VALIDATION OF NETWORK PLANNER RESULTS FOR GIS-BASED ENERGY ACCESS PLANNING FOR GHANA

By

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A Thesis submitted to the School of Graduate Studies, Kwame Nkrumah University of Science and Technology, Ghana, in partial fulfillment of the requirements for the Degree of

MASTER OF SCIENCE IN RENEWABLE ENERGY TECHNOLOGIES

Department of Mechanical Engineering

College of Engineering

June 2013

DECLARATION

I hereby declare that this thesis is the result of my own original research work undertaken under the supervision of the undersigned, that all works consulted have been referenced and that no part of the thesis has been presented for another degree in this University or elsewhere.

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CERTIFICATION

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DEDICATION

This work is dedicated to the Holy Spirit; my dependable teacher, helper and guide.

ACKNOWLEDGEMENT

I am most grateful to the Late Professor Abeeku Brew-Hammond, my initial thesis supervisor, for not only accepting to supervise my work, but for providing true and insightful guidance which has led to the success of this work. To Dr. Lena Mensah who stepped in Prof. Abeeku's shoes to steer this work to a successful end, I say, I am eternally grateful.

Special commendation goes to my lovely and supportive wife Veronica. You have indeed showed that "behind every successful man, there is a woman"! To Rev. Fr. Peter Claver, Francis Kemausuor, Eric Essandoh, Eben Nyarko, Joseph Nunoo, and all my family and friends who have lent support in diverse ways, I say thank you and God bless you.

Thank you Lord, for bringing me thus far.

EMMANUEL NARTEH NARH

June 2013

ABSTRACT

This thesis examines the validity of rural electrification options determined in a GIS-Based Energy Access Project (GIS-EAP) undertaken by The Energy Center of the Kwame Nkrumah University of Science and Technology. It also examines the effect of steep decreases in solar PV prices on electrification costs using Network Planner, an electrification planning tool used in the GIS-EAP project for proposing grid, mini-grid or off-grid (solar PV) electrification technologies for un-electrified communities in Ghana.

Background studies, input parameter authentication, software assisted analysis, and comparisons of results obtained in this study with those in the previous study, were utilized in ascertaining the validity of the GIS-EAP results. Sensitivity analysis was carried on solar PV costs by varying panel costs alone, battery costs alone, and then both panel and battery costs. Panels were varied from a base value of 4,000$/kW down to 100$/kW and batteries from 125$/kWh down to 5$/kWh. Levelized costs for all electrification options were found to decrease with decreases in solar PV costs. Reduction in the prices of solar panels was found to have a much greater impact on the modeling results than was reduction in the prices of solar batteries. At two points, the levelized costs of grid and off-grid became equal – when solar panels cost 750$/kW or when solar panels cost 1,400$/kW and batteries cost 40$/kWh. As compared to the GIS-EAP which had eight (8) out of the ten (10) regions being off-grid compatible, in this study, none of the regions was off-grid compatible. The results of the EAP were found to be broadly valid albeit some inconsistencies were caused by the lack of specification of some input values used and in-consistency in the use of others. This implies a necessity for future works to communicate all input parameters clearly and to ensure consistency in their usage.

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ABBREVIATIONS

AIDS	Acquired Immune Deficiency Syndrome
AS	Ashanti Region
BA	Brong-Ahafo Region
CR	Central Region
EAP	East-Asia Pacific
ECOWAS	Economic Community of West African States
ENACT	Energy Access Interactive Tool
ENPEP	Energy and Power Evaluation Programme
	Environmental Impacts
EPRAP	Energy for Poverty Reduction Action Plan
ER	Eastern Region
EUEI-PDF	European Union Energy Initiative – Partnership Dialogue Facility
FINPLAN	Model for Financial Analysis of Electric Sector Expansion Plans
GDP	Gross Domestic Product
GEAR	GIS-Based Energy Access Review
GEDAP	Ghana Energy Development and Access Project
GIS	Geographic Information Systems
GR	Greater Accra Region
HIV	Human Immunodeficiency Virus
IEA	International Energy Agency
ISED	Indicators for Sustainable Energy Development
ISO	International Standards Organization
JPEG	Joint Photographic Experts Group

KNUST	Kwame Nkrumah University of Science and Technology
LAC	Latin American Countries
LCOE	Levelized Cost of Electrification
LEAP	Long range Energy Alternatives Planning System
LPG	Liquefied Petroleum Gas
MAED	Model for Analysis of Energy Demand
MDGs	Millennium Development Goals
MESSAGE	Model for Energy Supply Strategy Alternatives and their General Environmental Impact
NDPC	National Development Planning Commission
NES	National Electrification Scheme
NP	Network Planner
NR	Northern Region
OECD	Organization for Economic Co-operation and Development
PMBOK	Project Management Body of Knowledge
PR	Penetration Rate
PV	Photo Voltaic
RUN 1	NP results for 2010 study
RUN 2	NP results for this study
SHEP	Self Help Electrification Programme
SIMPACTS	Simplified Approach for Estimating Environmental Impacts of Electricity Generation
SSA	Sub-Saharan Africa
TEC	The Energy Center
UE	Upper East Region

UN	United Nations
UNDP	United Nations Development Programme
UTM	Universal Transverse Mercator
UW	Upper West Region
VR	Volta Region
WASP	Wien Automatic System Planning Package
WR	Western Region

CHAPTER 1 - INTRODUCTION

1.1 BACKGROUND

Energy is the engine for the production of goods and services across all economic sectors: agriculture, industry (mining, manufacturing), transportation, commerce, public administration, etc. It is equally vital to the provision of basic civic services (health care, clean water, sanitation, etc.), to improving access to education and, ultimately, to raising incomes (International Atomic Energy Agency, 2010). Of the total energy consumed in Ghana, biomass (fuel wood and charcoal) accounts for about 63%, petroleum accounts for 27% with electricity accounting for the remaining (Government of Ghana-National Development Planning Commission(NDPC), 2010).This means that over 63% of the energy consumed in Ghana is not from modern energy sources. As part of national policy, Ghana currently seeks to promote off grid decentralized renewable energy power sources as well as alternatives to biomass (fuel wood and charcoal) (Government of Ghana-National Development Planning Commission(NDPC), 2010).

A broad range of energy access data is critical not only to understand countries' energy access situation but also for developing policies and programmes that address energy poverty and also for financing the expansion of access to modern energy services. (Legros et al, 2009). "Off-grid renewable solutions are increasingly acknowledged to be the cheapest and most sustainable options for rural areas in much of the developing world" (Renewable Energy Policy Network for the 21st Century(REN21), 2011). This has led to some countries exploring renewable energy sources as part of their rural energy planning efforts.

To facilitate access to modern energy services such as planned by nations, international bodies and development organizations, a rapid and systematic planning tool needs to be adopted. One such tool was developed and utilized as part of a project conducted by The Energy Center (TEC) of the Kwame Nkrumah University of Science and Technology (KNUST) to facilitate the rapid and efficient planning of Energy Access in Ghana (Kemausuor, et al., 2010). The project which was titled "GIS-Based Support for Implementing Policies and Plans to Increase Access to Energy Services in Ghana" - hereafter referred to as the 2010 study, was undertaken with funding from the European Union Energy Initiative – Partnership Dialogue Facility (EUEI-PDF). The study utilized a Geographic Information System (GIS) tool in conjunction with the Network Planner (NP) Energy Model as an Energy Access planning tool for Ghana. This thesis seeks to validate the results obtained from the above named study and to run scenario analysis on the effects of steep decreases in solar Photovoltaic (PV) costs.

1.2 JUSTIFICATION

Kemausuor et al (2010) recommended the use of planning tools such as Network Planner in energy planning. However, this can only be achieved when users have a high degree of confidence in the results generated by such planning tools. To ensure that the results of the GIS-Based study captured in Kemausuor, et al.,(2010) can be relied upon, a validation test needs to be performed. Such a process will give credence to the results of the study and improve stakeholder confidence in its usage. As noted by Legros et al, (2009); ***"Continued efforts are required to improve the quantity and quality of statistical information related to energy access,*** as a basis for designing policies and programmes to address energy poverty challenges." There is therefore the need for independent verification of the dataset used by Kemausuor et al (2010). This thesis is expected to review the original study done by the above mentioned reference. Based on the conclusions of this thesis, it is expected that a more robust energy access planning model for Ghana will be realized.

1.3 OBJECTIVES

The main objective of this study is to validate the results obtained from the GIS-Based energy access project undertaken by The Energy Center (TEC), KNUST in 2010.

The specific objectives are outlined below:

1. Run Network Planner using dummy or proxy data for familiarization.
2. Rebuild the database used in the 2010 study
3. Rerun the Network Planner using the rebuilt database
4. Compare results from runs in this study with those in the 2010 study
5. Undertake scenario analysis to explore the effects of steep decreases in solar PV costs on the cost of the various electrification technologies considered in the 2010 study

1.4 METHODOLOGY

This thesis was accomplished by using the following sequence of actions to constitute the methodology:

1. Acquiring the necessary tools, software and infrastructure for the thesis
2. Undertaking familiarization runs of the Network Planner software

3. Consulting with previous project team members to gain better understanding of the project, the Network Planner software, and the results of the study.
4. Reviewing relevant literature for background information
5. Collating the necessary data and information from the previous study. This shall include input data, and published reports of the study.
6. Rerunning Network Planner using data and information gathered.
7. Comparing results of runs in this study with those from the previous study.
8. Undertaking scenario analysis to explore the effects of steep decreases in solar PV costs.
9. Making conclusions and recommendations based on the results obtained.

1.5 SCOPE OF WORK AND THESIS ORGANIZATION

This thesis work is presented in five chapters. **Chapter One** gives an introduction to the work and includes the background, justification, objectives, methodology, scope and thesis structure. **Chapter Two** gives an overview of relevant works and of theory rrelevant to the thesis. Particularly, this chapter gives an overview of the work this thesis seeks to validate. **Chapter Three** captures the Methodology used to accomplish this thesis. **Chapter Four** presents the results of this thesis. This chapter also discusses the results obtained. The last chapter which is **Chapter Five** , presents the conclusions drawn out of the thesis work. This chapter also presents some recommendations.

CHAPTER 2 - LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 ENERGY ACCESS

Access to clean and affordable modern energy is critical to fostering lasting social and economic development, and achieving the Millennium Development Goals (MDGs). A Worldwide report reveals that, almost 3 billion people rely on traditional biomass for cooking and heating, and about 1.5 billion have no access to electricity, with 1 billion more having access only to unreliable electricity networks (United Nations Foundation, 2012).

Energy access usually refers to access to **electricity** for lighting, industrial use, social use, domestic use, etc.; access to **modern fuels** such as Liquefied Petroleum Gas (LPG), natural gas, kerosene, etc.; and access to **mechanical power** for activities such as milling, grinding, etc. (Legros, Havet, Bruce, & Bonjour, 2009).

2.1.1 Effects of Energy Poverty

Energy poverty can be defined as the lack of adequate modern energy for the basic needs of cooking, warmth and lighting, and essential energy services for schools, health centers and income generation (PRACTICAL ACTION, 2009). It has also been defined as the absence of sufficient choice in accessing adequate, affordable, reliable, clean, high quality, safe and benign energy services to support economic and human development (DFID/Halcrow Ltd., 2002).

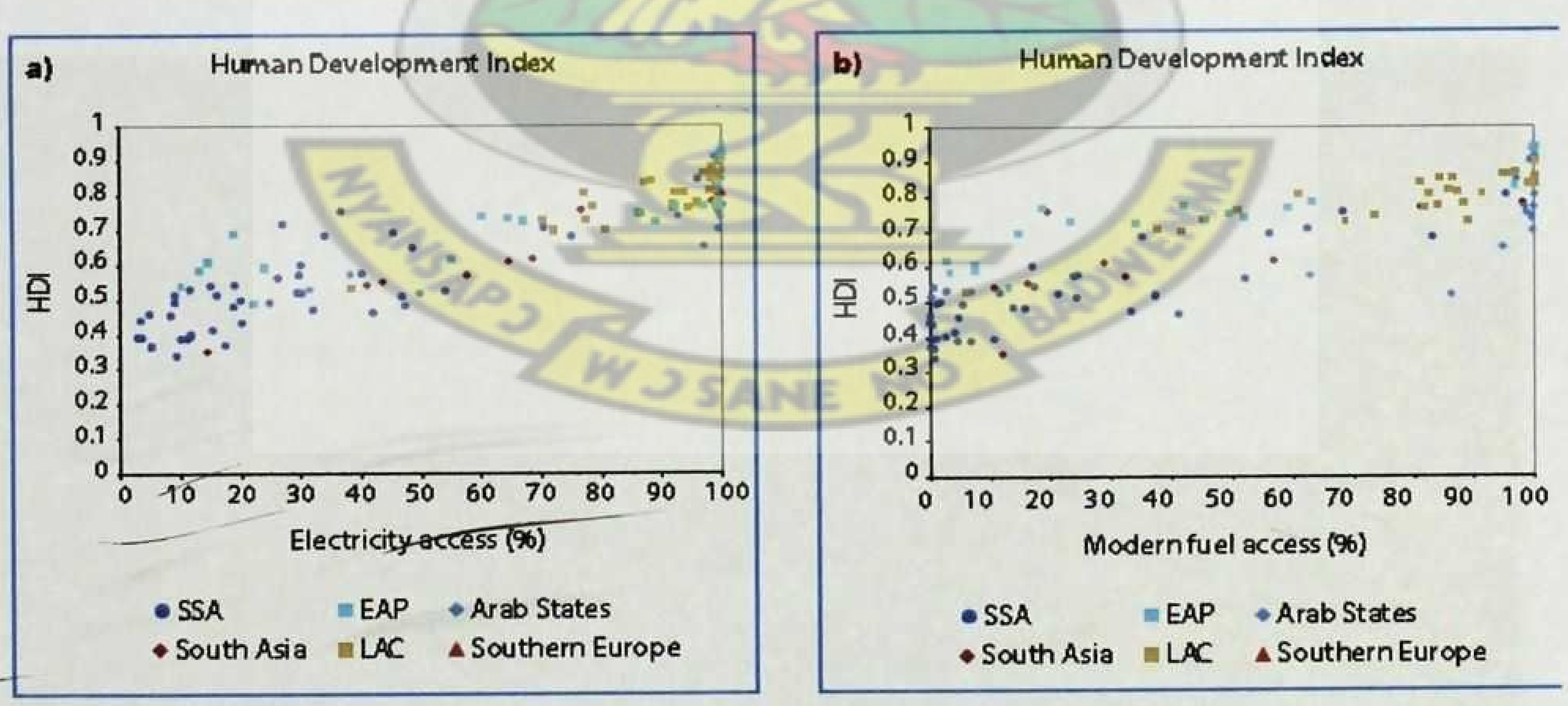
The lack of modern energy services stifles income-generating activities and hampers the provision of basic services such as health care and education. In addition, smoke from polluting and inefficient cooking, lighting, and heating devices kills nearly two million people a year and causes a range of chronic illnesses and other health impacts. These emissions are important drivers of climate change and local environmental degradation. They also consume time that women and girls could spend in more productive activities and pose security risks for them as they forage for fuel (United Nations Foundation, 2012).

"Using World Health Organization (WHO) estimates, linked to our projections of biomass use, it is estimated that household air pollution from the use of biomass in inefficient stoves would lead to over 1.5 million premature deaths per year, over 4,000 per day, in 2030, greater than estimates for premature deaths from malaria, tuberculosis or HIV/AIDS" (OECD/IEA, 2010).

2.1.2 Global Energy Perspectives

Energy and access to modern energy sources has become a topical issue in global affairs in recent times. In the words of Ban Ki-moon, Secretary General of the United Nations, "Universal energy access is a key priority on the global development agenda. It is a foundation for all the Millennium Development Goals" (UN Secretary-General, 2010). Further thoughts about energy are also captured by the United Nations Development Programme (UNDP) – "Energy is central to sustainable development and poverty reduction efforts. It affects all aspects of development -- social, economic, and environmental -- including livelihoods, access to water, agricultural productivity, health, population levels, education, and gender-related issues. None of the Millennium Development Goals (MDGs) can be met without major improvement in the quality and quantity of energy services in developing countries." (UNDP, 2013)

As depicted in Figure 2.1, there is a high degree of correlation between the Human Development Index (HDI) and access to modern sources of energy such as electricity and modern fuels, across the various regions of the world. HDI is a summary composite index that measures a country's average achievements in three basic aspects of human development: longevity, knowledge, and a decent standard of living. Longevity is measured by life expectancy at birth; knowledge is measured by a combination of the adult literacy rate and the combined primary, secondary, and tertiary gross enrollment ratio; and standard of living is measured by Gross Domestic Product (GDP) per capita. The Human Development Index (HDI), reported in the Human Development Report of the United Nations, is an indication of where a country is development wise. The index can take values between 0 and 1. Countries with an index over 0.800 are part of the High Human Development group. Between 0.500 and 0.800, countries are part of the Medium Human Development group and below 0.500 they are part of the Low Human Development group (Glossary.EconGuru.com, 2008).



Key:
SSA –Sub-Saharan Africa
EAP –East Asia and the Pacific
LAC – Latin American Countries

Figure 2.1: Relationship between HDI and access to Modern Energy

Source: (Legros et al, 2009)

Access to electricity varies widely across the various regions of the world. Developing countries generally have a low electricity access rate. The percentages of people without access to electricity in the developing countries of the world are depicted in a map in Figure 2.2. Figure 2.3 depicts a composite image of the world at night. Dark areas correspond to areas with low electricity and generally low population density whiles areas of high luminance depicts areas with high electricity and generally high population densities.

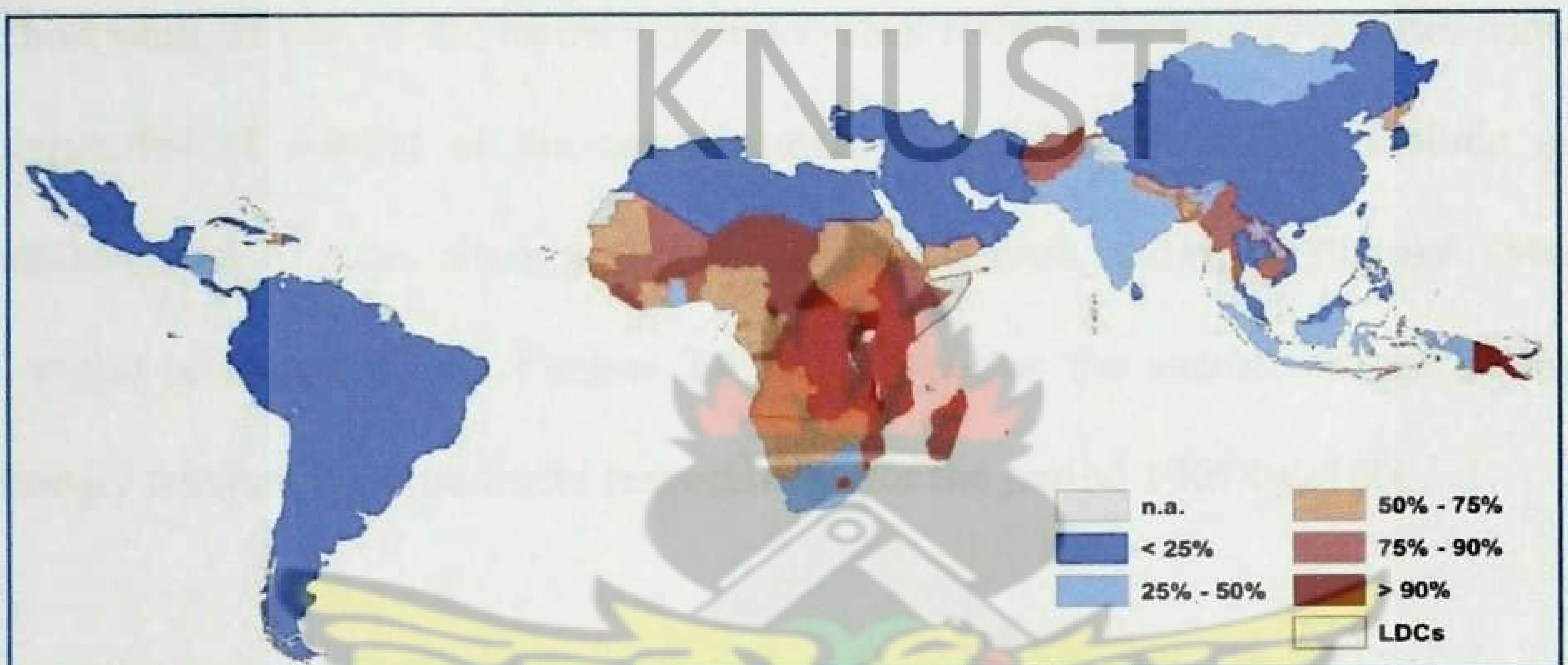


Figure 2.2: Electricity access distribution in the world as at 2008
Source: (Legros et al, 2009)

Figure 2.3: Composite image of the world at night
Source: (National Aeronautics and Space Administration, 2012)

The world consumes energy from different sources. Energy is consumed from both conventional and renewable sources. Conventional energy sources refer to energy sources that are commonly used, widely available and cost effective in current circumstances such as coal, natural gas, nuclear power, hydroelectric power, petroleum, and propane. They usually take millions of years to form and are therefore not easily replenished after use. (Brooks, 2013). Renewable or non-conventional energy sources on the other hand, are sources of energy that are replenished within a short time, as part of the earths' natural cycles. Renewable energy sources cannot be exhausted at current or anticipated rates of consumption. They include energy sources such as solar, wind, geothermal, tidal, biomass, and ocean thermal. (National League of Cities, 2012). Figures 2.4 and 2.5 shows the sources of energy and the energy consumed in the world respectively, for the period 1965 to 2100.

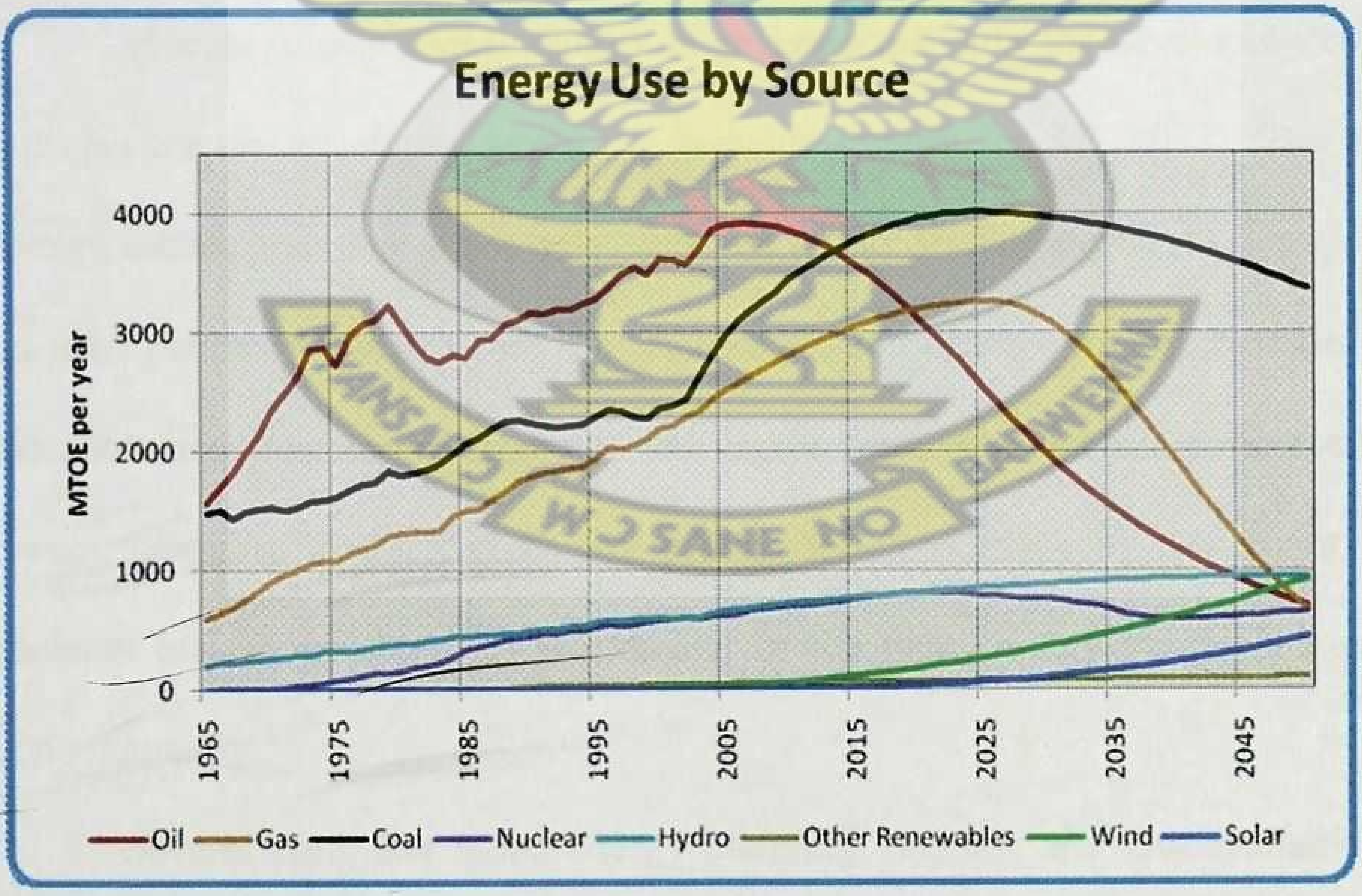


Figure 2.4: World energy use by source, 1965 to 2050

Source: (Chefurka, 2007)

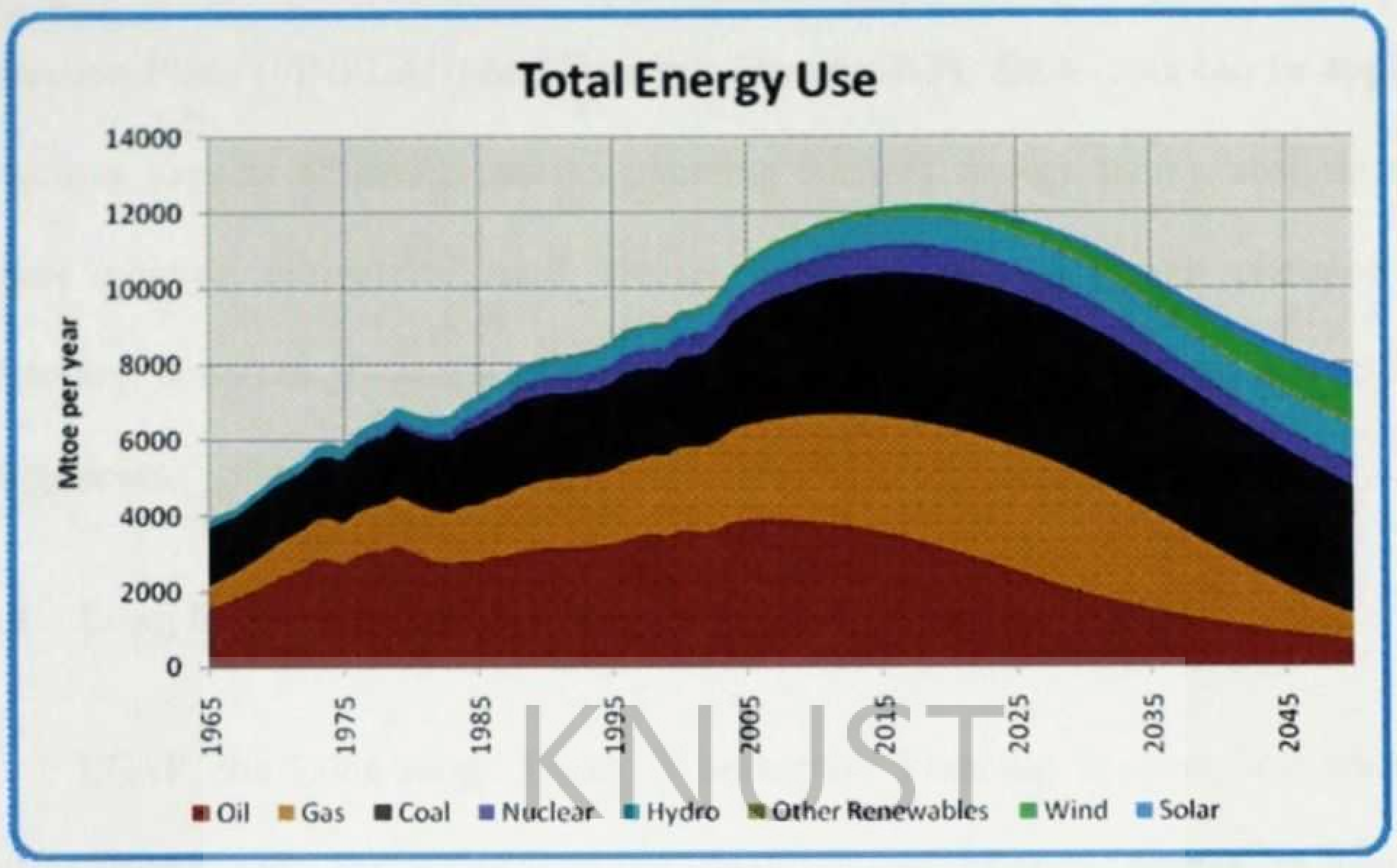


Figure 2.5: World total energy use, 1965 to 2050

Source: (Chefurka, 2007)

2.2 ENERGY ACCESS PLANNING AND PLANNING TOOLS

Access to sustainable energy is an issue not only for developing countries, but also for the developed world (Sustainable Energy for All, 2013). The need for energy access planning is not only confined to the developing world. Energy access must be planned to ensure that it is sustainable and offers optimum benefits both in the short and long terms .There is the urgent need to adopt scientific methods of energy planning in the day to day policy decisions made by key energy policy decision makers in countries worldwide. In the past, energy access planning was done manually.

