Evaluating the potential of adoption of solar photovoltaic systems to enhance electricity reliability in Ghana

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By

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The candidate confirms that the work submitted is his own, except where work which has formed part of jointly-authored publications has been included. The contribution of the candidate and the other authors to this work has been explicitly indicated below. The candidate confirms that appropriate credit has been given within the thesis where reference has been made to the work of others.

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Abstract

The adequacy and security of electricity supply in most developing and under-developed countries is affected by intermittencies. This makes the need for alternate source of electricity generation very vital. However, most published studies on electricity supply security overlook the significance of household consumers. This gap in research and the limited understanding of this phenomenon supports aim of this study.

The general purpose and aim of the study was to assess the potential of household consumers to become prosumers (producers and consumers of electricity) to enhance supply security in Ghana. The constraints on economic growth due to the lack of supply security was a key reason why the study was carried on Ghana.

In this study the technique of Agent-Based Modelling (ABM) was used with extracts from the adoption model of the Complex Adaptive Systems, Cognitive Agents and Distributed Energy (CASCADE) model. The model was used to simulate how three different classes (lower, middle and higher income) of consumers in three different towns adopt Photovoltaic (PV) energy as a result of electricity outages.

The results show that in a town with 1,000 households, 0.3%, 0.4%, 0.2% and 0.1% of the population have the potential to generate electricity between 0 – 50 kWh, 51 – 300 kWh, 301 – 600 kWh and 600+ kWh respectively. This was carried out for two other towns with household populations of 4,000 and 40,000.

The results further show that middle class households that fall between tariffs band 51 – 300 kWh and 301 – 600 kWh have the most potential to contribute to electricity supply security. They contribute to about 60% of the total PV generation.

List of Acronyms

ABM .... Agent-Based Modelling

AF .... Adoption Frequency

AMES .... Agent-Based Modelling of Electricity Systems

CASCADE .. Complex Adaptive Systems, Cognitive Agents and Distributed Energy

DOI .... Diffusion of Innovation

DG .... Distributed Generation

ECG .... Electricity Company of Ghana

EMCAS .... Electricity Market Complex Adaptive System

FREC .... Faculty Research Ethics Committee

GDP .... Gross Domestic Product

GIS .... Geographical Information System

GRIDCO .... Ghana Grid Company

IEA .... International Energy Agency

IPP .... Independent Power Producers

IRENA .... International Renewable Energy Agency

IRR .... Internal Rate of Return

ISSER .... Institute for Statistical and Social Research

MAS .... Multi Agent System

MCDM .... Multi-Criteria Decision-Making

MCS .... Monte Carlo Simulation

MTTF .... Mean Time To Failure

MTTR .... Mean Time To Repair

MW .... Mega Watt

MWp .... Mega Watt peak

NEDCO .... Northern Electricity Distribution Company

NPV .... Net Present Value

PP... Payback Period

PURC .... Public Utilities Regulatory Commission

RO .... Regulator Optimizer

PV.. Photovoltaic

TEA .... Techno-Economic Analysis

VRA .... Volta River Authority

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CHAPTER 1

1.0 Introduction

This thesis describes the demonstration of the behaviour of consumers in an Agent-Based Model (ABM) centred on the supply of electricity. In the context of this study, the main focus is on domestic consumers and their potential to enhance electricity reliability in Ghana. In this study the term reliability as discussed by Li (2013) is defined to be the consistent supply of electric power at any given time from the grid such that in any circumstance of system failure the flow of power to the consumer remains undisturbed.

The research was carried out with the use of extracts from a wider ABM framework called CASCADE, a complexity science project which models various aspects of a potential smart grid in the UK. The open source template is available (www.github.com/rsnape/cascade) and can be adapted for similar studies. To suit the study area of this research, the author of the adoption segment of the CASCADE project was contacted to streamline the computer coding.

The scope of this research is subject to restrictions, facts and assumptions on data concerning the supply of electricity to domestic consumers in 3 key locations in Ghana. The sample taken from the census data from the Ghana Statistical Service is representative of the size of different districts in the country (Ghana Statistical Service, 2010).

1.1 Global Electricity supply

The International Energy Agency (2015) estimates renewable energy generation to increase from 3,000 terawatt hours in 2014 to 15,000 terawatt hours in 2040. An estimate of the source of global electricity generation from 2014 to 2040 is shown in Figure 1.1. The potential growth for solar energy within the same period is significant. However, to meet the target of generating electricity by renewables, complexity relating to the energy trilemma needs to be considered (Gunningham, 2013).

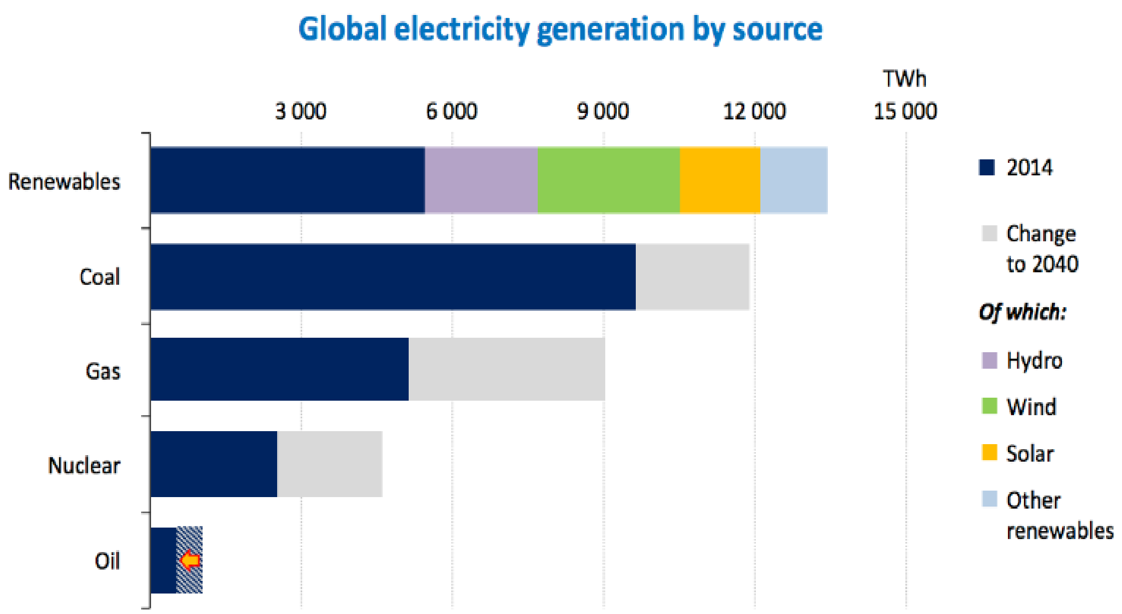

Figure 1.1: Global electricity by source, 2014 – 2040 (International Energy Agency, 2015).

In developed countries, the case of the energy trilemma enforces governments to adhere to requirements of carbon emissions, security of supply of energy and the need to make cost at a very low price (Boston, 2013; Heffron et al., 2015). This makes increasing complexity of electricity grids, varying demand requirements and supply of reliable electricity very important. Modern technology provides a fundamental platform by linking all agents to enhance real-time communication to ensure an efficient transmission.

On the other hand, developing countries mostly focus on the consistent supply of electricity with less priority on carbon footprints. The need for economic and environmental friendly energy supply calls for the implementation of renewables as the main source of electricity. However, it is forecasted by the world energy outlook that about 84% of energy would still be generated from fossil fuel in 2030 (WEO 2007). This raises concerns on how soon clean and efficient means of generating electricity globally can be provided especially to developing and under developed countries.

1.2 Electricity supply in Ghana

The World Bank (2015) estimates that Ghana's value of sales lost due to power outages stands at a high 15.8%. The frequency of the unpredictable electricity supply adds to the economic problems (Reuters, 2015). This makes Ghana an interesting case for this research. The electricity network in Ghana can be categorized into generation, transmission and distribution. In Figure 1.4, the Volta River Authority (VRA) and other independent power producers (IPPs) generate electricity which is then transmitted by the Ghana Grid Company (GRIDCO). The transmitted power is then distributed to consumers largely by the Electricity Company of Ghana (ECG) and the Northern Electricity Distribution Company (NEDCO).

Figure 1.2 shows the structure of the electricity network in Ghana. In the context of this study, we focus on the electricity supply from the ECG to residential (domestic) consumers.

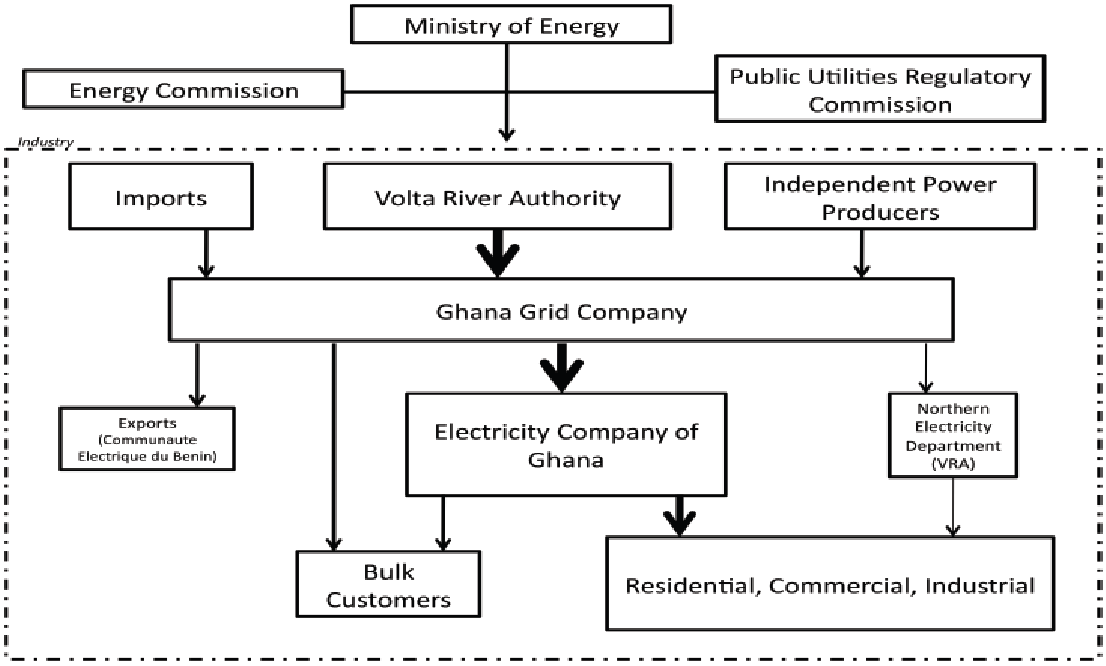

Figure 1.2: Ghana electricity transmission network (International Atomic Energy Agency, 2012).

1.2.1 Ghana electricity problem

According to the Electricity Company of Ghana (2013), factors that affect the supply of electricity to consumers in Ghana include:

- Overloaded networks, third party damages and power theft
- Shortfalls in generation and transmission failures
- Maintenance of generating equipment
- Fluctuating cost of fuel for thermal plants
- Increasing demand for electricity

In 2014, the distribution losses for ECG and NEDCO was 25.2% and 24.0% respectively (Energy Commission, 2015).

The problems highlighted above provides an avenue for consumers to contribute to electricity supply by becoming prosumers. The term prosumer here refers to consumers who produce electricity with alternate energy such as solar or wind. In this research, the potential insolation resource in Ghana and incentives for Feed-in Tariffs justifies the focus on adoption of PV as a source of alternate energy to enhance electricity reliability.

1.3 Aims and Objectives

Due the problems that affect electricity reliability in Ghana, it was clear that there should be measures taken by different agents in the electricity network. In this research, the aim was to assess the potential of household consumers to become prosumers (producers and consumers) to enhance reliability in the electricity grid in Ghana. This queried the study to answer the following research questions:

1. How might a study evaluate the electricity outage statistics in Ghana over a five year period?
2. What is the solar energy potential for the adoption of photovoltaic systems in Ghana?
3. Given available government incentives such as Feed-in-tariff, can the adoption of photovoltaic systems by households be a cost-effective measure to electricity outages in Ghana?
4. How would the interaction of techno-economic factors impact the adoption of photovoltaic systems in Ghana?
5. What is the potential electricity generation from modelled adoption of PV?

The research takes a unique approach due to the different actors in the electricity distribution network. The main point of concern was to investigate the reliability of the electricity grid at the consumer viewpoint. The set of proposed outcomes to accomplish the aim of the study are as follows:

1. Analyse the trend of outages in the supply of electricity in Ghana with data collated from the ECG.
2. Assess the potential for solar energy in Ghana to determine the suitability photovoltaics using an existing study by United Nations Environmental Program (UNEP).
3. Estimate of the economic potential of solar photovoltaic systems to households with the availability of feed-in-tariffs.
4. Model and simulate how techno-economic and social factors affect the adoption of solar photovoltaic systems.
5. Analyse the potential electricity generation by the adoption of PV.

1.4 Scope, limitations and relevance of the research

An efficient and continuous supply of electricity is key to the economic growth of every country. The importance of the security and adequacy of electricity supply at the consumer viewpoint (detailed in section 2.2) supports the basis of this study. The research focuses on electricity supply in Ghana from the viewpoint of domestic consumers. This makes the study limited to only countries with similar profiles like that of Ghana.

In using an agent-based model, an advantage is the use of large data set and different parameters which gives a rich outlook on the outcomes of a study. However, due to time constraints, the research used less sophisticated approaches that could have measured complex situations. This makes affects the generality of the study to analyse other projects.

A key objective of this study was to show how domestic consumers can contribute to the electricity outlook of developing and under-developed nations. The research is expected to serve as a guide for domestic consumers of electricity in Ghana to appreciate their potential to enhance supply. To an extent, countries with similar profile like Ghana can employ the outcomes of the study for their tailored analysis.

1.5 Outline of Thesis

In this section, a detailed structure on how the chapters in this thesis is presented is shown below.

Chapter 1 focuses on the introduction and background of the study. It also includes the aims and objectives of the research.

Chapter 2 presents a detailed review of existing literature in the context of this study. It identifies the gap in research and the appropriate techniques for this study.

Chapter 3 contains the methodology that was used to obtain the techno-economic parameters for the agent-based model (ABM). A detailed procedure of the ODD protocol that governs the development and operation of the ABM is also explained.

Chapter 4 shows the results and analysis of the research in the context of outages of electricity supply, insolation potential for solar PV and Feed-in Tariff parameters.

Chapter 5 presents the model results and analysis of the study and discusses the findings.

Chapter 6 concludes the research and provides recommendations for future work.

CHAPTER 2

2 Literature review

2.1 Introduction

The use of electricity over the years has become an integral part to human life which fuels economic activities in every country. A lot of exploits on enhancing electricity reliability have presented the scenario of energy trilemma in terms of low carbon emissions, cost and reliable supply of electricity (Bolton and Foxon, 2013; Boston, 2013; Heffron et al., 2015).

The complex aspect of the increasing global population and the impact of climate change highlights the need for more reliable and sustainable ways to meet demand (Omer, 2008). Even so, the importance of electricity would be of little impact if there exist constraints on its access and reliability. In Ghanaian terms, electricity reliability referred to as “dumsor” is the persistent, unpredictable and irregular interruption of electricity (Ibrahim et al., 2016). The severity of dumsor in Ghana over a five-year period is presented in the results section in chapter 4.

This chapter presents an introduction and background to the theory of electricity reliability. Section 2.2 explains the concept of electricity reliability in the context of this research and establishes two main viewpoints (utility and consumer viewpoint). In Section 2.3, major electricity outages that have occurred globally are discussed in relation to the importance of securing sustainable ways to enhance electricity reliability.

A closer look at the challenges of electricity reliability in Section 2.4 is mentioned with a detailed focus on electricity outages in Ghana. In Section 2.5, the social and technical characteristics that affect the dynamics of behaviour are considered as factors that can enable the current electricity network to transition into an adaptable and more reliable grid. It identifies the gap in research on how agent-based modelling can be used as a technique to evaluate the potential of domestic consumers to contribute to enhance electricity reliability and Section 2.6 and 2.7 reviews types of evaluating methods.

The concept of solar resource in Section 2.8, solar PV technologies in Section 2.9 and policy that guide their implementation in Section 2.10 are also deliberated on. Last, the theory of diffusion of innovations is discussed in Section 2.11 and summary of the Chapter is provided in Section 2.12.

2.2 Concept of electricity reliability

The reliability of a system can be defined as the probability that it will perform its assigned function under specified operating limits (Rausand and Høyland, 2004).

In Eq. 2.1, reliability *R(t)*, is calculated using the sum of probabilities of failure from time interval *0* to *t*:

$$\boldsymbol{R(t) = 1 - \mathrm{F}(t) = 1 - \int_0^t f(s)\, ds} \qquad (2.1)$$

Where: $\mathbf{F}(\boldsymbol{t})$ = probability that a failure occurs before time *t.*

In the operation of electricity systems, failures are bound to occur due to internal and external factors. The system failure is the incapability of a component or the whole system to perform its expected function at a particular time under definite operating conditions (Frankel, 2013).

Failure in a system is specified by its failure rate (λ) and repair rate (μ). Failure rate can be given as the mean time to failure (MTTF), which is the estimated failure time during which a component is expected to perform successfully (Kundur et al., 2004). It is given by,

$$\boldsymbol{MTTF} = \int_{\mathbf{0}}^{\infty} \boldsymbol{t}\,\boldsymbol{f}(\boldsymbol{t})\,\boldsymbol{dt} \tag{2.2}$$

On the other hand, repair rate can be given as the mean time to repair (MTTR), which is the number of repairs of a system within a specified time (Kundur et al., 2004). It can be expressed as,

$$\boldsymbol{MTTR} = \int_{\mathbf{0}}^{\infty} \boldsymbol{t}\,\boldsymbol{g}(\boldsymbol{t})\,\boldsymbol{dt} \tag{2.3}$$

The normal distribution can be used to evaluate failure rates in a symmetrical dispersion. The dumbbell shape is based on the mean and the spread is calculated by variance. The larger the value, the flatter the distribution. The reliability function is given by

$$\boldsymbol{R}(\boldsymbol{t}) = \int_{\boldsymbol{t}}^{\infty} \frac{\mathbf{1}}{\boldsymbol{\sigma}\sqrt{\mathbf{2}\boldsymbol{\pi}}}\, \boldsymbol{e}^{-\frac{1}{2}\left(\frac{s-\mu}{\sigma}\right)^2}\, \boldsymbol{ds} \tag{2.4}$$

Where $\boldsymbol{\mu}$ = mean value and σ = standard deviation

However, failure rates are typically explained with exponential distributions because of the constant failure rate property. As a result, the lifetime of a system and its components can be modelled for the long flat “intrinsic failure” portion of the bathtub curve (Munir et al., 2015).

The exponential distribution is given by

$$R(t) = \quad 1 - \int_0^t \lambda . e^{-\lambda s} \; ds \qquad (2.5)$$

The reliability of the system until time *t* can be derived from Equation 2.5.

In general, the concept of reliability in the electricity system can be categorized in the following (Billinton and Allan, 2012; Li, 2013).

- *Adequacy*, refers to the required facilities to meet consumer demand or system constraints.
- *Security*, refers to the ability for the system to withstand fluctuations in electricity supply.

The facilities considered here are the physical equipment needed for generating, transmitting and distributing electricity to the end consumer.

The term reliability has different range of viewpoints. In electricity reliability, the two main viewpoints are the *utility viewpoint* and *consumer viewpoint* (Morris et al., 2000).

The utility may consider factors at generation, transmission and distribution that define reliability based on the service at load points and supply (Short, 2014). On the other hand, the consumer considers any occurrence of electricity outages as undesirable. They require electricity continuously to meet a perfect situation.

In Figure 2.1, a range of concerns on electricity reliability from the utility viewpoint and consumer viewpoint are reviewed (Morris et al., 2000). In relation to this study, focus is given to the consumer viewpoint based on service cut (electricity outages). This shows the most appropriate definition of electricity reliability.

