major load center	0.055	#	1<=	0	0.00	#	1<=	0	0.00	#	1<=		0.00
GDP/cost estimate ratio	0.162	#	5<	0.00	0.00	#	5<	0.80	0.13	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.4	0.15	y/n	Y	0.6	0.22	y/n	Y	0	0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.15				0.35				0.00

Criteria	Weights	South Sudan				Sudan				Swaziland			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	1	0.41	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=		0.00	#	1<=	1	0.06	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.20	0.03	#	5<	0.60	0.10	#	5<	1.00	0.16
Political stability	0.372	y/n	Y	0	0.00	y/n	Y	0	0.00	y/n	Y	0.6	0.22
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.03				0.56				0.52

Criteria	Weights	Tanzania				Timor-Leste				Togo			
		Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)	Natural units	Value	Utility 0-1	Score (U x W)
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	1	0.41	%	5	0.66	0.27
Has DER > 200km away from any major load center	0.055	#	1<=		0.00	#	1<=	0	0.00	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.20	0.03	#	5<	0.20	0.03	#	5<	0.00	0.00
Political stability	0.372	y/n	Y	0.6	0.22	y/n	Y	0.4	0.15	y/n	Y	0.6	0.22
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.26				0.59				0.49

		Tuvalu				Uganda				Vanuatu			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0	0.00	%	5	0	0.00	%	5		0.00
Has DER > 200km away from any major load center	0.055	#	1<=	0	0.00	#	1<=	0	0.00	#	1<=		0.00
GDP/cost estimate ratio	0.162	#	5<	0.40	0.06	#	5<	0.40	0.06	#	5<	0.80	0.13
Political stability	0.372	y/n	Y	1	0.37	y/n	Y	0.4	0.15	y/n	Y	0.8	0.30
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.44				0.21				0.43

Kepner-Tregoe Decision Analysis		Republic of Yemen				Zambia				Zimbabwe			
Criteria	**Weights**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**	**Natural units**	**Value**	**Utility 0-1**	**Score (U x W)**
Has tertiary enrollment of > 5%	0.411	%	5	0.33	0.14	%	5	0	0.00	%	5	0.33	0.14
Has DER > 200km away from any major load center	0.055	#	1<=	1	0.06	#	1<=	0	0.00	#	1<=	0	0.00
GDP/cost estimate ratio	0.162	#	5<	0.40	0.06	#	5<	0.20	0.03	#	5<	0.20	0.03
Political stability	0.372	y/n	Y	0	0.00	y/n	Y	0.6	0.22	y/n	Y	0.2	0.07
					0.00				0.00				0.00
					0.00				0.00				0.00
					0.00				0.00				0.00
Total	1.000				0.26				0.26				0.24