Several computer aided energy planning methods are now available. These include the PISCES Energy Delivery Model Tool, Long Range Energy Alternatives Planning System (LEAP), HOMER, Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE), Energy and Power

Evaluation Programme (ENPEP), Model for Financial Analysis of Electric Sector Expansion Plans (FINPLAN) and Network Planner (NP). Such tools can be applied to various aspects of energy access planning such as energy policy analysis and climate change mitigation, rural energy access planning, power planning in developing countries, financial analysis for energy projects, assessment of multiple energy access policies, inter alia.

2.2.1 Long Range Energy Alternatives Planning System (LEAP)

LEAP, the Long range Energy Alternatives Planning System, is a widely-used software tool for energy policy analysis and climate change mitigation assessment developed at the Stockholm Environment Institute. LEAP has been adopted by thousands of organizations in more than 190 countries worldwide. Its users include government agencies, academics, non-governmental organizations, consulting companies, and energy utilities. It has been used on many different scales ranging from cities and states to national, regional and global applications. LEAP is used by countries for undertaking integrated resource planning, greenhouse gas (GHG) mitigation assessments, and Low Emission Development Strategies (LEDS) especially in the developing world. LEAP is not a model of a particular energy system, but rather a tool that can be used to create models of different energy systems, where each requires its own unique data structures Figure 2.6 shows a screen shot of the LEAP energy planning tool (Heaps, 2012).

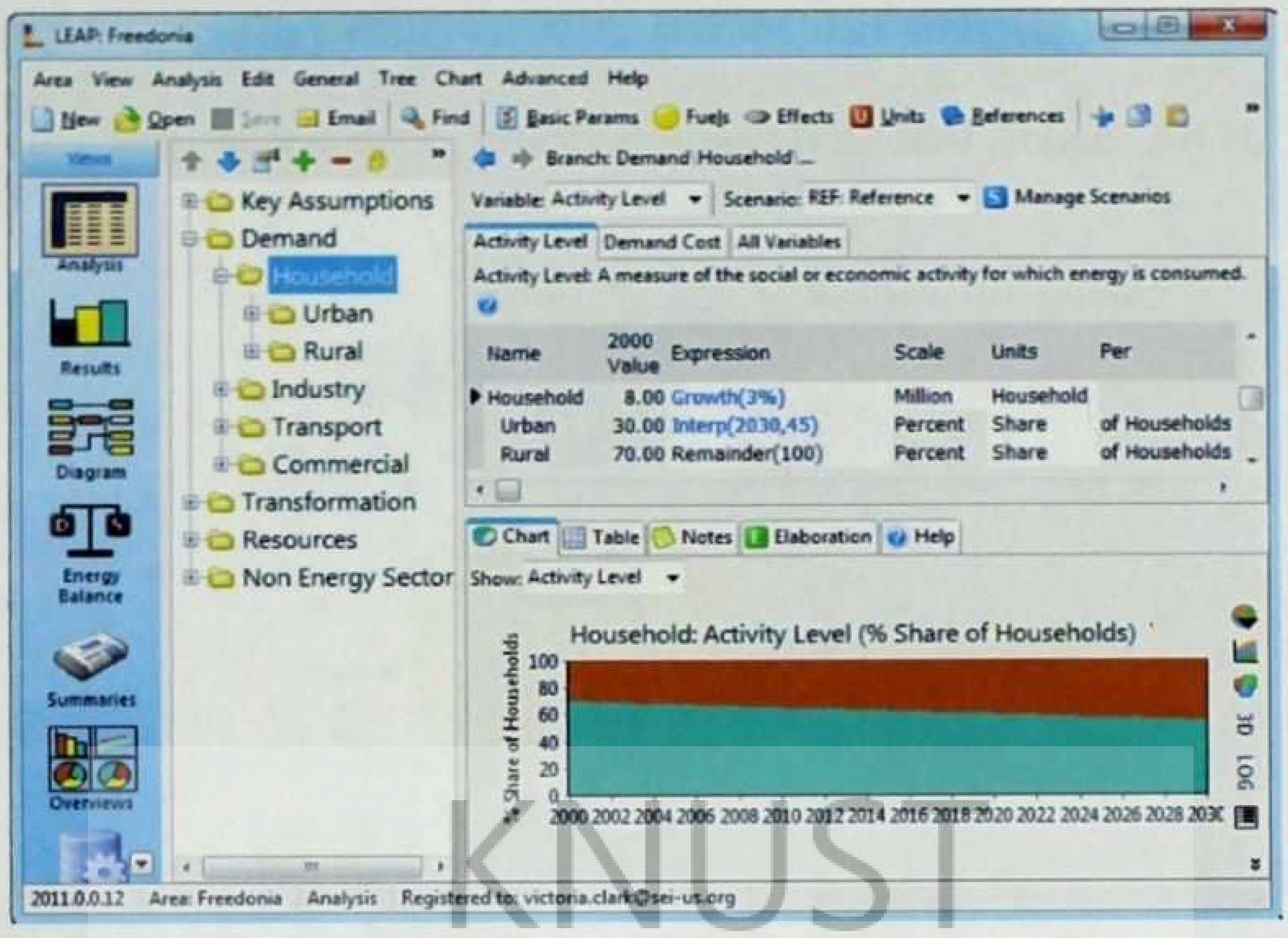


Figure 2.6: Screen shot of LEAP

Source: (Heaps, 2012)

2.2.2 PISCES Energy Delivery Model Tool

This tool has been developed to **stimulate discussion** and **reflection** on effective approaches to rural energy access. The tool highlights where particular combinations of energy sources, maintenance plans, management structures and financing may be incompatible, and provides targeted advice that can help practitioners to overcome the barriers to scaling-up projects and create a lasting impact. The programme creates a customised market map based on information entered by the user, allowing project designers and practitioners to better understand the wider environment that might affect the success of their project. The Energy Delivery Model tool is designed to provide preliminary analysis for planners and designers of new energy access projects, as well as to improve existing ones. Examples are provided documenting the options used by real energy access projects that have achieved success, allowing users to learn from the experiences of others.

The tool enables users to identify all of the stakeholders who will need to be involved in delivering energy access for a particular project (Practical Action, 2013).

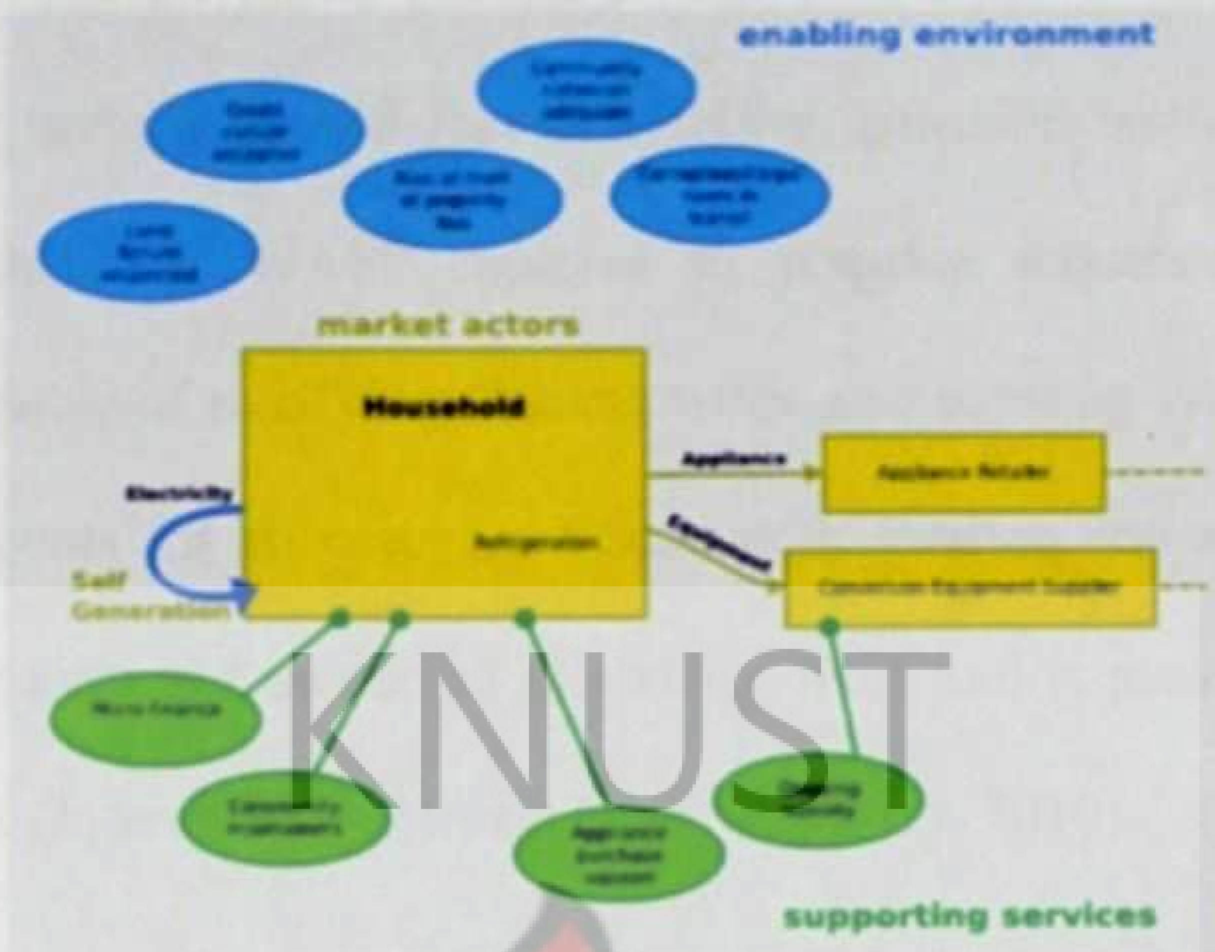


Figure 2.7: Screen shot of an output of the PISCES Energy Delivery Model Tool

Source: (Practical Action, 2013)

2.2.3 Model for Analysis of Energy Demand (MAED)

MAED evaluates future energy demand based on a set of consistent assumptions on medium to long term socioeconomic, technological and demographic developments in a country or a region. Future energy needs are linked to: (i) the production and consumption of goods and services; (ii) lifestyle changes caused by increasing personal incomes; and (iii) mobility needs, etc. Energy demand is computed for a host of end use activities for three main "demand sectors": household, services, industry and transport. MAED provides a systematic framework for mapping trends and anticipating change in energy needs, particularly as they correspond to alternative scenarios for socioeconomic development. (International Atomic Energy Agency, 2010)

2.2.4 Wien Automatic System Planning Package (WASP)

WASP is an exceptionally effective tool for power planning in developing countries. It defines 'optimal' power generation within constraints identified by local analysts, which may include limited fuel availability, emission restrictions, system reliability requirements, etc. WASP explores all possible sequences of capacity additions that are capable of satisfying demand while also meeting system reliability requirements. It accounts for all costs associated with existing and new generation facilities, reserve capacity and un-served electricity. This tool is provided under the auspices of the IAEA (International Atomic Energy Agency, 2010).

2.2.5 Simplified Approach for Estimating Environmental Impacts of Electricity Generation (SIMPACTS)

SIMPACTS is a user friendly model that estimates and quantifies the health and environmental damage costs, the so-called externalities, of different electricity generation technologies. It can be used for comparative analyses of fossil, nuclear and renewable electricity generation, sighting of new power plants or cost effectiveness of environmental mitigation policies. A key strength of SIMPACTS is that it already delivers useful results even when limited data are available. The model is provided under the auspices of the IAEA. (International Atomic Energy Agency, 2010)

2.2.6 Indicators for Sustainable Energy Development (ISED)

ISED framework is a series of 'snapshots' of ratios (indicators) reflecting the interaction of energy with the economic, environmental and social pillars of sustainable development over time. It provides a flexible tool for analysts and decision makers at all levels to better understand their national situations and trends, the impacts of recent policies and the potential impacts of policy changes. ISED was developed by the IAEA in collaboration with the UN Department of Economic and Social Affairs (UN DESA) and other partners (International Atomic Energy Agency, 2010).

2.2.7 Model for Energy Supply Strategy Alternatives and their General Environmental Impacts (MESSAGE)

MESSAGE combines technologies and fuels to construct so-called "energy chains", making it possible to map energy flows from supply (resource extraction) to demand (energy services). The model can help design long term strategies by analysing cost optimal energy mixes, investment needs and other costs for new infrastructure, energy supply security, energy resource utilization, rate of introduction of new technologies (technology learning), environmental constraints, etc. MESSAGE is provided by the IAEA (International Atomic Energy Agency, 2010).

2.2.8 Energy and Power Evaluation Programme (ENPEP)

ENPEP is designed to simulate the energy market clearing mechanism, with the aim of concurrently maximizing benefits to both producers and consumers. The model combines MAED and WASP results to determine the long term energy supply-demand balance through computation of market clearing prices and quantities. ENPEP is provided by the IAEA. (International Atomic Energy Agency, 2010).

2.2.9 Model for Financial Analysis of Electric Sector Expansion Plans (FINPLAN)

Financial constraints are often the biggest obstacle to implementing optimal energy strategies. FINPLAN clarifies the feasibility of electricity generation projects by computing important financial indicators while taking into account financing sources, costs, revenues, taxes, etc. It is particularly helpful for establishing the long term financial viability of projects by preparing cash flows, income statements, balance sheets and financial ratios. FINPLAN is provided by the IAEA (International Atomic Energy Agency, 2010)

2.2.10 Energy Access Interactive Tool (ENACT)

ENACT is an interactive web-based scenario analysis tool which allows the assessment of multiple energy access policies. It is designed to assist national and regional policymakers and analysts in their strategic policy planning processes to improve energy access for the rural poor in developing countries. It allows the assessment of different policies for achieving universal access to modern energy by 2030. The tool is used to visualize costs and benefits that each policy or combination of policies could bring. It thus enables analysts and decision makers to compare a large number of alternate energy access futures within a common framework. This allows them to gain a ~~quick~~ understanding of how alternate policies can shape the future of energy access in dramatically different ways. Among the information generated by the tool for each policy investigated are: funding requirements, potential policy effectiveness, the implications of the policy for energy demand, the policy's effect on greenhouse gas emissions and air pollution, as well as the impacts on health. (International Institute for Applied Systems Analysis, 2012). A screenshot of an output page for ENACT is shown in Figure 2.8

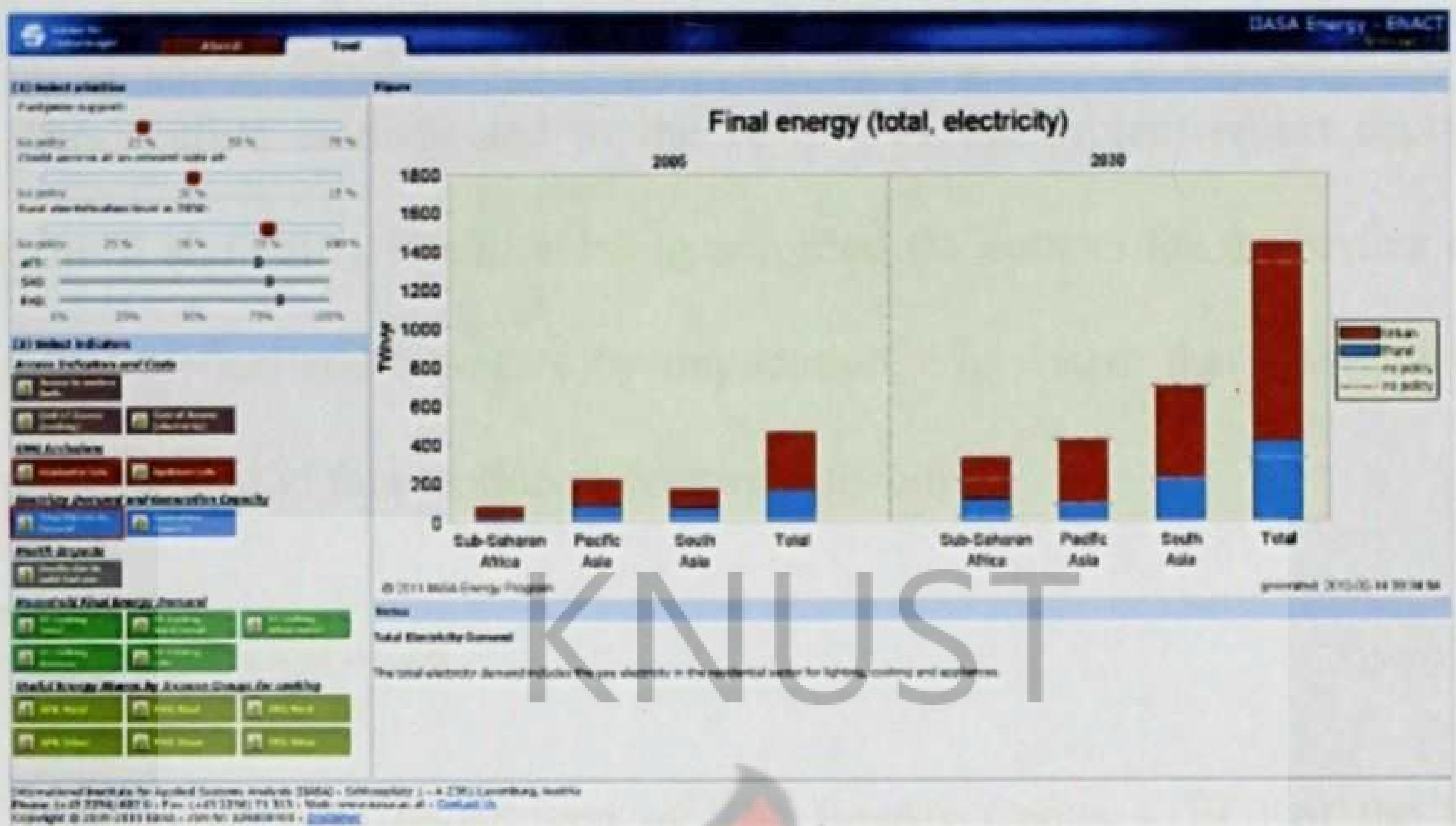


Figure 2.8: Screen shot of an output page for ENACT

Source: (International Institute for Applied Systems Analysis, 2012)

2.2.11 Network Planner (NP)

NP is a tool for grid, mini-grid and off-grid electrification planning with a particular emphasis on the kind of planning that is needed in countries that have low levels of electrification at present, and look towards rapid expansion. Network Planner is an online tool and can be used for electrification planning from the community to national scales (Modi Research Group, 2012). NP is discussed in detail in section 2.4.

2.3 REVIEW OF REPORT ON "GIS-BASED SUPPORT FOR IMPLEMENTING POLICIES AND PLANS TO INCREASE ACCESS TO ENERGY SERVICES IN GHANA"

This section is dedicated to the review of the project report captured in Kemausuor et al. (2010). Credit is being accorded the authors for the review of their work in this section and therefore by implication, every item that was culled from their work and used in this section is deemed duly cited.

2.3.1 Project Background

This project was undertaken by The Energy Center (TEC) of the Kwame Nkrumah University of Science and Technology (KNUST) with funding from the European Union Energy Initiative – Partnership Dialogue Facility (EUEI-PDF) to ensure timely cross-sectoral coordination of plans and data in energy access planning. The assessment sought to employ and complement existing policies, strategies, plans and recommendations from the Energy for Poverty Reduction Action Plan (EPRAP) and the Ghana Energy Development and Access Project (GEDAP) to achieve national goals and the MDGs. This was a pilot project whose results are intended to be replicated in other sub-regional countries of the Economic Community of West African States (ECOWAS). The work commenced in the year 2009 and was completed in the year 2010.

2.3.2 Project Objectives

The objectives of the project were:

1. To review existing energy policies, strategies and plans for increasing energy access in Ghana with reference to the targets set in the Government's policy statements/documents, the ECOWAS White Paper, and the MDGs.
2. To use GIS to collate and analyze national level data and provide timely information on population distribution, services, economic activities, and status of energy access programs.
3. To identify the gaps in energy policies and plans for achieving expected energy access targets by 2020 and proffer timely mitigation measures.
4. To develop methods and tools to facilitate business models, investment plans and capacity development to complement current planned activities to achieve the energy access targets by 2015.
5. To facilitate project identification, planning implementation and impact assessment for the Energy Commission of Ghana, the Ghana Ministry of Energy and the ECOWAS Commission for timely development, implementation and monitoring of energy access strategies.

2.3.3 Review of Energy Trends, Policies and Plans in Ghana

The project undertook an energy policy review to assess the trends, policies, plans and programmes developed over the years to ensure increased access to energy services in Ghana by 2020 and beyond. Highlights of the review are presented in this section. First, it was found that there has been a remarkable growth in electricity supply from the late 1990s as a result of the implementation of the National Electrification Scheme (NES) and later the Self Help Electrification Programme (SHEP) (under the NES). This has raised electricity access rates to about 72% in 2010 (Figure 2.9), a feat only rivalled by Cape Verde and South Africa in sub-

Saharan Africa, but with disparity in rural and urban areas. Disturbingly, biomass in the form of wood fuel, remain the most prominent fuel in Ghana for cooking and heating. Firewood and charcoal contribute about 63% to the total energy consumption of the country and is a major source of worry considering the effects on deforestation and the health problems associated with indoor pollution from the use of biomass. Even though some strides have been made in LPG consumption in urban areas, especially in the Ashanti and Greater Accra Regions, access to LPG is still lower than expected and even worse in the rural areas. Renewable energy has not made much contribution to the energy mix in Ghana. Gains in solar PV have been modest when compared to the country's potential. Wind energy and small hydro resources have not been exploited fully and biofuel programmes are still in the research and development stage (feedstock stage) with little to show in terms of the production of commercial fuels.

Ghana faces several challenges which frustrate efforts to achieve national energy access targets and goals. These challenges include growing demand for energy but with inadequate investment to match the demand, high levels of end-use inefficiency culminating in waste of final energy forms and inefficient pricing of energy services resulting in poor financial positions of the energy providers.

There have been several plans, policies and programmes aimed at increasing access to energy services in Ghana over the last few decades. Governments over the years have had the provision of energy services high on the developmental agenda but despite the good intentions of all these governments to increase access to energy services, existing policies and plans have not delivered the best results, especially in the rural areas. Policies aimed, especially at reducing biomass usage and promoting environment friendly cooking fuels, have achieved very little results.

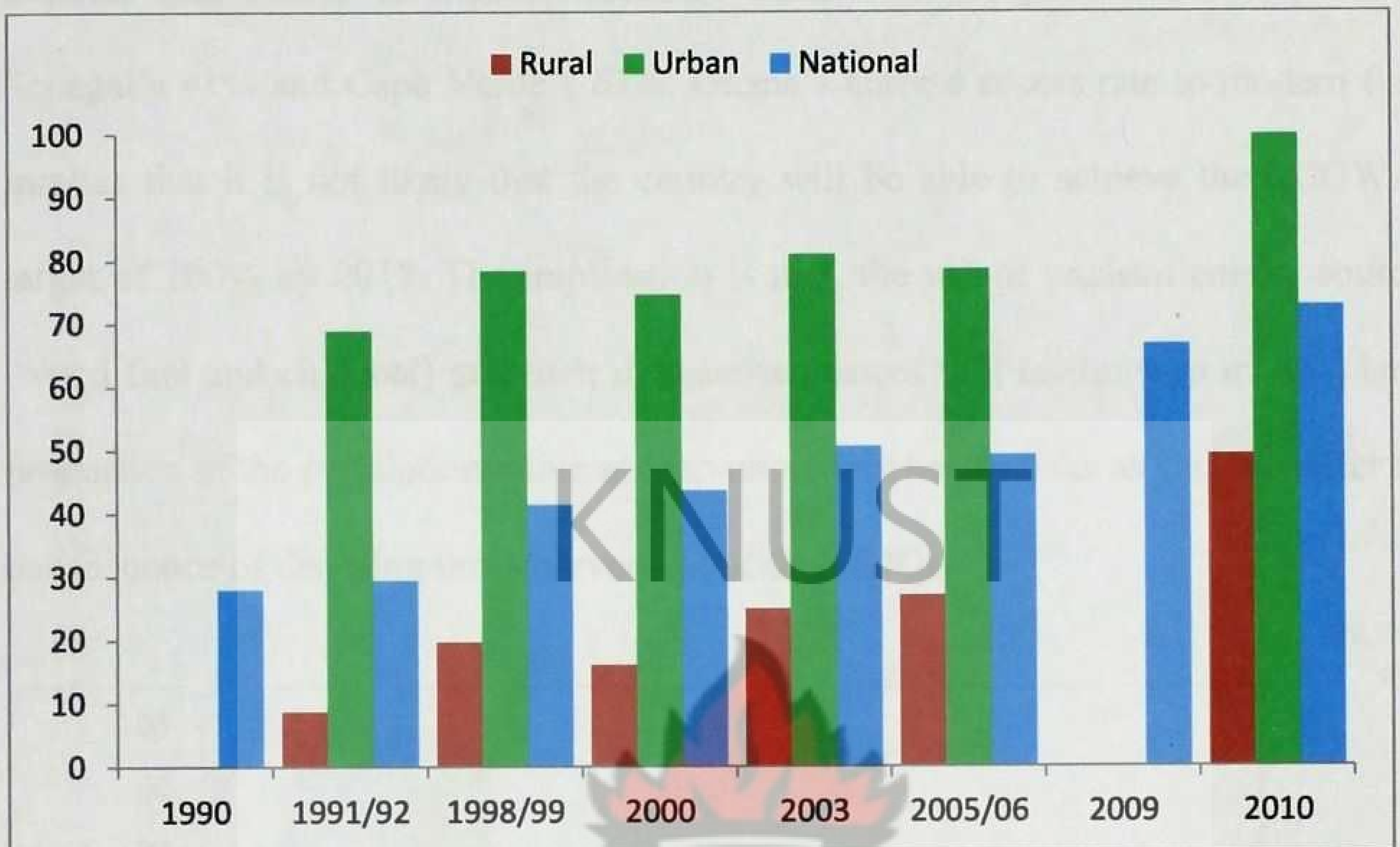


Figure 2.9: National, urban and rural electricity access rates for Ghana

Source: (Kemausuor, et al., 2010)

2.3.4 Assessment of Energy Needs and Comparison with ECOWAS targets and MDGs

A comparative analysis of the country's electricity access with ECOWAS targets reveals that, Ghana has made significant strides in its efforts towards the provision of electricity accessibility to its citizens. As of mid-2010, Ghana had surpassed the ECOWAS rural electricity targets of 36% access and is close to achieving the 100% urban access by 2015 (Figure 2.10). More so, Ghana is placed second to only Cape Verde in terms of electricity access in the ECOWAS and ranked higher than Nigeria, Cote d'Ivoire and Senegal given an estimated electricity access rate of 72% (percent of population) in 2010. However, Ghana's impressive electricity access rates have not translated into increased access to modern fuels for cooking and heating as countries like Cape Verde and Senegal. Access rates available for 2008 indicate that access to modern fuels in Ghana was only 12% as compared to Senegal's 41% and Cape Verde's 63%. Ghana's current access rate to modern fuels implies that it is not likely that the country will be able to achieve the ECOWAS target of 100% by 2015. The implication is that, the use of unclean energy sources (wood fuel and charcoal) and their dire consequences will continue to make a large proportion of the population vulnerable to numerous health risks as well as suffer the consequence of derailing the achievement of the MDGs.