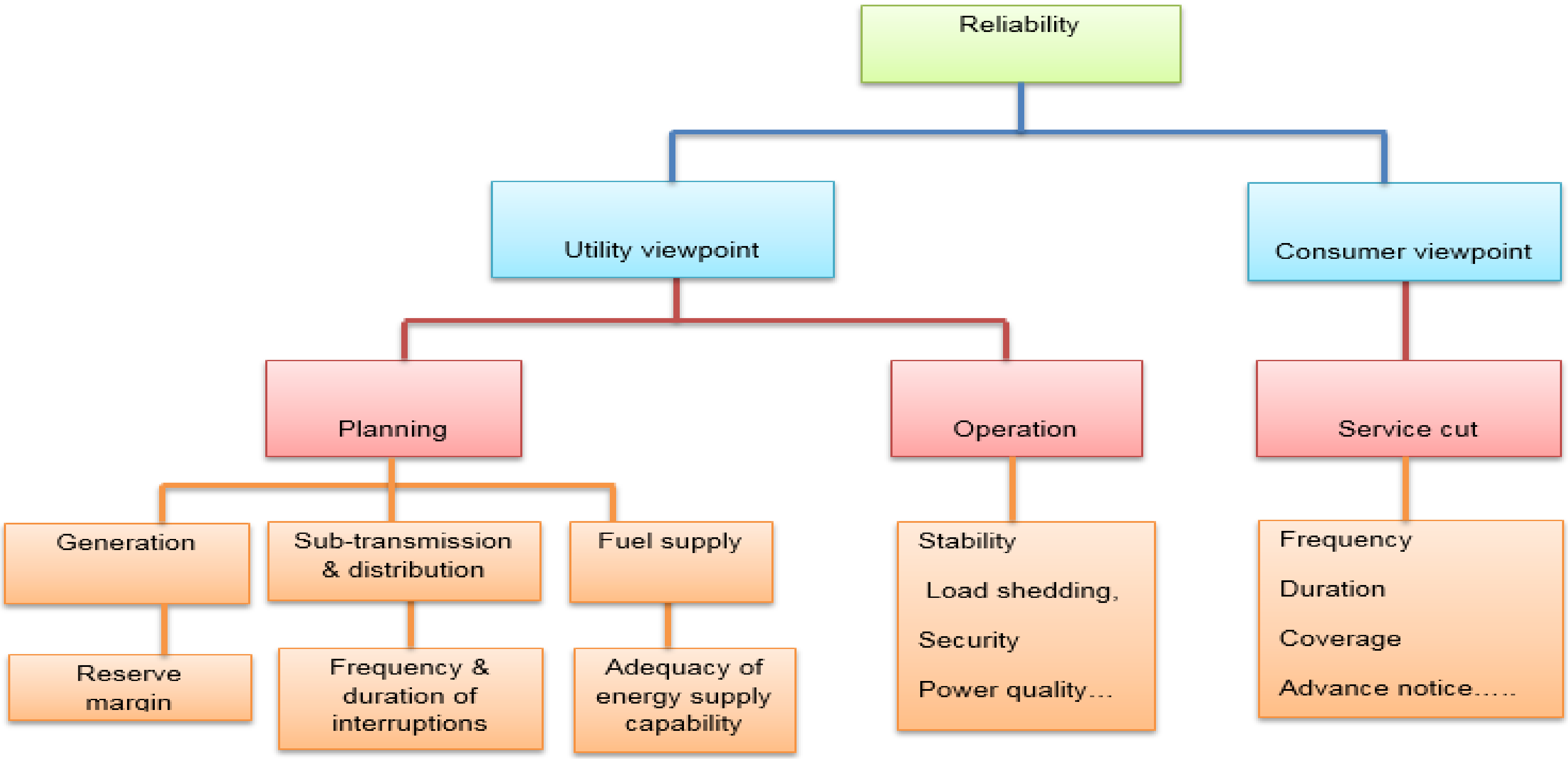

Figure 2.1: Different viewpoints of electricity reliability, adapted from (Morris et al., 2000).

2.3 Major electricity outages

According to the International Energy Agency (2005), massive power outages have happened across the world over the years. Figure 2.2 highlights the impact and locations where these outages have occurred (Amin and Stringer, 2008). The major cause of electricity outages in developed countries like Denmark, United Kingdom and the Unites States of America is as a result of natural disasters. Technical faults can also affect the supply of electricity in developed countries. For instance in Figure 2.2, Denmark and Italy in 2003 experienced electricity outages through system faults which affected 5 and 50 million people respectively (Amin and Stringer, 2008).

Through experience with electricity outages most developed nations have established resilient ways to curb such situations. However, in the 21st century power outages continue to exist especially in developing and under-developed nations. The alarming issue is that the frequency at which it occurs presents a significant effect on the various segments of their economies including agriculture, manufacturing, and healthcare, education, etc.

In terms of cost, Bennett (2011) supports the need to evaluate reliability failures through an economic breakdown. But, Willis and Garrod (1997) explains that it is difficult to rate the monetary value of electricity reliability to consumers. However, in modern times estimating the cost of failures is possible. A general measure for cost of electricity failures is given below (Frankel, 2013).

- Cost of salary: A simple calculation on the hourly rate of pay can be used to estimate the wasted salary. This is given by the annual salary divided by the average working days and divided by the average number of daily work hours.

- Lost income: This is another simple calculation to estimate the cost of electricity outages. This is given by, (total income divided by the number of operational days) and divided by the number of operational hours.
- Auxiliary cost: This can be used to calculate the extra cost associated to correct occurred outages. This is given by, auxiliary cost divided by average electricity outage hours[1].
- Damages: these can result in legal fines especially for consumers who have business contracts with clients. The total cost of any fines can also be used to calculate cost as a result of electricity outages.

The cost of outages for instance in the United States is estimated to be in the margins of $ 79 billion per year (LaCommare and Eto, 2006).

Aside the cost associated with electricity outages, a modern and growing society requires continuous supply. Li (2013) explains that the randomness of equipment and system failures makes consistent supply of electricity difficult. In review, transient power supply has been an overriding impact on continuous power flow in Ghana. As demand for electricity keeps on increasing, it makes it vital to find ways to address intermittencies in electricity supply.

In any attempt to curb the electricity reliability problem, a comprehensive list of activities recommended by Sunday (2009) to reduce outages in the transmission network include the following below.

- Planned and routine maintenance to reduce spans of collapse on the transmission network.
- Improvement of long and delicate lines to enhance voltage stability.

[1] Average electricity outage hours per industry benchmark is 3 hours (UPS, 2015).

- Appropriate clearing of vegetation along transmission lines to reduce trapping.
- Introduction of more substations in the distribution network

However, such recommendations do not highlight the bigger picture of ensuring a key role for domestic prosumers. This has driven the aim of this research to delve into the aspect of electricity reliability in Ghana to assess the relevance of prosumers.

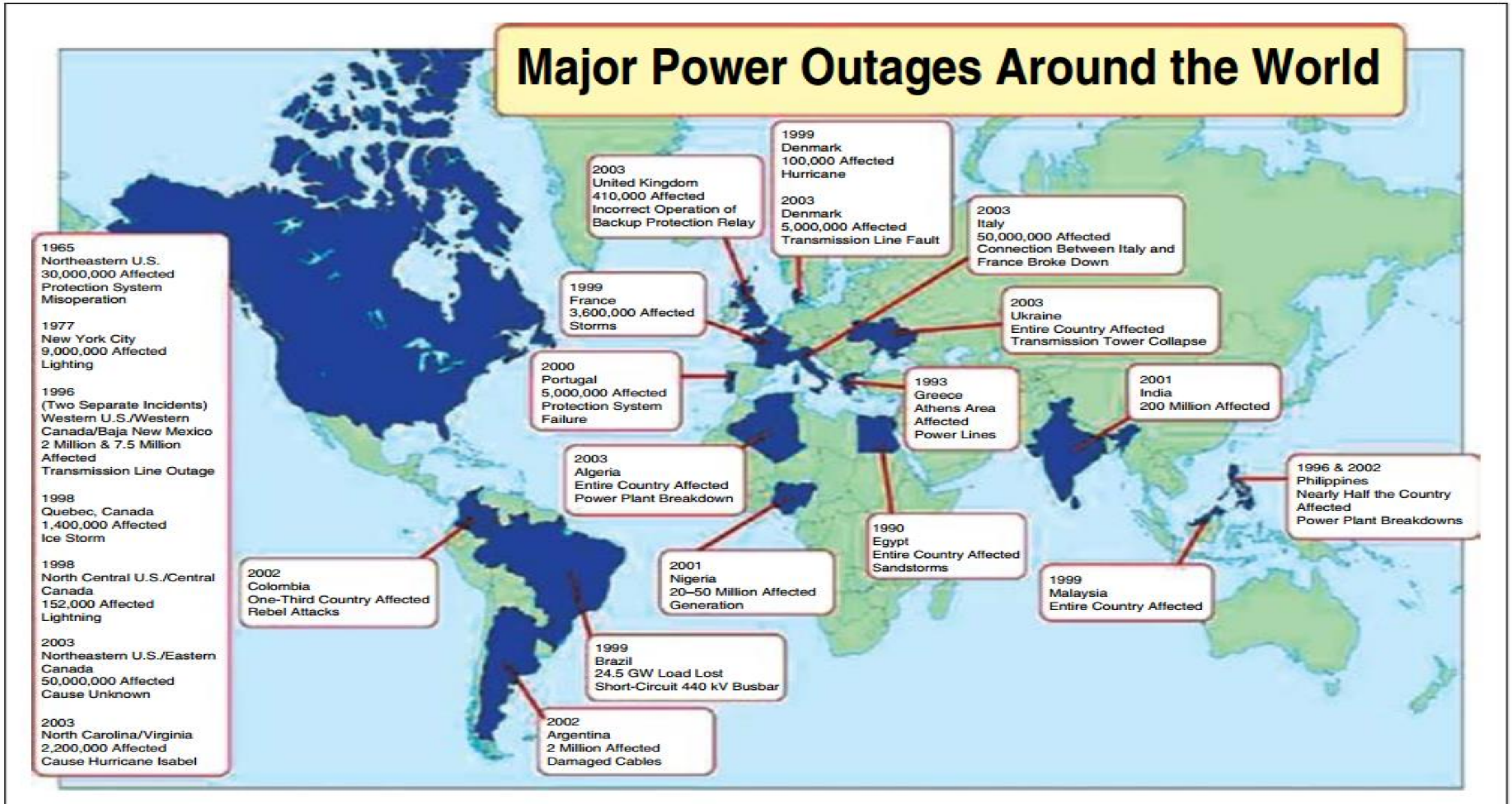

Figure 2.2: Impact of major global electricity outages (Amin and Stringer, 2008).

2.4 Challenges of electricity reliability

According to Gronewold (2009), a quarter of people globally have no access to reliable electricity with an estimate of 1.5 billion. Another evaluation by the IEA shows that about 95 percent of people in sub-Saharan African and developing Asian countries have no access to reliable electricity (International Energy Agency, 2015). Although, the design and operation of power grids always factor reliability as a very important component, there exist poor quality in terms of supply to consumers. This undermines the benefits of electricity supply which include the provision of healthcare, portable water, transport, and telecommunications amongst others.

A lot of studies on the challenges on the distribution of electricity have been explained in (Amin, 2002; Driesen and Belmans, 2006; Mohd et al., 2008). The prospects of alternate energy in the generation mix have been highlighted to enhance supply. In terms of integrating renewable energy to the electricity grid, Boyle (2012) enlightens on the difficulties in variability of different power generation sources. However, the studies that attempt to offer solutions give limited consideration for domestic consumers (Lasseter and Paigi, 2004; Lave et al., 2007). In section 2.4.1, the challenges of electricity reliability in the case study are delved into.

2.4.1 Challenges of electricity reliability in Ghana

In developing countries like Ghana, Nigeria and other similar countries there exists the problem of imbalances in supply and demand (Oyedepo, 2012). This concern mainly is influenced by the poor quality and the frequency at which power is supplied. The challenges of electricity reliability on the various aspects of Ghana’s economy has been appraised in (Adjei, 2016; Forkuoh and Li, 2015; Ibrahim et al., 2016). These studies indicate that power outages increase the operating cost of businesses which results in a negative effect on economic growth.

Most often, electricity reliability issues are caused by overloaded networks, third party damages, and power theft (Electricity Company of Ghana, 2013). Also highlighted are concerns about vegetation overgrowth affecting the quality of electricity. Another significant cause of unstable power supply are shortfalls in generation and transmission failures. However, this creates the possibilities for prosumers to find alternate source of power to enhance electricity reliability (Alanne and Saari, 2006; Munasinghe and Gellerson, 1979; Newbery, 2005).

Distribution and utility companies have introduced the installation of additional transformers and prepayment metering projects in an effort to enhance electricity reliability. Also, the idea of enhancing distributed generation by implementing embedded generator and interconnection goes a step further to ensure electricity reliability. However, such projects in any scale comes at a very high premium. This presents utilities the cheap option of passing on uncertain and unsustainable cost to consumers.

In a geographic setting where there is a tendency for one of the outlined factors to restrict electricity reliability, it makes it more necessary to explore ways that presents ways domestic “prosumers” the ability to contribute to enhance supply. Unfortunately, in the energy market the main purpose of utility companies is to find ways to maximize their profit margin. However, Dave et al. (2011) argues that technology innovation can be managed with a precise measure in order to profit from it. The idea of exploring ways that domestic prosumers can contribute to enhance electricity reliability does not cut revenue in the power market. However, it rearranges the outlook of the power supply market which makes domestic prosumers active actors.

2.5 Socio-technical transitions and gap in research

Today's electricity network globally includes complex interactive agents, economic markets and physical systems. A socio-technical system as described by Geels (2005) is a cluster of elements that are linked together to achieve a functionality at the level of society such as technology, user practices, regulation, infrastructure and cultural meaning.

The dynamics of consumer behaviour defines changes in mechanisms to ensure electricity reliability. These are factors that needs to be considered for the current electricity network to transition into an adaptable and more reliable grid. Information at this level can be incorporated into the development of models to build knowledge on case studies to a wider platform like socio-technical systems of developed nations in Europe and the rest of the world.

In modelling socio-technical systems the appropriateness of the agent-based modelling (ABM) technique have been defined (Bergman et al., 2008; van Dam et al., 2012; Vespignani, 2012). In this study, agents are defined as "any entity which affects electricity reliability" which mainly include household consumers and an energy supplier. The model environment is influenced by exogenous and endogenous factors including policy, physical and economic parameters (e.g. weather, subsidy, capital and feed-in-tariffs).

The use of ABM in electricity modelling have been conducted previously in computational economics. Snape et al. (2011) highlights two significant models EMCAS (Conzelmann et al., 2005) and AMES (Sun and Tesfatsion, 2007). One major study by Elliston et al. (2012) simulated the Australian national electricity market to test scenarios with 100% renewable generation. The significant parameter considered in the system was the reliability of the whole grid. The results (100% renewable electricity meets the reliability standard) disputes Trainer's (2007) stance on renewable integration in reference to electricity reliability. However, Jones (2014) explains that although there is no “one-size way” solution for integrating renewable energy, a tailored power system can be used to enhance electricity reliability.

Important works in the modelling of electricity networks have emanated from the concept of the complex adaptive systems, cognitive agents and distributed energy (CASCADE) project. For instance, Boait et al. (2013) developed a demand response system which enables the regulator to mediate between the consumer and the market to reduce energy consumption. The results show that expected total demand can be shaped in a way to match simultaneously the renewable generation and satisfy network constraints.

Another study by Pakka et al. (2013) developed an ABM that involves electricity producers, suppliers and consumers as agents in a market environment. The study was based on an investigation of three scenarios using a mix of generating technologies including gas, coal and wind turbines and a measure of the aggregate demand response to signals through the balancing market. The outcomes on wind technology showed that higher percentage of electricity generation results in volatile prices is less than projected response from elastic loads.

Relevant to this research, the adoption of solar PV systems was assessed based on social, technical and economic factors. In the same framework of adoption, Boyle (2012) presents technical and operational solutions by examining the importance of the issue of inconsistency of electricity reliability. On the other hand, studies that have factored integration of renewable energy to households (Keirstead, 2007; Salmela and Varho, 2006) do not assess means of enhancing electricity reliability. The gap in research on considering domestic consumers supports this research’s objective of evaluating the potential solar PV adoption to enhance electricity reliability.

2.6 Evaluating electricity reliability

There are a number of ways to measure electricity reliability. According Li (2013), reliability evaluation can be categorized into analytical and simulations. The method of agent-based modelling (ABM) in the latter was used to assess the potential of household consumers to enhance electricity reliability based on techno-economic and social factors in this research.

The concept of the value and cost shown in Figure 2.3 gives a more comprehensive understanding of reliability (Billinton and Allan, 2012). The curves in the diagram indicates that increasing the cost of investment increases reliability. On the other hand, the cost of failures in reliability associated with the consumer decreases as reliability increases.

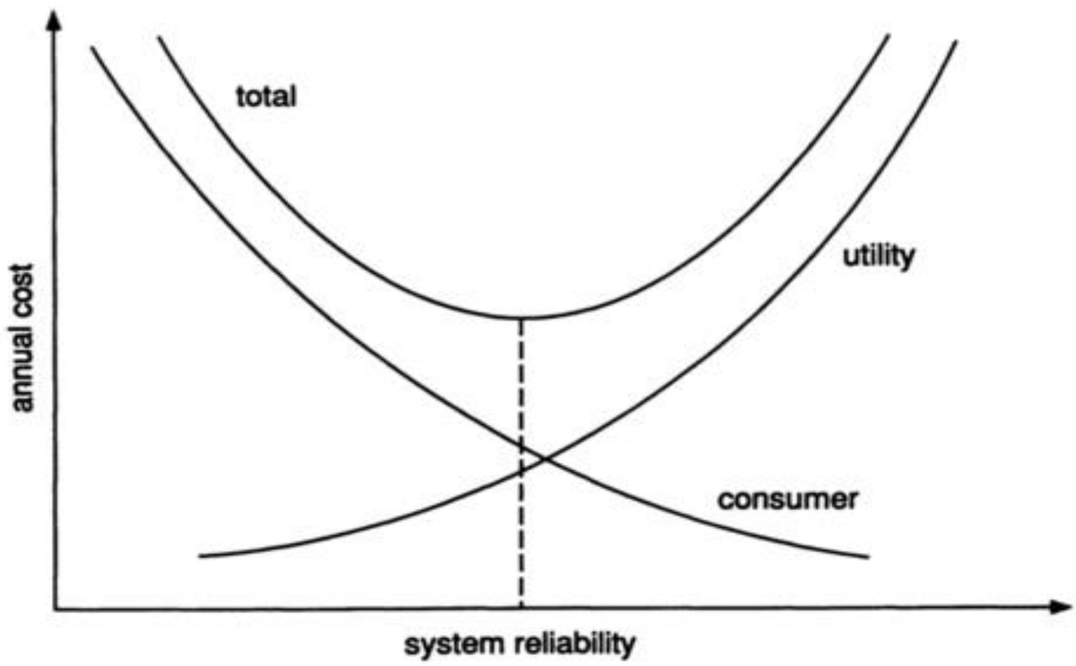

Figure 2.3: Total cost of reliability at the point of consumer and utility (Billinton and Allan, 2012).

Evaluating the cost of electricity reliability raises a variety of questions on its importance to consumers and the national economy as a whole. For instance, Allan and Billinton (1992) questions on the worth of electricity reliability include the following:

- Is it worth spending any money?
- How much should be spent?
- Should reliability be increased, maintained at existing levels, or degraded?
- Who should decide- the energy supplier, regulator or customer?
- On what principles should such decisions be made?

It is obvious that in the 21st century were electricity forms a parallel link with economic growth, the worth of ensuring reliable power supply is unquestionable.

2.7 Alternative methods for evaluating electricity reliability

Numerous studies and practices have been conducted on electricity reliability. The review of existing literature identified five alternate modelling methods that can be used to evaluate electricity reliability. The advantages and drawbacks of the options identified are discussed below.

2.7.1 Monte Carlo simulations

The Monte Carlo simulation (MCS) method can be used to simulate the uncertainty of electricity reliability by using random number generators to estimate the rate at which power is supplied and interrupted. An advantage of this technique is that it can prevent the design of a complex system where the added value in other approaches may be minimal.

Another benefit of this method is that the movement of individual agents can be modelled directly (Landau and Binder, 2014). In this study, the interaction between domestic consumers and the energy supplier can be modelled with this method. However, the purpose of investigating social factors can be challenging.

Billinton and Jonnavithula (1997) gives an advantage of the MCS method to provide an accurate measure of the “mean time to failure” (MTTF) and “mean time to Repair” (MTTR) in evaluating electricity reliability. However, the weakness of this measure is that it does not capture the variability and also the mean value of the indices do not show electricity reliability at the consumer end. This requires a further use of sequential time evolution of behaviour which demands large computational time (Billinton and Wang, 1999). In previous literature, MCS have been used in electricity reliability modelling of multiple infrastructures including power systems (Momoh, 2008). However, this method is not sufficient when substructures are accessed individually.

Other studies conducted with MCS include the measure of adequacy in electricity reliability with regards to several distributed generation systems (Hegazy et al., 2003). In the study, distributed generation units and margins of the system are estimated based on the amount of unsupplied loads. The results indicates that distributed generation can enhance the overall capacity of the distribution system and be used as an alternative to the substation expansion when demand growth is expected. However, the study does not consider circumstances when demand growth is unexpected. Also the relevance of consumers to enhance electricity reliability based on behaviour characteristics are not considered.

In Vallée et al. (2013), the MCS method is used to evaluate the statistical behaviour of prosumers (consumers with PV units) based on smart meters measurements. Two prosumers (3 kW PV installation for each of them) with a smart meter are equipped to simulate the impact of penetration rate of PV generation in a low voltage distribution grid and the influence of the correlation level between PV installations. The results show that the voltage at the low voltage connection point of the medium or low voltage transformer can be influenced by the decentralized generation connected at the medium voltage level.

2.7.2 Optimization tools

An advantage of the optimization technique is that they are cost-effective. This tool can capture multiple dimensions of the economical, technical and environmental aspects of electricity reliability. As a result, optimal solutions can be derived in relation to various objectives. Another advantage is that this technique is rigorous and has been used widely in electricity assessments.

Notable studies in literature that used this method include the reliability assessment for system distribution by Kjolle and Sand (1991), the optimal distribution for reliability by Borges and Falcao (2006) and optimizing reliability supply in the wholesale electricity market (Joskow and Tirole, 2007; Oleinikova et al., 2008). In Joskow and Tirole (2007), optimal prices and electric power investment program are evaluated in scenarios where price-sensitive and price-insensitive consumers can choose the level of rationing contingent based on real-time prices. The results show that wholesale electricity prices reflect the social opportunity cost of generation and rationing makes the use of electricity very efficient. However, the authors in Oleinikova et al. (2008) provide long-term solutions to electricity reliability.

In order to reduce network losses and enhance electricity reliability, Borges and Falcao (2006) presented an optimization process that combines genetic algorithms techniques to evaluate distributed generation impacts in system reliability, losses and voltage profile. The results from experiments with hypothetical systems and an actual distribution system revealed that the proposed method is applicable and produce solutions adequate to imposed constraints. However, the capabilities of domestic consumers in electricity reliability are not considered.

Studies that consider the role of consumers include Yang et al. (2016) tool for regional multi-energy prosumers in China whose energy demands are served by three interconnected energy hubs. The nodes considered are cooling, heating and electricity load nodes. Energy hub 1 serves industrial energy loads, energy hub 2 serves commercial energy loads and energy hub 3 serves residential energy loads. The simulation results indicate that prosumers can enhance electricity reliability by responding to the time-of-use electricity tariffs and then reduce the regional peak loads as a whole.