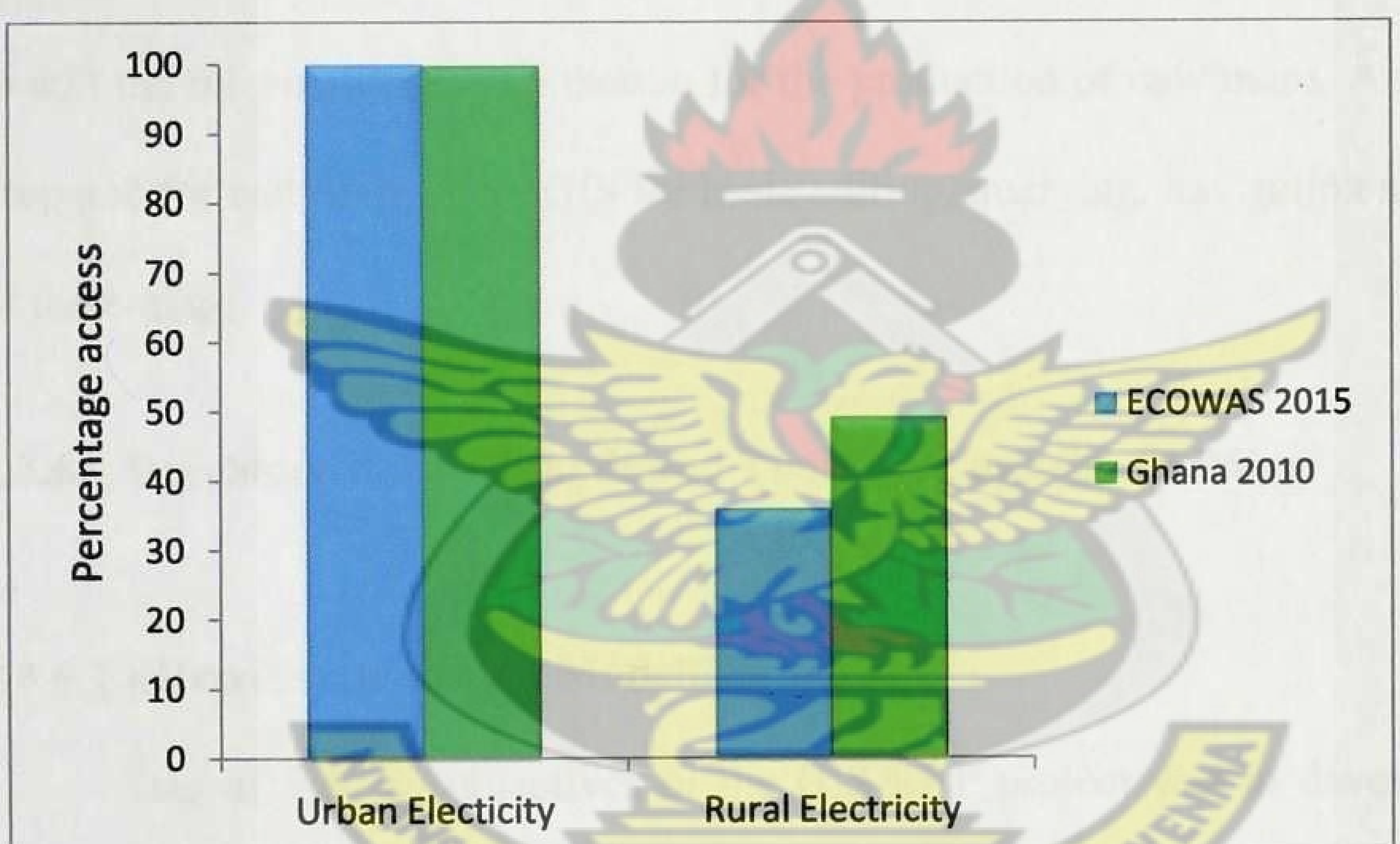


Figure 2.10: Comparing Ghana's electricity access rate with ECOWAS targets (Kemausuor, et al., 2010)

2.3.5 Development of GIS e-maps for Energy Services

Works undertaken by (Kemausuor, et al., 2010) in the development of GIS e-maps is summarized in this section of the thesis. The GIS e-maps were prepared for social services and amenities and the data mapped include Electricity Company of

Ghana substations, location of mini-hydro dams, potential wind sites, solar radiation, access to electricity in basic schools, access to electricity by hospitals and clinics and access to biogas. Geo-processing operations were carried out on the base maps using the WGS1984 UTM Zone 30N and 30S geographic projections. All the maps were exported to the JPEG format which can be opened on all computers with a picture editor or viewer. Immense effort was made to ensure that the data provided is very accurate and any apparent positional discrepancies between roads, railroads, forest reserves, rivers and town layers are due to the current Ghana Survey Department map accuracy that is available. To update and edit the developed GIS maps, any GIS software can be used. However specialized knowledge in GIS is required to be able to edit the information stored therein for the production of new maps. A manual was prepared for end users in ArcGIS for basic editing, querying, navigation and updating of the e-maps.

2.3.6 Development of Methods and Tools for Capacity Building

2.3.6.1 Electrification Costs Modelling

One of the key objectives of the GIS-EAP project was to develop methods and tools to analyse Ghana's energy access situation for capacity building of energy stakeholders in the country. The project team adopted a modelling tool called *Network Planner* developed by the Earth Institute of Columbia University to model electrification costs for un-electrified communities in the country. The network planner can be used to rapidly estimate connection costs and compare the energy economics for electrifying different regions and communities. The model determines the least-cost technology – either grid electrification or an off-grid alternative – to connect a community. The policy relevance of the model is to help planners estimate the investment requirements to support electrification programs and to identify opportunities for cost-effective grid expansion. Several input parameters were used in the Network Planner modelling exercise. These parameters are shown in Appendix A.

In this study, the year 2010 was chosen to be the base year with a time horizon of ten (10) years due to the country's energy target of universal electrification in 2020. All the input model data were acquired in 2010 except the population data of the un-electrified communities which were projected from the year 2000 to the year 2010 using a population growth rate proposed by the Ghana Statistical Services.

2.3.6.2 GIS-based Energy Access Review (GEAR) Toolkit

Proper re-structuring and the provision of up-to-date information on energy issues are needed to inform energy policy formulation. The GIS-Based Energy Access Review (GEAR) Toolkit (Figure 2.3) focused on the development of a platform that can enable users get information pertaining to electrified and un-electrified communities in Ghana. The Toolkit is intended to partly display results of the modelling exercise as well as LPG data in Ghana and show electrification trends in the country in order to facilitate planning.

The production of a digital map and a functional geo-database of the facilities proved useful for the adequate distribution of energy in the following areas: Creation of a geo-database (spatial/attribute) for the features for updating, based on their conditions; capturing of the geometric and attribute data of electrified and un-electrified communities; update and modification of information concerning facilities for electricity distribution such as electrified and un-electrified communities in

Ghana; faster and easier retrieval of information for instantaneous use in the area of planning, managing and monitoring of electrified communities as well as the trend of LPG access in communities.

Figure 2.11: GEAR Toolkit login interface

(Kemausuor, et al., 2010)

The GEAR toolkit allows a user or a planner to interrogate (query) the system to obtain a piece of information such as electrified and un-electrified communities with their corresponding spatial units. The system can also give a graphical report on electricity access rate for a community/town, district, and region or even at a national scale. Users of the program could be lay men, district planners, the utilities, Energy Commission, Ministry of Energy and their allied agencies.

2.3.7 Summary Results of The 2010 Study

The summary of the results obtained in the GIS-based energy access planning study is shown in this section. It was realized that the cost of electrification differs widely across the ten regions due to their varying socio-economic and existing grid situations. The Northern region had the highest level of "remoteness" whiles the Greater Accra Region had the highest concentration of people.

2.3.7.1 Results of Community Analysis

The results obtained from the analysis of the communities indicate that by the end of the ten (10) year period, the most cost-optimized option for majority of the un-electrified communities in each region will be grid connection, accounting for more than 70% of the total un-electrified communities in each region. This can be attributed to the extensive pre-existing grid network coverage over the country, which reduces the distances and thus the costs, to connect remaining communities. Among the two decentralized options, fewer un-electrified communities (6%) are designated for off-grid electricity (with two regions having no off-grid compatibility). It is worth noting that Northern region has the highest percentage of communities (20%) to be electrified by off-grid technology, followed by Upper West region (10%). The reason for these high values can be attributed to the low coverage of pre-existing grid network which results in high "remoteness" (defined as the distance from a community to the existing grid network) of the communities in these regions. Communities that are located far from the existing grid network tend to be electrified by any of the stand-alone options (Kemausuor, et al., 2010). The results are summarized in Table 2.1.

Table 2.1: Results obtained from the base scenario used for the 2010 study

Region	Number of un-electrified Communities	Percentage of each electricity technology recommended by the model to serve un-electrified Communities			Cost Of Off-Grid (US$) (10yr, initial + recurring)		Cost Of Mini-Grid (US$) (10yr, initial + recurring)		Cost Of Grid (US$) (10yr, initial + recurring)	
		Off-Grid	Mini-Grid	Grid	Total	Per HH	Total	Per HH	Total	Per HH
Ashanti	221	5%	15%	81%	3,121,441	3,563	8,320,534	3,224	49,685,160	2,213
Brong Ahafo	195	4%	21%	75%	2,562,549	3,564	10,327,660	3,255	48,416,833	2,152
Central	175	1%	3%	96%	401,384	3,431	2,229,429	3,101	54,516,496	1,886
Eastern	247	2%	6%	92%	1,701,894	3,598	3,540,105	3,192	44,607,487	2,120
Greater Accra	11	-	9%	91%	-	-	438,546	3,024	2,420,494	1,760
Northern	660	20%	10%	70%	28,575,697	3,491	16,451,983	3,302	102,249,319	2,397
Upper East	299	1%	1%	98%	706,083	3,395	939,066	3,109	59,990,598	1,882
Upper West	294	10%	9%	81%	7,709,352	3,378	7,009,443	3,229	54,001,590	2,252
Volta	179	2%	2%	96%	1,839,250	3,444	2,374,145	3,166	80,057,241	2,031
Western	319	-	6%	94%	-	-	5,997,600	3,334	95,648,882	2,126
High	660	20%	21%	98%	28,575,697	3,598	16,451,983	3,334	102,249,319	2,397
Average	260	6%	8%	87%	5,827,206	3,483	5,762,851	3,194	59,159,410	2,082
Low	11	1%	1%	70%	401,384	3,378	438,546	3,024	2,420,494	1,760

Source: (Kemausuor, et al., 2010)

2.3.7.2 Results of Levelized Cost of Electrification (LCOE) Analysis

Analysis was carried out to find out the levelized cost of connecting households in communities in the various regions of Ghana. The levelized cost of each electrification option is presented. Table 2.2 summarises the results obtained. From the table, it can be observed that the average levelised costs of grid electrification (US$ 0.57/kWh) is lower as compared to the levelised costs of the two decentralised technology options – diesel mini-grid (US$ 1.02/kWh) and solar off-grid (US$ 1.12/kWh). Here the levelised costs of each technology in each region represent the total cost of electrification of each technology including all recurring costs for the ten year planning duration, divided by the sum of all the electricity supplied in kWh of only those communities designated by each technology in each region.

Table 2.2: Regional levelized electrification costs

Region	Levelised Costs (US$ per kWh)		
	Off-Grid	Mini-Grid	Grid
Ashanti	1.15	1.04	0.61
Brong Ahafo	1.15	1.05	0.50
Central	1.12	1.01	0.51
Eastern	1.16	1.03	0.68
Greater Accra	-	0.97	0.56
Northern	1.10	1.02	0.66
Upper East	1.09	1.00	0.57
Upper West	1.08	1.01	0.67
Volta	1.11	0.99	0.38
Western	-	1.08	0.57
High	1.16	1.08	0.68
Average	1.12	1.02	0.57
Low	1.08	0.97	0.38

Source: (Kemausuor, et al., 2010)

It was observed that to a certain extent, the LCOE is inversely proportional to the total electricity demand. Higher demand typically justify investment in technologies that have higher initial costs, but lower long-run costs, at higher density, which tends to lower per unit costs of electricity delivery. This is typically true for the electricity grid: once a grid connection is established for communities, it is relatively inexpensive to provide power to that line, compared with solar and mini-grid, largely due to the high recurring costs of the stand-alone options (batteries for solar, and fuel for diesel).Stand-alone options can, however, have lower LCOE for some communities – particularly smaller communities, distant from the grid – where the high initial costs of grid extension will not prove cost-effective, even when averaged over several years.

2.3.8 Conclusions and Recommendations

The conclusions and recommendations of the study are summarised in this section. It was observed that Ghana made significant strides in electricity access due to long-range energy planning with clear targets, availability of external funding, political/popular demand and active role of central government in the implementation of energy policies. With urban electricity access rate of about 99% and rural access of 49%, the country has made a very good progress when compared with the ECOWAS target values of 100 for urban and 36% for rural households by 2015.

With the aid of electrification modelling, this project proposed that by the end of the ten year planning period (2020), the majority of un-electrified communities will be viable for grid expansion with some small percentage number being off-grid compatible. This is due to the Ghana's pre-existing network coverage reaching the whole country (at least running through every district capital in each region).

The need to ensure a proper integration of Solar PV and other renewable energy systems into electrification programmes at both national and sub-national levels was established. In some cases, as with most parts of Ghana, grid-connected solar PV systems can be employed so that the problems associated with the promotion of off-grid electrification options in soon-to-be-electrified areas would be avoided or at least reduced.

There is a need for more studies to generate a database for determining the pattern of energy access improvement over the years, challenges and prospects as well as the main drivers of energy access in the country. This will help provide useful information for accurate projections about how to achieve a certain time-bound access rate given certain sets of prevailing conditions especially in the case of access to LPG.

The project proposed the setting up of an Energy Access Data (EAD) Task Force. The intent of the proposed EAD Task Force is to facilitate the development of a shared database using harmonized methodologies on access to electricity and LPG in Ghana. The project directors recommended the formation of the EAD to the Minister of Energy and a forum for Energy-sector Board Chairs and CEOs and it was agreed that an EAD Task Force will be formed. The EAD Task Force will initially consist of the following agencies (with the power to co-opt additional members as needed):

1. Energy Commission (Convener and Chair);
2. National Petroleum Authority;
3. Volta River Authority /Northern Electricity Department;
4. Electricity Company of Ghana;
5. Ghana Statistical Service;
6. The Energy Center, KNUST
7. CERSGIS, University of Ghana
8. Ministry of Local Government & Rural Development (representing MMDAs).

The project recommended Msc/Mphil and PhD research works to address data gaps and to complement extant studies. The project also recommends further research into the energy demands by specific sectors of the economy such as health and education to facilitate sectoral energy access evaluation. In particular, it was recommended that further studies be undertaken on the availability of improved cook stoves in households and on the improvements made so far across the ten regions of Ghana.

2.4 NETWORK PLANNER

Network Planner is an online tool for planning Grid, Mini-grid and Off-grid electricity from community to national scale. (Modi Research Group, 2012). The tool is available online and is free of charge. However, there is a registration and account creation procedure that is required for all new users.

2.4.1 Source and Cost of Network Planner

Network Planner was designed by the Modi Research Group of the University of Columbia. The software is freely available as indicated above and is accessible through the website address: http://networkplanner.modilabs.org. The source code of Network Planner is freely available and accessible through a link on the Network Planner website. Currently, the source code is available at: https://github.com/modilabs/networkplanner. Figure 2.4 shows a screen shot of the home page of the Network Planner.

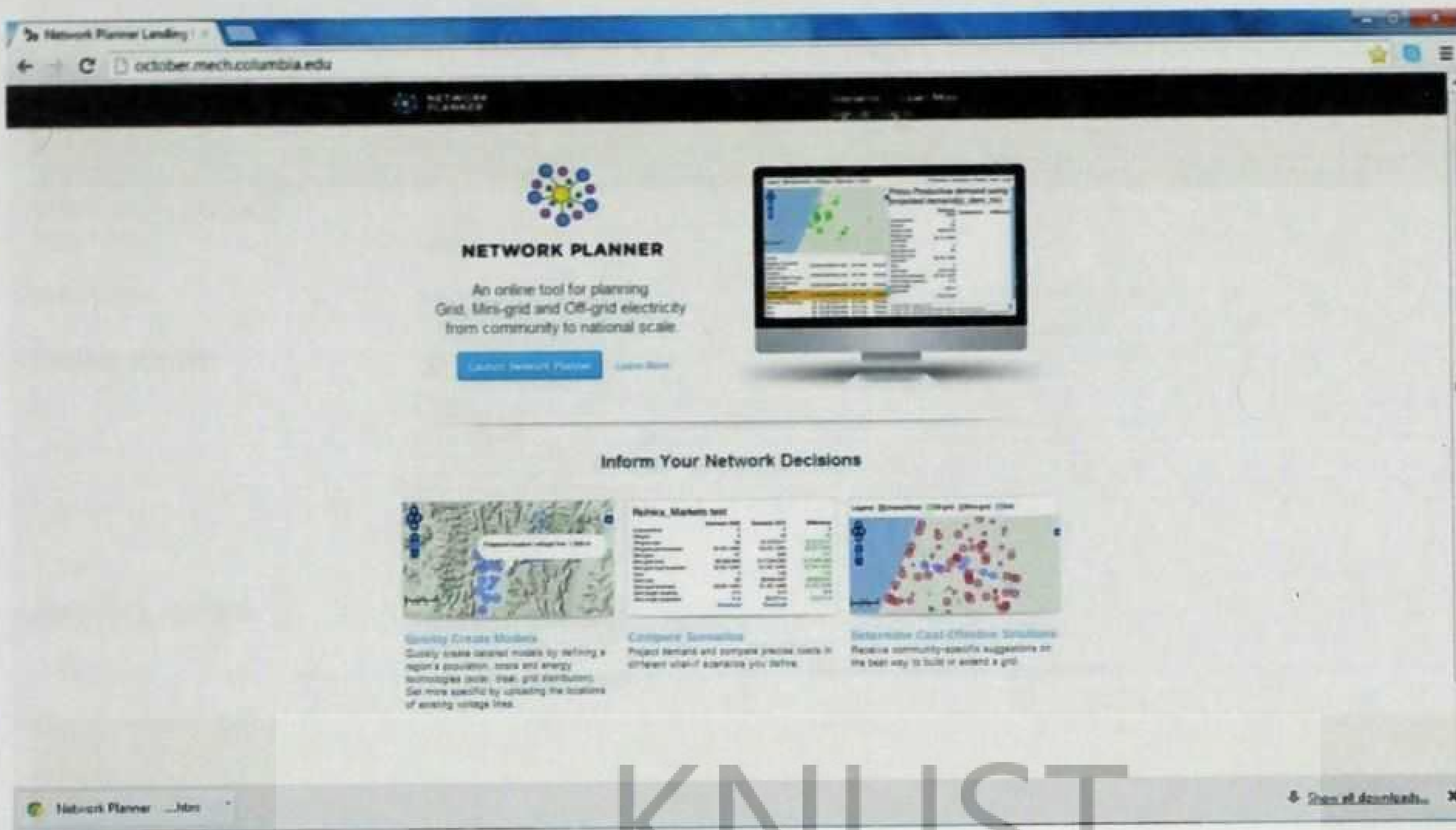


Figure 2.12: Screen shot of Network Planner home page

Source: (Modi Research Group, 2012)

2.4.2 Benefits of Network Planner

Network Planner has the following benefits:

1. Reduces planning time
2. Reduces cost of planning
3. Allows planners to use the amount of data presently available and build on their work when more data becomes available

2.4.3 How Network Planner is Used

To use the network planner software, one would first have to create an account by logging on to the home page of the software. After account creation, one can then create a new scenario to work with. The screen for creating a new scenario is shown in Figure 2.13.

Figure 2.13: Screen shot of new scenario page for Network Planner

(Modi Research Group, 2012)

At the new scenario page, several parameters will have to be chosen. First, the scenario is named. Second, one would have to choose a file in .shp format that contains location data of the area for which the electrification planning is to be done. Next, a metric model is chosen. There are two models: mvMax3 and mvMax2. Various parameters under the categories of Finance, Demographics, Demand, Distribution and System are then filled in. An appropriate network model is then selected. Next, a shape file containing the existing electricity infrastructure for the area under consideration is then uploaded. After, an algorithm for the scenario is chosen. Finally, the "Add this scenario to the queue" button on the scenario landing page is clicked for the new scenario to be added to the network planner processing queue. After processing, the work would then be available for viewing, cloning, or downloading. (Modi Research Group, 2012). Figure 2.14 is an example of a results page.

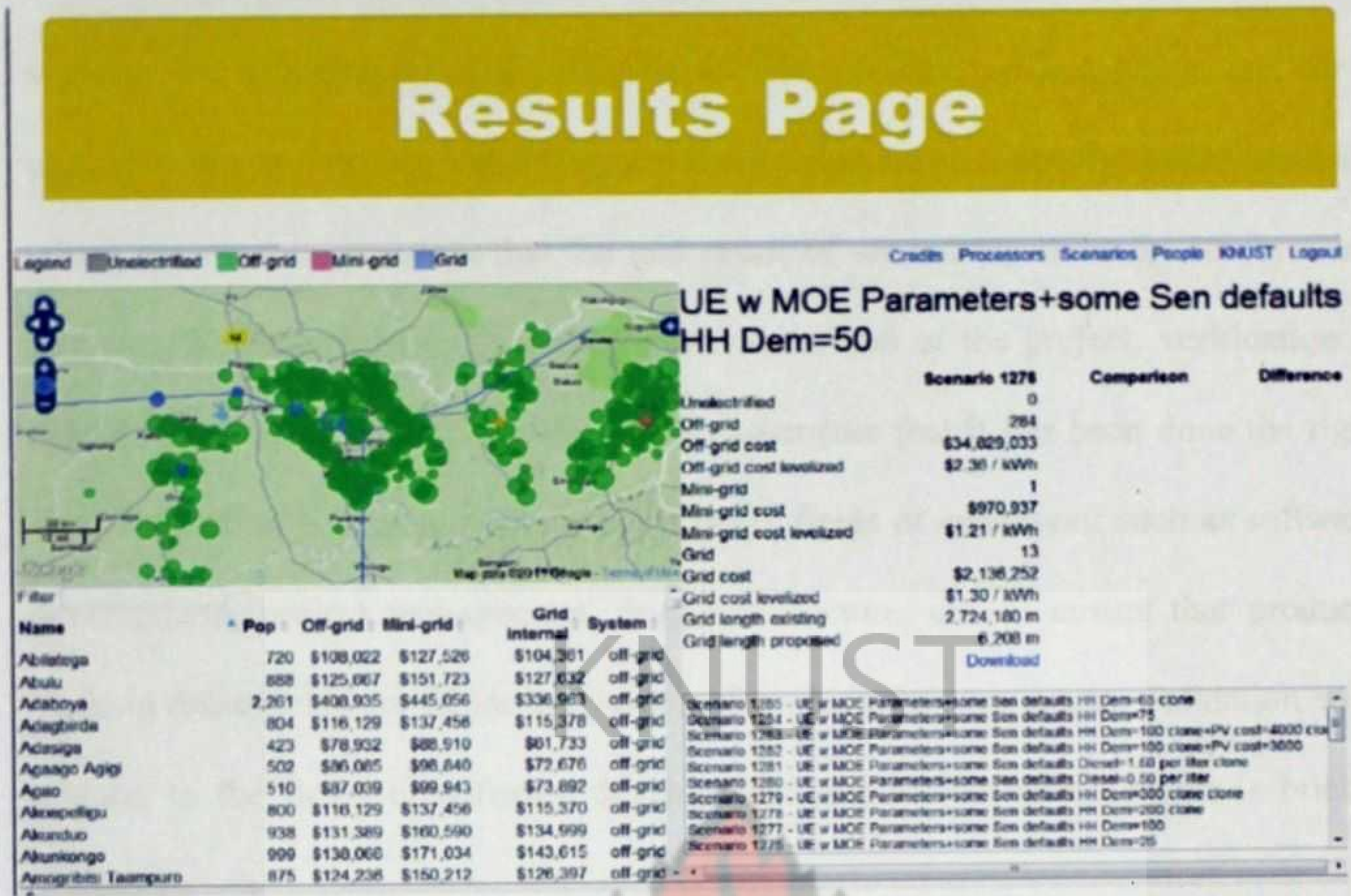


Figure 2.14: Screen shot of Network Planner result page

Credit: (The Energy Center, KNUST, 2011)

2.5 VALIDATION

The Collins Dictionary defines validation as "the act of confirming or corroborating something". It also defines validation as "the act of proof or confirmation that someone or something is valuable or worthwhile" (Collins, 2012). The ISO 9000 standard deals with Quality Management. Section 3.8.5 of this standard defines validation as follows:

> Confirmation, through the provision of objective evidence, that the requirements for a specific intended use or application have been fulfilled.
>
> NOTE 1: The term "validated" is used to designate the corresponding status.
>
> NOTE 2: The use conditions for validation can be real or simulated. (ISO, 2005)

Validation usually involves a process by which we are able to confirm the veracity and authenticity of a particular service, product, project, thing, etc. for a particular use or purpose. Validation and verification are two closely related methods which are used to ascertain that the end result of an activity is fit for its intended purpose. Whiles validation is usually done at the end of the project, verification is usually done concurrently with the activity to ensure that it has been done the right way. Validation is usually undertaken in many fields of endeavour such as software development, project management, drug manufacture, etc. to ensure that products made in these fields are fit for the purpose for which they are made. Validation with relation to the fields of software development and project management is briefly discussed.

2.5.1 Validation: - Software Development

According to (Boehm, 1979), validation is the process to establish the fitness or worth of a software product for its operational mission. Validation is also defined as: "The process of evaluating a system or component during or at the end of the development process to determine whether it satisfies specified requirements." (Insititute of Electrical and Electronic Engineers (IEEE), 1990). Verification and Validation are independent procedures that are used together for checking that a product, service, or system meets requirements and specifications and that it fulfills its intended purpose. These are critical components of a quality management system such as ISO 9000. The words "verification" and "validation" are sometimes preceded with "Independent" (or IV&V in symbols), indicating that the verification and validation is to be performed by a disinterested third-party. In software project management, software testing, and software engineering, verification and validation

(V&V) is the process of checking that a software system meets specifications and that it fulfills its intended purpose. It may also be referred to as software quality control. It is normally the responsibility of software testers as part of the software development lifecycle.

2.5.2 Validation: - Project Management

As part of efforts to deliver quality outcomes, project managers usually undertake validation as part of their project management efforts. The Project Management Body of Knowledge (PMBOK) Guide -4th Edition, defines validation as "The assurance that a product, service, or system meets the needs of the customer and other identified stakeholders. It often involves acceptance and suitability with external customers" (Project Management Institue, Inc., 2008).

Validation is one of the most important phases of project management. The process of validation may occur as a single step or in multiple steps at different stages of the project and is used to determine if the project is meeting specifications. Specifications for projects are usually detailed and it is up to the project manger to evaluate the validation process to be sure the project is meeting the requirements. Experience in project management can assist supervisors in evaluating the different phases and steps of validation. The validation procedure helps advance the project by measuring the progress ~~of delivery~~ of the expected outcomes. (Project Management Knowledge, 2007-2010).

CHAPTER 3 - METHODOLOGY

3.1 INFORMATION AND TOOLS ACQUISITION

A plan of action was implemented to enable the acquisition of all the necessary information and tools for the validation exercise. These included face to face meetings, online discussions, acquisition of related software, and literature review. Highlights of some of these activities are presented in the next sub-sections.

3.1.1 Infrastructure Preparation

To enable the smooth execution of this thesis work, a conscious effort was made to ensure that the necessary tools for the work were acquired. A windows based laptop with appropriate word processing software was acquired and folders were created on it for storing and organizing data and information. Other necessary software such as Adobe Reader were also installed. The Zotero software was initially used to aid in citing and referencing the works of other authors. Later, the inbuilt referencing tool of Microsoft Word was used for referencing. Word Processing was also done in Microsoft Word. The use of Network Planner is discussed in the next paragraphs.

A Network Planner log in account was created for use in this thesis work. The account was created by logging in to the Network Planner website at: http://networkplanner.modilabs.org/. A screen shot of the website is shown below:

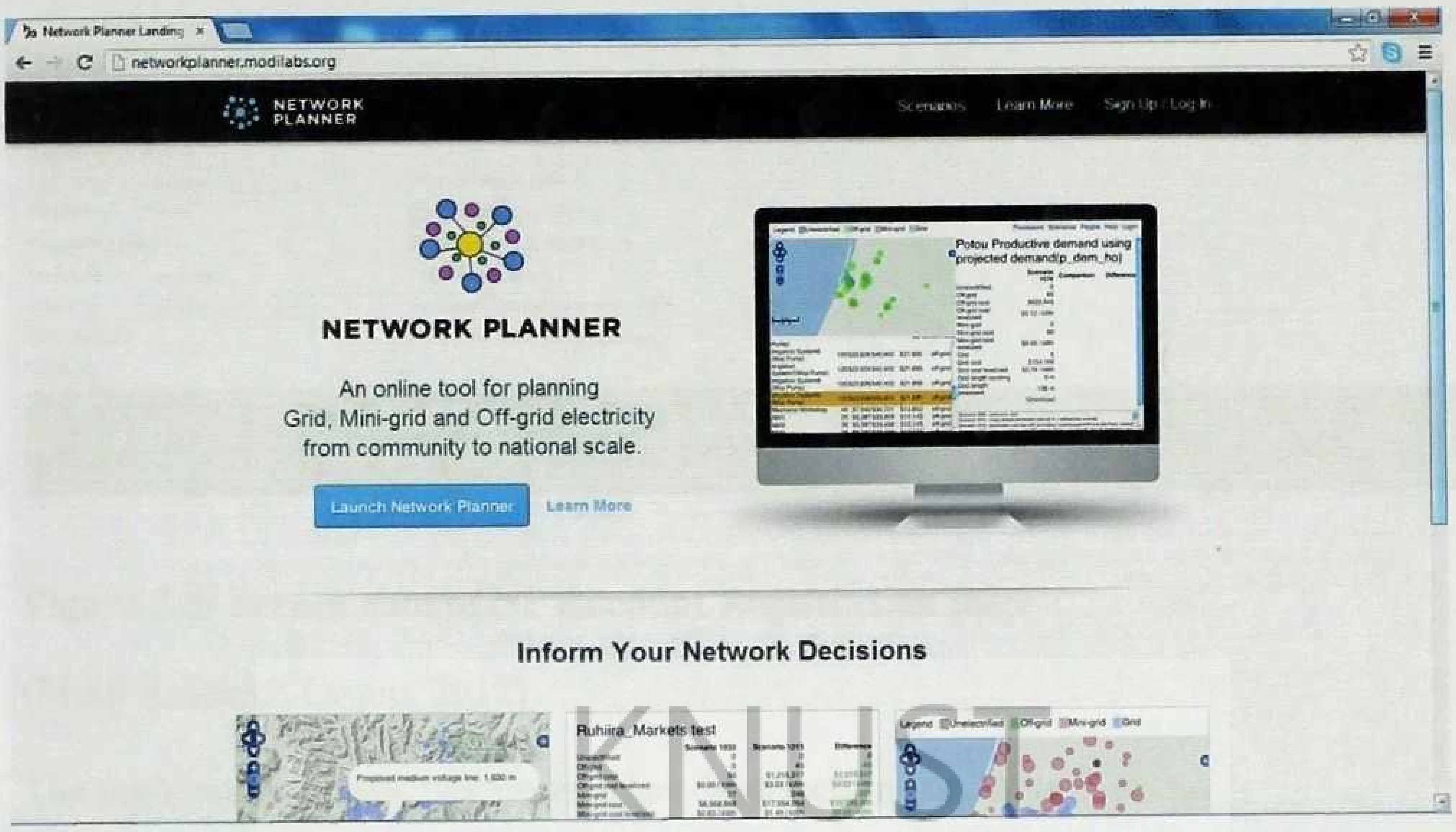


Figure 3.1: Screen shot of Network Planner home page

Source: (Modi Research Group, 2012)

At the homepage, a new account was created by first clicking on the link "Sign Up/Log In" which was located at the upper right corner of the web page. A new page then opened to allow for registration of new users or for log in of old users. A snapshot of the page is as shown in Figure 3.2. The "Register for an account" link on the page was then clicked.

Figure 3.2: Screen shot of NP Account Registration and Login page

(Modi Research Group, 2012)

The new page that opens after the "Register for an Account" link is clicked is shown in Figure 3.3:

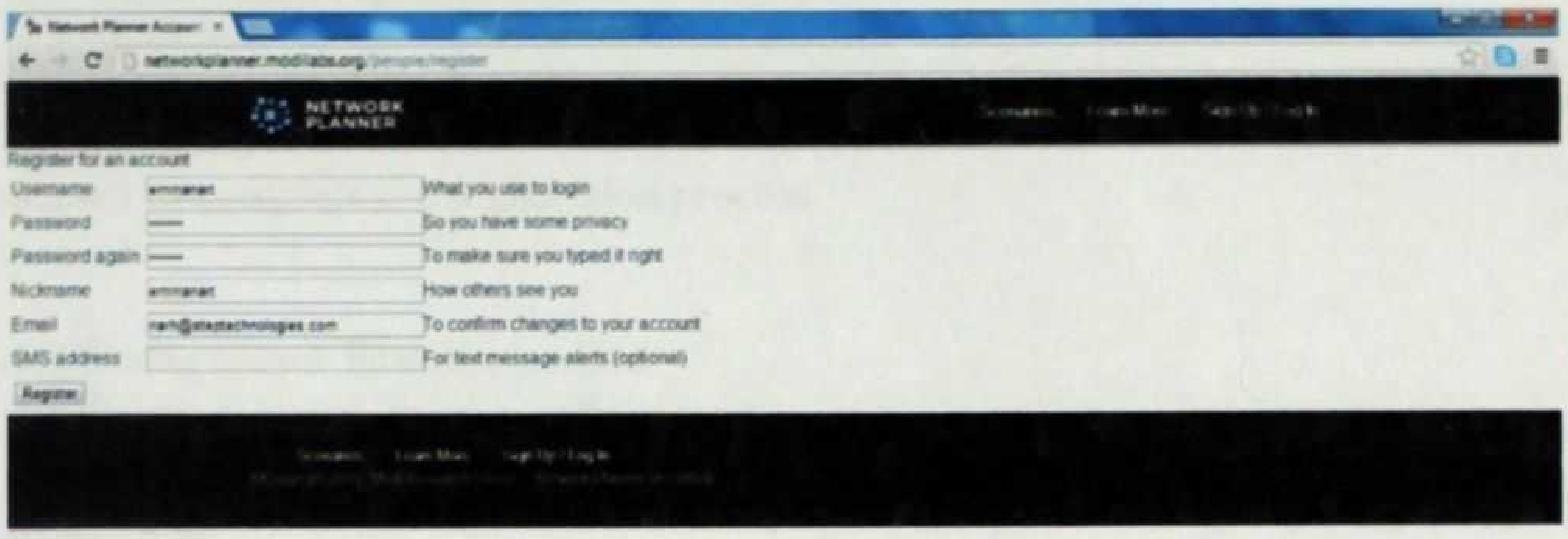


Figure 3.3: Screen shot of NP Account Registration page

(Modi Research Group, 2012)

The registration details were entered as described in the Table 3.1:

Table 3.1: Description of how Network Planner Registration Details were entered

Number	Registration Parameter	Comments on Parameter
1	Username	At least a six (6) digit alphanumeric character was required.
2	Password	At least a six (6) digit alphanumeric character was required.
3	Password again	The same password entered under "Password" was re-entered.
4	Nickname	At least a three (3) digit alphanumeric character was required.
5	Email	A valid email was required
6	SMS address	Error: "An email address must contain a single @" always appeared when a phone number was entered. This field was therefore left blank.

The final step in the registration process involved email confirmation. A message was sent from the NP support team. A confirmation link in the mail was assessed to complete the registration process.

3.1.2 Background Familiarization

To get a firm grasp of the GIS-based Energy Access Planning project which this thesis work seeks to validate, a lot of background familiarization activities were undertaken. These included meetings, familiarization runs of NP and literature review.

3.1.2.1 Consultative Meetings

The first set of familiarization meetings were facilitated by Mr. Daniel Ladzagla, one of the members of the project whose work this thesis is validating. The meetings were held in the third week of June 2012 within a span of one week, at The Energy Center, KNUST-Kumasi. Other participants of the meeting were three (3) other MSc in Renewable Energy Technologies (RETs) students who are working on related thesis topics. The meetings provided a good introduction to the whole concept of the project, the results that were obtained, challenges that were encountered, amongst others. During these meetings, we were able to create user accounts for NP, go through the parameters that are required to run the NP energy model, and also to do some trial runs with the NP platform. The meetings also afforded the participants an introduction to the GIS-GEAR Toolkit which was developed by Mr. Daniel Ladzagla, the facilitator of the meetings who happens to be an associate member of The Energy Center. Specifically, an introduction was given on how the results of NP can be further utilized and analyzed using the GIS-GEAR Toolkit. In the later stages of this study, consultations were made with Mr. Francis Kemausuor, Fellow of The Energy Center and Isaac Adu-Poku, an associate member of The Energy Center who helped with information and guidance on various aspects of the study being validated.

3.1.2.2 Familiarization Runs of Network Planner

Apart from the consultative meetings, further action was taken to get a firmer grasp of the NP energy planning software. The various parameters that were necessary as inputs to the NP energy model were looked at. Time was also taken out to appreciate the various features of the NP software. A cursory look at the NP documentation was taken in order to get a good overview of the perspectives of the Modi Research Group, the providers of the NP solution, on the NP platform. A screen shot of one of the test runs of NP is next shown.

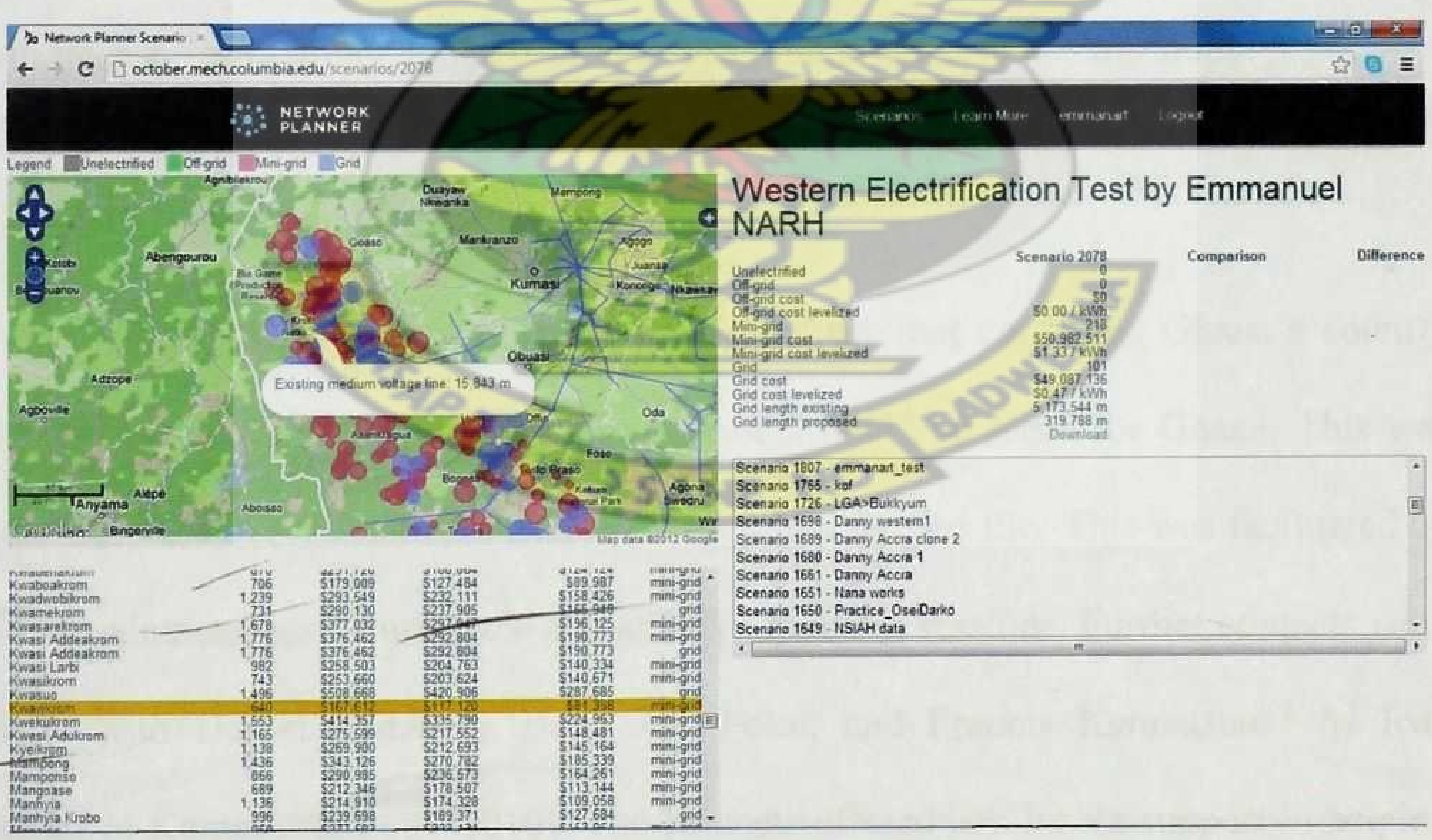


Figure 3.4: Screen shot of a NP Familiarization Run

(Modi Research Group, 2012)

3.1.2.3 Literature Review

Information gathered from the consultative meetings helped in identifying the essential materials for further literature review. The main document that was reviewed was Kemausuor et al (2010). The full title of this document is "GIS-Based Support for Implementing Policies and Plans to Increase Access to Energy Services in Ghana". It was published by the European Union Energy Initiative – Partnership Dialogue Facility (EUEI PDF) in Germany. This document details the project which this thesis seeks to validate; hence much of the initial literature review focused on it.

The works of various other authors were also considered. Materials were sought to help understand the Energy Access situation in Ghana and other developing countries, particularly in Sub-Saharan Africa. Further research was also made to understand the various Energy Access Planning methods that were being used worldwide and especially in Ghana. Work was also done to seek out materials that will help in formulating an appropriate validation procedure for this study.

3.2 REBUILDING OF DATABASE

There was the need to rebuild the database that contained Ghana's country data before the Network Planner energy model could be rerun for Ghana. This was necessary to have the data for Ghana collated in a unified file. This was facilitated by earlier contacts made during the consultative meeting sessions. Further contacts were made with Daniel Ladzagla, Isaac Adu-Poku, and Francis Kemausuor, the lead author of Kemausuor et al (2010). The contacts offered invaluable support in helping to collate and rebuild the database for the work.

A software tool was used to aid in comparing different versions of the database during the rebuilding exercise. The database used was in Microsoft Excel format. However, Microsoft Word Excel 2007 and other currently available versions do not have a file compare feature. This necessitated a search for a third party add on or a full featured software to do the comparisons. One of such tools was 'Synkronizer', an add on for Microsoft Excel. The free version of this tool could only compare data within the range: A1:Z100. That is, data which fits into twenty six (26) columns by hundred (100) rows. A screen shot of the Synkronizer tool with the data comparison limitation message is shown below:

Figure 3.5: Screen shot of 'synkronizer' Software

Due to the limitation of the 'synkronizer' software, alternative comparison software was sought. Tools that were given consideration included 'Beyond Compare', 'Diff Doc', 'Compare It!', 'Merge' and 'Compare It!' (AKS-Labs, 2000 - 2012). In the end, the 'Compare Suite' software was chosen and used in the database comparison exercise. Below are selected screen shots from the usage of 'Compare Suite' in the database comparison and rebuilding exercise.

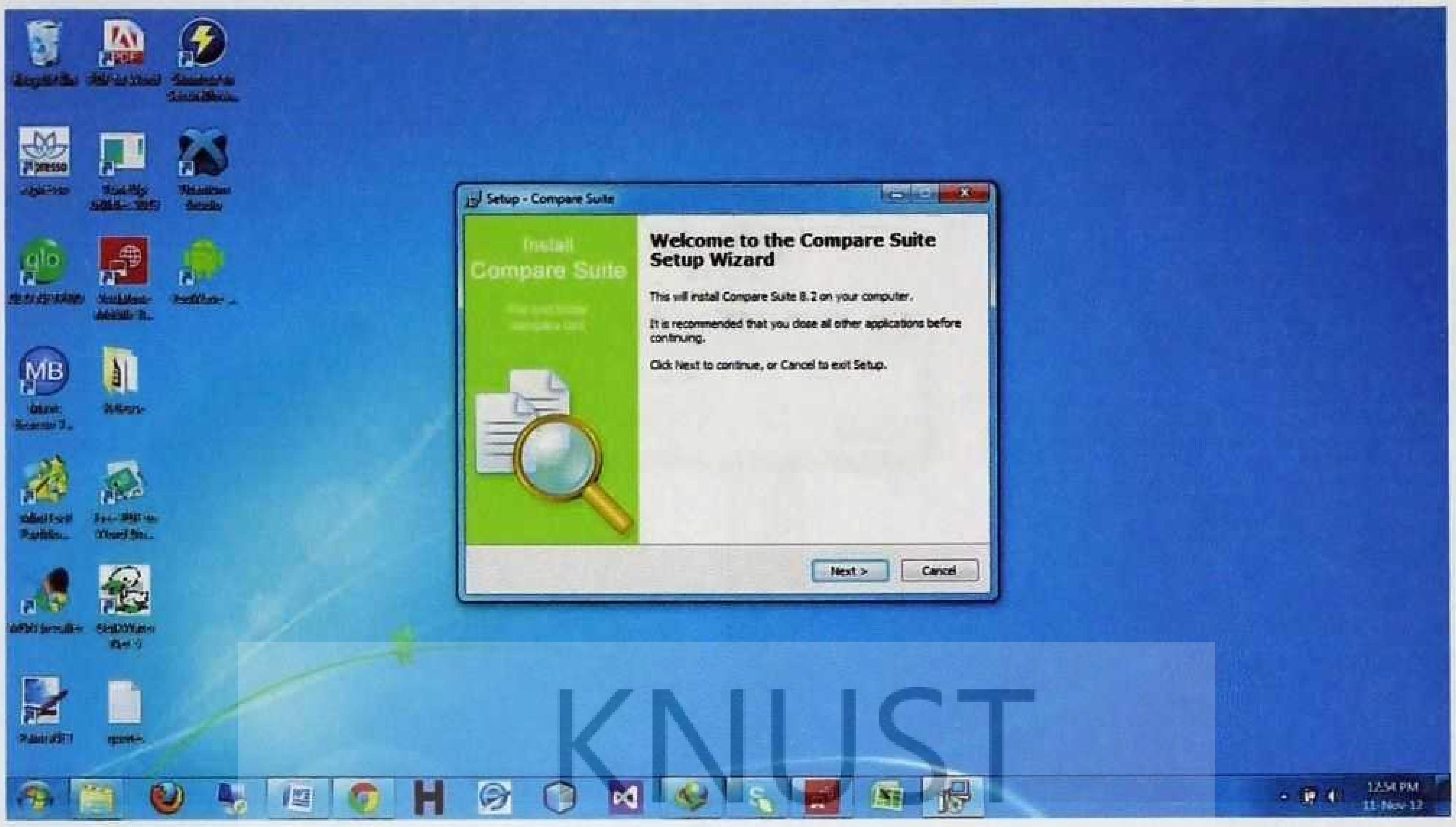


Figure 3.6: Screen shot of 'Compare Suite' Software Installation

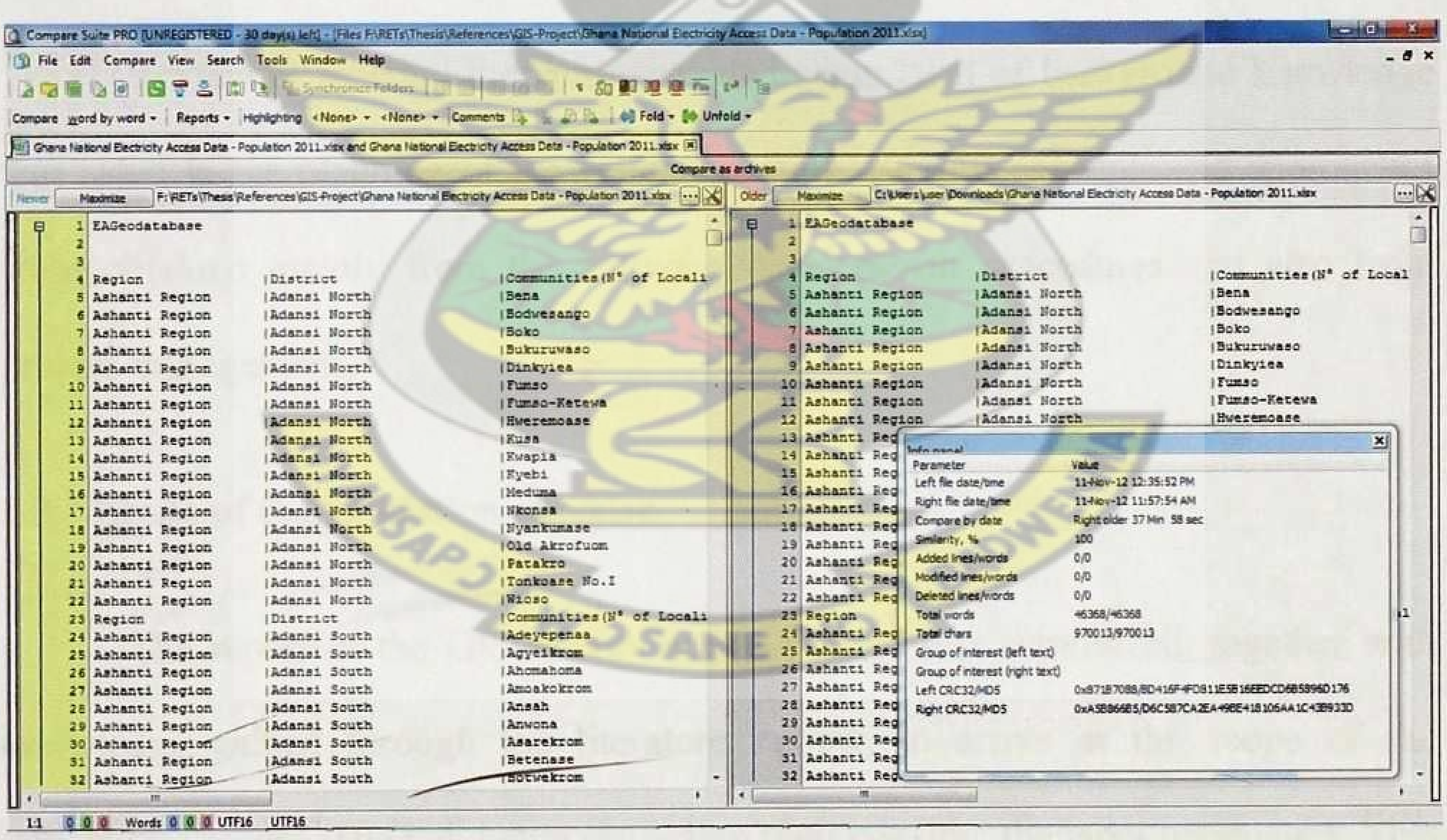


Figure 3.7: Screen shot of Two (2) databases loaded into 'Compare Suite' for Comparison

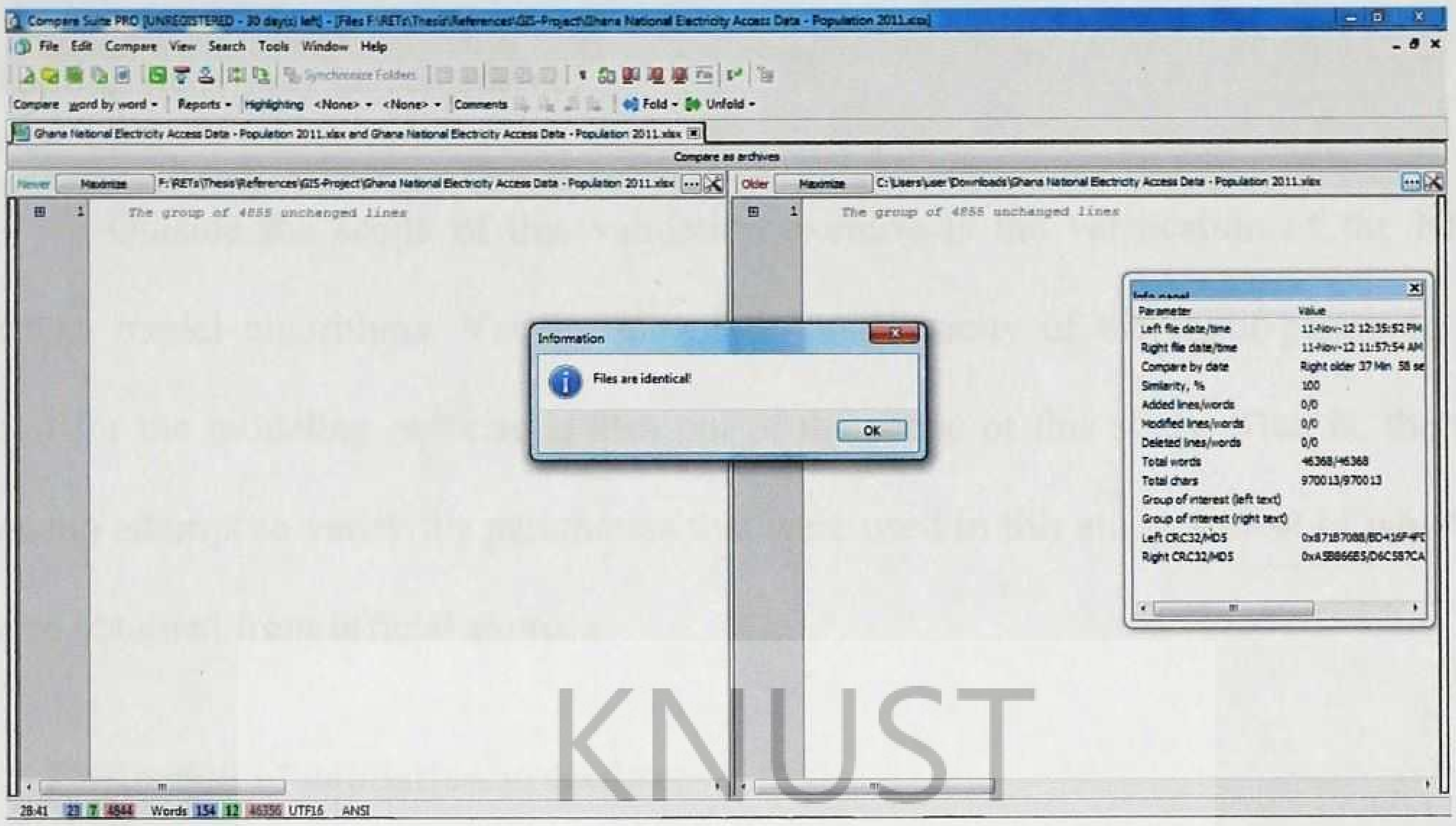


Figure 3.8: Screen shot of results of a database comparison exercise

3.3 Planning of the Validation exercise

Review of existing literature provided some level of background knowledge that aided in the planning of the validation work. Several concepts and approaches were obtained mainly from the software development procedures and also from project management.