Zhang et al. (2015) assessed a more interactive study which involve residential consumers and prosumers to adopt distributed renewable energy in a test feeder system with 6 energy cells. The study identifies new roles of utilities and distributed electricity prosumers for future retail electricity market. The results indicate all 6 energy cells can generate electricity using roof-top photovoltaic panel, small wind turbine, diesel generator, and distributed energy storage system.

In this research, the main advantage would be the ability to capture the multiple dimensions of the agents (household consumers and the energy supplier). Also, results can be further analyzed and refined to consider the concerns of consumers on electricity reliability and the performance of the regulator in relation to electricity supply interruptions. However, the use of such models can be time consuming and require computer platforms which are not flexible in terms of transferring from one machine to the other.

An essential weakness of this method is that elements of risk and uncertainty are difficult to estimate. Also for the purpose of this study, the optimization technique may be difficult to implement due to the abstraction of the reality of occurrences of consumer behaviour to electricity reliability.

2.7.3 Multi-Criteria Decision-Making

The main advantage of the Multi-Criteria Decision-Making (MCDM) method is the use of multi-criteria features to obtain a cohesive decision-making result. This method can provide a good framework to capture the relationship between agents in this research. In previous studies, Wang et al. (2009) evaluated the conditions of energy supply systems based on the technical, economic, environmental and social aspects. The results locate investment cost in first place and then CO_2 emission follows based on environment protection.

Another study by Polatidis and Dias (2008) applied an integrated renewable energy planning and design framework to a Greek island in the Aegean Sea. The planning activity considered takes technical, economic, environmental and social aspects of the MCDM. The complexity of energy planning process by Polatidis and Dias (2008) is shown in Figure 2.6. The evaluation criteria from the study is applicable to the Greek case based techno-economic indices.

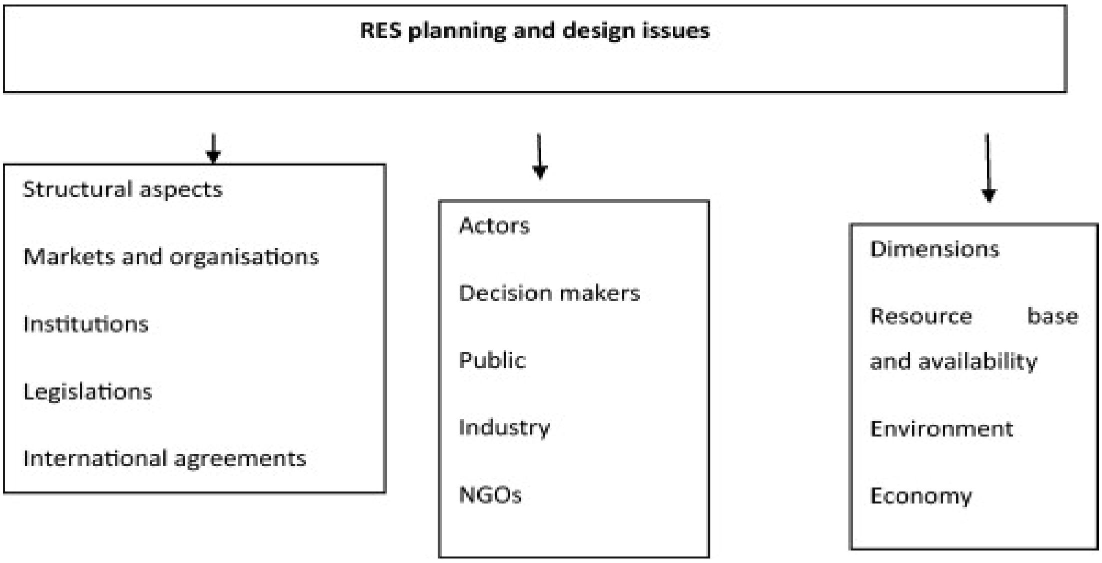

Figure 2.4: Renewable energy planning issues (Polatidis and Dias, 2008).

No study has used the MCDM method to evaluate electricity reliability by considering behaviour of the key agents. In this research, the main advantage will be the ability of the MCDM to focus on the decision-making on PV adoption based on the rate of electricity reliability. Another advantage is that the conflicting objectives (rate of electricity reliability and associated cost) can be considered to find the best compromise. However, such analysis do not provide the optimum solution but the best compromise. Another drawback is that the use of this method may require exceptional computing platforms.

2.7.4 Spreadsheet based and computational systems

Two software techniques (Spreadsheet-based tools and computational mathematics systems) can be implemented as an alternative to developing agent-based models (Macal and North, 2005). Spreadsheet-based tools, such as Microsoft Excel present the simplest approach to develop models. An advantage is that, it is easy to combine different tools in this modelling approach. However, these models limit the diversity of agents and restrict behaviours of agents. Also, this tool suffers from poor scalability and may require macro-level programming using Visual basic. In previous studies, Paidipati et al. (2008) estimated the techno-economic potential for PV adoption in the United States of America. Results indicates that the technical potential increases over time for two reasons: rooftop area grows over time and system efficiencies increase over time.

Also, PV is estimated to contribute 27% to 91% of planned capacity additions. However, the adoption of PV in the study do not consider electricity reliability. Manz et al. (2008) used a spreadsheet-based model to evaluate reliability of photovoltaics (PV) during a utility outage. The parameters considered in this analysis include three geographic regions (Golden, Colo., Hanford, Calif., and Sterling, Va.), three community sizes (10 homes, 100 homes, and 1,000 homes), and various combinations of battery capacity (0 to 10 kWh) and solar PV penetration (0%, 5%, 10%, 30%, 50%). The results show that more than 5 kWh of battery capacity per home reduced each index to nearly zero (a 100% reduction). The contribution of PV to enhance electricity reliability indices was less significant, contributing to 25% reduction in each index at 50% PV penetration.

Computational systems such as Mathematica and MATLAB can be used as well. But, these systems provide limited capabilities for modelling agents. Other programming languages including C, C++, Java and Python can be used as an alternative to ABM. However, it is difficult to develop from the basis with the associated cost and require specific agent modelling tools. In general, no study has used this method to evaluate the impact of consumers’ behaviour in adopting PV due to electricity reliability.

To attain a baseline for assessment, this research employs two methods (techno-economic analysis and agent based model). A detailed review of the methodology are presented in chapter 3.

2.7.5 Techno-economic analysis

This method has been used by many researchers to assess the feasibility to adopt an individual solar PV or a combination of systems. For instance, Shaahid and El-Amin (2009) evaluated the techno-economic feasibility of a hybrid PV–diesel–battery power systems to meet the load requirements with analysis of solar radiation data in a remote village (Rawdhat Bin Habbas) in the Kingdom of Saudi Arabia. The results show that for a hybrid system composed of 2.5 MWp capacity PV system and 4.5 MW diesel system (three 1.5 MW units) and a battery storage of 1 h of autonomy, the distribution of PV adoption is 27%. The cost of generating electricity (COE, US$/kWh) from the hybrid system was 0.170$/kWh.

Another study was conducted by Mahmoud and Ibrik (2006) in a remote village in Palestine. The study differs from Shaahid and El-Amin (2009) as it compares three energy systems (PV systems, diesel generators and electric grid). From the results, adopting PV systems for rural electricity is more economically feasible than the other systems. In Malaysia, Ismail et al. (2013) used techno-economic analysis (TEA) to assess the design of a hybrid system that consists of PV panels, a battery system and a diesel generator. The study analyzed individual scenarios based on a standalone PV and the diesel generator. Through a simulation program, the scenario that meets the load requirements with a minimum cost is selected. The results show that the systems that ensures electricity reliability with an optimal scenario consists of a hybrid system with PV panels, battery bank and diesel generator.

Also in Malaysia, another hybrid system (wind-solar) was assessed with TEA by Chong et al. (2011) with the life cycle cost (LCC) which is a different method compared to Ismail et al. (2013). The calculations indicate a system that is mounted on the top of a 220 m high building with the power-augmentation-guide-vane (30 m diameter and 14 m high) and an H-rotor vertical axis wind turbine (17 m diameter and 9 m high), the estimated annual energy savings is 195.2 MW h/year.

However, there is limited phenomenon on how techno-economic analysis can be used to provide a guideline to assess the behaviour of consumers to adopt solar PV systems to enhance electricity reliability.

The advantages and drawbacks of techno-economic analysis considered for this research are described below.

2.7.5.1 Advantages and drawbacks of techno-economic analysis

This method has been used to evaluate the cost-effectiveness of PV to enhance electricity reliability (Chandel et al., 2014; Jamil et al., 2012; Thakre and Subroto; Yankey et al., 2016). The advantages of TEA in evaluating electricity reliability with PV systems are listed below:

- It helps in the comparison of different capacity of PV systems to evaluate how each affects the purpose of enhancing electricity reliability.
- It provides a framework to assess the particular PV system a consumer can adopt based on available capital.
- It enables a consumer to evaluate the economic benefits of investing in a particular PV system (i.e. payback, profits and risks).

Aside the advantages of TEA, the following drawbacks were studied carefully:

- The absence of metrological data associated to a particular location may affect the sizing of a PV system.
- Using TEA as a general method to assess appropriateness of PV systems does not capture a good amount of analysis. It requires data on relevant cost (operation, system and maintenance cost) along with outcomes from the case studies to accomplish the main objective.

2.7.6 Agent-based modelling

Agent-based modelling as defined by Janssen (2005), "is the computational study of social agents as evolving systems of autonomous interacting agents". This is a trending technique under complex adaptive systems. Figure 2.4 shows a conceptual view of the characteristics of an agent within a model environment (Macal and North, 2009).

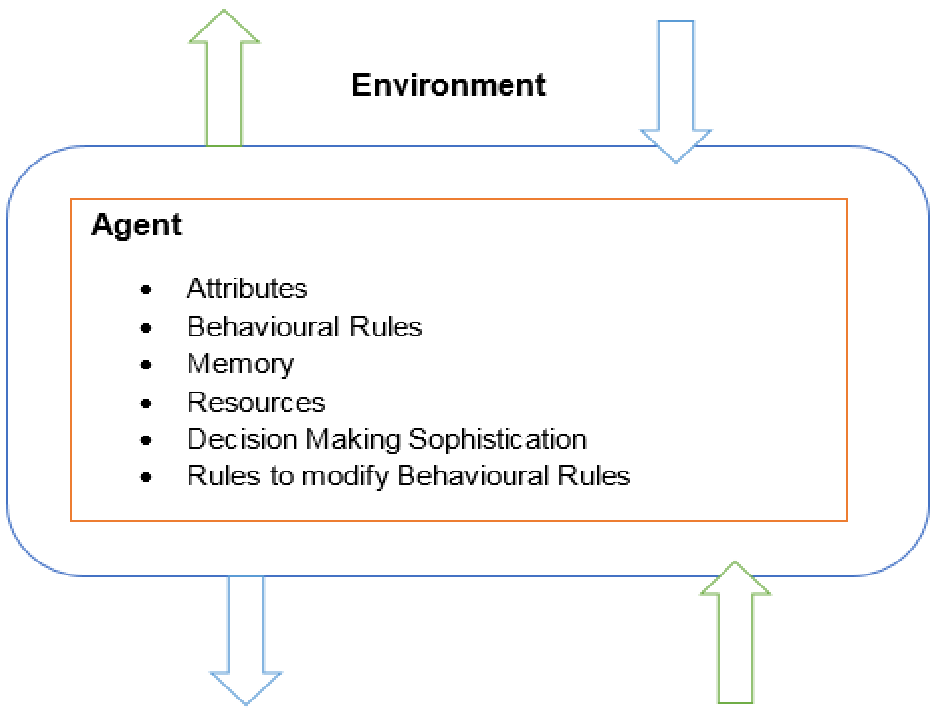

Figure 2.5: Characteristics of a typical agent, adapted from Macal and North (2009)

Some scholars question the need to use complex approaches to solve electricity reliability problems. These queries contemplate whether equation based models are not enough (Macal and North, 2009). In this research, techno-economic analysis and agent-based modelling approach was used over other methods such as Monte Carlo, optimization techniques, multi-criteria decision-making, spreadsheet based and computational systems that are described in section 2.7.

The suitability of the ABM technique in the modelling of electricity networks have been described in past research.

Beck et al. (2008) used an ABM to explore a new method to optimize electricity reliability in South Africa based on decision-making of autonomous agents. The agents make investment decisions based on an internal rate of return (IRR)-threshold whilst decisions to buy and/or sell bagasse are made on purely economic grounds. The results suggests that bagasse[2]-based power generation can easily meet the renewable energy target in South Africa. However, the study relies heavily on assumptions relating to the model and thus requires a thorough sensitivity analysis to assess the results.

Another study on ABM was the demonstration of a model for the electrical network for developing countries. In the study, Alfaro and Miller (2011) assessed the electrification process based on characteristics of the energy sector within a defined area in Liberia. The main simulation with the geographic information feature in Netlogo is the map of the world which shows agents and their locations.

In modelling a wide range of scope, ABM is more flexible over other methods. For instance, attributes like heterogeneity, diversity and the dynamic nature as shown in Figure 2.4 endorses the qualities of ABMs (Macal and North, 2009). Its implementation

[2] Bagasse is the fibrous elements that remain from the crushing of sugarcane or sorghum

can be custom across a variety of domains and spectrum especially for simulations of an electrical grid.

2.7.6.1 Advantages and drawbacks of ABM

The advantages of agent-based modelling in evaluating electricity reliability over other techniques have been considered carefully in the statements below (Koesrindartoto et al., 2005; Macal and North, 2009; Rylatt et al., 2013).

- Natural description: ABM provides a natural depiction of simulating a system that is composed of behavioural entities. This makes the model a better representation of reality. For example, it is more natural to describe the step-by-step approach on how domestic consumers receive unstable electricity supply from an energy supplier and the role the regulator plays to enhance electricity reliability. This method can enable the use of a model to study aggregate properties (PV adoption and the electricity reliability rate).
- Emergence of phenomena: Through the interactions of individual units, ABM captures new occurrences. Emergent phenomenon can have features that are separate from individual properties of a system. For example, assessing the interactions between agents (household consumers and energy supplier) in this study can show factors that affect the supply of electricity which might not be possible with other methods in section 2.6.
- Flexibility of ABM: The scale of using multiple dimensions (heterogeneity) makes ABM flexible. For example, it is easy to add different agents to the model. In this study, ABM provides a natural framework for developing a complex environment of agents with behaviour rules, degree of rationality, ability to learn and evolve. Another form of flexibility is the ability to alter levels of aggregation

and description. For example, collection of agents with different subgroups of agents can be described at different levels simultaneously in the model.

- Cost-effective: The use of ABM is an effective tool for reproducing and analysing a complex case like the electricity grid (Beck et al., 2008). Once the model environment is established for the purpose of evaluating electricity reliability in this study, the cost of the research is very low as compared to other methods. Rather than implementing a real system without knowing the outcome (success or failure), the system can be modelled to assess its effectiveness.

Besides the advantages of ABM, the following challenges have been considered carefully:

- The social occurrences of too many complex factors is challenging (Bazghandi, 2012). For example in this study, consumer behaviours towards electricity reliability may vary differently with geographic location and change in time for a particular period.
- Toolkits used in ABM include performance restrictions: enormous number of agents, reduces execution speed. However, modern computer processing speed can enhance time of execution of codes (computer programmes).

2.8 Solar resource

The sun releases solar radiation in different directions through which a quota touches the surface of the earth. The earth's surface on the average receives about $\mathbf{1.2 \times 10^{17}\ W}$ of the total energy from the sun (Markvart, 2000).

"*The amount of energy reaching the Earth's surface every hour is greater than the amount of energy used by the Earth's population over an entire year*." (Markvart, 2000).

In an optical medium, the air mass (AM) is used to determine the distance that it takes electromagnetic radiation to reach the surface of the earth (Honsberg and Bowden). This is given by,

This is given by,

$$\boldsymbol{AM = \frac{1}{\cos\theta}} \qquad (2.6)$$

where $\boldsymbol{\theta}$ *is the zenith angle which is measure from the vertical.*

The elevation angle which is also known as the altitude angle is measured from the horizontal (Honsberg and Bowden). The elevation and zenith angles are shown in Figure 2.7.

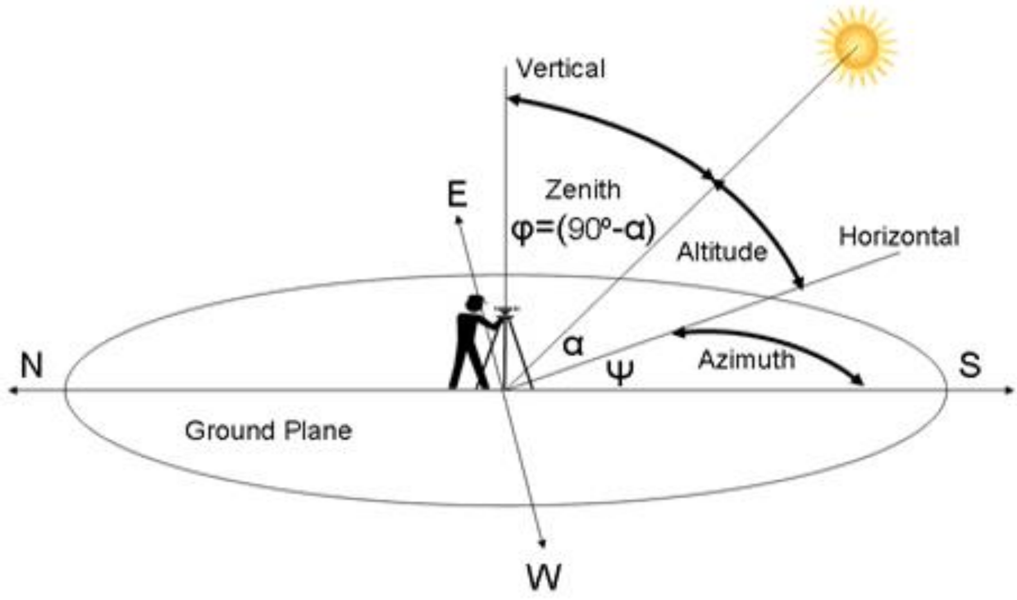

Figure 2.6: A graphical representation of zenith and altitude angles (MPOWER, 2013)

The following equation holds when the elevation is at an angle of 0^{O} and the zenith is at a maximum angle of 90^{O}.

$$\boldsymbol{\theta} = \mathbf{90^{o}} - \boldsymbol{\varphi} \tag{2.7}$$

where $\boldsymbol{\varphi}$ is the zenith angle and $\boldsymbol{\theta}$ is the elevation angle

Figure 2.8 shows the effect of air mass on the solar spectrum (Sekuler and Blake, 1985). At AM0, the extra-terrestrial spectrum is significant for the application of satellite for solar modules. On a clear day, a typical solar spectrum, AM1.5 is used for calibration of solar modules with a total irradiance at 1 kW/ m^2.

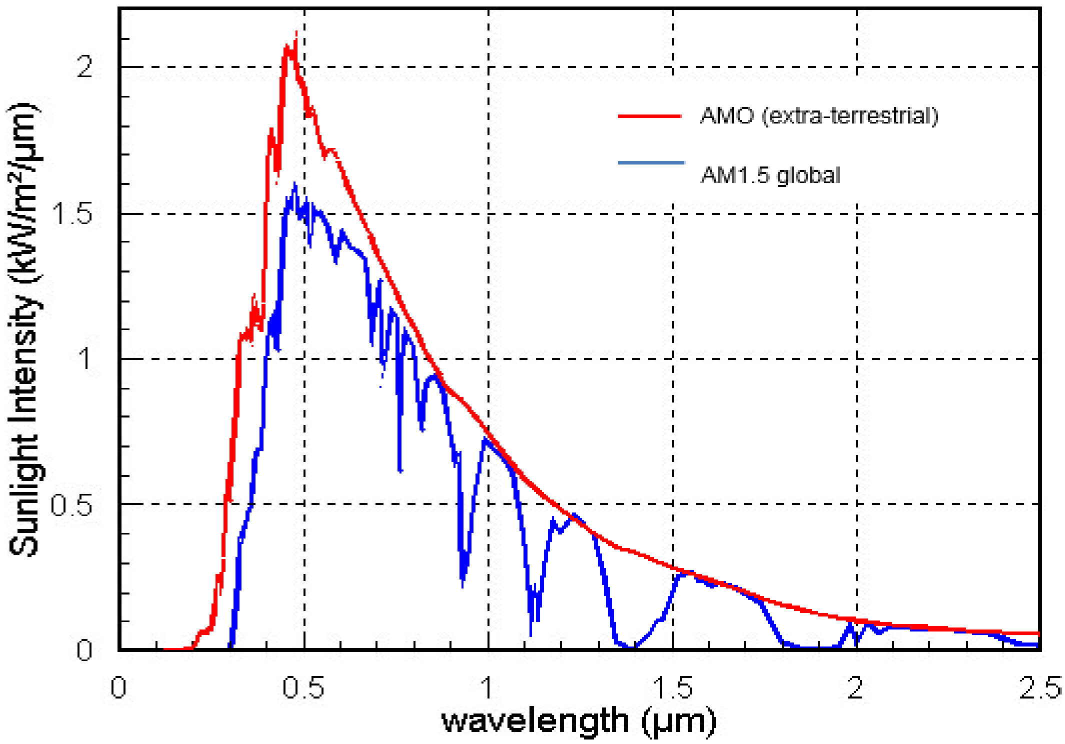

Figure 2.7: The solar spectrum with air mass at AM0 and AM1.5 (Sekuler and Blake, 1985).