3.3.1 Scope of the validation exercise

The report of the GIS-Energy access project was scrutinized, together with knowledge gained through the literature review, to arrive at the scope of the validation process. The validation procedure shall consider the input parameters. This shall include several processes to verify the integrity of the input data used for the modeling exercise. This is one of the most important procedures of this exercise. As the jargon goes “garbage in, garbage out”. The results was also be compared to verify the ‘consistency’ of the NP energy model. Other factors that will be seen to have an effect on the reliability of the results of the GIS-based energy access planning study may be considered.

Outside the scope of this validation exercise is the verification of the NP energy model algorithms. Verification of the authenticity of the input parameters used for the modeling exercise is also out of the scope of this study. That is, there was no attempt to verify the parameters that were used in this study – most of which were obtained from official sources.

3.3.2 Selection of validation procedure

Various techniques were employed in ascertaining the reliability of the results of the study under validation. Computer analysis, desktop research, and other related means were employed in the validation process. Tools such as Microsoft Excel and other software packages were used.

3.4 VALIDATION

Input Parameter Validation

Various checks were performed on the input parameters used for the modeling exercise. These included: checking to see if the parameters entered in the modeling exercise are the same as those provided on the default parameter sheet, if the parameters were consistently used across the various runs, and if all values used were properly communicated in the final report.

3.4.1.1 Data Entry Verification

The input variables used for the 2010 study were scrutinized per the list of input variables given in the demand parameter list which is shown in Appendix A. A sample screen shot showing the comparison of the Finance parameters is shown below. The left window shows the expected values whiles the right window shows the actual parameters that were used in the 2010 study.

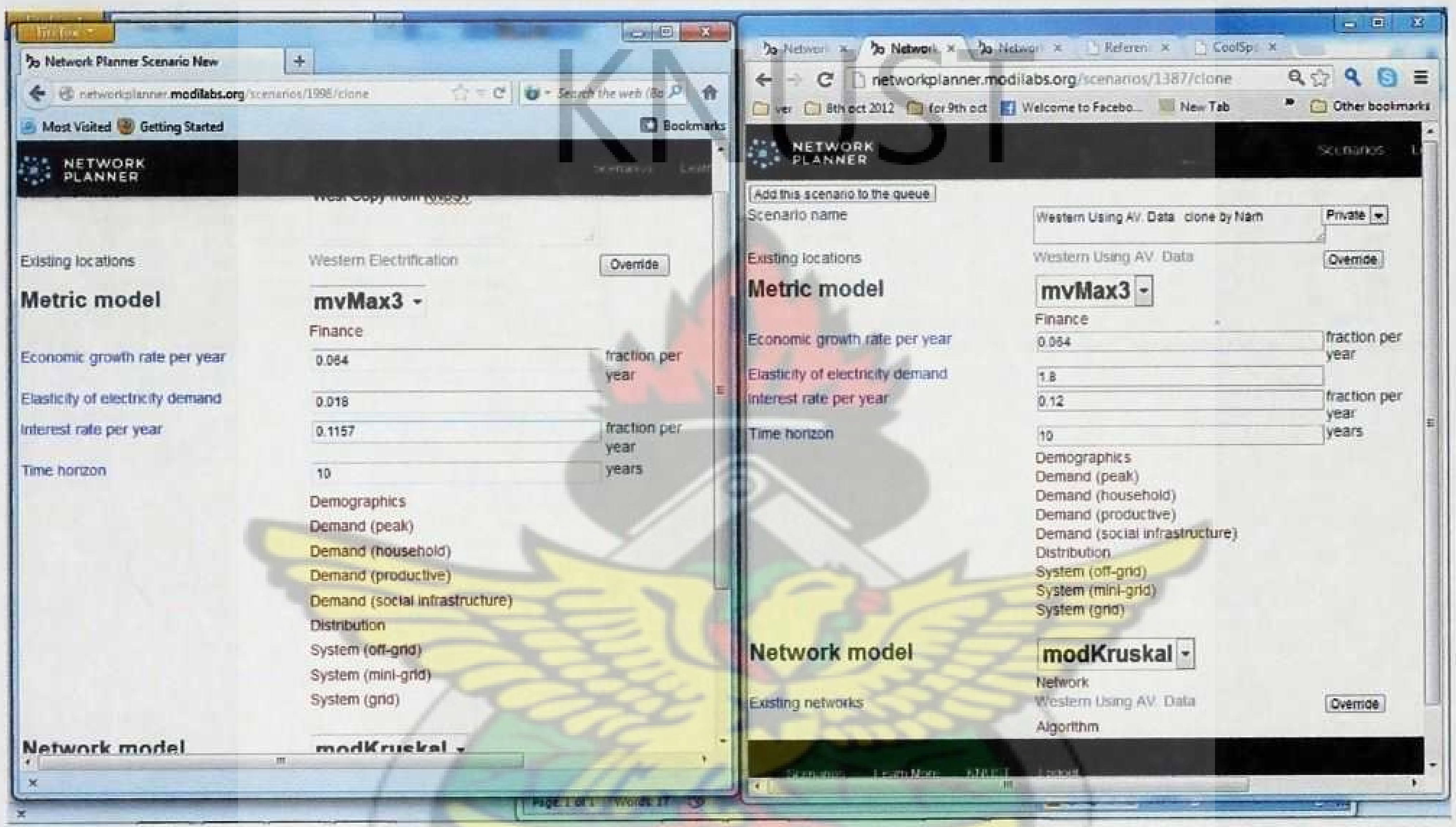


Figure 3.9: Screen shot showing verification of Finance input parameters

3.4.1.2 Verification of consistency of Input variables across the various runs

Tests were carried out to check if the input parameters entered in the various runs were uniform, with the exception of those values that were deliberately changed. To achieve this, input values from runs of four (4) different regions from different runs were compared. For each region, two (2) communities were chosen at random. The output data from the NP planner that contains the input variables is a large file that has a total of one hundred and eighty (180) Excel columns. To analyze this, an excel formula was developed that checked the values and flagged columns that contained values that were not identical. The formula that was used for checking the Economic Growth Rate per Year is shown below for illustration:

=IF(OR((G3<>G4),(G4<>G5),(G5<>G6),(G6<>G7),(G7<>G8),(G8<>G9),(G9<>G10)),"CHECK","")

A screen shot of the Excel sheet used is shown in Figure 3.11

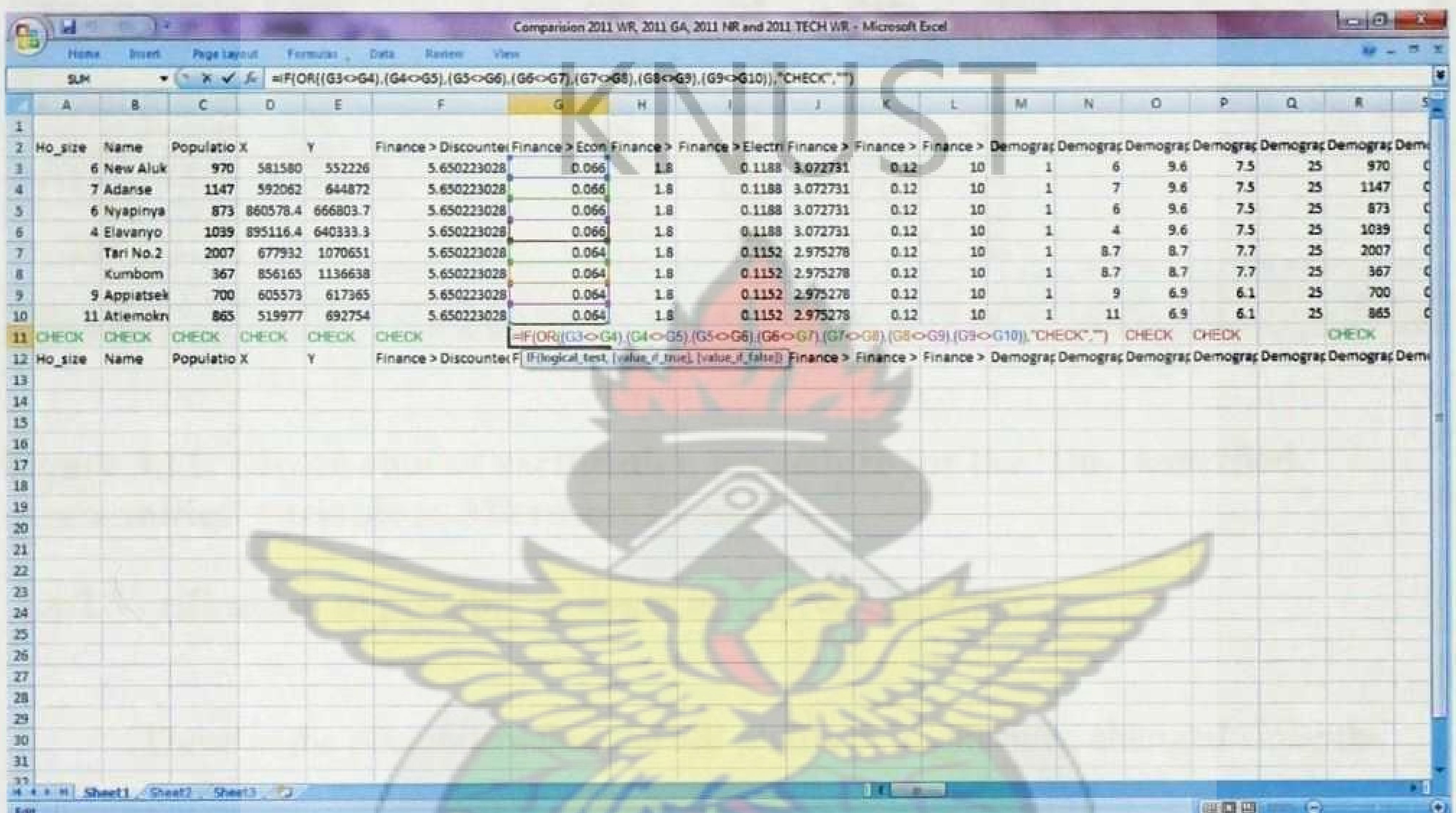


Figure 3.10: Screen shot illustrating process used to verify consistency of input variables across runs of the NP energy model

3.4.1.3 Verification of Input Value: Un-Electrified Communities

To verify the input data that was used for each community for the variable "Un-Electrified Communities", an excel formula was used. The excel formula used has the syntax: **COUNTIF (Range, criteria).** Where 'Range' is the Excel sheets where the validation is to be made and criteria is the criteria to be used. For the specific instance of Ashanti Region, the formula used was:

=COUNTIF (F1:F579, "Unelectrified").

A screen shot of a sample verification sheet is shown in Figure 3.11:

	A	B	C	D	E	F	G	
563	Ashanti Region	Sekyere East	Oguaa	686647	751787	Electrified	816.8376419	
564	Ashanti Region	Sekyere East	Okaakurom (Okaikurom)	685567	755081	Electrified	2383.231575	
565	Ashanti Region	Sekyere East	Oyoko	678655	760131	Electrified	1175.321086	
566	Ashanti Region	Sekyere East	Senkye (Senchi)	685330	753088	Electrified	2561.947662	
567	Ashanti Region	Sekyere East	Woraso	690352	759475	Electrified	4696.027988	
568	Region	District	Communities(N° of Localities =11)	X	Y	Electrification	Population(Total =43710.8336012)	Pop. Electrified (Total
569	Ashanti Region	Sekyere South	Bipoa	666282	770081	Electrified	4073.675498	
570	Ashanti Region	Sekyere South	Boanim	667143	777499	Electrified	3468.143347	
571	Ashanti Region	Sekyere South	Dawu	668797	772859	Electrified	746.4024784	
572	Ashanti Region	Sekyere South	Domi	666465	779627	Electrified	535.0969881	
573	Ashanti Region	Sekyere South	Funfuni	657761	785981	Electrified	443.6364027	
574	Ashanti Region	Sekyere South	Jamasi	669085	771224	Electrified	9562.361893	
575	Ashanti Region	Sekyere South	Kokoteasua	661357.692	787039.846	Unelectrified	676	
576	Ashanti Region	Sekyere South	Kona	665051	759877	Electrified	6153.089727	
577	Ashanti Region	Sekyere South	Konya/Brenhoma	673463	762968	Electrified	2005.825252	
578	Ashanti Region	Sekyere South	Odumasi	663798	762979	Electrified	2746.971375	
579	Ashanti Region	Sekyere South	Wiamoase	663941	779262	Electrified	13299.63064	
580						=countif(F1:F579		
581								
582	Region	District	Communities(N° of Localities =31)	X	Y	Electrification	Population(Total =116112)	Pop. Electrified (Total
583	Brong Ahafo Regi	Asunafo North	Abebrese	534796.531	772693.614	Unelectrified	581	
584	Brong Ahafo Regi	Asunafo North	Abigyan	523393	767252	Electrified	734	
585	Brong Ahafo Regi	Asunafo North	Akrodie	546629	735863	Electrified	6703	
586	Brong Ahafo Regi	Asunafo North	Akwaadro	540630	751377.066	Unelectrified	340	
587	Brong Ahafo Regi	Asunafo North	Antwi-Adjei Krom	515042.093	742410.215	Unelectrified	602	
588	Brong Ahafo Regi	Asunafo North	Anyimaye	525079.508	739790.194	Unelectrified	547	
589	Brong Ahafo Regi	Asunafo North	Asummra	526331	740299	Electrified	1280	
590	Brong Ahafo Regi	Asunafo North	Atom	517757	738197	Electrified	2062	
591	Brong Ahafo Regi	Asunafo North	Ayesuako	524900.775	739052.79	Unelectrified	400	
592	Brong Ahafo Regi	Asunafo North	Ayomso	546369	747317	Electrified	4952	

Figure 3.11: Screen shot of verification procedure for the 'Un-electrified communities' variable in Microsoft Excel

3.4.2 Verification of possible changes in the NP platform

There is the possibility that the NP platform might have changed since the 2010 study, which can have an impact on the results obtained during this study. To check this, a copy of a run for Western Region that was undertaken in the 2011 study was compared with a new scenario that was run for Western Region with the same input parameters and dataset as the one used in the previous study.

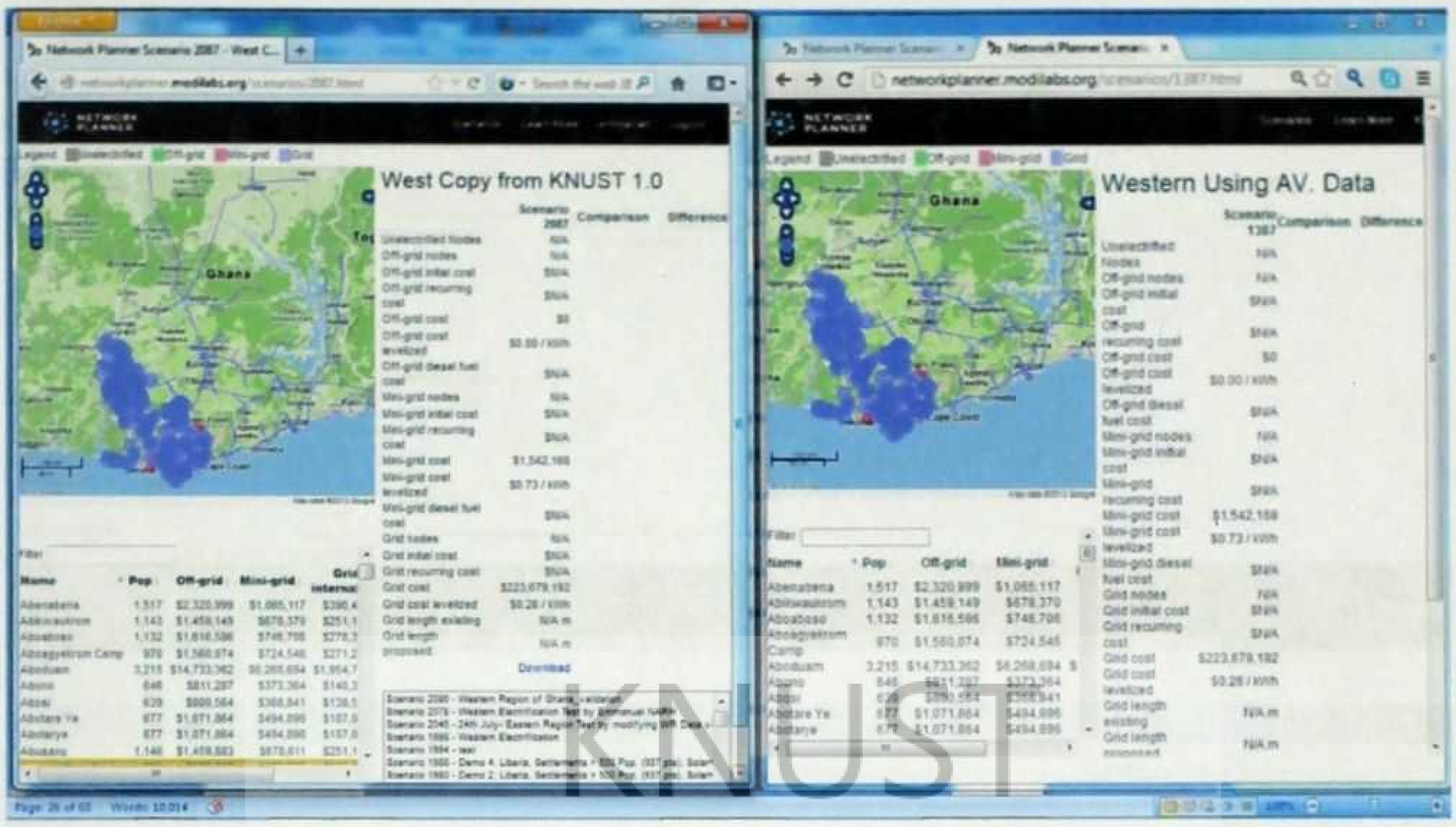


Figure 3.12: Screen shot showing output of activity to verify any changes in the NP energy model algorithms

3.4.3 Re-run of Network Planner

The NP energy model was re-run using the default parameter values shown in Appendix A. The parameter sheet shown was obtained during the consultative meetings held as part of this work. Runs were carried out for all the ten (10) regions of Ghana. Figure 3.14 shows a screen shot of a NP run for a region.

During the re-run, challenges were encountered with respect to the stability of the NP platform. The site went down on several occasions and the site administrator had to be called upon to restore the platform. Over-loading of the platform was given as the cause of the down-times. Two (2) screen shots of server failure are shown in Appendix E.

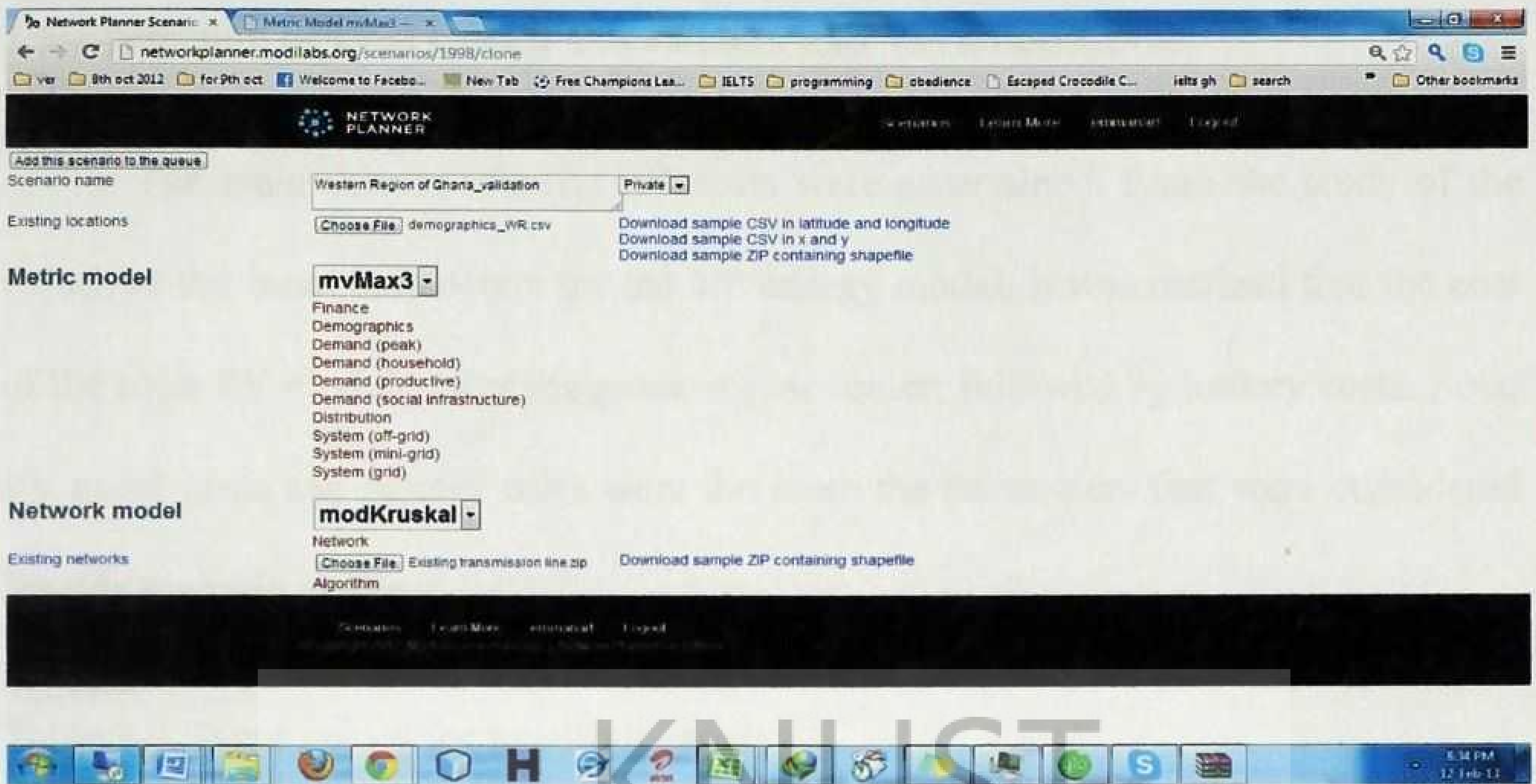


Figure 3.13: Screen shot showing the re-run of Network Planner for validation purposes

3.5 SENSITIVITY ANALYSIS

3.5.1 Selection of Region and Base Scenario Input Parameter Values

Sensitivity analysis was carried out to study the effect of steep decreases in solar PV costs. Due to the large number of runs that have to be run for each regional scenario, it became necessary to select a region for this scenario analysis. According to Kemausuor et al (2010), the Northern region had the highest percentage of off-grid compatible communities (20%). This region was chosen for the scenario analysis since a reduction of solar PV costs will have the greatest impact on this region since solar PV was the only off-grid technology being used by NP, the tool for this scenario analysis.

To get results that will reflect the realities of NR, some of the parameters given in the base scenario of the 2010 study were over-ridden. The new parameter values were obtained from the team that undertook the 2010 project during one of the consultative meetings. The list of over-ridden parameters is given in Appendix F.

3.5.2 Selection of Cost Center Parameters and Variation Levels

The main drivers of solar PV costs were ascertained. From the study of the values of the input parameters for the NP energy model, it was realized that the cost of the solar PV modules was the greatest cost center; followed by battery costs. Solar PV panel costs and battery costs were therefore the parameters that were considered for this scenario analysis.

Table 3.2: Input values for sensitivity analysis

Scenario Group I Variation of solar PV panel costs only		**Scenario Group II** Variation of solar PV battery costs only		**Scenario Group III** Variation of solar PV panel and battery costs		
Scenario Number	Panel Cost ($/KW)	**Scenario Number**	Panel Cost ($/KW)	**Scenario Number**	Panel Cost ($/KW)	Battery Cost ($/KW)
1	3,000	6	100	11	3,000	100
2	2,000	7	75	12	2,000	75
3	1,000	8	50	13	1,000	50
4	500	9	25	14	500	25
5	100	10	5	15	100	5

The sensitivity analysis was carried out by first varying the prices of solar PV modules; then the prices of solar batteries; and finally, the prices of both solar PV modules and batteries. The original prices used in the 2010 study are: solar PV panel cost:- $4,000/kW and solar batteries: $125/kWh. For all the scenarios, five (5) price levels were looked at. Table 3.15 summarizes the input values that were used for the various scenarios. Apart from the parameters shown in Table 3.15 that were varied, all other input parameters of the NP energy model were held constant.

CHAPTER 4 - RESULTS AND DISCUSSION

The results of this study are presented in this chapter. The results shall also be analyzed and discussed in this chapter.

4.1 RESULTS OF VALIDATION OF INPUT PARAMETERS OF 2010 STUDY

The results of the analysis of the input parameters are summarized in Tables 4.1 and 4.2. It must be emphasized that though the NP requires several input variables, only those with perceived anomalies are presented in the results in Table 4.1 and 4.2. For each region (scenario), the results from two (2) communities are presented. Finally, it must also be emphasized that variations in the input parameters across the regions and scenarios during the sensitivity analysis were not considered as errors.

From Table 4.1, it can be seen that there is an approximation of the low voltage line equipment cost per connection in the Northern region scenario. During this study, it was observed that a couple of other input parameters were approximated. This has the potential of introducing errors into the final results. There are un-explained differences in the values of other three (3) input parameters in Table 4.1. They are:

i) System (off-grid) > Photovoltaic panel cost per photovoltaic component kilowatt

ii) System (mini-grid) > Diesel generator cost per diesel system kilowatt

iii) System (grid) > Transformer lifetime

Table 4.1: Critical discrepancies in input parameters for 2010 NP energy model

Scenario name	Distribution > Low voltage line equipment cost per connection	System (off-grid) > Photovoltaic panel cost per photovoltaic component kilowatt	System (mini-grid) > Diesel generator cost per diesel system kilowatt	System (grid) > Transformer lifetime
2010 Western Region	250	4000	368	30
	250	4000	368	30
2010 Greater Accra	250	4000	368	30
	250	4000	368	30
2011 Northern Region	249.7	2000	441.8	20
	249.7	2000	441.8	20

Other non-critical discrepancies were noted in some of the input parameters. These differences have been classified as non-critical because those parameters were mentioned as changed in the report – only that their new values were not reported. Section 2.6 of the report of the 2010 study had this statement. "The modelling was done on a regional basis to understand the total cost of electrification for the un-electrified communities in each region since each region has different characteristics of some of the inputs model parameter that have to be considered" (Kemausuor, et al., 2010). The reason why it is classified as a discrepancy is because the actual variation in the values across the runs (regions) were not categorically stated. This implies that it would not be possible for any third party to repeat the work and get the same results as was obtained by the study undertaken in 2010.

Table 4.2: Benign discrepancies in input parameters for 2010 NP energy model

Scenario name	Finance > Economic growth rate per year	Finance > Electricity demand growth rate per year	Demographics > Mean household size (rural)	Demographics > Mean household size (urban)	System (off-grid) > Peak sun hours per year	System (grid) > Transformer lifetime
2010 Western Region	0.066	0.1188	9.6	7.5	1734	30
	0.066	0.1188	9.6	7.5	1734	30
2010 Greater Accra	0.066	0.1188	9.6	7.5	1916	30
	0.066	0.1188	9.6	7.5	1916	30
2011 Northern Region	0.064	0.1152	8.7	7.7	2099	20
	0.064	0.1152	8.7	7.7	2099	20

4.2 RE-RUN OF SCENARIOS AND COMPARISON WITH 2010 RESULTS

The NP software was run with the default parameters shown in Appendix A. Those parameters were obtained from the 2010 GIS-based energy access planning project team. Screen shots of the output page for each of the regions are shown in Appendix B. The results obtained are presented and discussed in this section.

4.2.1 Comparison of Regional Electrification Results

Table 4.3 presents some of the results obtained from this study for the various regions. Comparing, a lot of differences can be seen between these results and those obtained from the 2010 study (reference Tables 2.1 and 4.3). The percentage differences (changes) between the 2010 results and the results of this study are presented in Table 4.4. The 2010 study was used as the base case.

Table 4.3: Results obtained from NP re-run using default parameters from 2010 study

Region	Number of un-electrified Communities	Percentage of each electricity technology recommended by the model to serve un-electrified Communities			Cost Of Off-Grid (US$) (10 yr, initial + recurring)		Cost Of Mini-Grid (US$) (10 yr, initial + recurring)		Cost Of Grid (US$) (10 yr, initial + recurring)	
		Off-Grid	Mini-Grid	Grid	Total	Per HH	Total	Per HH	Total	Per HH
Ashanti	221	-	25%	75%	-	-	13,723,764	1,809	49,522,620	2,391
Brong Ahafo	195	-	32%	68%	-	-	17,229,424	368	50,143,131	431
Central	175	-	12%	88%	-	-	5,682,221	2,833	42,961,998	2,087
Eastern	247	-	11%	89%	-	-	6,568,344	413	46,017,777	394
Greater Accra	11	-	27%	73%	-	-	1,062,586	440	18,39,521	356
Northern	660	-	26%	74%	-	-	48,283,499	2,045	156,243,154	2,363
Upper East	299	-	3%	97%	-	-	2,536,371	320	73,674,207	343
Upper West	294	-	19%	81%	-	-	16,633,948	96	69,511,754	1,764
Volta	179	-	7%	93%	-	-	4,998,831	486	74,532,130	405
Western	319	-	9%	91%	-	-	9,278,245	2,160	143,610,761	2,680
High	660	-	32%	97%	-	-	48,283,499	2,833	156,243,154	2,680
Average	260	-	17%	83%	-	-	12,599,723	1,097	70,621,753	1,321
Low	11	-	3%	68%	-	-	1,062,586	96	18,39,521	343

Note: Percentage changes are expressed as positive if the change in the new study is bigger than that in the 2010 study and negative if the value obtained in the new study is less than that of the 2010 study

Table 4.4: Percentage difference (changes) between 2010 NP base scenario results and results obtained from this study using 2010 default parameter list

Region	Number of un-electrified Communities	Percentage of each electricity technology recommended by the model to serve un-electrified Communities			Cost Of Off-Grid (US$) (10 yr, initial + recurring)		Cost Of Mini-Grid (US$) (10 yr, initial + recurring)		Cost Of Grid (US$) (10 yr, initial + recurring)	
		Off-Grid	Mini-Grid	Grid	Total	Per HH	Total	Per HH	Total	Per HH
Ashanti	0.0%	-	66.7%	-7.4%	-	-	64.9%	-43.9%	-0.3%	8.0%
Brong Ahafo	0.0%	-	52.4%	-9.3%	-	-	66.8%	-88.7%	3.6%	-80.0%
Central	0.0%	-	300.0%	-8.3%	-	-	154.9%	-8.6%	-21.2%	10.7%
Eastern	0.0%	-	83.3%	-3.3%	-	-	85.5%	-87.1%	3.2%	-81.4%
Greater Accra	0.0%	-	200.0%	-19.8%	-	-	142.3%	-85.4%	-24.0%	-79.8%
Northern	0.0%	-	160.0%	5.7%	-	-	193.5%	-38.1%	52.8%	-1.4%
Upper East	0.0%	-	200.0%	-1.0%	-	-	170.1%	-89.7%	22.8%	-81.8%
Upper West	0.0%	-	111.1%	0.0%	-	-	137.3%	-97.0%	28.7%	-21.7%
Volta	0.0%	-	250.0%	-3.1%	-	-	110.6%	-84.6%	-6.9%	-80.1%
Western	0.0%	-	50.0%	-3.2%	-	-	54.7%	-35.2%	50.1%	26.1%
High	0.0%	-	52.4%	-1.0%	-	-	193.5%	-15.0%	52.8%	11.8%
Average	0.0%	-	112.5%	-4.6%	-	-	118.6%	-65.7%	19.4%	-36.6%
Low	0.0%	-	200.0%	-2.9%	-	-	142.3%	-96.8%	-24.0%	-80.5%

The number of communities was the only parameter that remained the same for all the regions across the two runs under discussion. The number of un-electrified communities remained constant across the two runs, hence the 0.0% change in that figure. A few other values did not change significantly. For instance, the percentage of communities to be electrified by grid technology in the Upper East, and the total cost of grid for the Ashanti region had changes of only -1% and -0.3% respectively.

A number of variations were noted. Whereas only two regions - Greater Accra and Western were not off-grid compatible in the 2010 study, none of the regions was off-grid compatible in this study. In this study, all the regions were recommended for either mini-grid or grid electrification. The variations were high with the highest being as much as 300%.

4.2.2 Comparison of Levelized Costs for the various electrification options

The results of the levelized costs obtained for the various electrification technologies is presented in Table 4.5. The result of the levelized costs obtained in the 2010 study was presented in table 2.2.

Table 4.5: Regional levelized costs for each electrification technology from re-run of NP using default parameters from 2010 study

Region	Levelized Costs (US$ per kWh)		
	Off-Grid	Mini-Grid	Grid
Ashanti	-	0.87	0.55
Brong Ahafo	-	0.87	0.45
Central	-	0.87	0.53
Eastern	-	0.87	0.63
Greater Accra	-	0.87	0.54
Northern	-	0.87	0.57
Upper East	-	0.87	0.53
Upper West	-	0.87	0.59
Volta	-	0.87	0.38
Western	-	0.86	0.34
High	-	0.87	0.63
Average	-	0.87	0.51
Low	-	0.86	0.34

A comparison of the results is shown in Figure 4.1. The regions were represented by the abbreviations as: Ashanti Region(AS), Brong-Ahafo Region(BA), Central Region(CR), Eastern Region(ER), Greater Accra Region(GR), Northern Region(NR), Upper East Region(UE), Upper West Region(UW), Volta Region(VR), and Western Region(WR). The results of the 2010 study are labeled (1) and the results of this study are labeled (2).

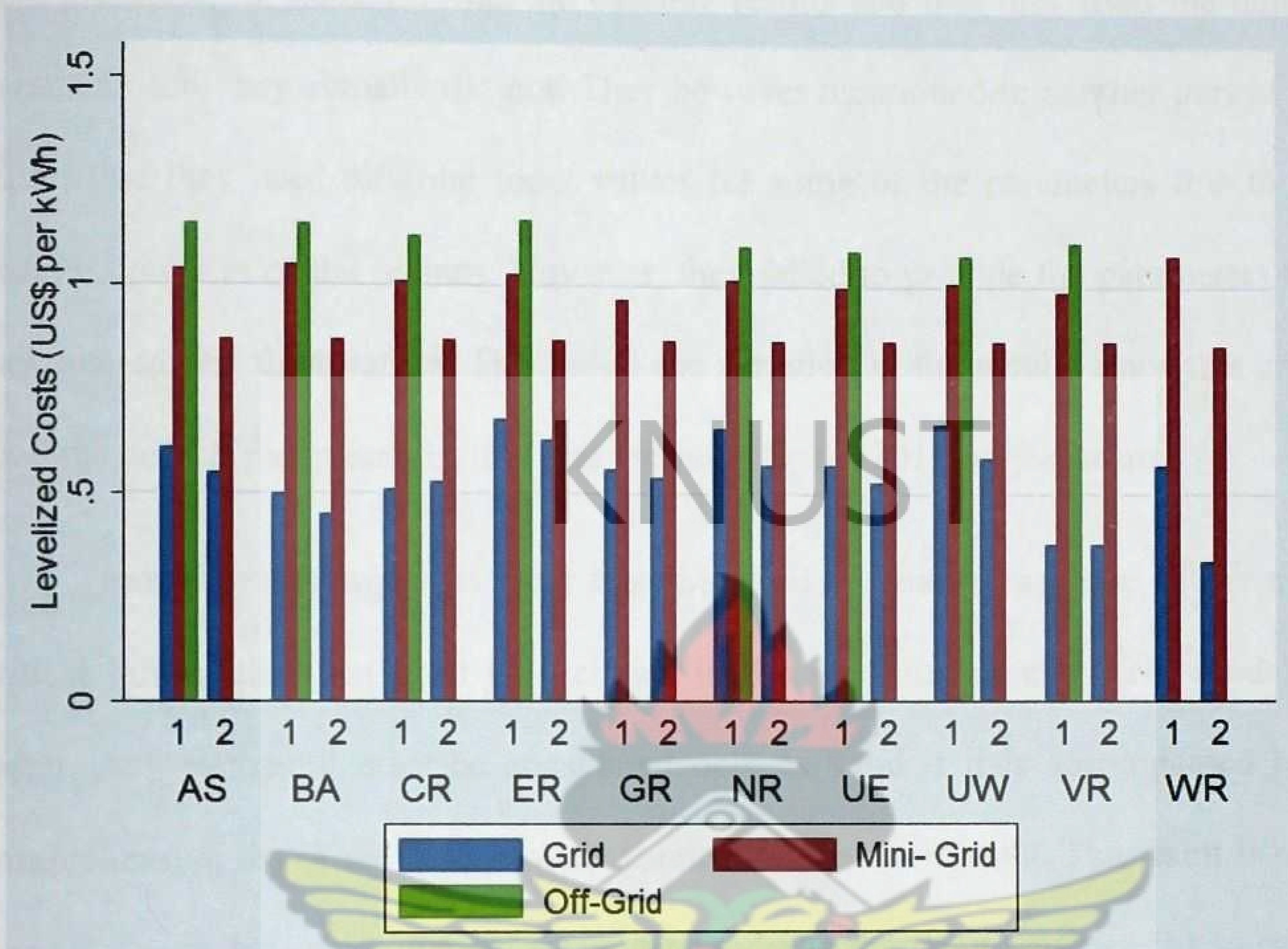


Figure 4.1: Comparison of levelized costs between runs 1(2010 study) and 2(this study) for all regions of Ghana.

Referring to Figure 4.1, the levelized cost of mini-grid electrification was always higher for the 2010 study (run 1) than for this study (run 2). For grid electrification, 8 of the regions had higher costs in run 1 than in run 2; VR had an almost equal value for both runs; and CR had a higher value in run 2 than in run 1. The levelized costs of off grid had the greatest level of disparity. Whereas there were values for all but two regions (GR and WR) in run 1, run 2 had no levelized cost for off grid since none of the regions were off grid compatible.

4.2.3 Explanation of Discrepancies

Further analysis reveal that although the 2010 team reported that the results they presented in Table 2.1 was the baseline results and that they used the default parameter list, they actually did not. They however mentioned in another part of the report that they used different input values for some of the parameters due to the different profiles of the regions. However, they failed to provide the parameters that they altered and their values. This led to the variation in the results since this study used the default parameter list that was provided by the 2010 project team.

From the ensuing, it is clear that the input parameters are one of the most critical information that must be included in the reporting of every NP modeling result. Any NP result must be considered only as valid if it is accompanied by a comprehensive list of the values of **all** parameters that were used. The result is only good if it contains such a listing, since differences in the input parameters can cause wide variations in the result obtained.

4.3 SENSITIVITY ANALYSIS

The results of the sensitivity analysis on the effects of steep decreases in solar PV costs are presented in this section.

4.3.1 Decreased Solar PV panel Cost

The results of the sensitivity analysis carried out to establish the effects of steep decreases in solar PV panel costs are presented in this section. First, a summary of the results is presented in Table 4.6. Second, the variation of the levelized costs for the various electrification technologies is presented in Figure 4.2.

Table 4.6: Effect of steep decreases of solar PV panel cost on electrification costs

Model Output Value	Base Scenario *(Cost of solar Panel: $4,000/kW)*	Scenario 1 *(Cost of solar Panel: $3,000/kW)*	Scenario 2 *(Cost of solar Panel: $2,000/kW)*	Scenario 3 *(Cost of solar Panel: $1,000/kW)*	Scenario 4 *(Cost of solar Panel: $500/kW)*	Scenario 5 *(Cost of solar Panel: $100/kW)*
Off-grid cost ($)	26,426,898	56,949,960	83,564,095	91,720,209	74,054,618	55,328,889
Levelized off-grid cost ($/kWh)	1.06	0.85	0.63	0.42	0.32	0.24
Percentage of off-grid proposed communities (%)	15.9	38.9	68.5	97.4	99.8	100.0
Mini-grid cost ($)	14,687,084	0	0	0	0	0
Levelized mini-grid cost ($/kWh)	1.00	0.00	0.00	0.00	0.00	0.00
Percentage of mini-grid proposed communities (%)	9.5	0.0	0.0	0.0	0.0	0.0
Grid cost ($)	124,369,353	91,765,517	46,889,589	4,793,721	61,680	0
Levelized Grid cost ($/kWh)	0.65	0.56	0.47	0.32	0.40	0.00
Percentage of grid proposed communities (%)	74.5	61.1	31.5	2.6	0.2	0.0

The results as summarized in Table 4.6 and Figure 4.2 shall now be discussed. Levelized costs are seen to generally reduce for all the electrification options as the cost of solar PV panels decrease. An exception occurred when the cost of solar PV panel reduced to $1,000/kW in scenario 4. At that point, the levelized cost of off-grid electrification (0.32 $/kW) was less than that for grid electrification (0.4 $/kW). Extrapolating from the graph in Figure 4.2, it can be deduced that for the levelized cost of off grid electrification to be less than that of grid electrification, solar PV panels will have to be reduced to a cost of **750 $/kW**.

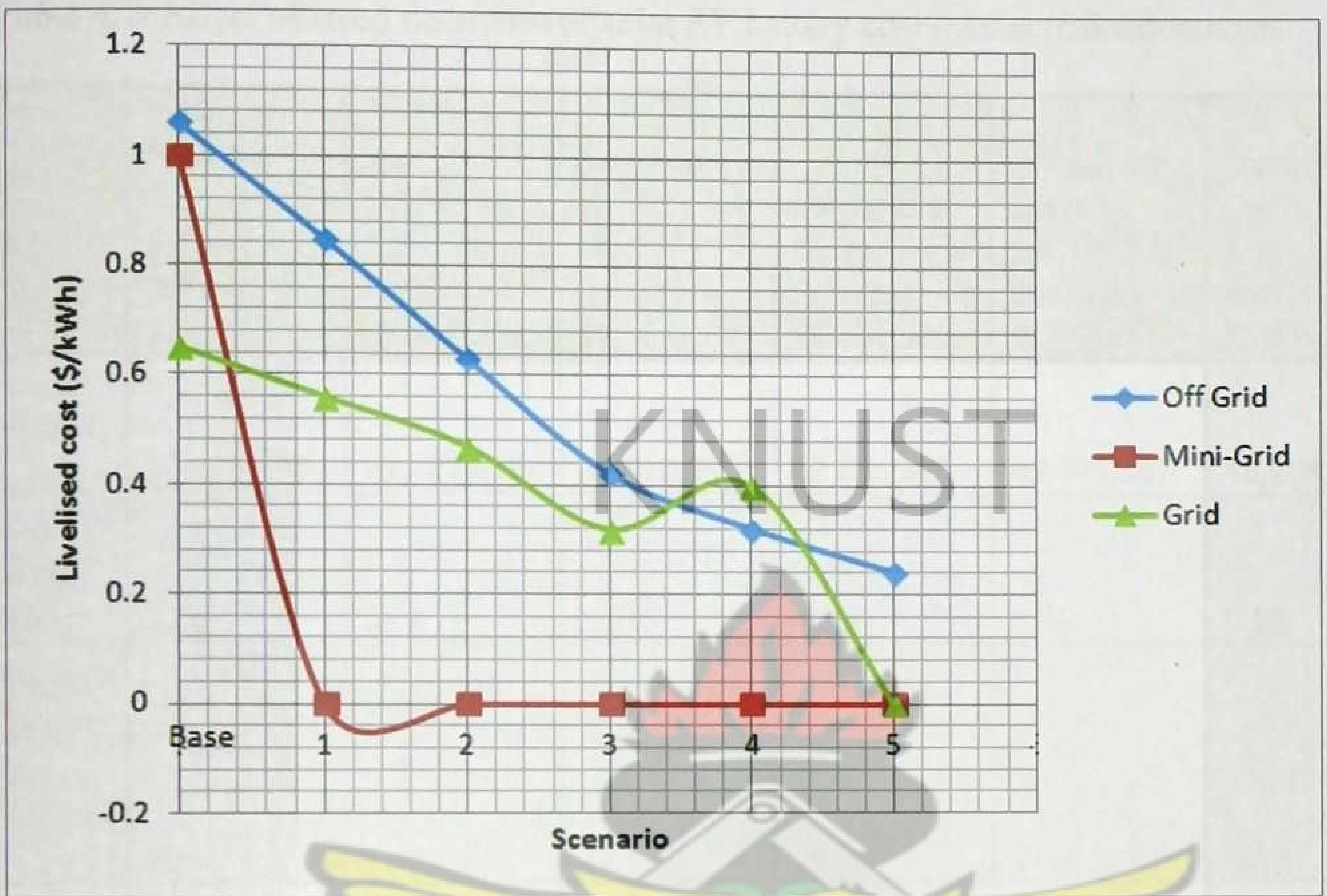


Figure 4.2: Variation of levelized costs with decreases in solar PV panel costs

A linear relationship is observed between the percentage of recommended communities for an electrification technology and the total cost for that electrification technology. To illustrate the above, the percentage of communities recommended for off grid increases across the runs, likewise the total cost for off grid electrification; whiles the percentage of communities recommended for grid decreases together with the total cost for grid electrification. This relationship is due to the fact that the more the number of communities recommended for electrification by a particular technology, the more the resources needed for that electrification technology and vice versa.

4.3.2 Decreasing of Solar PV battery costs, while keeping all other parameters constant

Table 4.7: Effect of steep decreases of solar PV battery cost on electrification costs

Model Output Value	**Base Scenario** *Cost of Solar Battery: $125/kWh*	**Scenario 6** *Cost of Solar Battery: $100/kWh*	**Scenario 7** *Cost of Solar Battery: $75/kWh*	**Scenario 8** *Cost of Solar Battery: $50/kWh*	**Scenario 9** *Cost of Solar Battery: $25/kWh*	**Scenario 10** *Cost of Solar Battery: $5/kWh*
Off-grid cost ($)	26,426,898	29,522,619	34,010,990	42,685,365	45,495,347	48,188,985
Levelized off-grid cost **($/kWh)**	1.06	1.04	1.01	0.99	0.96	0.94
Percentage of off-grid proposed communities (%)	15.9	18.3	21.1	25.9	27.9	30.3
Mini-grid cost ($)	14,687,084	12,202,305	8,907,556	4,682,713	3,625,803	1,924,334
Levelized mini-grid cost **($/kWh)**	1.00	0.99	0.98	0.97	0.96	0.96
Percentage of mini-grid proposed communities (%)	9.5	7.7	5.9	3.3	2.6	1.4
Grid cost ($)	124,369,353	121,393,469	119,472,346	113,540,969	110,360,354	107,456,992
Levelized Grid cost **($/kWh)**	0.65	0.63	0.63	0.62	0.61	0.60
Percentage of grid proposed communities (%)	74.5	73.9	73.0	70.8	69.5	68.3

Figure 4.3: Variation of levelized costs with decreases in solar battery costs

The results of the effect of steep decreases in solar PV battery costs are presented in Table 4.7 and Figure 4.3. Across the runs, nominal changes were noted. The levelized cost of the various electrification technologies changed as follows: off grid: 1.06 to 0.94(11.3 %), mini-grid : 1.0 to 0.96(4%) and grid : 0.65 to 0.60 (7%). As compared to the effect of decreasing solar PV panel costs, the effect of decreasing solar PV battery costs was more linear and 'gentle'.

It was found that decreasing the cost of solar PV batteries had a generally linear but less pronounced effect on levelized costs, percentage of communities proposed for electrification by a technology, and the total cost of that technology. The effects are less pronounced when compared to the effect that decreasing cost of solar PV panels had on these same variables.

4.3.3 Decreasing of Solar PV panel and battery costs, while keeping all other parameters constant

The last set of scenarios involved decreasing both solar PV panel and battery costs. The results obtained are summarized in Table 4.8 and Figures 4.4 and 4.5. The results of these scenarios are discussed in the subsequent paragraphs.

Table 4.8: Effect of steep decreases in solar PV panel and battery costs on electrification costs

Model Output Value	**Base Scenario** Solar Panel: $4,000/kW; Solar Battery $100/kWh	**Scenario 11** Solar panel: $3,000/kW; Solar Battery: $100/kWh	**Scenario 12** Solar panel: $2,000/kW; Solar Battery: $75/kWh	**Scenario 13** Solar panel: $1,000/kW; Solar Battery: $100/kWh	**Scenario 14** Solar panel: $500/kW; Solar Battery: $100/kWh	**Scenario 15** Solar panel: $100/kW; Solar Battery: $100/kW
Off-grid cost	26,426,898	60,886,976	87,201,431	82,117,468	53,559,164	30,655,776
Off-grid cost levelized	1.06	0.82	0.59	0.35	0.23	0.13
Percentage of off-grid proposed communities	15.9	42.3	75.2	99.8	100.0	100.0
Mini-grid cost	14,687,084	0	0	0	0	0
Mini-grid cost levelized	1	0.00	0.00	0.00	0.00	0.00
Percentage of mini-grid proposed communities	9.5	0.0	0.0	0.0	0.0	0.0
Grid cost	124,369,353	86,326,976	37,795,540	61,680	0	0
Grid cost levelized	0.65	0.55	0.45	0.40	0.00	0.00
Percentage of grid connected communities	74.5	57.7	24.8	0.2	0.0	0.0

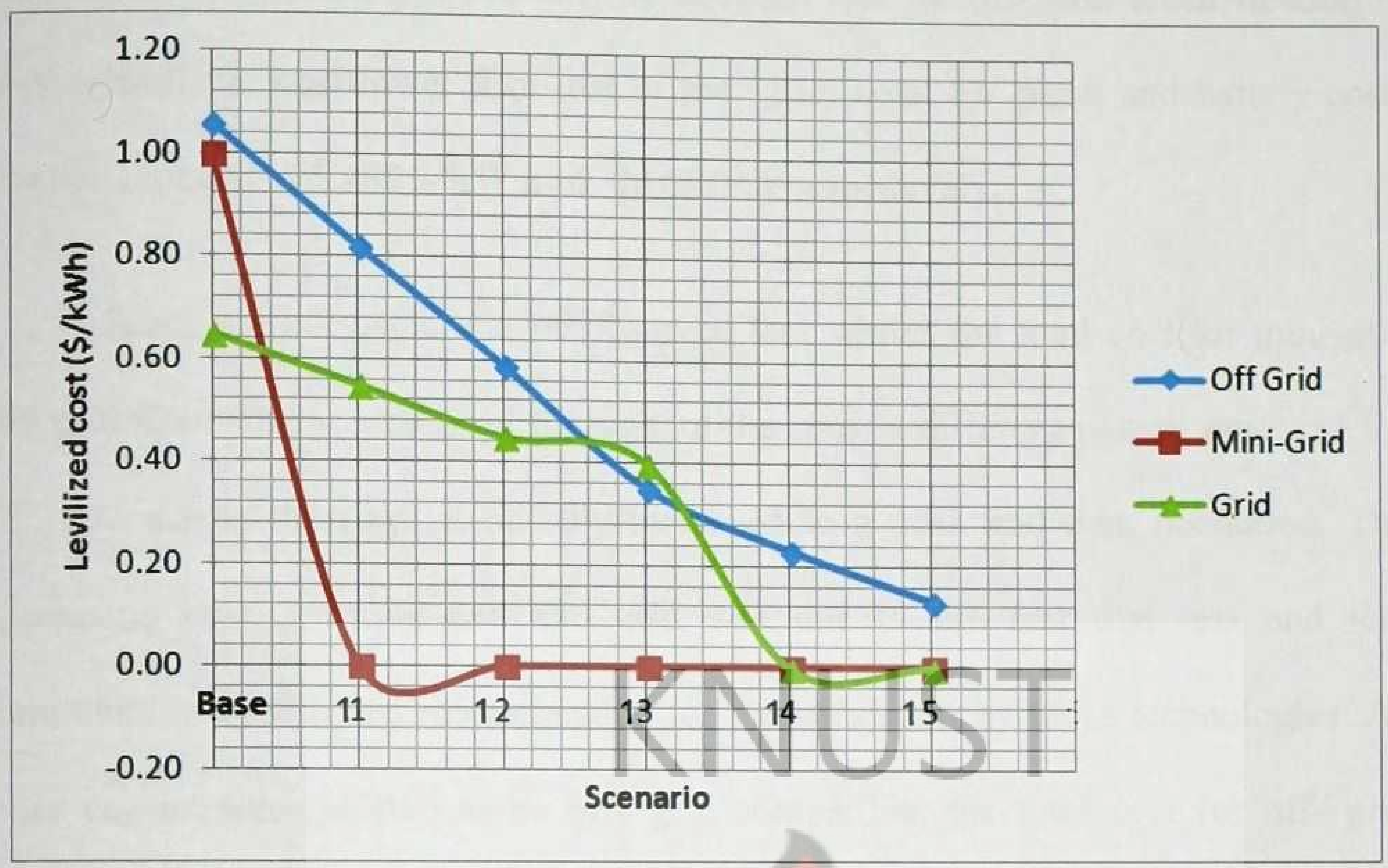


Figure 4.4: Variation of levelized costs with decreases in solar PV pane1 and battery costs