The solar insolation is the total amount of solar energy received at a particular location during a specific time (Markvart, 2000). The intensity of solar radiation of a given location is affected by the longitude, latitude, day and time of the year. Other factors including cloud cover, altitude and climate affect solar irradiance.

2.9 Solar PV technologies

Solar energy comes from an infinite source in the form of solar radiation directly and an indirect form. Globally, PV is considered as one of fastest growing technology in power systems (Branker et al., 2011). In Figure 2.9, solar PV modules convert received sun energy to electricity with the use of photovoltaic cells (CECS, 2015).

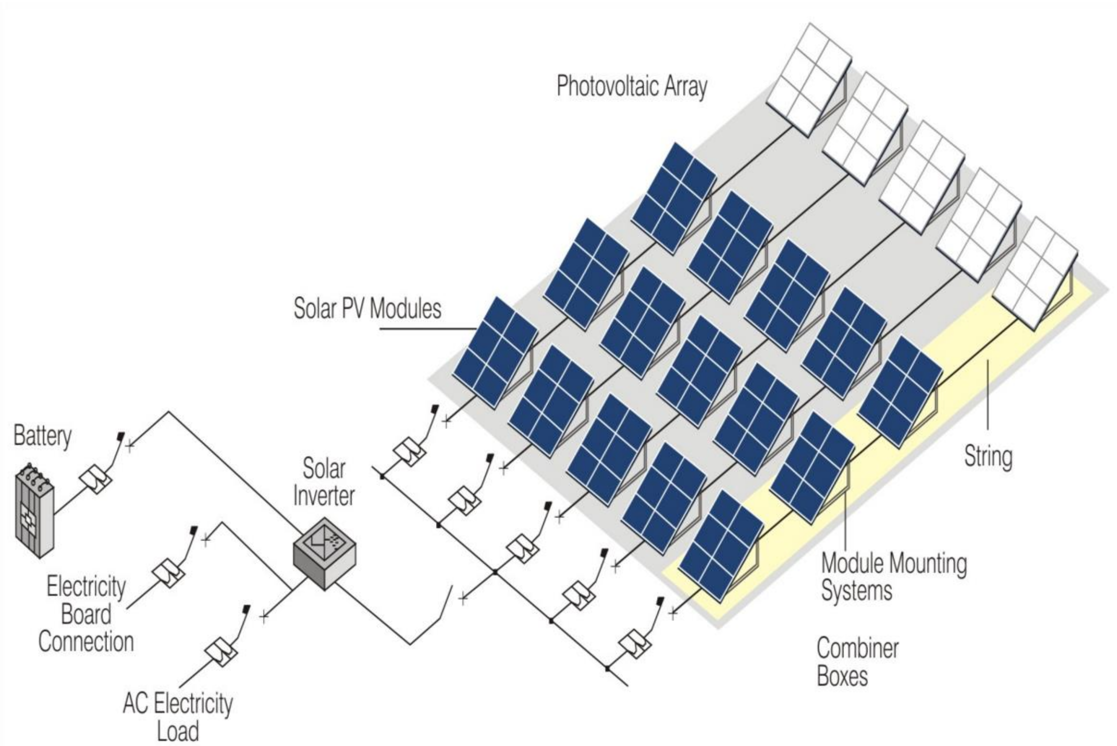

Figure 2.8: Solar PV based power generation system (CECS, 2015).

The current status of photovoltaic (PV) technologies entails the use of silicon amongst different semiconductor materials in production which is widely accepted (Reddy, 2012). Silicon has a simple advantage of being abundant and has a low cost of production which reduces the payback time for any investment made. Solar PV technologies are divided into residential, commercial and large ground-mounted platforms. In this study, solar PV is considered from the perspective of residential domain. The reason for adopting PV technology as feedstock is that solar irradiation in the study area (Ghana) is high. As discussed in Chapter 4 technologies, solar energy is abundant with an average irradiation of 4.4 and 5.6 kWh /m2 / day (Musa et al., 2012; Opoku, 2010).

Moreover, solar energy schemes (feed-in tariffs, subsidy, etc.) are organized at the moment (Gyamfi et al., 2015; Mendonça and Jacobs, 2009). Katiraei and Agüero (2011) highlights the challenges of storage with the integration of PV. Similarly, others studies have evaluated the limits of solar PV and their corresponding performance (Denholm and Margolis, 2007; Tiwari and Sodha, 2006). However, the element of the technology improvement and the decreasing cost of the technology makes it economically feasible.

2.10 Policy on solar PV

Most countries have a policy to guide the implementation of renewable energy. This is as a result of the increasing issues with fossil fuels including climate concerns, supply constraints and the search for alternate sustainable energy.

The need for solar energy to power modern electricity is from the fact that it is clean, largely available and unlimited in supply (Komor, 2004). However, some renewable energy sources in itself have limitations of being intermittent (or not reliable) and expensive. Thus, there is the need for government policy to promote the renewable energy sources such as PV that are viable for electricity production. An energy policy can be put in place by governments to tackle issues of energy development in sustainable aspects of production, distribution and consumption (Solangi et al., 2011). This plan comes in the form of regulations, government incentives and international treaties. Other studies globally have appraised renewable strategies (Sovacool, 2009; Winkler, 2005).

This has led to current energy policies from the development of previous works. However, these policies require a comprehensive framework to guide their execution fully. The renewable energy strategies for sustainable development in Africa have reviewed solar energy as a good prospect (ENERGY, 2003). Table 2.1 shows how policy on solar PV have started gaining strategies for effective deployment in Ghana (IRENA, 2015).

In previous studies policy on solar PV have been discussed as an effective way to enhance electricity reliability (Alnatheer, 2005; Ocaña and Hariton, 2002; Sioshansi, 2011). These reviews includes the use of various forms of renewable energy technology as alternate power source. On the contrary, Sovacool (2009) explains that the importance of an all-inclusive policy promotes efficiency and electricity reliability. However, these strategies do not highlight the prospects of enhancing reliability domestically. In this research, adoption of solar PV is assessed as an essential component to enhance reliability.

Table 2.1: Renewable energy priority projects in Ghana (IRENA, 2015)

Potential renewable energy projects	Expected installed capacity (MW)	Investment requirement (US$)	Accelerated timeline	Status
On-grid solar PV plants	50	100 – 150	2012 – 2014	2 MW constructed; construction of a 20 MW plant on-going
Medium-small hydro	150 – 300	200 – 650	2018 – 2020	230 MW feasibility study ongoing
Grid-tied rooftop Solar (net metered)	50	100 – 150	2012 – 2014	19 existing installations with total capacity of approximately 1 MW
Wind parks	150 – 300	200 – 600	2018 – 2020	Wind resource assessment underway at 16 sites sponsored by VRA and the Energy commission.

2.11 Diffusion of innovations

Diffusion of Innovation (DOI) is a theory that seeks to explain how, why and at what rate new ideas and technology spread through cultures (Di Benedetto, 2010). A number of studies have been conducted using ABMs to assess the concept of DOIs.

For instance, Garcia (2005) assessed the trends of innovation between heterogeneous interactive agents with the purpose of a new product development. In an agricultural discipline, Berger (2001) employed DOI using a multi-agent on heterogeneous farm-household models to capture their social and spatial interactions clearly.

Another study with a different concept employed ABM to assess a random and scale-free social network to predict faster adoption (Kuandykov and Sokolov, 2010). In terms of Policy, Lopolito et al. (2013) used an ABM to determine the effects of dynamic characteristics (interactions and policy intervention) on a niche expansion process. The study proves the dominance of information diffusion over subsidies and confirms the significance of policy intervention.

The theory of DOI using ABM was also used to appraise the adoption and aggregated distribution of solar electric systems in a domestic setting (van Blommestein and Daim, 2015). Results from the model is proposed to benefit stakeholders in the electric energy sector.

The uptake of solar PV in Ghana from the year 1991 to 2003 is shown in Figure 2.10 (Obeng and Evers 2009). However, there is lack of data from 2003 to current date (2017). Also, there is limited research on the phenomenon of DOI on the adoption of solar energy in Ghana. The gap in research supports the use of ABM to test how domestic consumers can adopt PV to contribute to an enhanced electricity reliability.

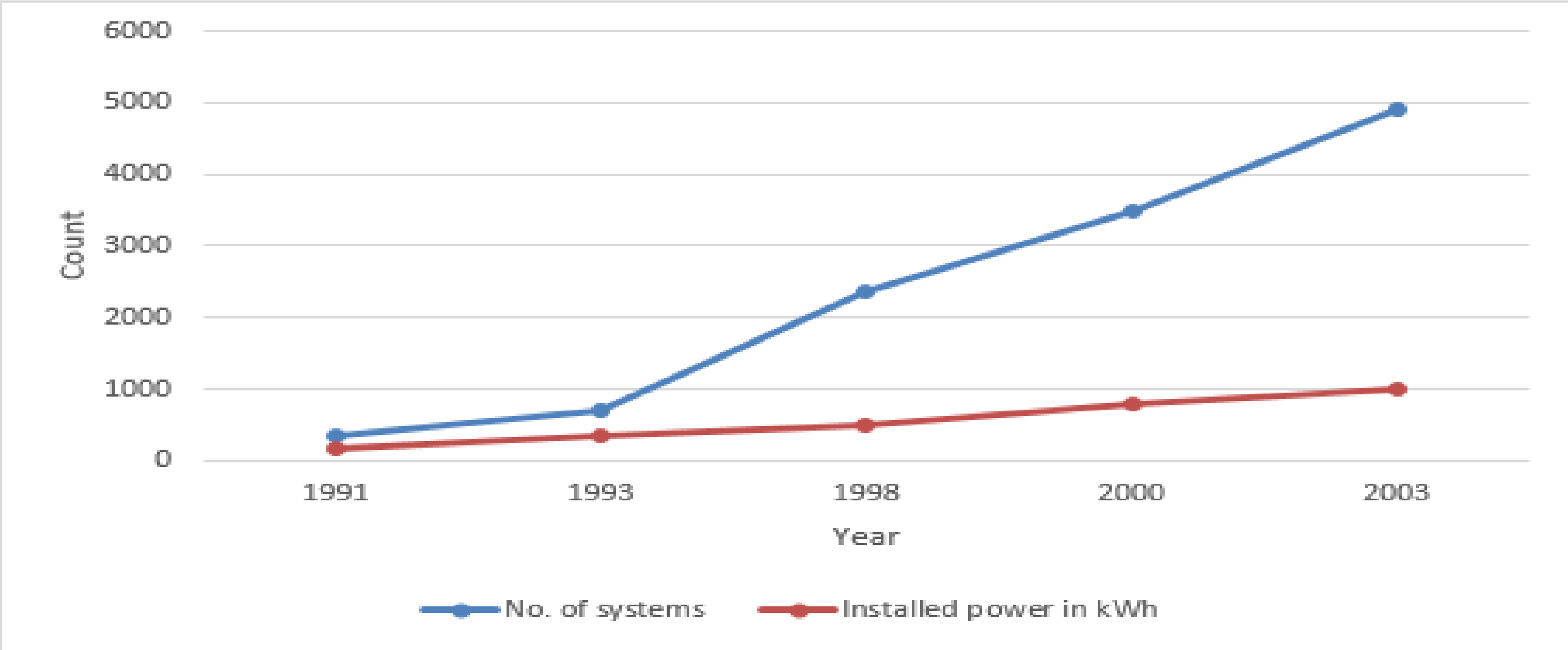

Figure 2.9: Uptake of solar PV installations in Ghana from 1991 to 2003, records are not taken at regular intervals (Obeng and Evers 2009)

2.12 Chapter summary

The intermittent supply of electricity is considered as key factor affecting human life especially in developing and under-developed countries. Domestic consumers have been identified to be play a significant role in contributing to an electricity reliability in section 2.3.

Other studies that used renewable energy for domestic households in section 2.5 did not consider the prospects of enhancing electricity reliability. The gap in research highlights the significance of this study.

The use of techno-economic analysis and agent-based modelling in sections 2.7.5 and 2.7.6 will be used to model data collected for the research to analyze patterns in PV adoption. This would be used to understand how different parameters of diffusion of innovations (by way of PV adoption) contribute to enhance electricity reliability.

The next chapter provides the methods on how techno-economic analysis and agent-based modelling was used to evaluate how domestic consumers can enhance electricity reliability to alleviate power outages.

CHAPTER 3

3 Research methodology

This chapter describes the methods that were used to achieve the outcomes in chapters 4 and 5. The methods used in this chapter were applied in order to answer the five research questions in section 1.3. In section 3.3, the process model that was followed to answer the research questions is explained.

The data collection methods and type of secondary data collated are also described in section 3.4. Next in section 3.5, the method of analysis employed is explained to show how collated data is formatted for the purpose of this study. In section 3.6, an overview, design concepts and details (ODD) protocol as defined by Grimm et al. (2010) is used to describe the procedure in the model.

The chapter concludes by deliberating on the ethics considered in the research.

3.1 Introduction

The initial objective of the research was to assess the electricity outages in Ghana. This was to estimate the frequency of outages and investigate the potential for households to alleviate the problem with solar generation. As a result, adoption of individual household solar photovoltaic systems (to become prosumers[3]) was explored as a route to enhance reliability of the national utility grid in Ghana. Although there is substantial research on the prospects of prosumers as reviewed in literature (in section 2.5), there is limited focus on their role in enhancing electricity reliability.

The novelty of this work was to investigate how techno-economic and social factors interactively impact on the adoption of photovoltaic systems within a given community. Two methods were used: techno-economic analysis and agent-based modelling (ABM) using constructs from the adoption model in the complex adaptive systems, cognitive agents and distributed energy (CASCADE) project to form a representation of an electricity network of household consumers and the energy supplier (Rylatt et al., 2013).

In Section 3.2, a detailed review of the components under the CASCADE model is explained. The extracts adopted from CASCADE is described underlining the originality in the context to this research. For the purpose of clarity, CASCADE was a complexity-based study developed by researchers in De Montfort and Cranfield Universities. The contributions made by each researcher in portions used in this thesis is acknowledged in the coding section in the appendices.

3.2 The CASCADE structure

The CASCADE model was designed to explore the smart grid concept using agent-based modelling[4]. The configuration of the model encompasses of the soft-linkage of

[3] Prosumers are defined as consumers and producers of electricity who can sell back to the energy supplier.

[4] The CASCADE project was a complexity science-based research into the smart grid concept which was funded by the EPSRC (reference: EP/G059969/1). The link to the CASCADE project is http://rsnape.github.io/CASCADE/docs/html/index.html

the engineering, supply and demand and the electricity market module as shown in Figure 3.1 (Rylatt et al., 2013). The engineering module considers the physical network of the electricity grid. The features of aggregators which are informed by weather predictions under the supply and demand substructure are categorized into retail and wholesale trading. Prosumer agents, also located under retail trading in the supply and demand module transmit energy production and consumption data to the aggregators. In return, aggregators correspond with signals via smart devices. Another function of aggregators is dealing with different agents (i.e. independent power producers, utilities and power purchasers) under wholesale trading. In the market module, two main sectors considered are the power exchange and balancing mechanism through which energy is traded.

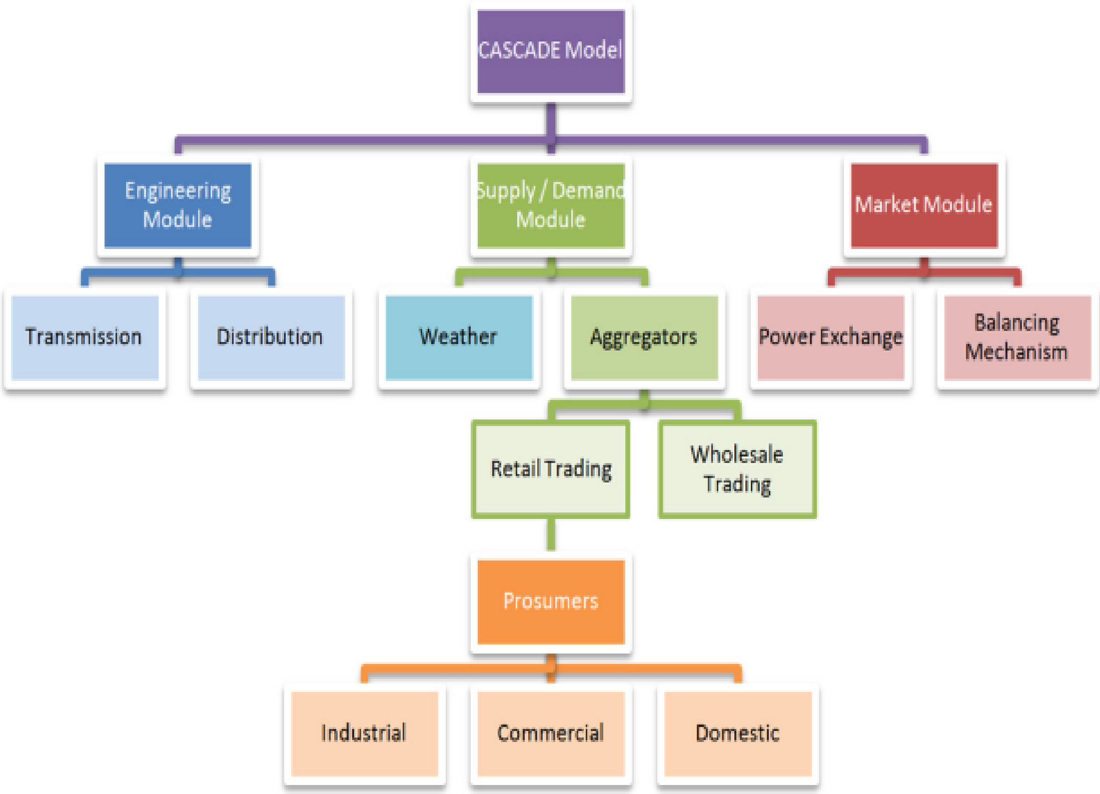

Figure 3.1: Structure of components in the CASCADE model. Source: Rylatt et al. (2013)

As shown in Figure 3.2, aggregators and prosumers located in the supply and demand module are soft-linked to the engineering substructure (Rylatt et al., 2015). The data flow indicating the interactions in the framework are represented by arrows.

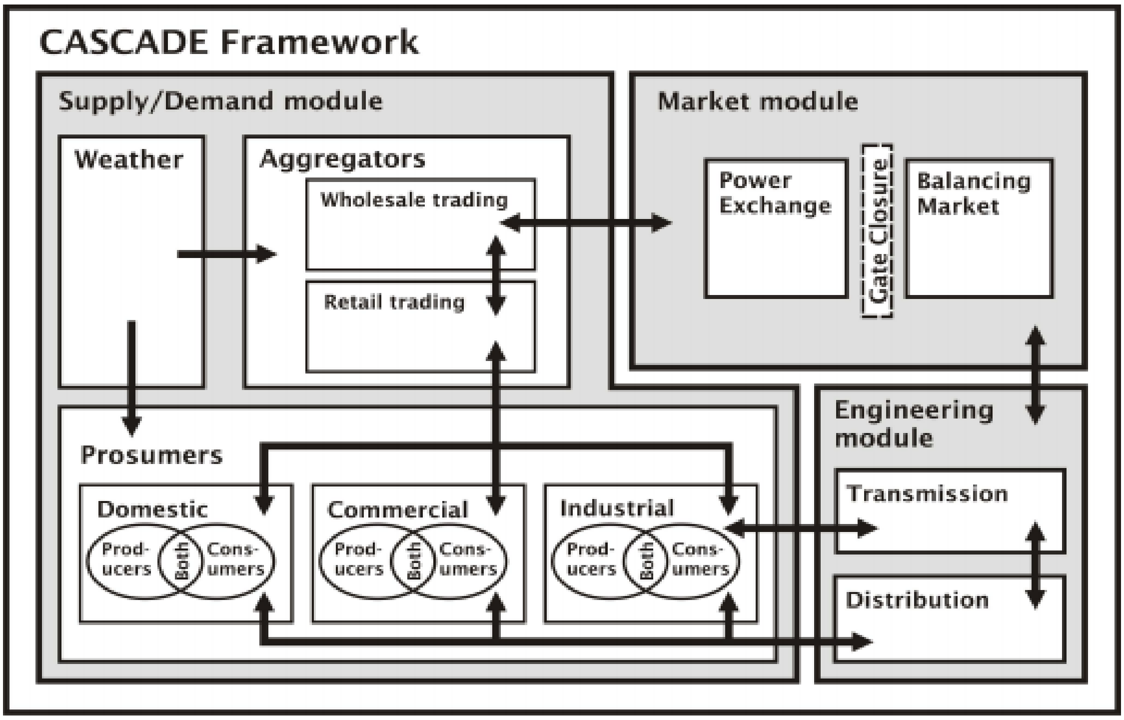

Figure 3.2: A detailed overview of the interactions between modules in CASCADE and agents. Source: (Rylatt et al., 2015).

In the context of this thesis, the focus is on the supply and demand module illustrated in Figure 3.3 by modifying the actions of household agents to answer our research questions about the potential to enhance electricity reliability. The behaviour of household agents in this research are influenced by electricity outage hours defined in the ODD protocol in Section 3.6.

The internal data flows in the supply and demand module in Figure 3.3 are soft-linked with the two other modules (Rylatt et al., 2013). The connection with the engineering module is initiated by the balance of accumulated supply and demand, which is defined as a direct measure of frequency and voltage at any given time in the network (Järventausta et al., 2010; Rylatt et al., 2013).

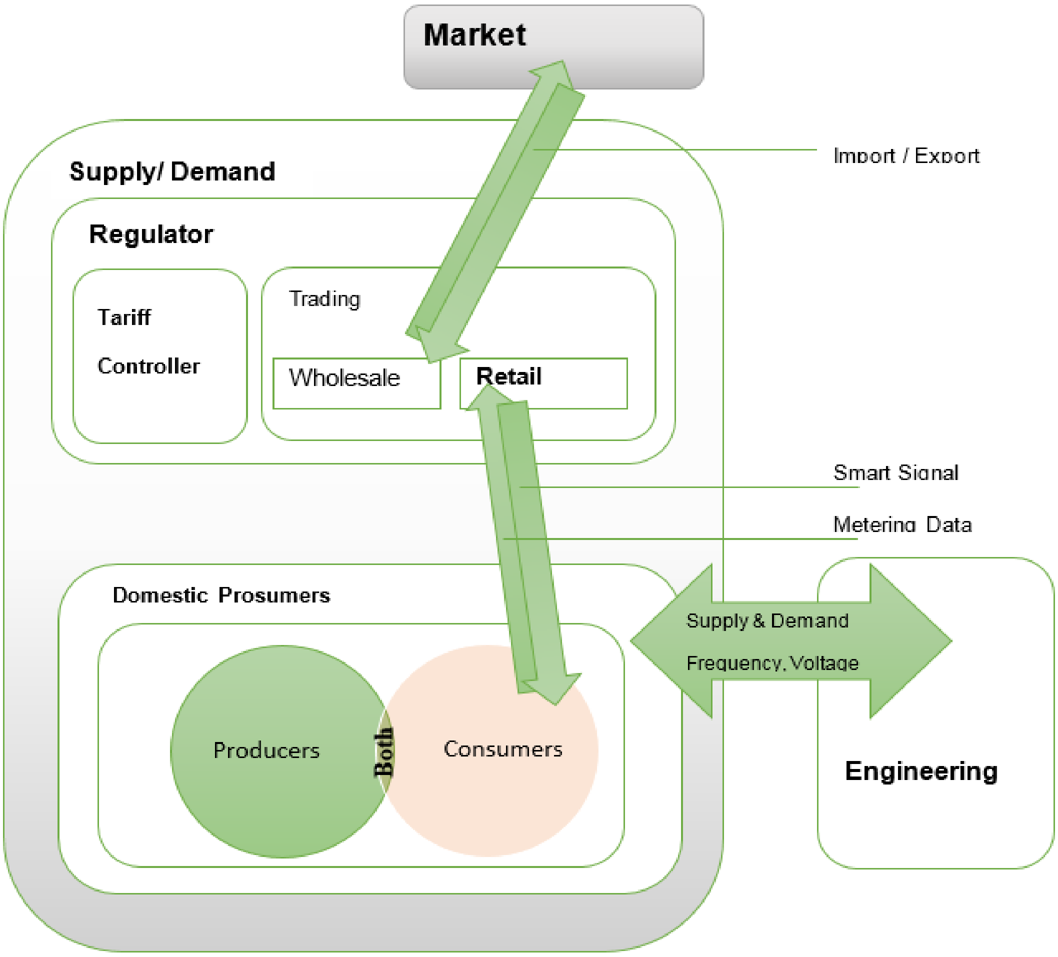

Figure 3.3: Supply and demand module in CASCADE, adapted from Rylatt et al. (2013).

Snape et al. (2011) demonstrates that the dynamic pattern of energy consumption is heavily influenced by the behaviours of consumers. To date, behaviour theory on the issue of electricity reliability has not been widely explored. This supported the method of using ABM to address the aim of this study. The open source template of the

CASCADE project was as a suitable alternative to building a new model because it was a fit to investigate the potential of prosumers in enhancing electricity reliability.

3.3 Process model

The process model used in this study (in Figure 3.4) shows the procedure of gathering and processing data into a suitable format for the agent-based model in order to produce an output that answer the research questions. The required data flow for the model parameters include input (electricity outage hours), internal (PV – cost, PV – capital, observed radius, population, feed-in tariff and insolation) and output (number of PV installed). The detailed sequence of interactions is defined in the ODD protocol in Section 3.6.

In Figure 3.4, the defined research questions informed the collection of required empirical data[5]. The data collected were refined to remove any redundancies[6] and then formatted by encoding in a file. The technique of techno-economic analysis (TEA) described in Section 3.5 is then used to make the refined data applicable to the parameterizations in the adoption model.

The next step is the running of the model which produces an output (adoption of PV by household agents) based on the input and internal parameters mentioned earlier. In this research, scenario analysis are used to test possible outputs and its significance to changes in parameters in the model. The use of scenario analysis is important because there is limited data on PV adoption in Ghana to validate the model results. The model

[5] The methods employed in the data collection are described in Section 3.4.
[6] Data redundancy is a condition where the same piece of data are repeated in separate places in a database Schultz, S.M. et al. 1992. *Data redundancy and recovery protection*. Google Patents. .

results are then used to answer the research question on the potential of household consumers to enhance electricity reliability.

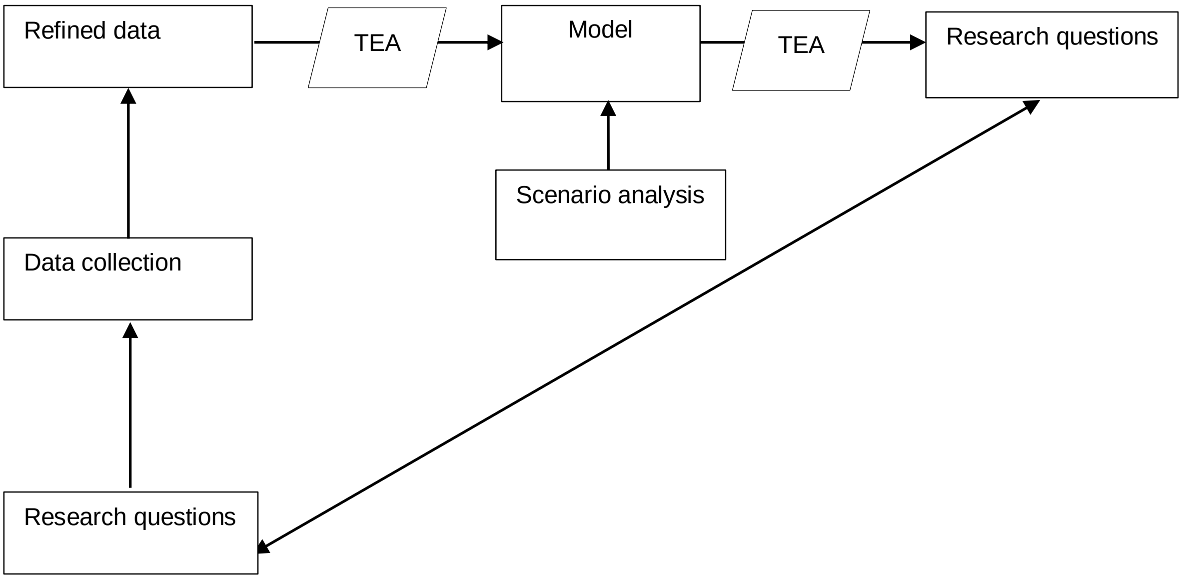

Figure 3.4: Research model showing different procedures

3.4 Research data

The method for collecting data in this study involved an information-gathering process in selected institutions in Ghana. A field trip in Ghana was conducted on electricity supply to domestic consumers for a period of six weeks (September – October 2016). This was necessary because most of the required secondary data were not readily available online.

The importance of the data collected gives a geographic outlook of the electricity supply, the potential of insolation for PV adoption, incentives for adoption (Feed-in tariffs) in

Ghana. The details of data collected described in Table 3.1 are tailored to define the agent-based model (restricted population) instead of general electricity outlook for Ghana.

3.4.1 Electricity data

Different data on electricity use were obtained from the Electricity Company of Ghana (ECG). With regards to consumption data, a 1-hour temporal resolution is categorized into four different groups of consumption (0 – 50 kWh, 51 – 300 kWh, 301 – 600 kW and over 600 kW).

The temporal resolution on electricity outage frequency is measured half-hourly (30 minutes) in a daily range of 0 – 24 hours. The temporal coverage of electricity consumption and outage frequency is from 2010 to 2015 and spatial coverage in 3 major regions (Greater Accra, Ashanti and Western) in Ghana.

The temporal resolution for the cost of electricity is 1 year from 2010 to 2015 which is priced between 0.08 – 0.24 US$/kWh (per the four consumption groups) in all 10 regions in Ghana.

3.4.2 Insolation data

The insolation data is sourced from a study executed by the solar wind and energy resource assessment (SWERA) under the backing of the United Nations Environment Programme (UNEP). The data has a 1-hour temporal resolution and a time coverage from 2004 to 2014. The spatial coverage is in all 10 regions where weather data in taken from the SWERA project.

3.4.3 PV data

In terms of small-scale solar systems, there were no records on the up-take of PV in Ghana. The available data on PV was only the cost in US$/ kWh. The PV data has a temporal resolution of 1 year and a temporal coverage from 2010 to 2014. The installation costs for household solar systems in Ghana ranges from US$ 550 – US$ 20,000 (Smartec, 2017).

3.4.4 Feed-in-Tariff

Data on Feed-in-tariffs (FiT) gathered from the PURC has a temporal resolution of 1 year and is priced between 0.15 – 0.16 US$/kWh (between solar PV without storage and with storage) for the whole of Ghana. The temporal coverage of FIT is from 2014 to 2015 across the 10 regions in Ghana. An FiT contract for household producers of electricity with PV is fixed for 15 years.

3.4.5 Household expenditure data

Data on household expenditure from the Ghana statistical service is used to estimate purchasing power as opposed to income data because in Ghana, there is no regular income data on majority of the people employed in the informal sector (Ghana Statistical Service, 2014). The temporal resolution for the average household expenditure was 6 years which is categorized into three income classes (low, middle and upper). The temporal coverage is from 2002 to 2014 and spatial coverage across all 10 regions in Ghana.

3.4.6 Population data

Population data is taken from the 2010 census organized by the Ghana Statistical Service (Ghana Statistical Service, 2012). The sampling unit is the number of households in a selected area for model analysis. An average household consists of 3.9 persons. A sample of 1,000, 5,000 and 40,000 households was found to representative of the population of households in Town A, B and C respectively[7] (districts in Greater Accra region). The sample sizes were chosen to reflect three main categories of population of households in districts in Ghana.

The temporal resolution for households is 10 years. The temporal coverage for data gathered is for only for the year 2010 representing all 10 regions in Ghana.

[7] The name of the sampled district in Greater Accra is made anonymous by the name “Town A, B and C” due to confidentiality agreement with the electricity company of Ghana (ECG).

Table 3.1: Summary of data collected during fieldwork in Ghana

Type of data	Units	Temporal resolution	Temporal coverage	Spatial coverage	Source of data	Remarks
Electricity outage frequency	Number	30 minutes	2010 – 2015	3 regions in Ghana (Greater Accra, Ashanti and Western regions)	Electricity company of Ghana (ECG)	The number of times electricity supply is interrupted is calculated within a 0 – 20 outages interval for every 24 hours. A typical outage lasts for 2 hours.
Electricity consumption	kWh	1 hour	2010 – 2015			Data from the Electricity Company of Ghana is categorized into 5 groups of consumption levels.
Electricity cost	US$/kWh	1 year	2010 – 2015	All 10 regions in Ghana		The cost of electricity is reviewed annually for the various consumption groups.
Insolation	kWh/m^2	1 hour	2004 – 2014		United nations environment program (UNEP)	Ground measurements data are taken from a study by

						Solar and wind energy resource assessment.
Total PV installation cost	US$/kWh	1 year	2010 – 2014		Smartec energy	The cost of buying a PV system and cost of installing it in Ghana.
Feed-in tariff	US$/kWh	1 year	2014 – 2015		Public utilities regulatory commission (PURC)	The tariff range is between solar PV without storage and with storage. The FiT is fixed for 15 years when PV is adopted.
Household expenditure	US $	6 years	2002 – 2014		Ghana statistical service (GSS)	A percentage of household expenditure on gas and electricity is used as available capital for PV investment.
Household population	Household	10 years	2010			A 10 % sample was taken from the 2010 census data for a target community in Ghana.

3.5 Techno-economic analysis

The technique for analyzing input data for the model is describe in this section.

3.5.1 Technical potential

The estimated generation from a PV system depends on the roof area and the ability to pay for the cost. Mathematically, annual electricity generation from PV system is calculated as (Kalogirou, 2013):

$$\boldsymbol{E} = \boldsymbol{K} \times \boldsymbol{I} \times \boldsymbol{PR} \qquad (3.1)$$

Where *E* is the annual electricity generation in KWh, K represents the capacity of PV installed, I is the mean annual insolation in kWh/ m^2 and *PR* is the performance ratio (default value = 0.75).

The amount of electricity that a PV system can generate depends on a number of factors which includes the following:

- Installation capacity of the system
- Roof area, orientation and tilt of the installation.
- The number of sunshine hours per day
- Direct sunlight on a typical day

The above factors are assumed to be technical potential. As a result, they do not consider the flexibility of the national grid to the integration of energy generated through PV.

3.5.2 Economic potential

The feed-in tariff (FiT) structure defined by the Public Utilities Regulatory Commission (PURC) is formatted in reference to the electricity tariffs setup by the Electricity Company of Ghana (ECG). The analysis of FiT was done to answer the research the third question below.

Given available government incentives such as Feed-in-tariff, can the adoption of photovoltaic systems by households be a cost-effective measure to electricity outages in Ghana?

Solar PV systems in Table 3.2 are classified into grid stability (storage battery) and without grid stability (PURC, 2014). This is mapped against the four consumption or tariff bands (mentioned earlier in section 3.4.1) set by the ECG. In this context, the return on investment on any PV system is influenced by the tariff band and the FiT.

Table 3.2: Tariff categories for residential consumers (ECG, 2016). It includes the Feed-in tariff for Solar PV generation in Ghana (PURC, 2016).

Consumption category	Tariff band (kWh)	Approved Charge (US cents/ kWh)	Solar PV with storage (US cents/ kWh)	Solar PV without storage (US cents/ kWh)
A	0 – 50	8.67	22.41	16.30
B	51 – 300	17.40	22.41	16.30
C	301 – 600	22.58	22.41	16.30
D	600 +	25.09	22.41	16.30

Based on incentives for the feed-in tariff above, economic indicators must be considered to financially assess the implications of procuring a solar PV system.

In Table 3.3, the cost of electricity are referred to by the approved tariffs by the PURC. The inflation and interest rates are based on figures from the Bank of Ghana and Trading Economics websites.

The given economic indicators are used to estimate the cost of a solar PV system based the technical potential described in section 3.5.1.

Table 3.3: Financial assessment of solar energy based on sourced data and assumptions from [a] Trading Economics (2017), [b] Bank of Ghana (2017), [c] Smartec (2017), [d] GCP (2015), [e] ECG (2015)

Factor	**Solar variable**
Electricity cost	Approved tariff in Table 3.2
Interest rate	20.9%[a,b]
Inflation	15.8%[a,b]
FiT lifespan	20 years
FiT rates	Approved FiT in Table 3.2
Capital investments cost in US$/kW	Average of 2,014.52 (range: 1,429.3 – 2,599.7) [c,d]
Operation and maintenance expenditure	Between 0.2% and 1% [d,e]

3.5.2.1 Net present value and return on interest

The computation of the net present value (NPV) and return on interest (ROI) provides a basis to compare the installation capacities of solar PV. Mathematically NPV is expressed by,

$$\boldsymbol{NPV = PRV - C} \qquad (3.2)$$

Where *C* is capital expenditure and the present value, *NPV* is calculated by:

$$\boldsymbol{PRV = \sum_{t=1}^{N} r_t \frac{(1+f)^{t-1}}{(1+L)^t}} \qquad (3.3)$$

Where, *f* is the inflation rate, *t* is time, r_t is annual income, *L* is interest on loan and *N* is the lifespan of FiT.

The annual income is expressed as,

$$\boldsymbol{r_t = [G + P(x) + E(1-x)] \times Y - (KM)} \qquad (3.4)$$

Here, *G* represents the unit FiT generation rate, *P* is the export rate for FiT, E is the unit cost of electricity, Y is the amount of electricity generated in first year, K represents the installed capacity and M is the annual operating expenditure.

The return on interest, ROI is computed by:

$$\boldsymbol{ROI = \frac{NPV}{C}} \qquad (3.5)$$

3.5.3 Demographics

The details of the target population for this research is summarized in Table 3.4. Households are categorized into low, middle and high income based on a study conducted by the Ghana statistical service (GSS). An assumption is made in this thesis on the consumption category by the ECG to align with the household category by the GSS.

Table 3.4: Electricity profile per households. Based on sourced data and assumptions from, [a] Ghana statistical service (2014), [b] Electricity Company of Ghana (2016), [c] assumptions

Household category [a]	Population percentage [b]	Consumption category aligned [c]
Low	27.6	A
Middle	67.8	B and C
High	4.6	D

3.5.4 Electricity outages

The electricity outage data collected was to evaluate the research question below.

How might a study evaluate the electricity outage statistics in Ghana over a five year period?

A simple descriptive statistics on the quantitative electricity data was used to provide a measure outages. The accumulated number of times electricity supply is interrupted is then formatted between an interval of 0 – 20 for a three-month period. In the model, this is given randomly in equation. 3.1 as,

$$\boldsymbol{threeMonthOutage} = \boldsymbol{RandomHelper}.\boldsymbol{nextIntFormTo}(\mathbf{0}, \mathbf{20}) \qquad (3.1)$$

The urgency that prompts households in the model for adoption is given in the ODD protocol (in section 3.6).

3.5.5 Insolation

In order to assess the potential for solar energy in Ghana, data collected was considered into sunshine hours, irradiance and insolation. The solar data was used to determine an explanation for the second research question below.

What is the solar energy potential for the adoption of photovoltaic systems in Ghana?

Hourly time series for selected sites in Ghana were obtained from the SWERA study. The weather data is used to build a shapefile for the agent-based model as a measure of insolation. Based on the geographic coordinates of selected locations for model analysis, the solar data is formatted into a Typical Meteorological Year 2 (TMY2).

3.6 ODD protocol

In this section, the Overview, Design concepts and Details (ODD) protocol details defined by Grimm et al. (2010) in Table 3.5 was followed to describe the procedure used in the agent based model (ABM). Having already justified the suitability of the technique of modelling an ABM in Chapter 2, the ODD protocol is used here to describe the extracts taken from the CASCADE model to this study.

Table 3.5: The seven components of the ODD protocol defined by Grimm et al. (2010).

Overview	Purpose
	State variables and scales
	Process overview and scheduling
Design concepts	Design concepts
Details	Initialization
	Input
	Sub models

3.6.1 Overview of the model

The purpose, characteristics of entities and the processes in the model is structured with the protocols as described by Grimm et al. (2010). This section underscores the purpose of the model, the intended action of agents and the processes involved.

3.6.1.1 Purpose

The model is planned to evaluate how techno-economic and social factors interactively impact on adoption of photovoltaic (PV) systems within a given community in Ghana based on electricity outages. In detail, the model centers on the actions of households with the aim of augmenting electricity supply with solar energy. The key characteristics of the ABM are to depict the following:

Interaction – agents in the model cooperate within a social, economic and technical environment with supply of electricity.

Decision making – agents in the model follow an order of actions within a specified period.

Heterogeneity – different characteristics affect agents in decision making to adopt photovoltaic systems.

Learning – there exist social learning tendencies within model environment. For instance, agents can be influenced by their neighbours within a certain radius.

The main purpose of the model is to serve as guide to various scenarios in the adoption of photovoltaic energy to enhance electricity reliability. It does not present abilities of predictive power or an assessment of potential electricity outages.

3.6.1.2 State variables and scales

The basic entities in the model include households, energy supplier and patches (grid cells). The factors for adoption of PV in the model are driven by a threshold of electricity outages. The parameters to provide input data for consumers in the agent-based model to adopt solar PV are listed in Table 3.3.

The scale of the model is related an economic area in Ghana that receives electricity from the energy supplier. The target population per experiment is related to the value {1,000, 5,000, and 40,000} households as shown in Table 3.6.

Table 3.6: Variable in the agent-based model showing the parameters relating to agents

Parameters	**Variable name**	**Brief description**	**Value set**
Household	*Household*	Domestics consumers of electricity in the model environment	{Household}
Energy supplier	*Energy supplier*	The utility company responsible for the supply of electricity to households.	{Energy supplier}
PV – capacity	*PV capacity*	The capacity of PV installation by consumers	0.1 - 5 kW
PV cost	*PV cost*	The cost of buying a PV system and installing it	Quote
Available capital	*PV capital*	It is assumed that household expenditure on gas and electricity is used as available capital to pay for adoption.	[0,1]
PV lifespan	*PV lifespan*	The length of time that the PV system operates	25 years
Town	*Population*	The target population per experiment	{1000, 5,000, 40,000}
Insolation	*Insolation*	The weather condition within a community	
Building size	*Roof area*	The suitability of a building to install a PV system	Set 0 if unsuitable
Observed radius	*Observed radius*	The range (metres) within which households perceive their neighbours	{0,2.5,…..,15}
Physical characteristics	*Potential PV capacity*	The potential system capacity a household adopts	0.1 - 5 kW or 0 kW if unsuitable

3.6.1.3 Process overview and scheduling

The model considers one main process, adoption of PV to enhance electricity reliability. The urgency of the adoption decision as shown in Figure 3.5 is evaluated immediately or when the electricity outage threshold is reached.

The adoption process considers a techno-economic assessment to evaluate a suitable type of PV system that can be adopted to augment electricity reliability. Technical and economic factors that are considered as facilitators or obstacles to the adoption of PV include the following:

- PV capital
- Building size (roof area to install a suitable PV system)
- Weather (i.e. insolation is viable for PV output or generation)

The factors above are implemented in the model as Boolean variables as opposed to the scale of influence in the previous factors. As a result, adoption of PV cannot take place when a condition is not met.

In contrast to the Social Cognitive Theory (SCT) model employed in Snape (2015), this study focuses on techno-economic factors that affect individual households in any attempt for adoption.