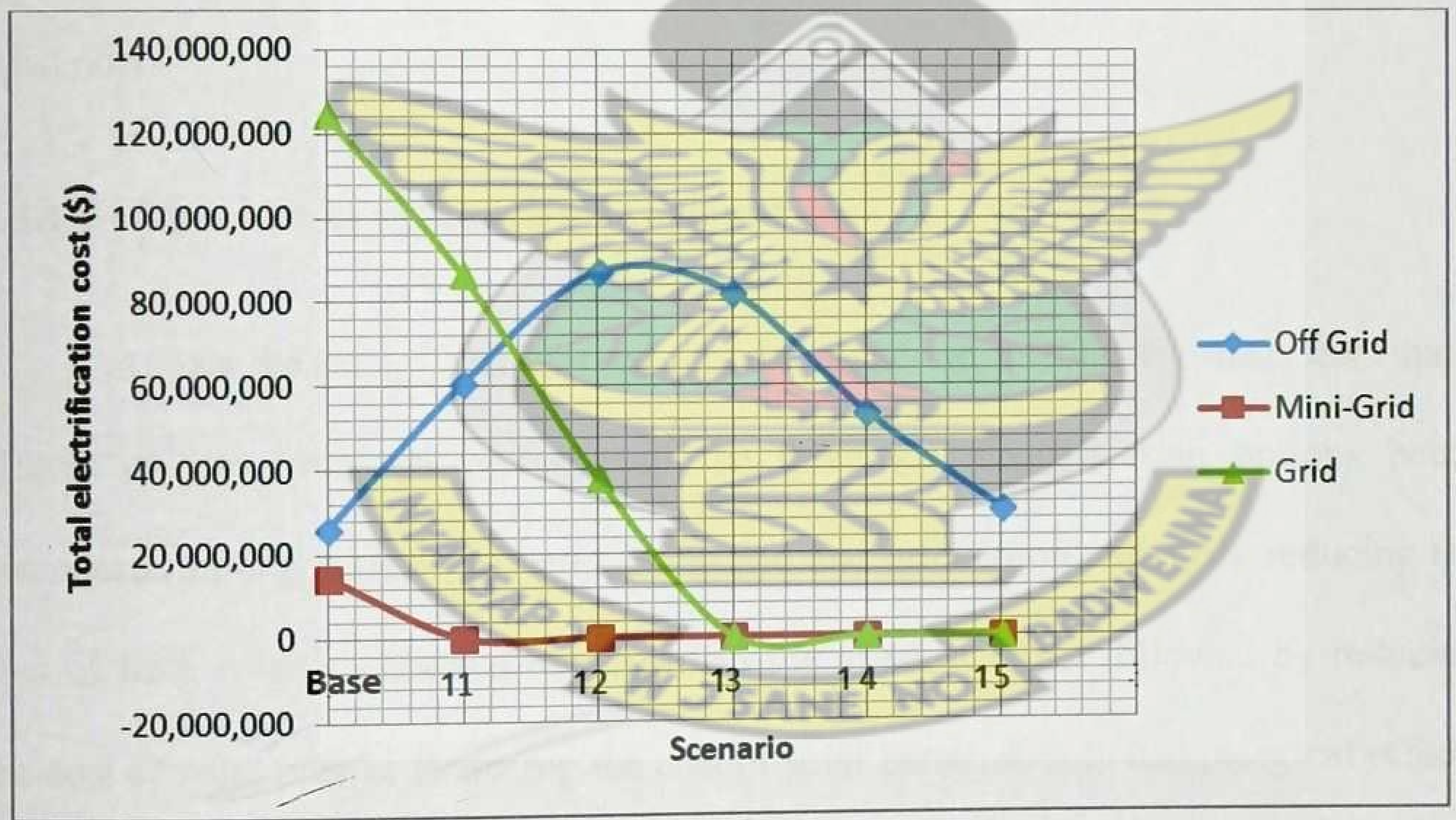


Figure 4.5: Variation of electrification costs with decreases in solar PV paned and battery costs

The levelized costs were reduced for all the electrification technology options under consideration. When solar PV panel and battery reduced to 1,400 $/kW and 40 $/kWh respectively, the levelized cost for off- grid became lower than that of grid

(See Figure 4.5). Hence, it can also be deduced that for off- grid electrification to have a levelized cost lower than that of the grid, solar PV panel and battery costs must be reduced to **1,400 $/kW and 40 $/kWh** respectively.

From Figure 4.4, it can be observed that whiles the total cost for mini-grid and grid electrification reduced throughout the runs, a different pattern emerged for off -grid across the runs, it initially increased to a peak and then decreased. The decreasing cost for mini-grid and grid was due to the fact that less and less communities were being recommended for electrification by those technologies. As more communities shifted to be off- grid compatible, the total cost for off- grid electrification started to increase. The rising cost for off- grid electrification was later offset by the very steep decreases in solar PV costs, resulting in a decline in total off -grid costs.

4.3.4 Comparison of results in the various runs

Across the runs, it is observed that the reduction in solar PV costs does have effects on the levelized cost for all the three (3) electrification options being considered in this work – off -grid, mini-grid and grid. Simultaneously reducing the cost of both solar panels and batteries had the greatest effect followed by reducing the cost of solar panels. Reducing the cost of solar batteries only had marginal effects on the levelized costs. It was shown that it is impossible for off- grid electrification to have a lower cost than that of the grid by decreases in solar PV batteries only. Decreasing costs of both solar batteries and solar panels had a greater influence on reaching the point where off- grid becomes more economical than grid, as compared to decreasing only the cost of solar panels.

CHAPTER 5 - CONCLUSION AND RECOMMENDATIONS

5.1 CONCLUSION

Validation was successfully carried out on the results of the 2010 project on "GIS-Based Support for Implementing Policies and Plans to Increase Access to Energy Services in Ghana" which was undertaken by TEC of KNUST. The effects of steep decreases of solar PV costs were also successfully studied.

The results of the 2010 project can be considered as broadly valid. However, the omission of certain input parameters used in the modeling from the final report of that work resulted in different results during the validation exercise. It can be concluded that without the full list of input parameters used, the results of the Network Planner are of little significance, since small variations in the input parameters led to wide variations in the output data. Some un-explained discrepancies were also noted in the input parameters used according to the runs. This has a potential of affecting the reliability of the output of the 2010 study.

The levelized costs for all the electrification options considered under this study were generally reduced when solar PV prices reduce steeply. In this regard, the reduction of prices of solar panels had a greater impact than that of solar batteries. If improved technology, friendly policy initiatives and entrepreneurship are able to drive down solar PV panels to 750 $/kW or solar PV panels to $1,400 **and** solar batteries to 40 $/kWh, then off- grid electrification powered by solar systems will become more competitive than grid electrification, according to results obtained using the network planner.

5.2 RECOMMENDATIONS

For easy checking and re-running of NP scenarios, it is recommended that an input parameter list be included for each scenario for which results are communicated. This will prevent ambiguity and errors when the scenarios are being run by a third party or oneself after a period of time. Also, due to the wide differences in results obtained during the validation, it has become obvious that the accuracy of the input parameters is crucial. It is recommended that periodic verification, update and testing should be carried out in order to come up with a well maintained and publicly accessible NP input parameter list for Ghana.

It will be helpful if NP has a feature to enable old scenarios to be re-loaded into it for further analysis. Currently, once a scenario is downloaded, there is no way of uploading it to re-run using the same parameters. This has a tendency of encouraging users of the software to keep their data on the NP servers, thereby clogging it over time. Once users are confident they can upload their data on a later date for analysis, they will be encouraged to download their scenarios. Since the output files of the NP include the input parameters, the ability of being able to upload old scenarios will also help in results sharing as one can easily upload the downloaded work of another user without having to input all the input parameters. One can then just go ahead to either view the initial results, or make further changes in the input variables for analysis.

Due to the down times that occasionally occur on the NP site due to work load, it is recommended that other servers be established to help with the load balancing. Since the NP software is open source, its source code can be obtained and deployed on an appropriate server.

More concrete steps need to be taken to make the NP energy access planning tool relevant to policy makers. To this end, it is recommended that further research be done to compare the NP results against actual electrification costs incurred by the utility companies. Any differences between the NP results and the actual electrification costs should be studied and corrected. Ultimately, if NP results are found to be good approximations of the real life costs and results, it will boost the confidence of stakeholders in adopting the NP for energy access planning.

Further research is also recommended to analyze the underlying algorithms used by the NP energy model. Moreover, research can be done to develop an indigenous energy planning software that can include other renewable and non-renewable energy options such as biomass, hydro, wind, nuclear and other potential energy sources within the country. Currently, some further calculations need to be done to extract useful information and trends from the results of the NP model. Hence, further work is recommended to develop plug-ins to aid in the analysis of the NP modeling results. This will boost speed, and eliminate possible errors introduced during calculations. Such plug-ins could either be stand alone or built as a layer on top of the NP software.

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APPENDIX

APPENDIX A: DEFAULT PARAMETERS USED IN MODELING ENERGY ACCESS FOR GHANA

APPENDIX A1: SOCIO-ECONOMIC DATA

SOCIO-ECONOMIC DATA	Details	Unit	Parameter	Sources
FINANCING PARAMETERS				
Time Horizon	Time horizon in years	(years)	10	
Interest Rate per year	Yearly interest rate	Dimensionless	0.1157	BOG
Economic Growth Rate per year		Dimensionless	0.064	BOG
Elasticity of Electricity Demand		Dimensionless	0.018	ECG
DEMOGRAPHICS PARAMETERS				
Mean Household Size (Rural)	mean household size (rural)	(persons)	5.4	
Mean Household Size (Urban)	mean household size (urban)	(persons)	4.7	
Urban Population Threshold	rural urban threshold	(persons)	5000	GSS
Mean Inter-household Distance	mean inter-household distance in meters	(meters)	25	Consultation with experts
Population Growth Rate per year (Rural)	Yearly growth rate	Dimensionless	0.005	UN Statistical Division
Population Growth Rate per year (Urban)	Yearly growth rate	Dimensionless	0.035	UN Statistical Division

APPENDIX A2: DEMAND PARAMETERS

DEMAND PARAMETERS	Details	Units	Parameter	Sources
HOUSEHOLD DEMAND				
Base Household Unit Demand per Household	Unit demand in kilowatts per year	(kWh/yr)	150	Based on consultation with experts and computation of available data
PRODUCTIVE DEMAND				
Base Productive Unit Demand (per Household)	Unit demand in kilowatts per year	(kWh/yr)	19.5	
SOCIAL INFRASTRUCTURE DEMAND				
Base Health Unit Demand (per Health Facility)	Unit demand in kilowatts per year	(kWh/yr)	1000	
Base Education Unit Demand (per Education Facility)	Unit demand in kilowatts per year	(kWh/yr)	1200	
Base Commercial Unit Demand (per Commercial Facility)	Unit demand in kilowatts per year	(kWh/yr)	250	
Base Public Lighting Unit Demand	Unit demand in kilowatts per year	(kWh/yr)	102	
PEAK DEMAND				
Fraction of total demand during peak hours (rural)	fraction of total demand during peak hours (rural)	Dimensionless	0.4	
Fraction of total demand during peak hours (urban)	fraction of total demand during peak hours (urban)	Dimensionless	0.4	
Annual peak usage hours	peak electrical usage hours per year	(hrs/yr)	1460	

APPENDIX A3: COST DATA

COST DATA	Details	Units	Parameter	Sources
SYSTEMS COST PARAMETERS				
OFF-GRID: PHOTOVOLTAIC SYSTEMS + STAND-ALONE DIESEL GENERATORS				
Photovoltaic Systems				
Available Panel System Sizes	system sizes	(kW)	4wp	
Panel cost per system kilowatt	panel cost per system kilowatt	(US$/kW)	4000	
Balance of System cost factor (as fraction of Panel cost)	balance cost as fraction of panel cost	Dimensionless	0.5	
Battery energy per system kilowatt	battery kilowatt-hours per system kilowatt	(kWh/kW)	4.5	
Battery cost per kilowatt-hour	battery cost per kilowatt-hour	(US$/kWh)	125	
Photovoltaic Systems Replacement				Based on consultation with experts and computation of available data
Panel lifetime	panel lifetime in years	(years)	20	
Balance of System lifetime	balance lifetime in years	(years)	10	
Battery lifetime	battery lifetime in years	(years)	5	
Operation and Maintenance (O&M)				
O&M Photovoltaic Systems cost factor (as fraction of total Panel System cost)	operations and maintenance cost as fraction of system cost	Dimensionless	0.05	

COST DATA	Details	Units	Parameter	Sources
MINI-GRID: DIESEL GENERATORS				
Diesel Generators				
Available Diesel Generator System Sizes Standard units for diesel generator system sizes are represented in kVA; kW=kVA*Power Factor	system sizes	(kW)	1000.0 750.0 500.0 400.0 200.0 150.0 100.0 70.0 32.0 19.0 12.0 6.0	Based on consultation with experts and computation of available data
Diesel Generator cost per kilowatt	engine cost per kilowatt	(US$/kW)	441.76	
Diesel Generator Installation cost factor (as fraction of Diesel Generator cost)	engine installation cost as fraction of engine cost		0.25	
Diesel Generator Replacement				
Diesel Generator lifetime	engine lifetime in years	(years)	5	
Fuel				
Fuel cost per litre	fuel cost per litre	(US$/L)	1.02	
Fuel litres consumed per kilowatt-hour	fuel litres consumed per kilowatt-hour	(L/kWh)	0.5	
Operation and Maintenance (O&M)				
Total hours diesel generator is in operation in a year	fuel hours per year	(h/yr)	2190	
Diesel Generator O&M cost factor (as fraction of Diesel Generator cost)	operations and maintenance cost as fraction of engine cost	Dimensionless	0.05	

MINI-GRID & GRID: Low Voltage Distribution Network	Details	Units	Parameter	Sources
Low Voltage Lines				
Low Voltage Line cost per meter	low voltage line lifetime in years	(US$/m)	US$ 12 and US$ 17	NED, EC
Low Voltage Lines Replacement				
Low Voltage Line Lifetime	low voltage line lifetime in years	(years)	20	NED
GRID: Transformers + Household & Social Infrastructure Connections + Extension				
Electricity cost per kilowatt-hour	electricity cost per kilowatt-hour	(US$/kWh)	0.12	EC, NED,ECG
Transmission and distribution loss factor (as fraction of grid system demand)	Distribution loss as fraction of system demand	Dimensionless	0.198	EC, NED,ECG
GRID: Transformers				
Transformer in Low Voltage Network				
Available transformer system sizes (kVA)	system sizes	kW	5 15 20 30 40 50 60 70 80 90 100 200 300 400 500 600 700 800 900 1000	
Transformer cost per kilowatt	transformer cost per kilowatt	(US$/kW)	152	Based on computation of available data
Transformer Replacement				
Transformer lifetime	transformer lifetime in years	(years)	20	
Operation and Maintenance (O&M)				
Transformer O&M cost factor (as fraction of Transformer cost)	transformer operations and maintenance cost as fraction of transformer cost	Dimensionless	0.03	

GRID: Household & Social Infrastructure Connections	Details	Units	Parameter	Sources
Connections to Low Voltage Network				
Equipment cost per connection	equipment cost per household (Up to 40 meters distance)	(US$/HH)	249.7	Calculation based on MOE data
Installation cost per connection	installation cost per household	(US$/HH)	70	NED
Equipment O&M cost factor (as fraction of Equipment cost)	equipment operations and maintenance cost as fraction of equipment cost	Dimensionless	0.01	
GRID: Medium Voltage Extension				
Medium Voltage Lines				
Medium Voltage Line cost per meter	material and labour cost in dollars per meter of grid extension	(US$/m)	25	NED
Medium Voltage Lines Replacement				
Medium Voltage Line Lifetime	lifetime in years	(years)	30	NED

Source: 2010 GIS-based energy planning project team

APPENDIX B: SCREEN SHOTS OF NP RE-RUNS

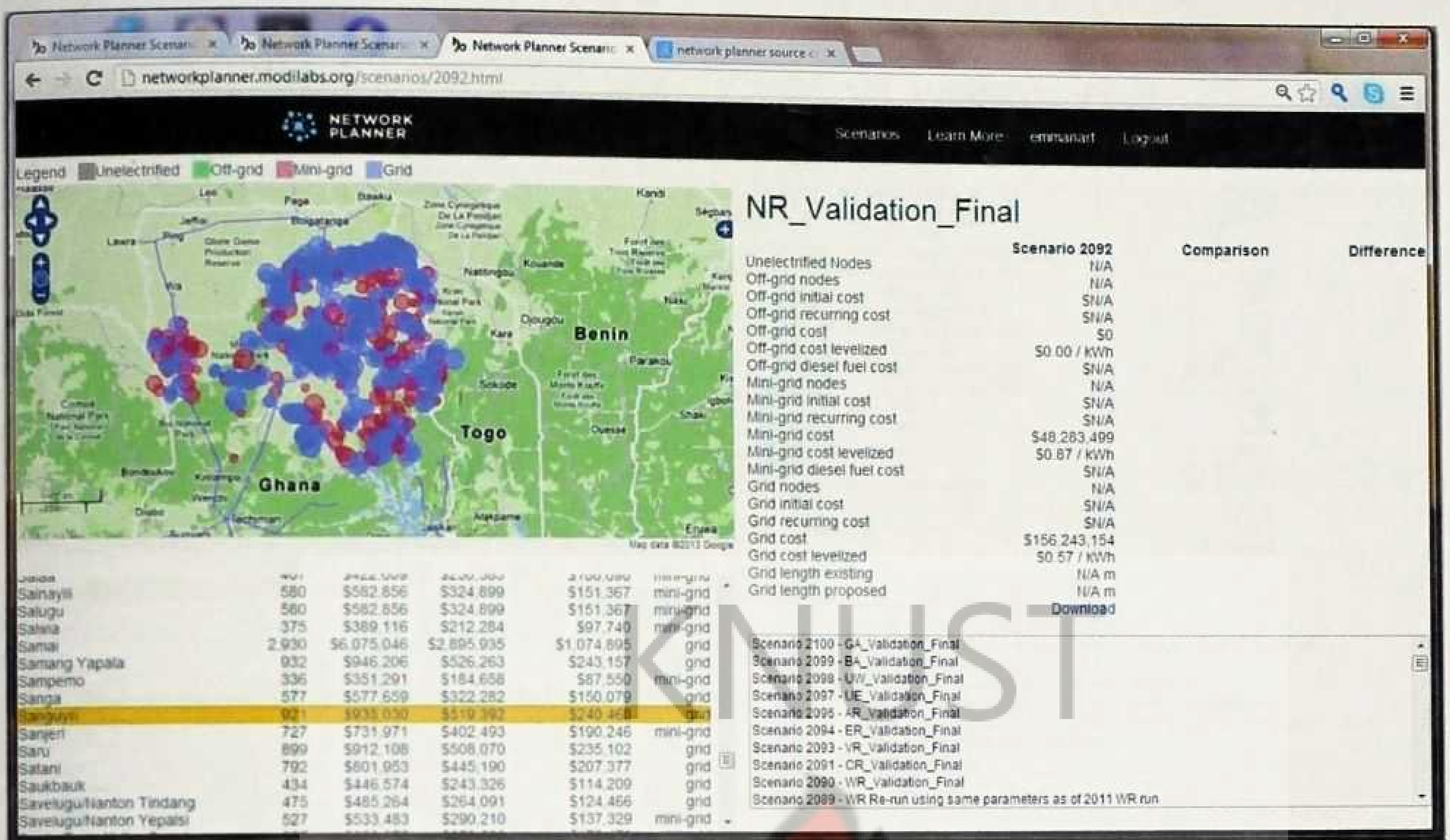

Figure B-1: Screen shot showing NP output for the Northern Region.