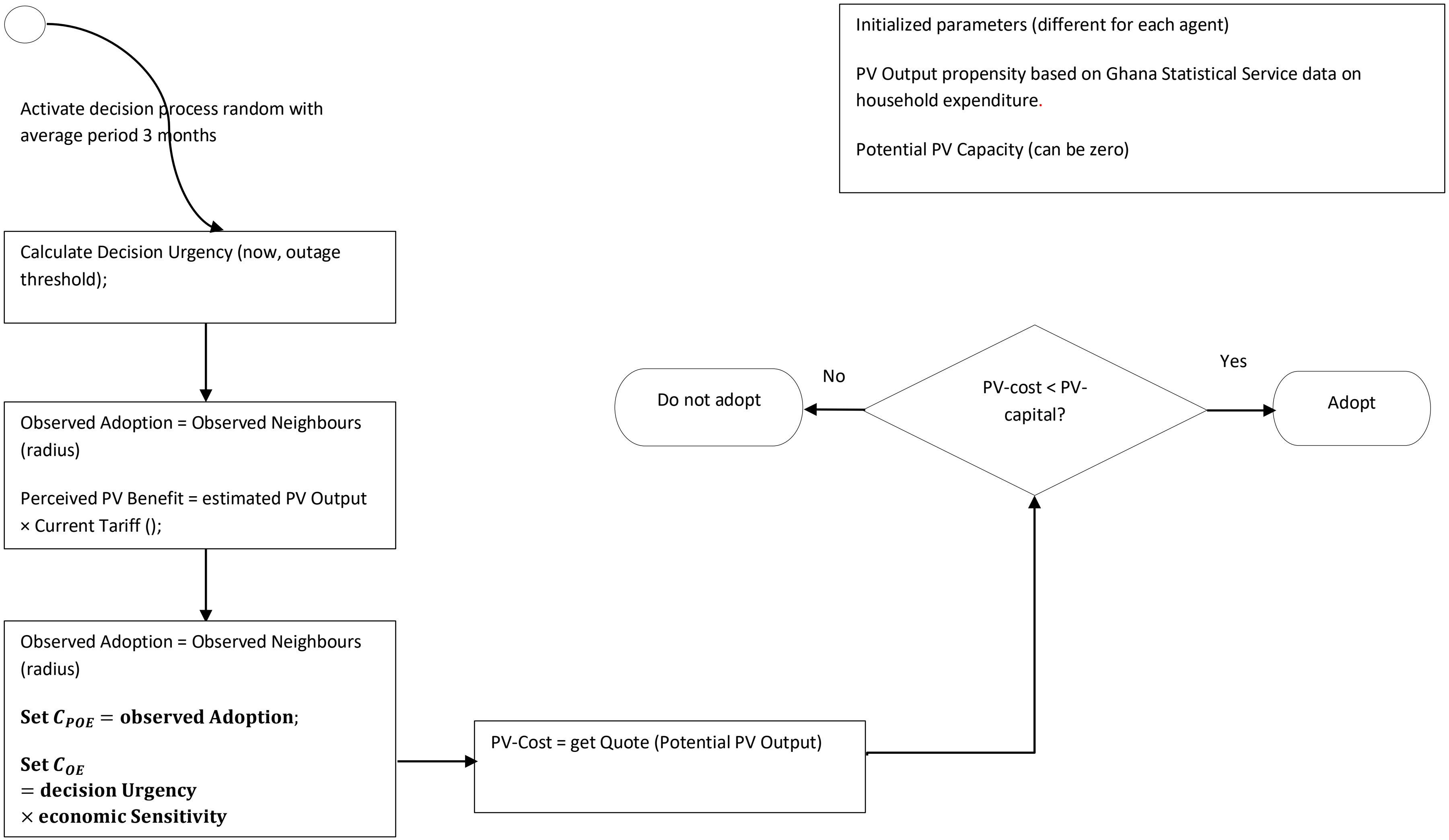

Figure 3.5: High level decision making algorithm flow, adapted from Snape (2015)

3.7 Chapter Summary

The technique of study consists of statistical analysis of electricity outage data, Feed-in tariff with the use of a computer model. Using simple descriptive statistics electricity outage data is evaluated.

The use of an ABM (in Section 3.6) is to evaluate the adoption of PV by domestic consumers in Ghana through simulation. The model uses technical and economic incentives for decision making.

The results and analysis for electricity supply in Ghana are described in Chapter 4, followed by a detailed presentation of the model results in Chapter 5

CHAPTER 4

4 Results and analysis

In this chapter, results from the quantitative data on electricity outages that concern household consumers in Ghana are presented. An estimate of electricity consumption in relation to outages are also described. The method for the techno-economic analysis and agent-based based modelling have both been detailed in chapter 3.The quantitative data that was required for the model consisted of electricity outage hours, demographic data, solar resource (mainly insolation) in Ghana and Feed-in-Tariff for photovoltaics (PV).

An agent-based model (ABM) was used to simulate the factors that influence the adoption of PV in Ghana. This was carried out through a period of five weeks from 29th June 2018 to 3rd August 2018. The methodology of the processes involved in the ABM are defined in section 3.5 with the use of an ODD protocol. The details of the results from the ABM simulations are presented in the next chapter.

4.1 Electricity outages in Ghana

Figure 4.1 shows the monthly averages for the total hours of electricity outages in Accra from 2011 to 2015 (ECH, 2016). Accra is the capital city for Ghana which is divided into 10 districts in the Greater Accra region. In this study, three different districts in Accra with varying populations[8] (1, 000, 5, 000 and 40,000 households) was used in the model work.

[8] The sample is representative of the main types of household population within the districts in Accra, Ghana.

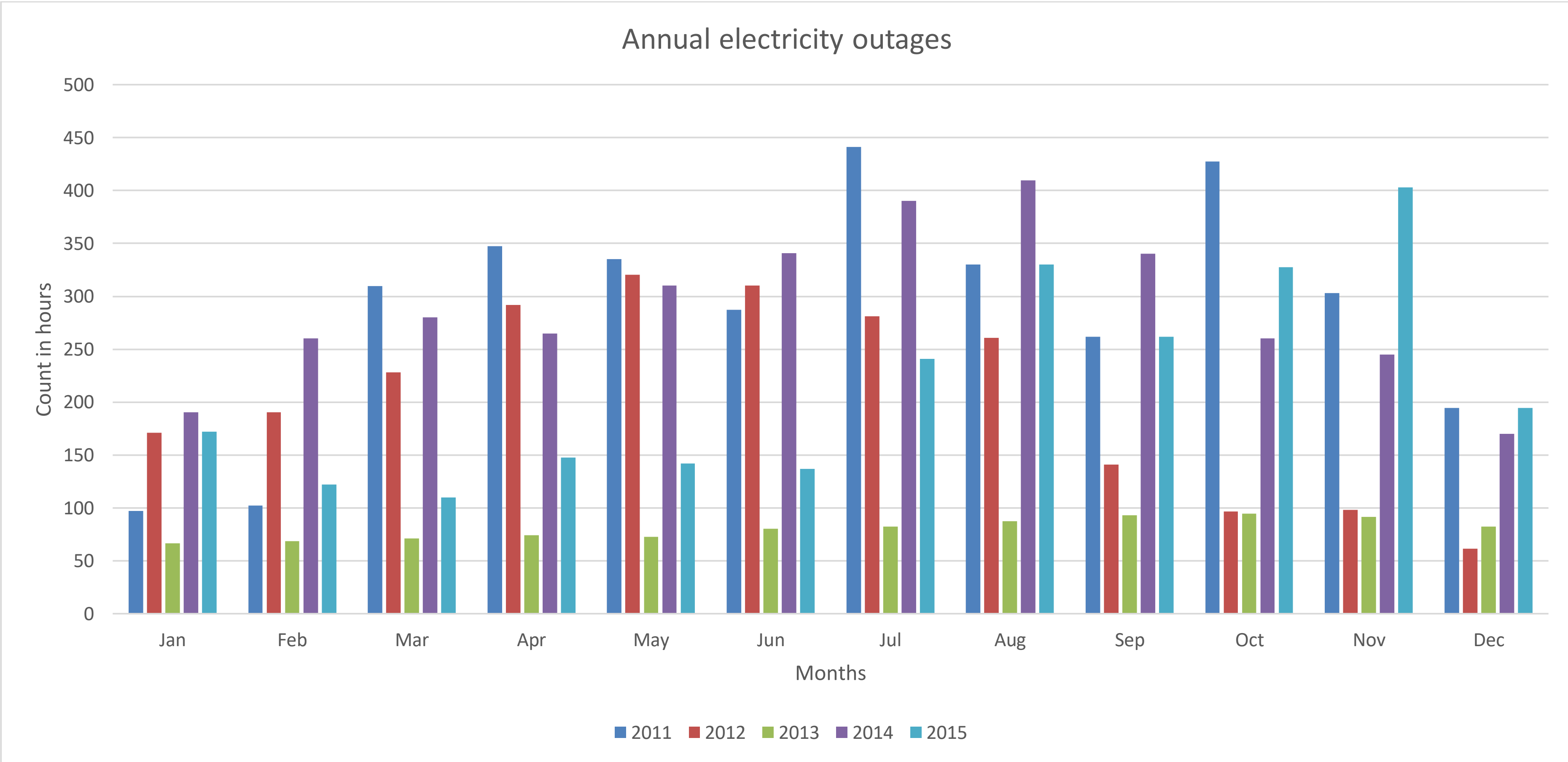

Figure 4.1: Average total electricity outage hours per month for Accra, from 2011 to 2015. Data was collected from the Electricity Company of Ghana (ECG, 2016).

Despite the factors that affect the supply of electricity in Ghana (in section 2.4.1), the unmatched demand from consumers can fluctuate based on social and economic events in the country.

For instance in 2013, the lowest count of the total outage hours was recorded within the 5 year period. The electricity outages in January and December from 2011 to 2015 was relatively low compared to other months. This can be attributed to the import of electricity and the reduced demand from industry especially during festive seasons (Ghana Energy Commission, 2015).

4.2 Domestic electricity consumption in Ghana

The monthly consumption trends for 4 different groups of consumers from 2011 to 2015 are shown in Figure 4.2. The 4 groups categorized by the ECG include consumers who use electricity in the following classes: 0 – 50 kWh, 51 – 300 kWh, 301 – 600 kWh, and more than 600 kWh. The different groups shows the varying demand requirements of household consumers.

The electricity demand for the consumption class (51 – 300 kWh) is highest and consumption class (0 – 50 kWh) was the lowest. It can be inferred from Figure 4.3 that majority of households consume between 51 – 300 kWh per month.

The electricity consumption per group does not indicate a continuous growth annually. For instance, there was a decline in consumption from 2013 to 2014 for households who consume more than 600 kWh per month. The same trend can be seen for consumers in the category of 51 – 300 kWh. However, households in 0 – 50 kWh and 301 – 600 kWh experienced an increase in consumption from 2013 to 2014.

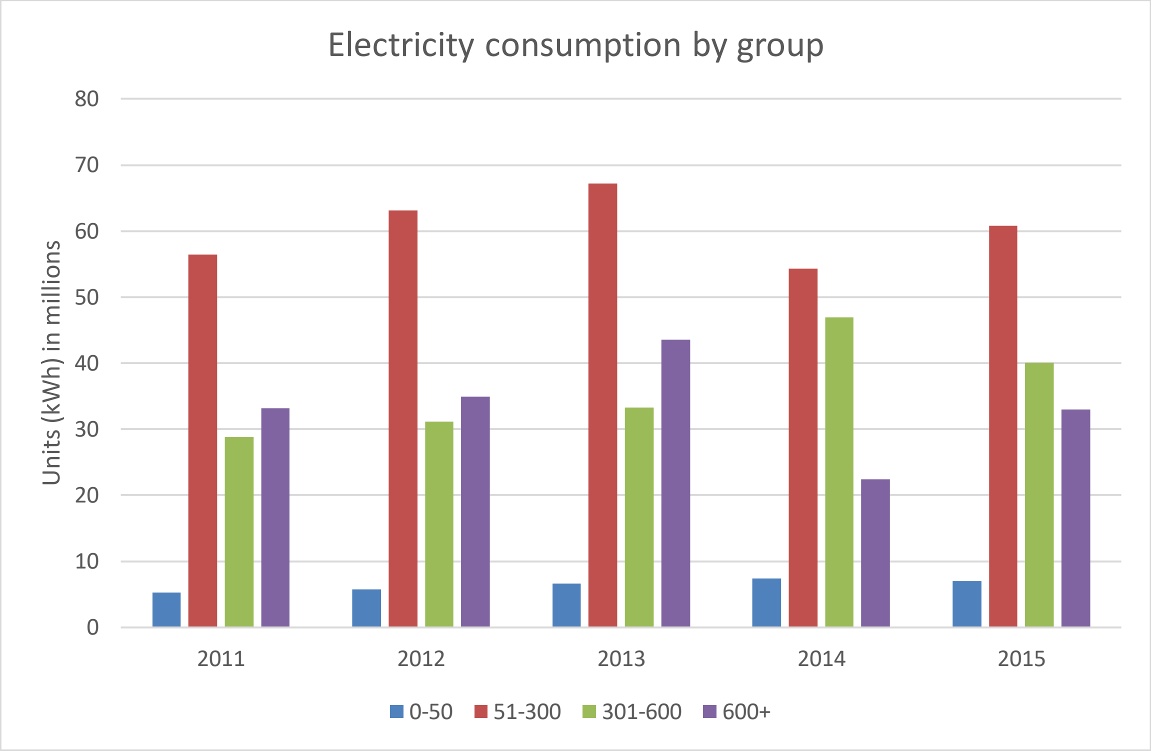

Figure 4.2: Monthly average electricity consumption in kWh, from 2011 to 2015. Data was collected from the Electricity Company of Ghana (ECG).

Factors that may affect the consumption trends can loosely be attributed to variations in electricity demand from households. The varying number of consumers in each group from 2011 to 2015 is shown in Figure 4.3. The total number of households in the consumption groups 0 – 50 kWh, 51 – 300 kWh and 301 – 600 kWh increased from 2011 to 2015. In contrast, the total number of households who consume more 600 kWh per month experienced fluctuations within the 5-year period.

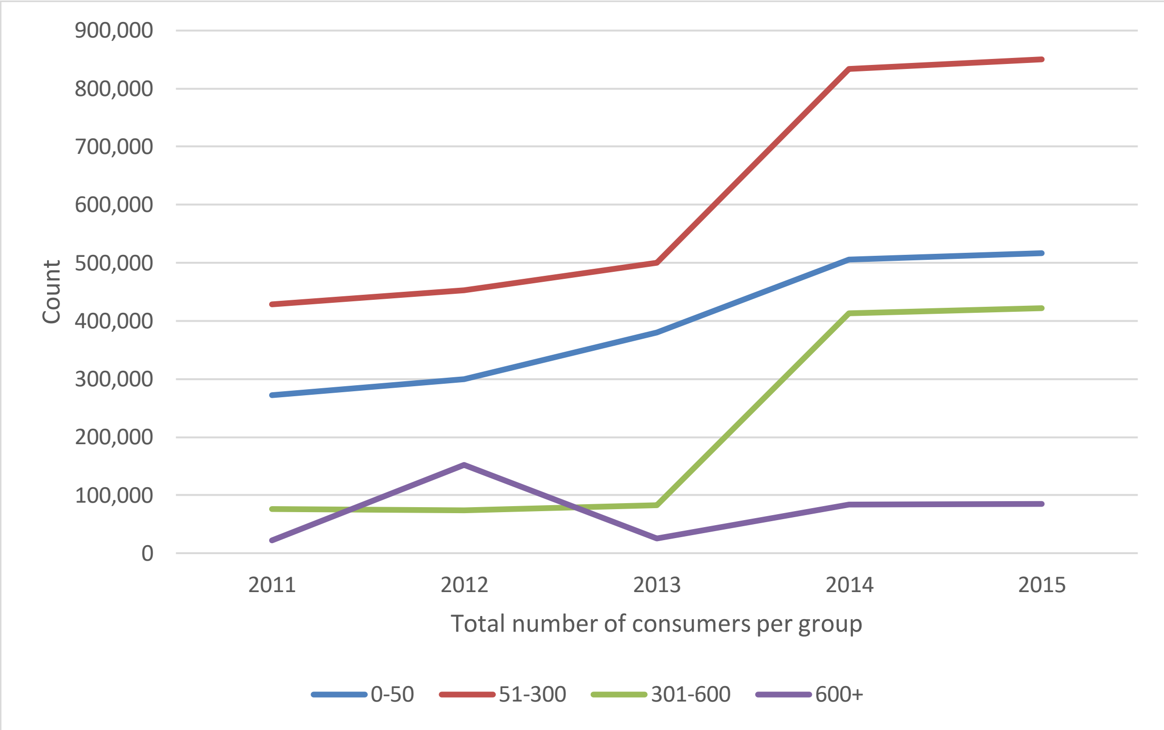

Figure 4.3: Total number of consumers within each group by the ECG from 2011 to 2015.

4.3 Electricity outages and consumption

In Figure 4.4, the relationship between the total electricity consumed and the average outage hours is shown. In general, the total electricity consumed annually is inversely proportional to the outage hours experienced. For instance, in 2011 to 2013 the number of outage hours decreased from 286.39 to 80.43. On the other hand, electricity consumption increased from over 1.2 million kWh to 1.8 million kWh.

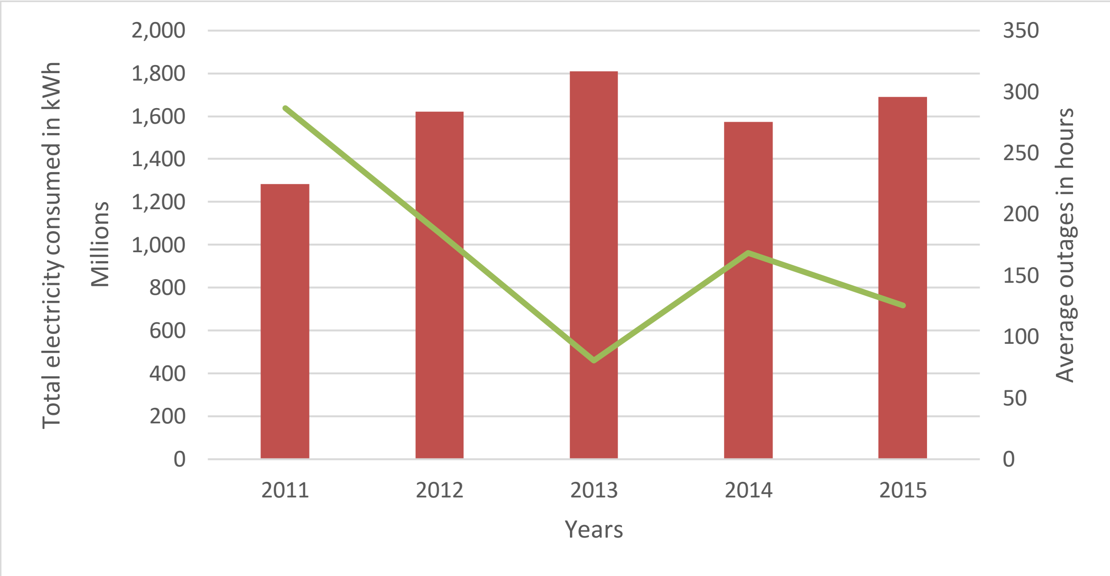

Figure 4.4: Total electricity consumed (in kWh) against the average outages hours in Ghana from 2011 to 2015.

4.4 Solar resource potential in Ghana

Figure 4.5 shows the amount of daily solar irradiation in kWh/m^2 in key potential locations in Ghana (SWERA, 2004). The project executed by SWERA assessed the solar energy potential at a high resolution.

The average duration of sunshine varies from a minimum of 5.3 hours per day in the cloudy semi-deciduous forest region to 7.7 hours per day in the dry savannah region. High diffuse radiation constitutes more than thirty (30) percent of total solar radiation in the country.

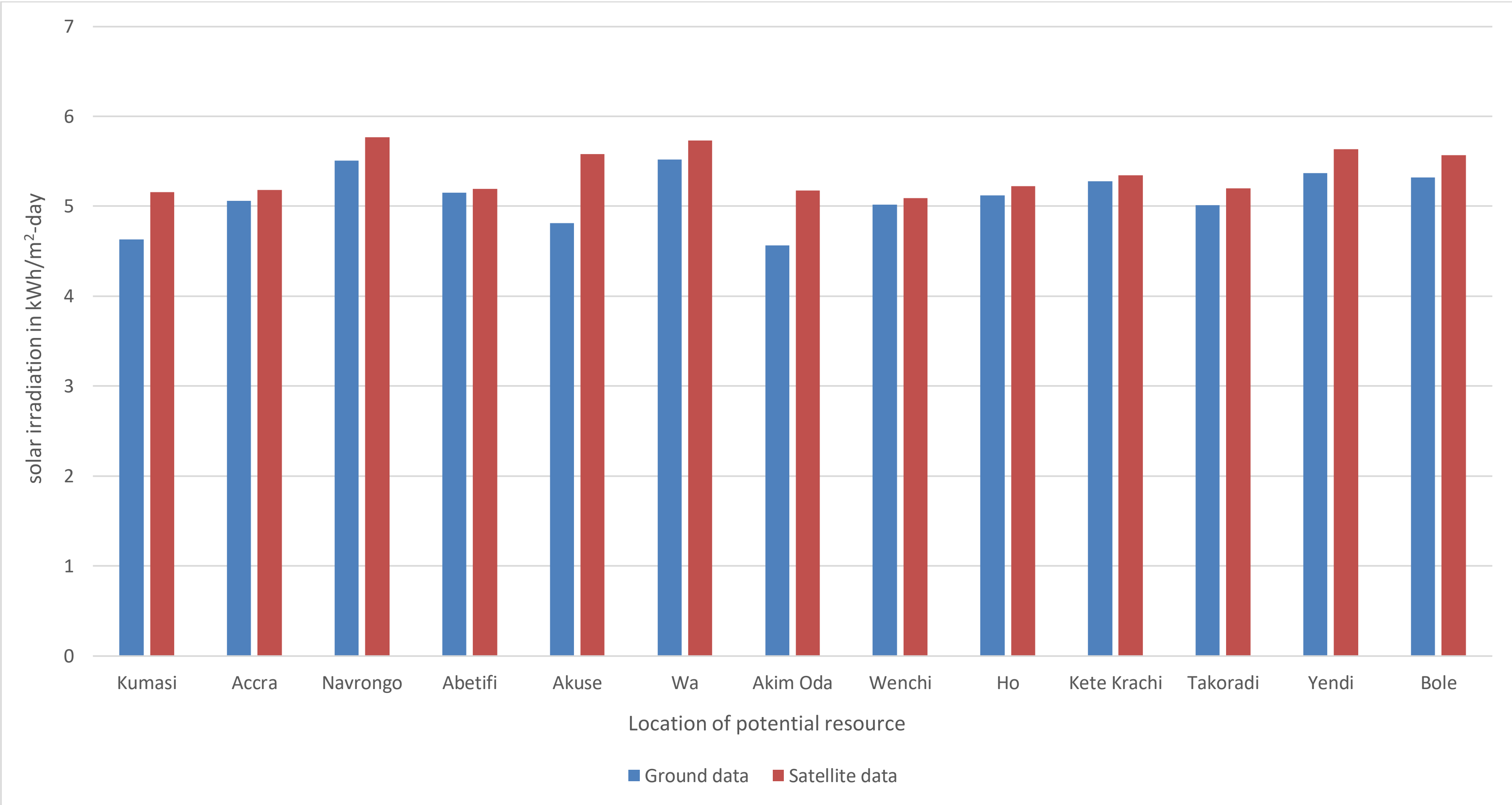

Figure 4.5: Location of potential solar energy resources in Ghana. A study conducted by the Solar and wind energy resource (SWERA, 2004).

4.4.1 Solar intensity

The intensity of solar energy in Table 4.1 indicates that the potential sunshine hours for electricity generation ranges from 4.0 to 6.5 kWh/m^2 per day. This shows that the potential for electricity generation with solar energy in Ghana is very high.

An average solar energy throughout the various regions in Ghana can be estimated to between 4 – 6 sun hours[9].

Table 4.1: Solar intensity areas in Ghana sourced from the Energy Centre, Kwame Nkrumah University of Science and Technology (KNUST, 2013)

Climatic zone	Location (region)	Intensity (kWh/m^2)
Savannah (close to the Sahel)	Upper East, Upper West, Northern, upper areas of Brong-Ahafo regions	4.0 – 6.5
Middle forest zone	Ashanti, Eastern, Western and areas of Central, Volta and Brong-Ahafo regions	3.1 – 5.8
Savannah (Coastal belt)	Greater Accra, Volta and coastal areas of Central regions	4.0 – 6.0

The enormous amount of solar resource that can be found throughout the 10 regions in Ghana is confirmed in Figure A1.

[9] 1 sun hour = 1 kWh/m2-day

4.5 Chapter summary

In this chapter, the electricity outage and consumption profiles of households have been analyzed with simple descriptive statistics. The results show that, annually the total electricity consumed is inversely proportional to the outage hours experienced. The enormous insolation levels in Ghana makes adoption efficient for generation of electricity.

In the next chapter, experimental results from the ABM are described in detail.

CHAPTER 5

5 Model results and analysis

In this chapter, the structure and outcomes from the agent-based model are presented in detail. The experimental design of the model is described in section 5.1 in the context of households or domestic consumers[10]. In section 5.2, the number of runs used for model simulations are explained. Results from the temporal diffusion of PV for each simulated town described. The effects of observation on the adoption of PV are analysed with the radius between households. The chapter concludes by estimating how PV adoption can contribute to enhanced electricity reliability.

5.1 Experimental design

5.1.1 Landscape of domestic consumers

The configuration of then model was done to represent districts in the greater Accra region of Ghana. This makes it possible to model different household populations to assess the level of adoption. In the context of this research, three different household populations (described in section 3.4.6) was used to evaluate how different parameters affect PV adoption.

[10] Household agents in the model represents domestic consumers of electricity. They are used interchangeably in the study.

5.1.2 Adoption inceptives

The main available incentive for PV adoption is the current feed-in tariff (FiT) to domestic consumers. This is categorised within different levels of electricity consumption detailed in section 3.5.2. Although FiT is beneficial, not all household agents can adopt PV without matching the cost of installation.

5.1.3 Cost of investment

This segment of the model uses the default setting in the CASCADE project (described in section 3.6). The cost of installing a PV system is randomly modelled when a consumer gets a quote in a range between 5% and 20%. The total installation cost includes the unit cost of the system size and the price to have it installed. Although the cost of a PV system may vary, it remains constant in the simulation process since it is not considered an important factor to change patterns in the temporal diffusion.

5.1.4 The grid

In the model, household agents that a connected to the grid do not receive constant supply of electricity. Electricity outages (described in section 3.6.1.3) is a key trigger for the adoption process. The potential household agents to enhance adequacy and security of electricity supply is an objective of this research.

5.1.5 Weather profile

All household agents in the selected districts for the model received the same amount of insolation data. Although the weather profile can affect generation electricity with PV that cannot be the case in this study because all districts in the modelled region have similar weather patterns. Therefore the weather in the geographic area cannot have an effect on PV adoption.

5.2 Results and analysis

In the simulation process, the number of runs coupled with the analysis of different scenarios is significant to provide outcomes that are valuable. The observation radius as a main parameter was used to test how household agent adopt PV by using 10 runs. Further model simulations were conducted with 50 and 100 runs (Figures 5.2 and 5.3) in order to examine the fitness of the results.

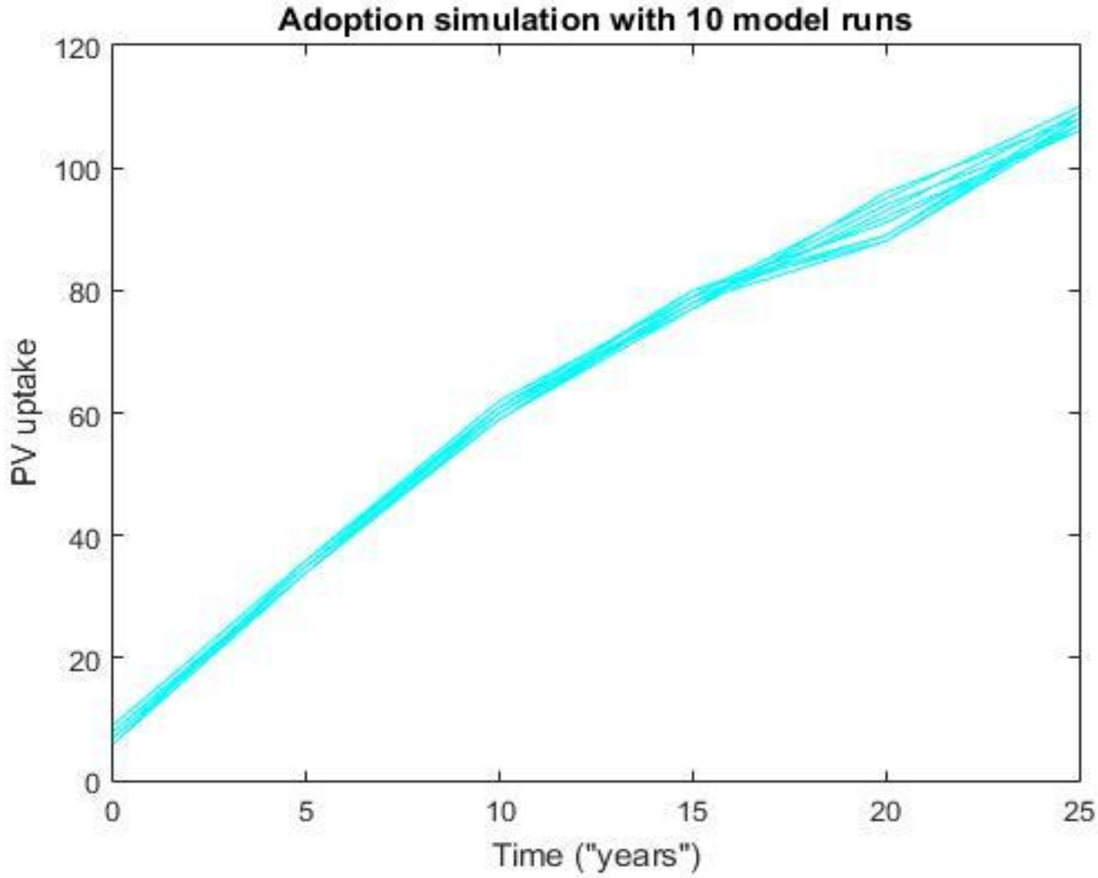

Figure 5.1: Simulated number of PV adopted with 10 model runs

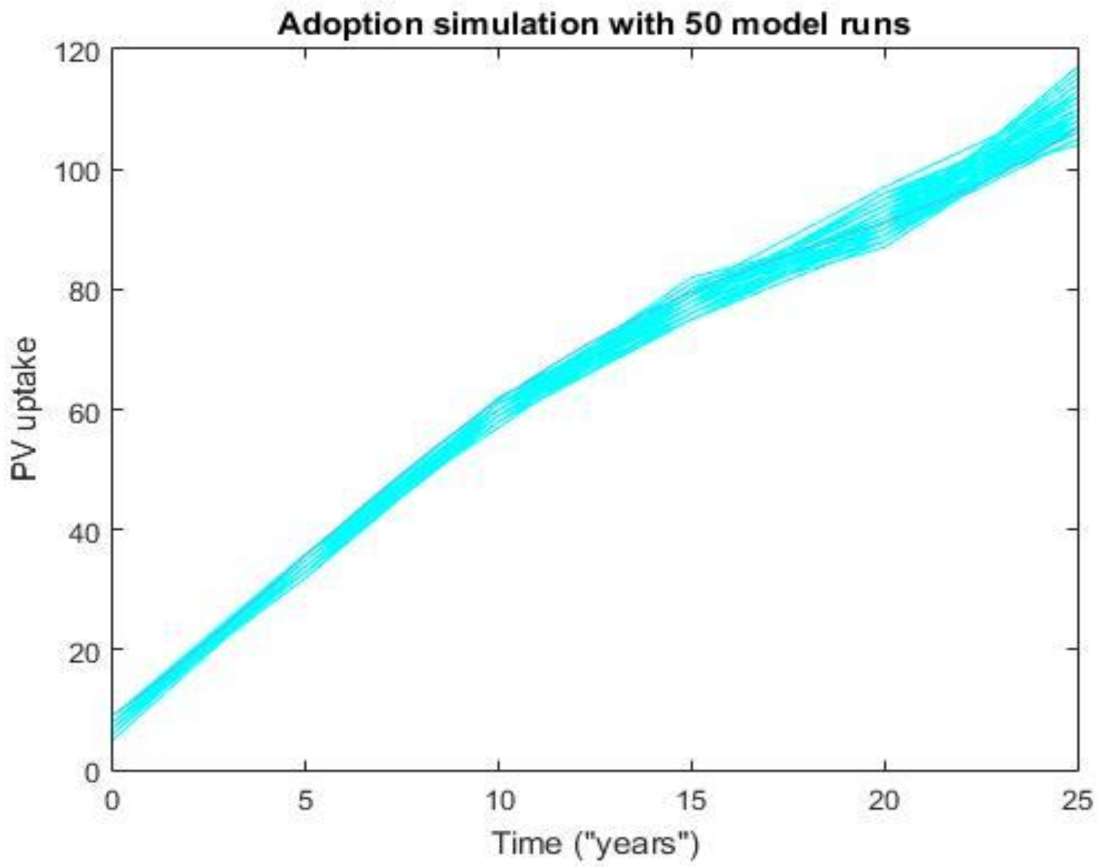

Figure 5.2: Simulated number of PV adopted with 50 model runs

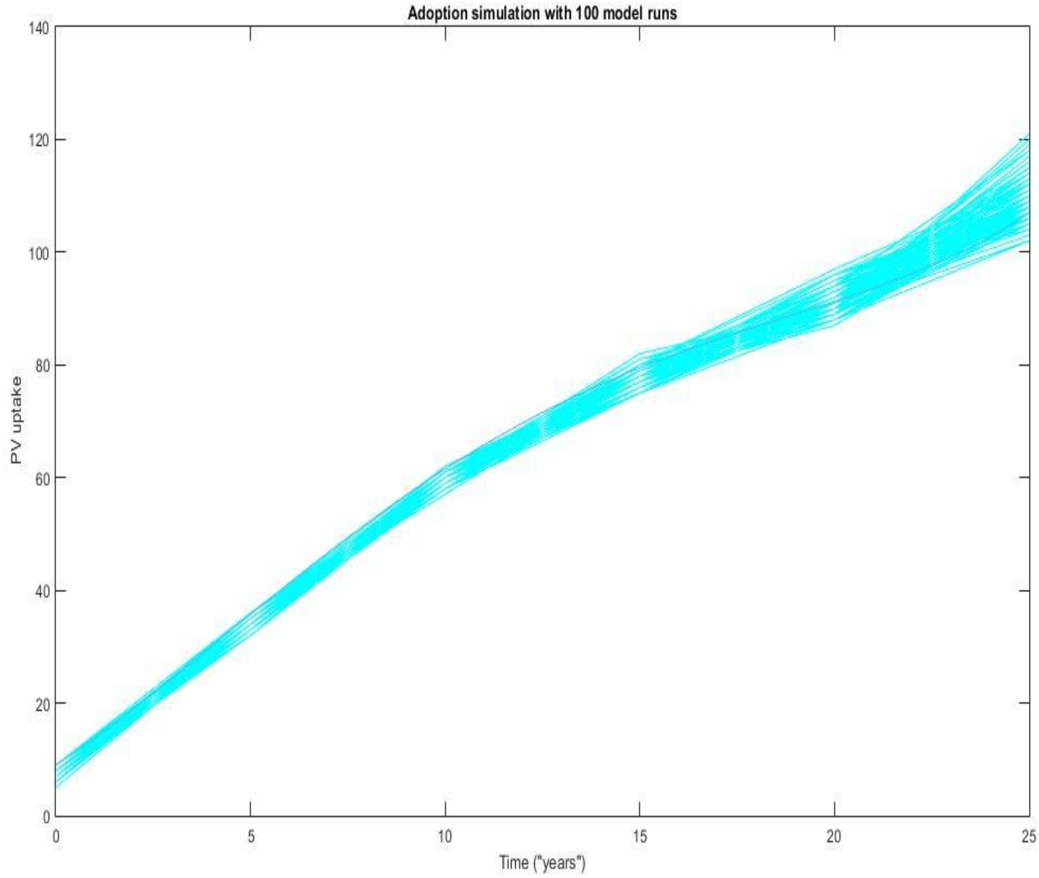

Figure 5.3: Simulated number of PV adopted with 100 model runs

5.3 Temporal diffusion of PV

In this section, the temporal diffusion of PV from the three towns modelled in Ghana are presented. The considered timeline for total adoption is 25 years.

Figure 5.4 shows the adoption of PV by households with different consumption profiles in Town A with a population of 1,000 households. At year zero, there are a total of 9 households with PV installed which represents 0.9% of all households in Town A.

Out of the households with PV installations, 0.3%, 0.4%, 0.2% and 0.1% of the population have the potential to generate electricity between 0 – 50 kWh, 51 – 300 kWh, 301 – 600 kWh and 600+ kWh respectively. After 25 years, a total of 107 households would have PV installations which represents 10.7% of population in Town A.

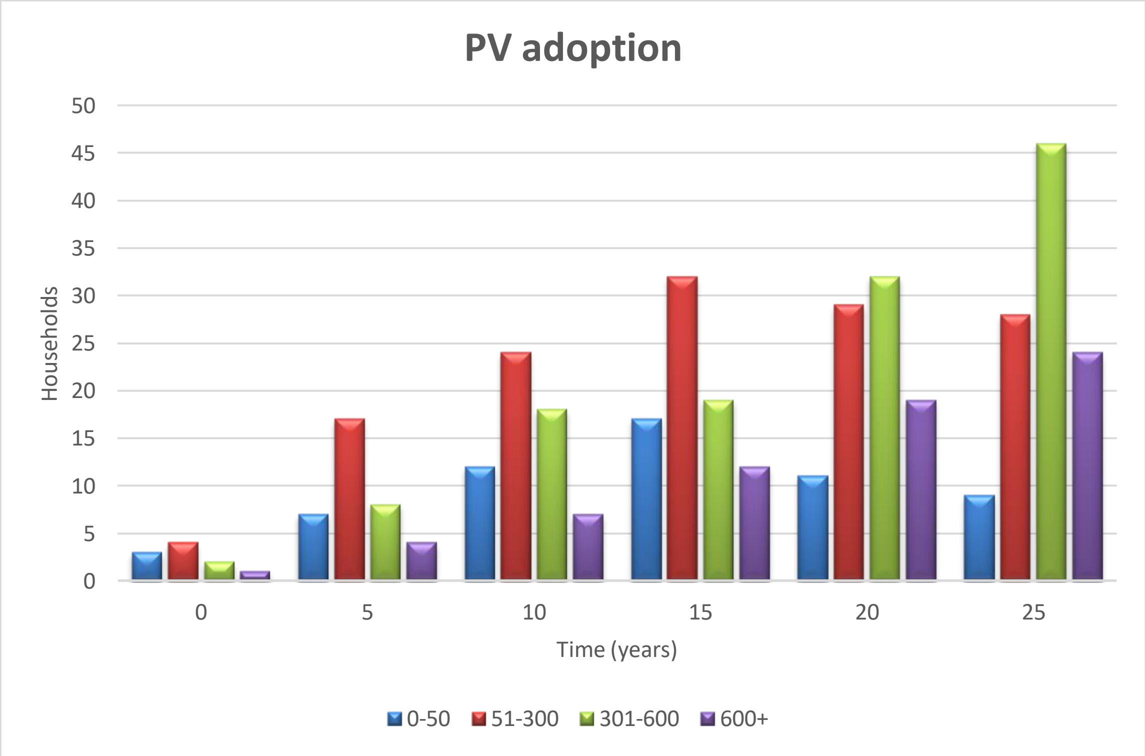

Figure 5.4: Temporal diffusion of PV in Town A with population of 1,000 households

Figure 5.5 shows a graph of the temporal diffusion of households with different consumption profiles in Town B with a population of 5,000 households. At the initial year, there are a total of 42 households with PV installations, representing 0.84% of all households in Town B.

Out of the households with PV installations, 0.12%, 0.18%, 0.42% and 0.12% of the population can produce electricity between 0 – 50 kWh, 51 – 300 kWh, 301 – 600 kWh and 600+ kWh respectively. After 25 years, a total of 510 households would have PV installations which represents 10.2% of population in Town B.

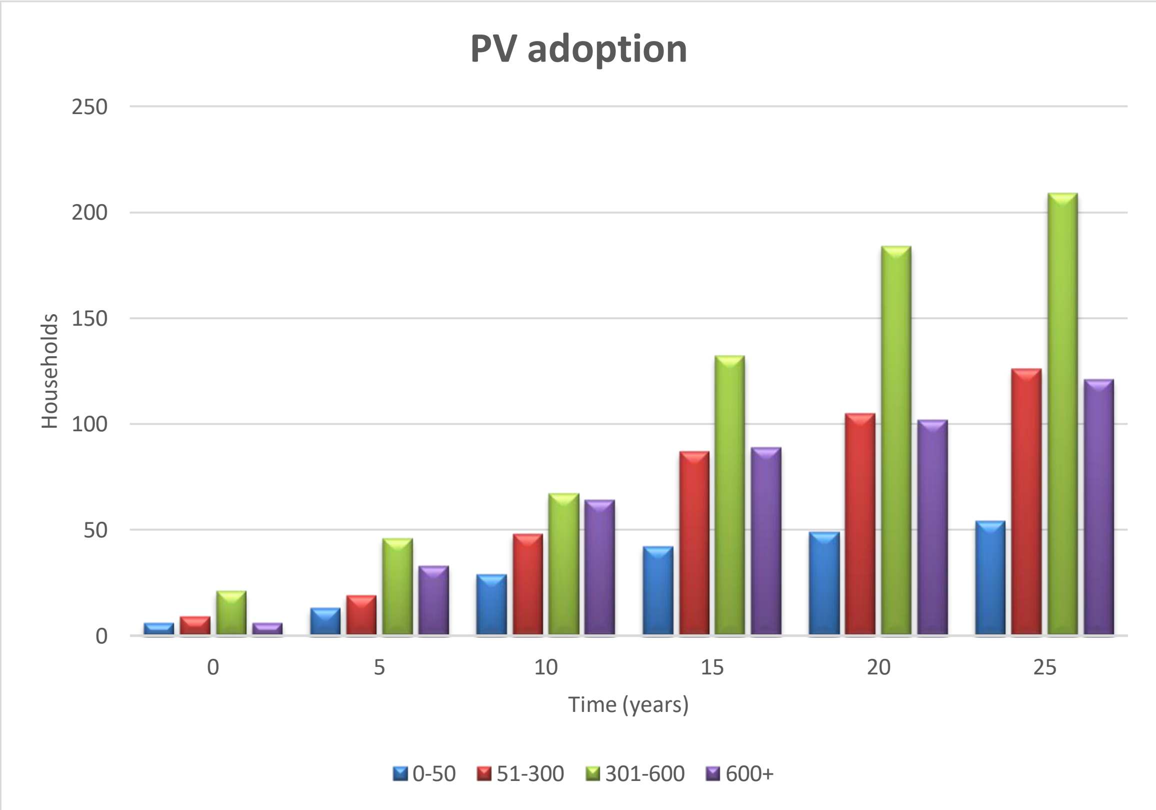

Figure 5.5: Temporal diffusion of PV in Town B with population of 5,000 households

In Figure 5.6, a graph of the temporal diffusion of households with different consumption profiles in Town C is shown. At the initial year, there are a total of 70 households with installed PV systems, representing 0.175% of all households in Town C. Out of the households with PV installations, 0.02%, 0.07%, 0.05% and 0.04% of the population will be able to generate electricity between 0 – 50 kWh, 51 – 300 kWh, 301 – 600 kWh and 600+ kWh respectively. A total of 4,030 households would have PV installations at the end of the 25-year period which represents 10.08% of the population in Town C.

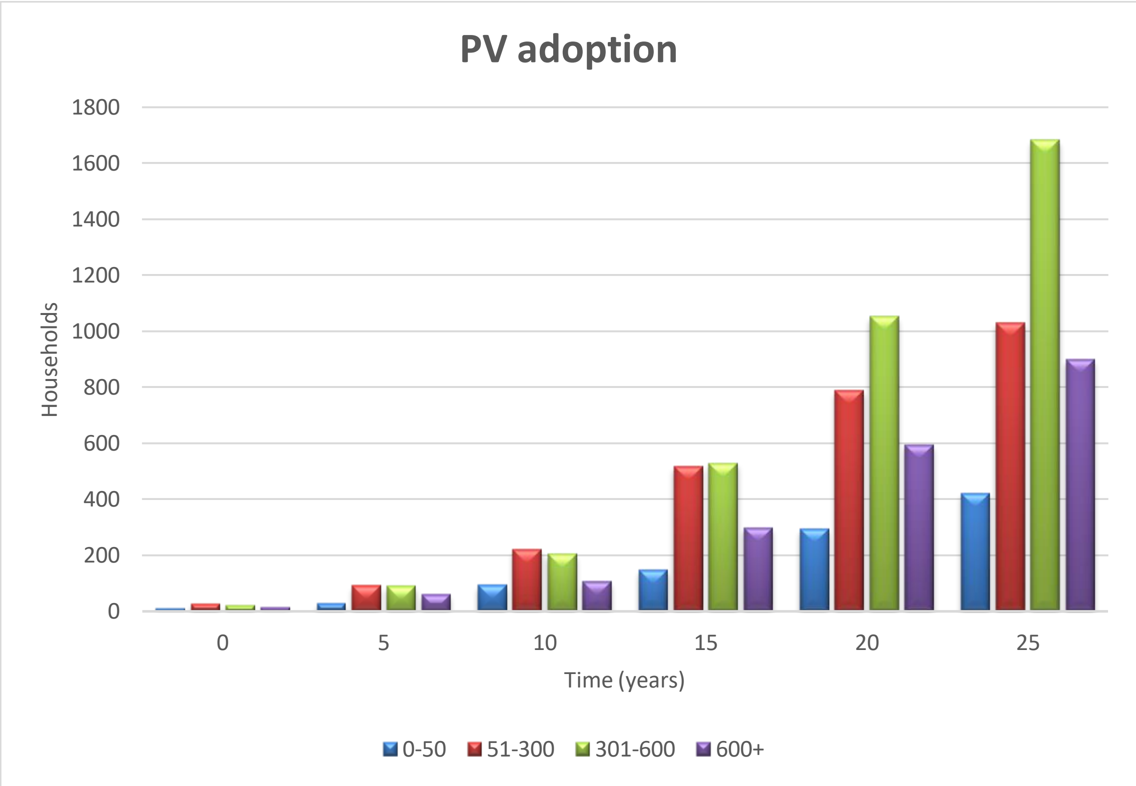

Figure 5.6: Temporal diffusion of PV in Town C with population of 40,000 households

5.4 Effects of observation on PV adoption

This section shows how varying neighbourhood radii would impact the temporal adoption of PV in the three modelled locations. The initial observation radius setup in the model is 2.5 metres, with increments of 2.5 to 15 metres for 25 years.

Figure 5.7 shows the number of households who have installed PV base on observation radius in Town A. In increment from 2.5 m to 5 m, the total number of households with PV, increases from 84 to 89, representing an 8.9% increase in PV adoption.

At the highest radius of 15 m, the total number of households with PV in Town A is 107 which represents 10.7% of the total population of households.

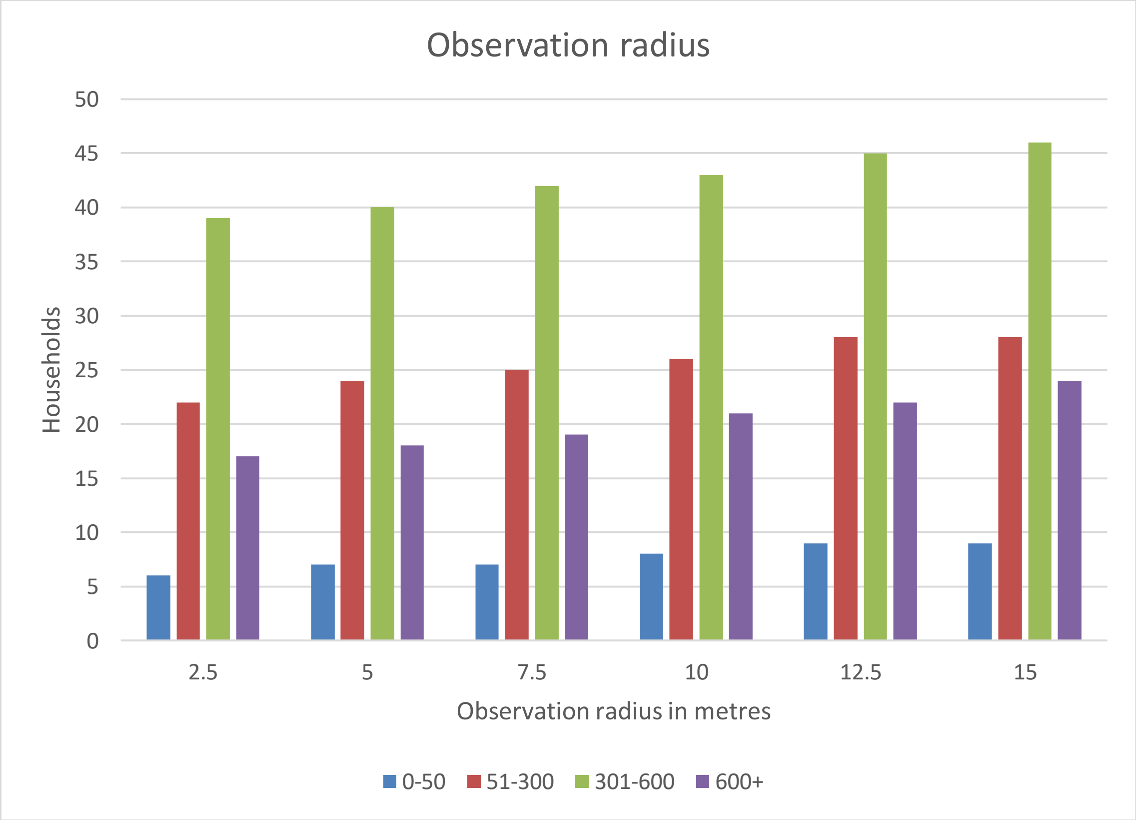

Figure 5.7: Effects of observation radius on adoption of PV after 25 years.

In Figure 5.8, the number of households who have installed PV base on observation radius in Town B is shown. In increment from 2.5 m to 5 m, the total number of households with PV, increases from 441 to 454, representing a 2.9% increase in PV adoption.

At the highest radius of 15 m, the total number of households with PV in Town B is 500 which represents 10% of the total population.

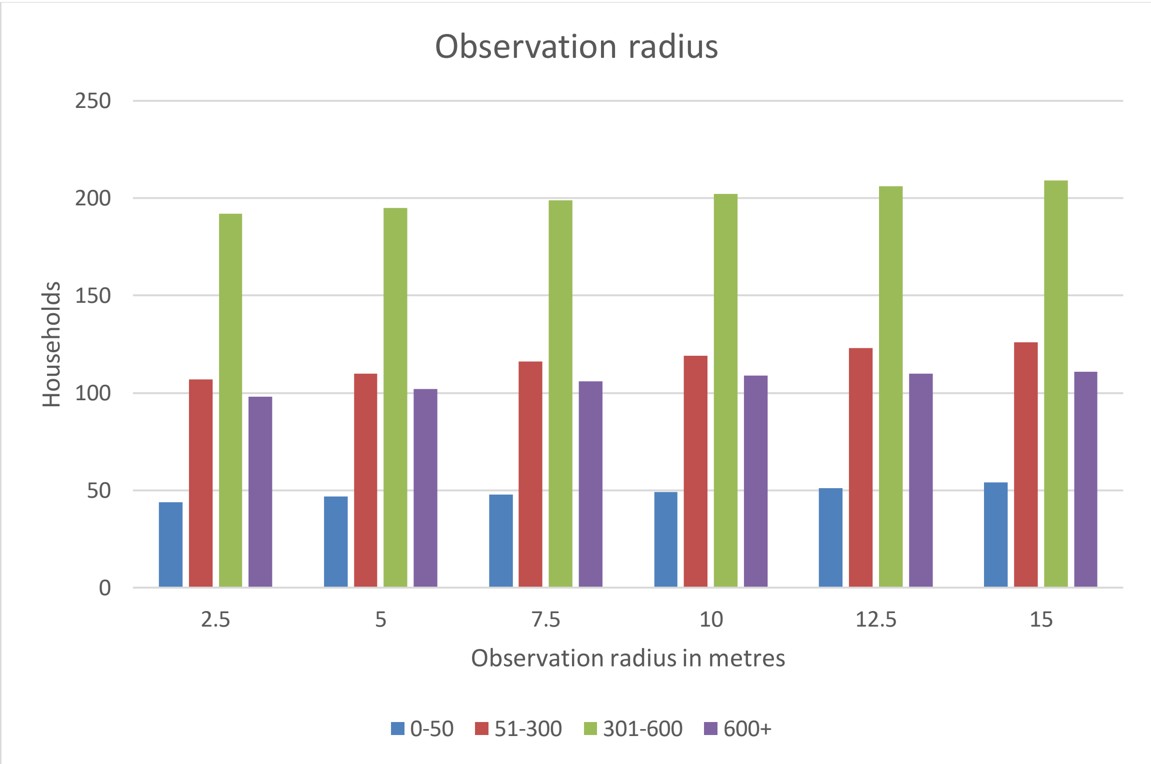

Figure 5.8: Effects of observation radius (in metres) on adoption of PV in Town B after 25 years.

Figure 5.9 shows a graph of the number of households who have installed PV base on observation radius in Town C. In increment from 2.5 m to 5 m, the total number of households with PV, increases from 3,498 to 3,650, representing 2.9% increase in PV adoption.

At the highest radius of 15 m, the total number of households with PV in Town C is 4030 which represents 10.1% of the total population.

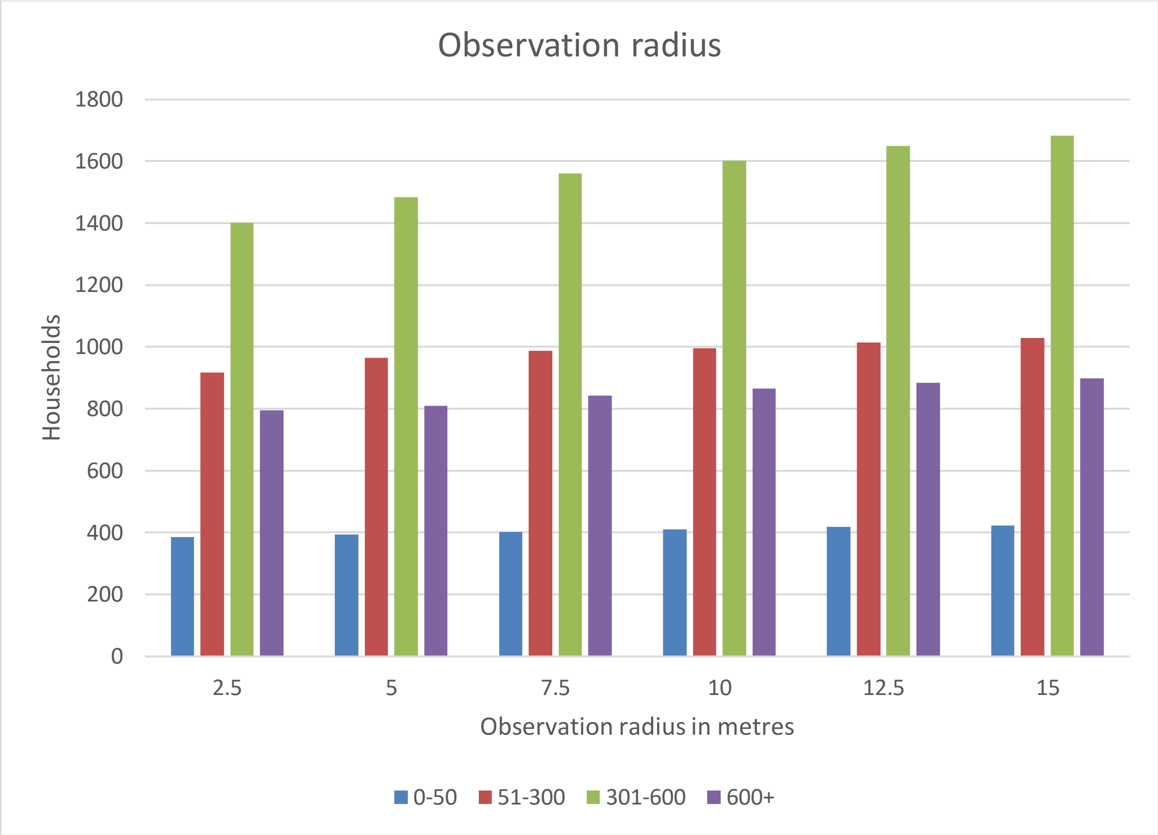

Figure 5.9: Effects of observation radius on adoption of PV in Town C after 25 years.

5.5 Chapter summary

The ABM used in the modelling process has demonstrated the ability to simulate characteristics of neighbourhood observation to show various scenarios. The heterogeneity of the ABM makes it possible to combine different parameters to examine resulting outcomes.

Amongst the three modelled towns, the middle class households (described in section 3.5.3) that fall between tariffs band 51 – 300 kWh and 301 – 600 kWh have the most potential to contribute to electricity reliability. They contribute to about 60% of the total PV generation. This can mainly be attributed to their demand requirements and the ability to purchase PV. Despite the available incentives for feed-in tariffs, households within the lower income category mostly are unable to adopt PV due to inability of their capital to match the cost of purchasing. The introduction of schemes to buy or subsidies has the potential to alter the outlook of the total adoption across the various groups.

Surprisingly, households who consume over 600 kWh of electricity who are perceived to be in the high class had a lesser adoption rate as compared to households in the middle class band. Factors that may affect their interest can loosely be linked to available of backup generators in their homes already (Energy Commission, 2015).

CHAPTER 6

6 Conclusion and future work

6.1 Conclusion

In this research the adoption of solar photovoltaic by domestic consumers have been examined as a potential to contribute to enhanced electricity reliability. A field trip in Ghana for the electricity informed the development of a model by modifying the adoption model in the CASCADE project. In the model, research data are used to simulate how domestic consumers adopt PV based on electricity outages. The originality of the study was combining techno-economic analysis and an ABM to simulate the adoption of PV as a result of electricity supply outages.

The results of the study show the potential of different household categories to produce electricity with PV. Although domestic consumers who fall in the lower class have the least potential to contribute enhanced electricity reliability, an introduction of other schemes (e.g. subsidies) in the model has the tendency to change the outlook. However in terms of capital investment, the introduction of subsidies by the Ghana government are not enough at the moment to enable PV adoption.

6.2 Summary of chapters

In chapter one a brief outlook on electricity supply is described to show how generation would be provided from 2014 to 2040. A focus on the electricity supply problem in Ghana is highlighted. The electricity reliability problem at hand creates an avenue for domestic consumers to adopt alternate technology for generation. A detailed review of literature on past works on the subject (in chapter 2) showed a gap in research where no study had explored the potential of domestic consumers becoming prosumers to contribute to generation shortfalls in Ghana.

This informed the collection key electricity data for the purposes of simulating the potential of prosumers. The procedure used in model analysis for the study have been detailed in Chapter 3 with use of the ODD protocol.

The results and analysis of key electricity data were presented in Chapter 4. A continuation of the results and analysis for the model work have also been presented in Chapter 5. The category of consumers with the highest prospect (60% of the total generation by households) of contributing to electricity reliability are households who consume within tariff band of 301 – 600 kWh.

In view of the above summary, it is apt to say that the adoption of solar PV has a high potential for enhancing electricity reliability. An important factor is that neighbourhood engagement within a district over a longer period of time has a significant effect on installation. The simulation of the model in Chapter 5 shows how such interactions coupled with techno-economic factors facilitate patterns in adoption.

6.3 Future work

Future work is intended to complement the research done so far by integrating more parameters and agents to enrich the functioning in the model. A number of investigations to make it essential for future works are listed below.

- Adding more agents at the commercial and industrial level to estimate the amount of generation that can be harnessed from these sources. It is important to note that commercial and industrial agents consume about 60% of the total electricity supply in Ghana (Electricity Company of Ghana, 2013).
- Modelling the integration of more government incentives such as subsidies at various level of consumers (domestic, commercial and industrial users).
- The option of making variables such as cost and tariffs updateable without the need to change manually over time.
- The ability to transition the model to make it more decentralized so that any updates made can be reflected on other locations where the system has been installed.

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APPENDIX

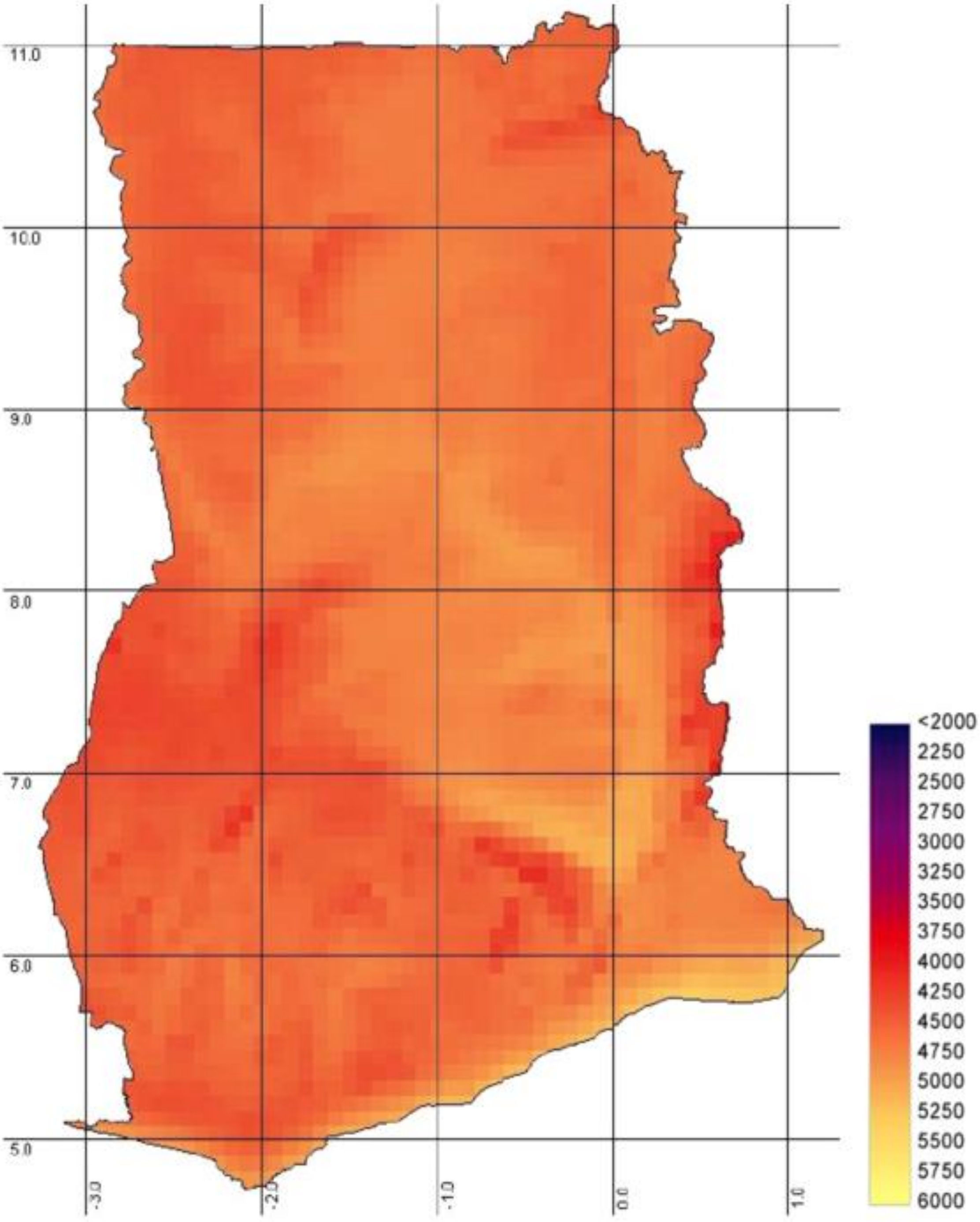

Figure A1: Annual average total daily sum of the global horizontal irradiation in Wh/m^2 per day in Ghana. A 3-year average by SWERA, 2004.