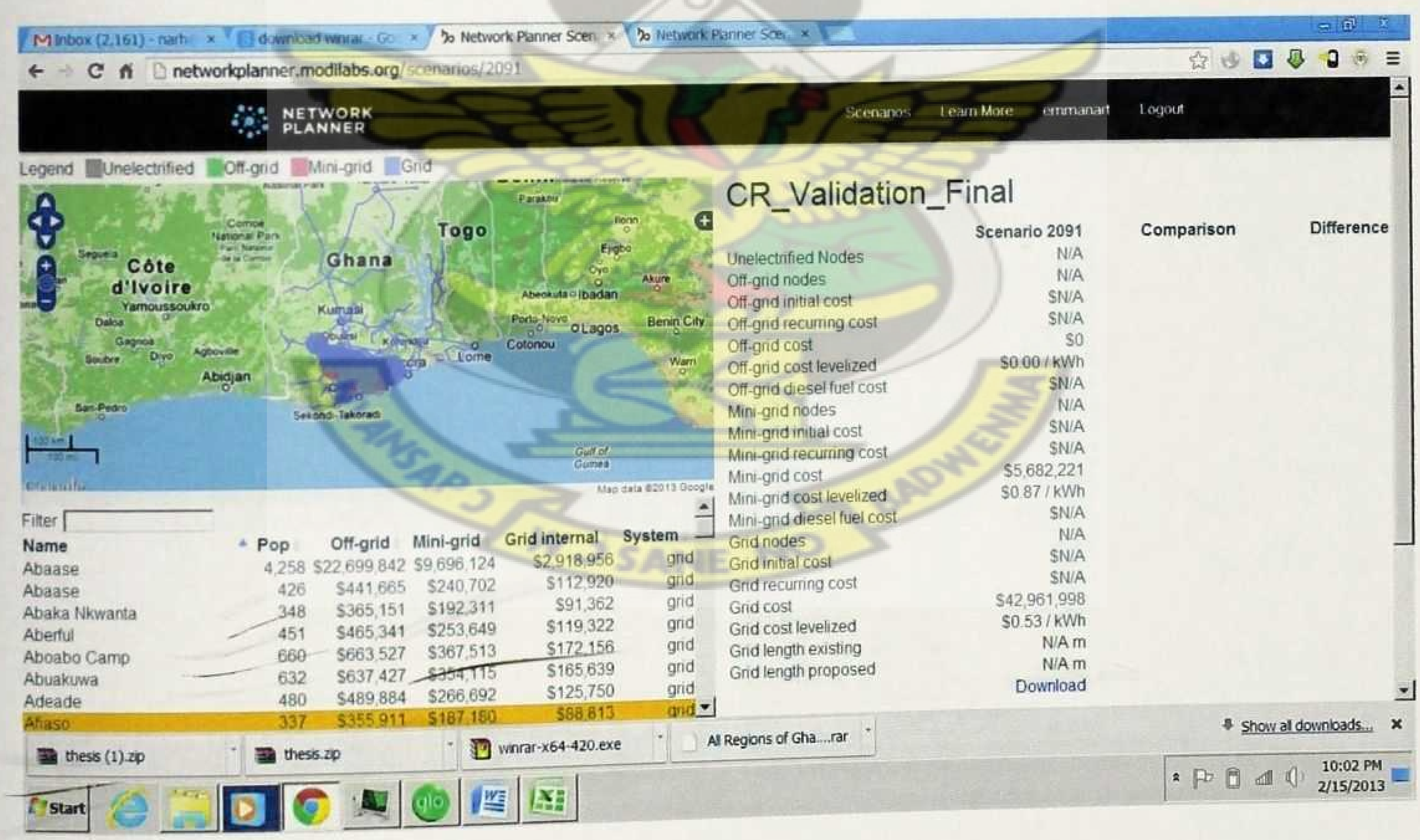

Figure B-2: Screen shot showing NP output for the Central Region

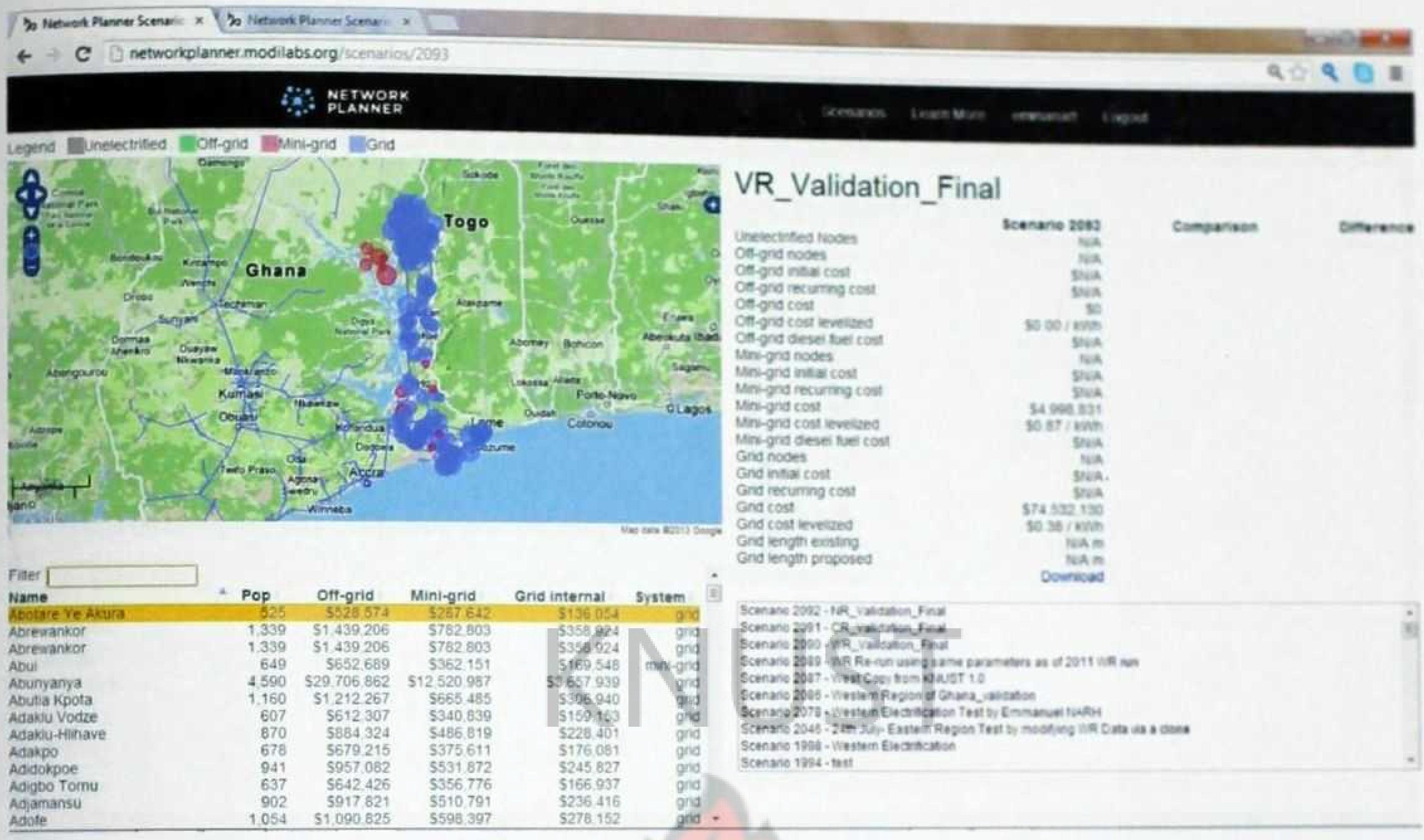

Figure B-3: Screen shot showing NP output for the Volta Region

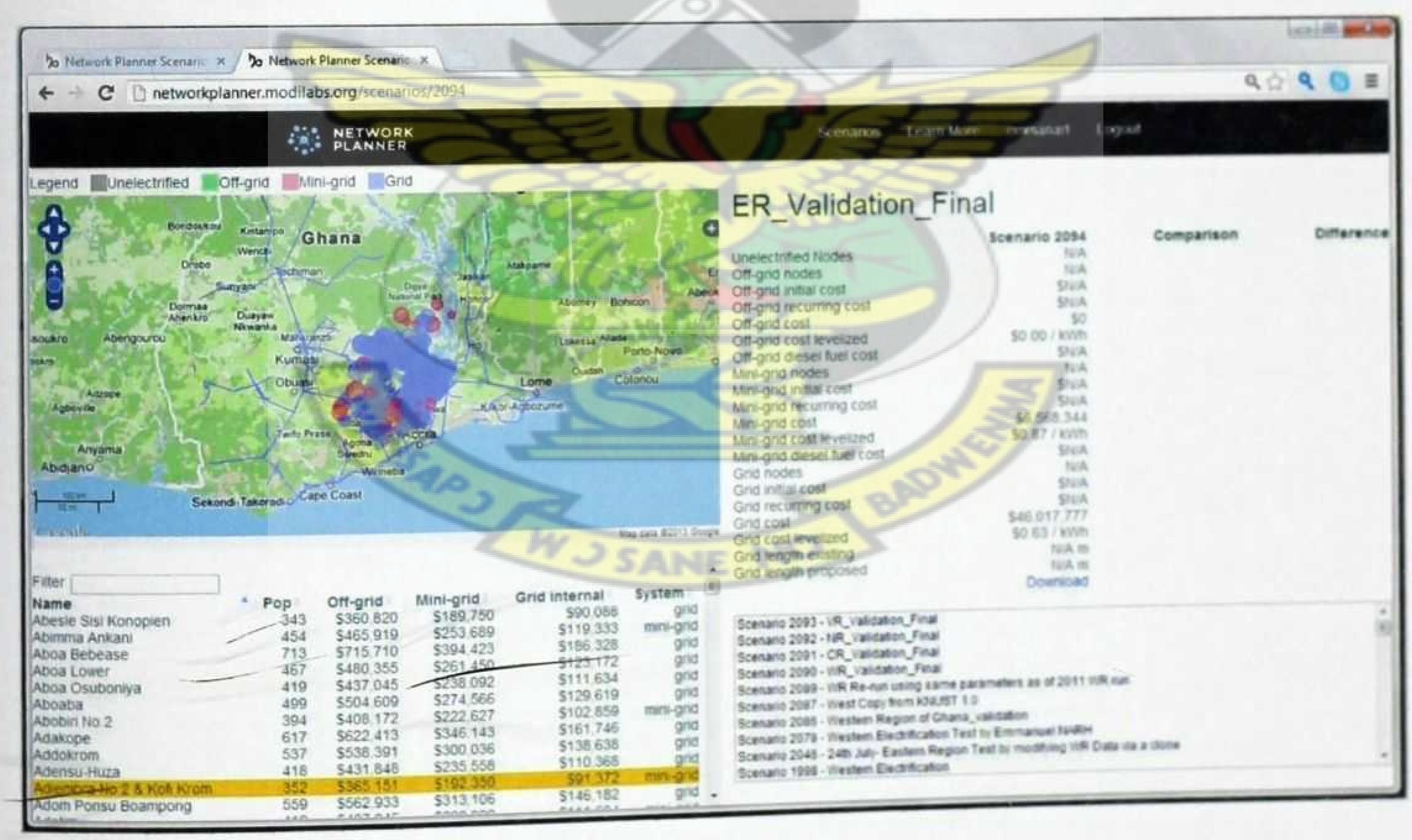

Figure B-4: Screen shot showing NP output for the Eastern Region

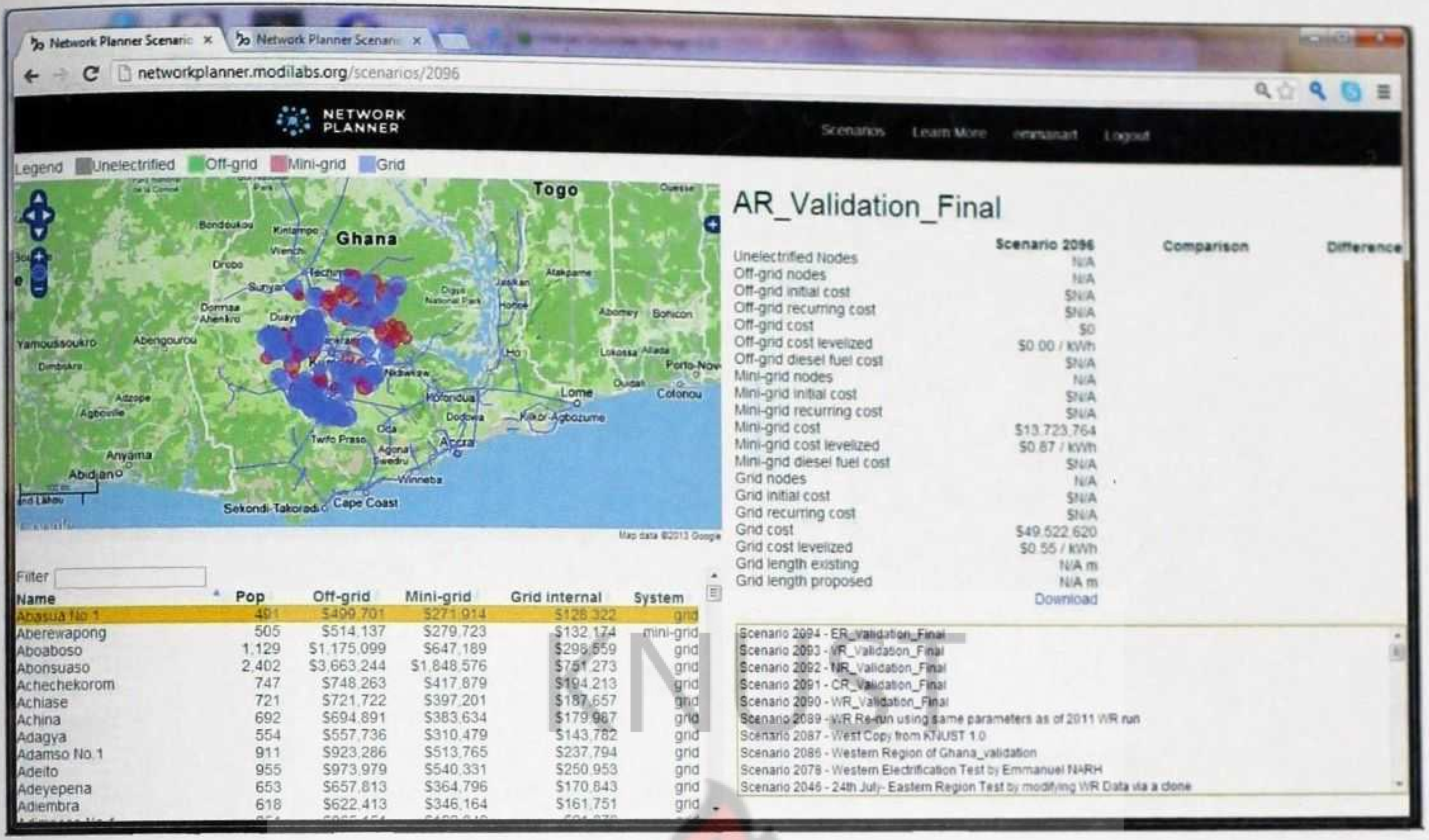

Figure B-5: Screen shot showing NP output for the Ashanti Region

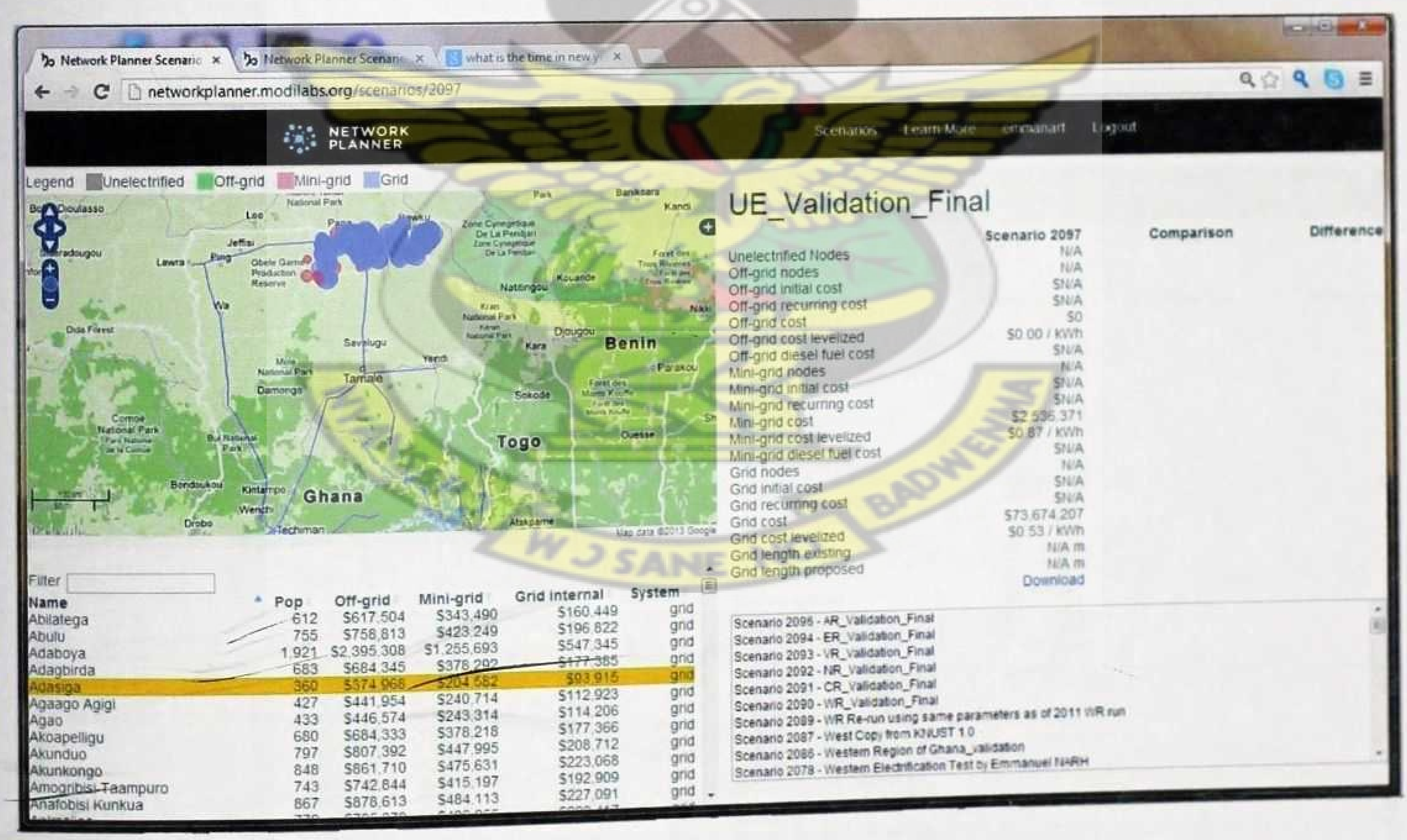

Figure B-6: Screen shot showing NP output for the Upper East Region

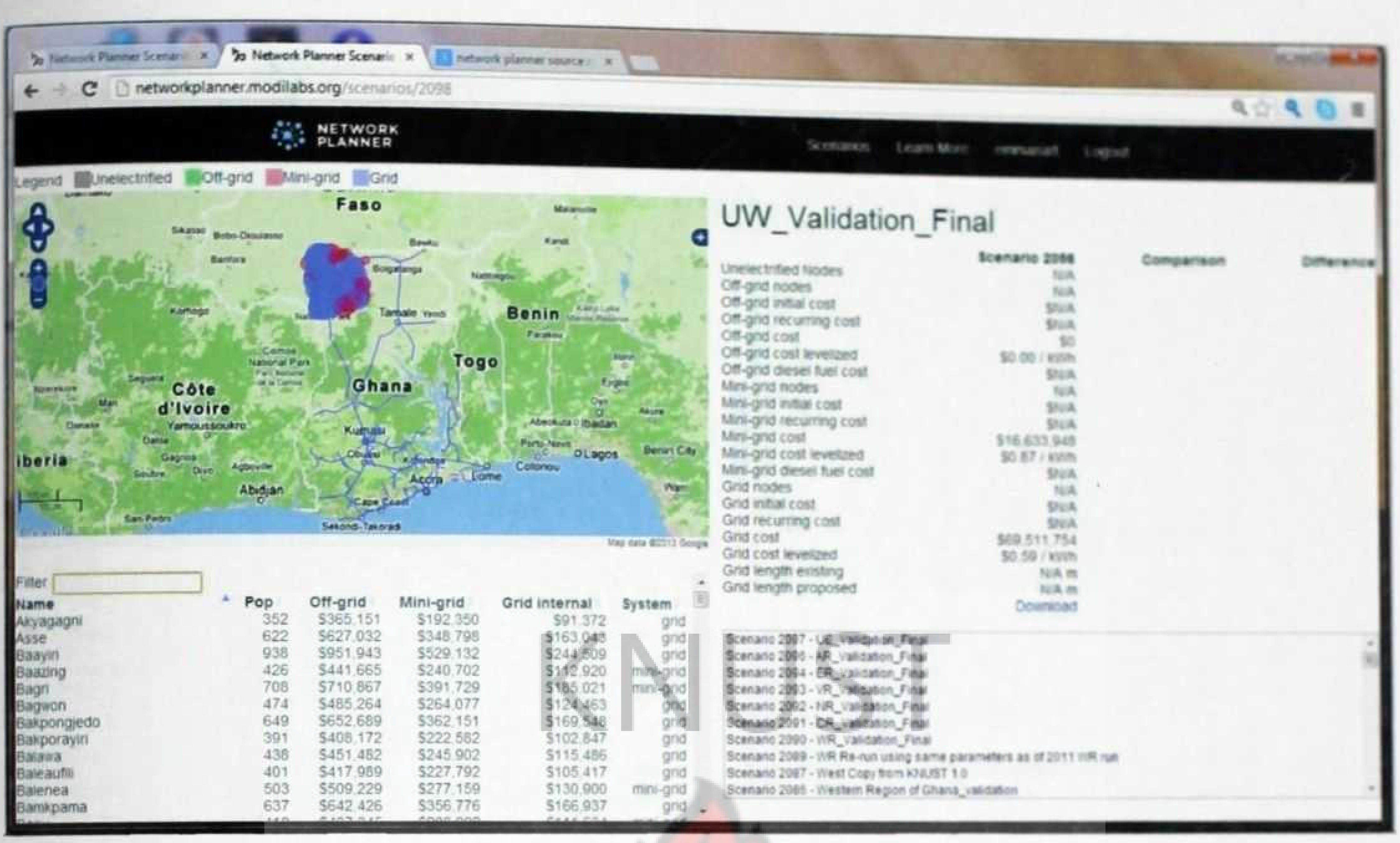

Figure B-7: Screen shot showing NP output for the Upper West Region

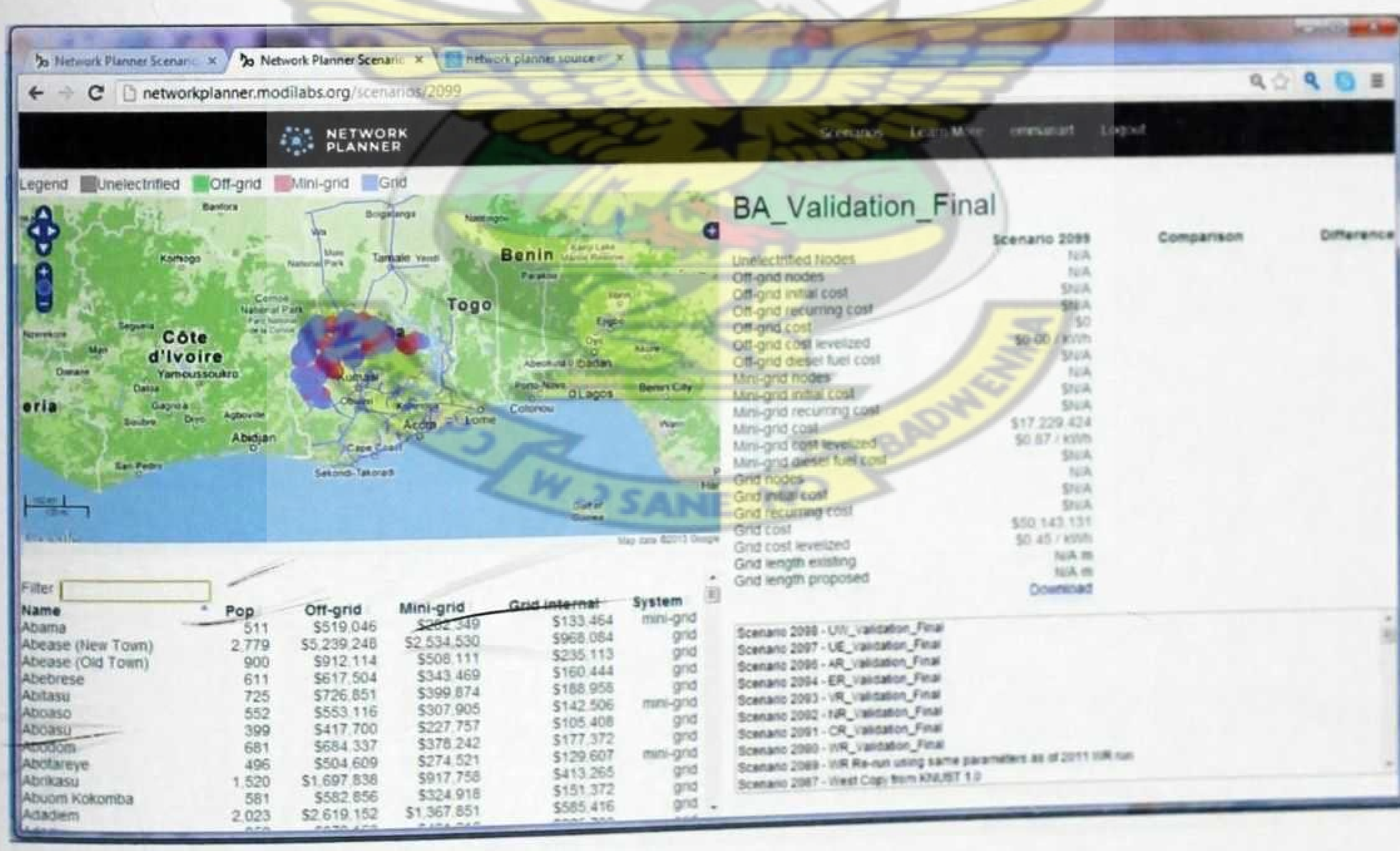

Figure B-8: Screen shot showing NP output for the Brong-Ahafo Region

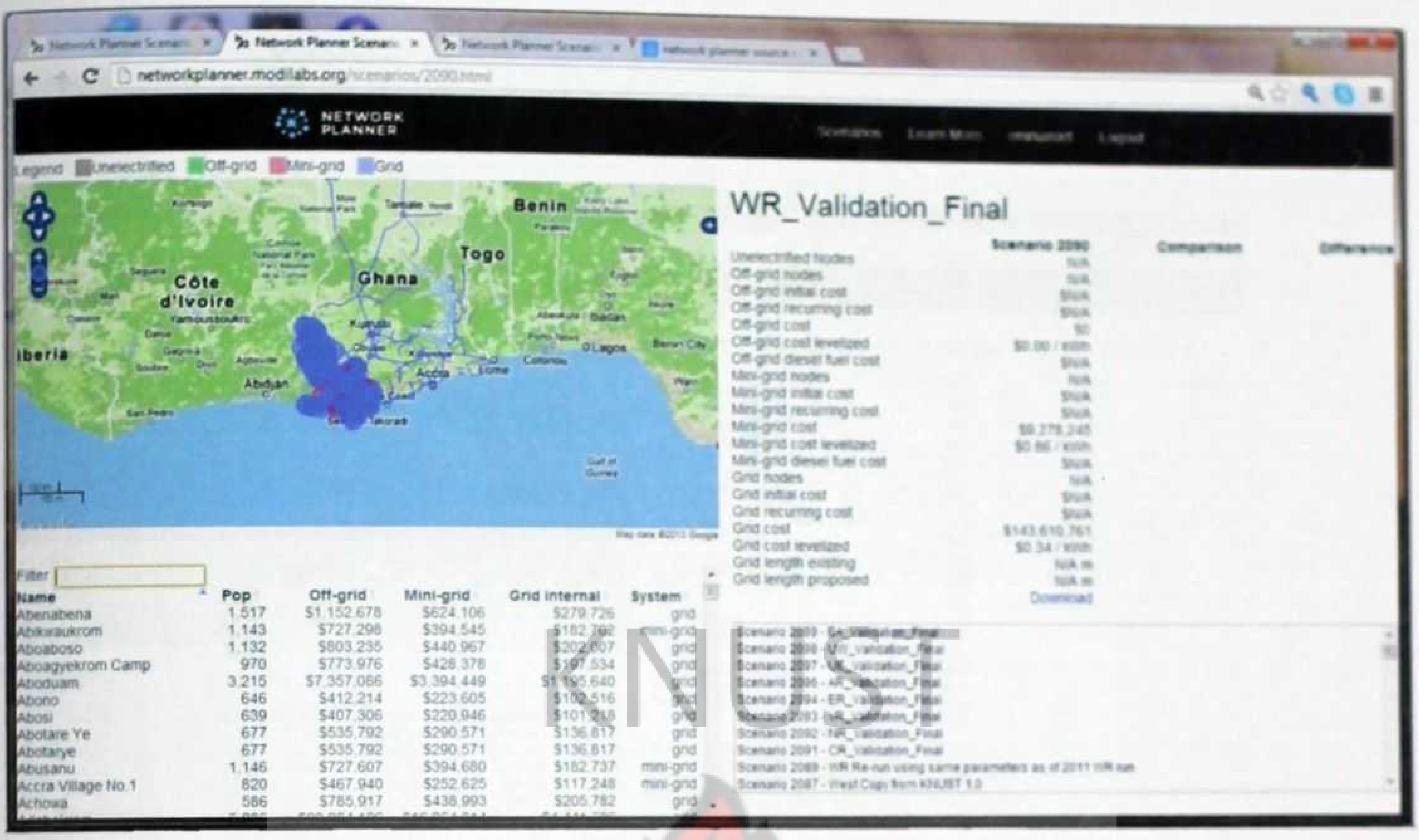

Figure B-9: Screen shot showing NP output for the Western Region

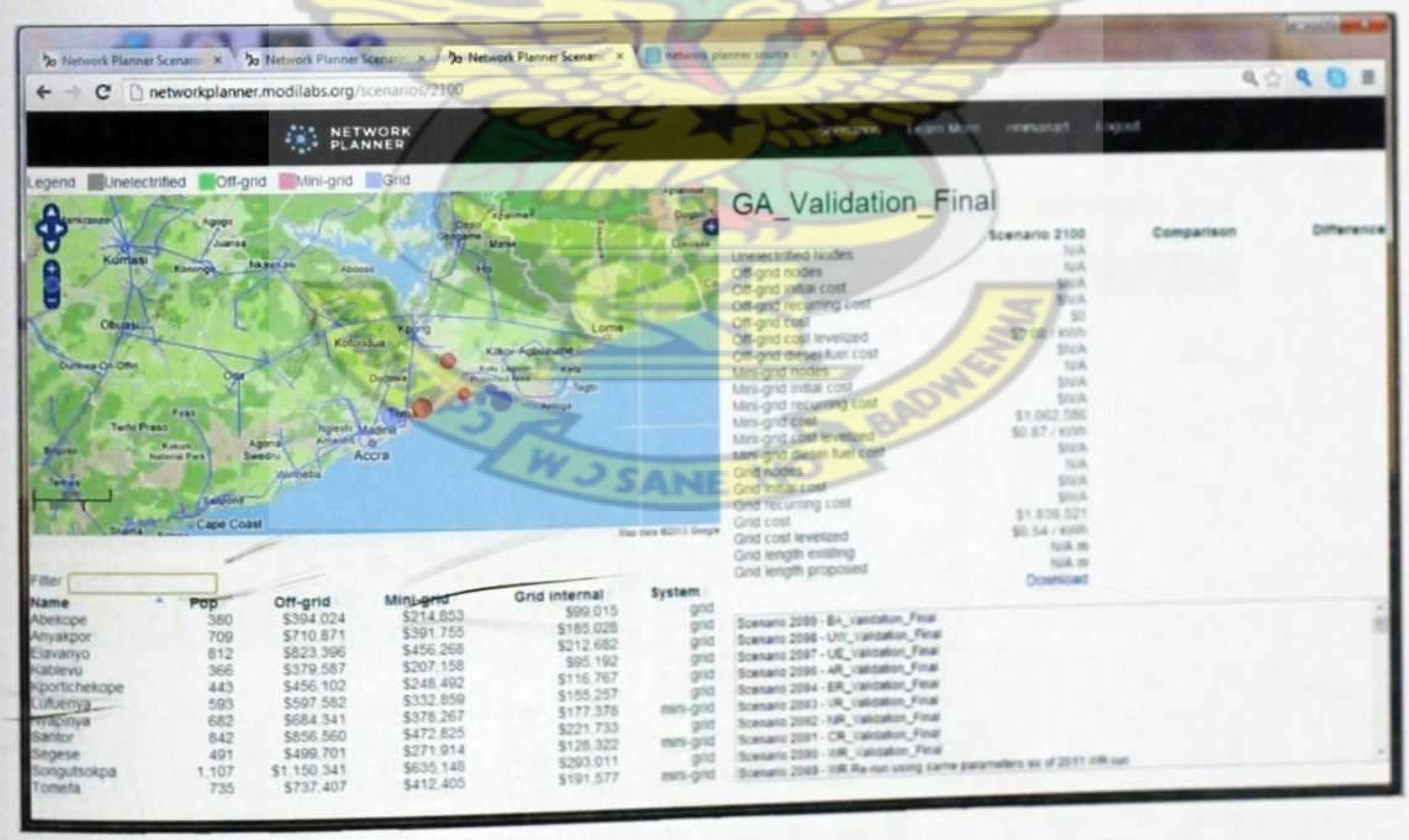

Figure B-10: Screen shot showing NP output for the Greater Accra Region

APPENDIX C: SCREEN SHOT OF NP RE-RUN FOR THE NORTHERN REGION USING VALUES FROM 2010 NP ACCOUNT

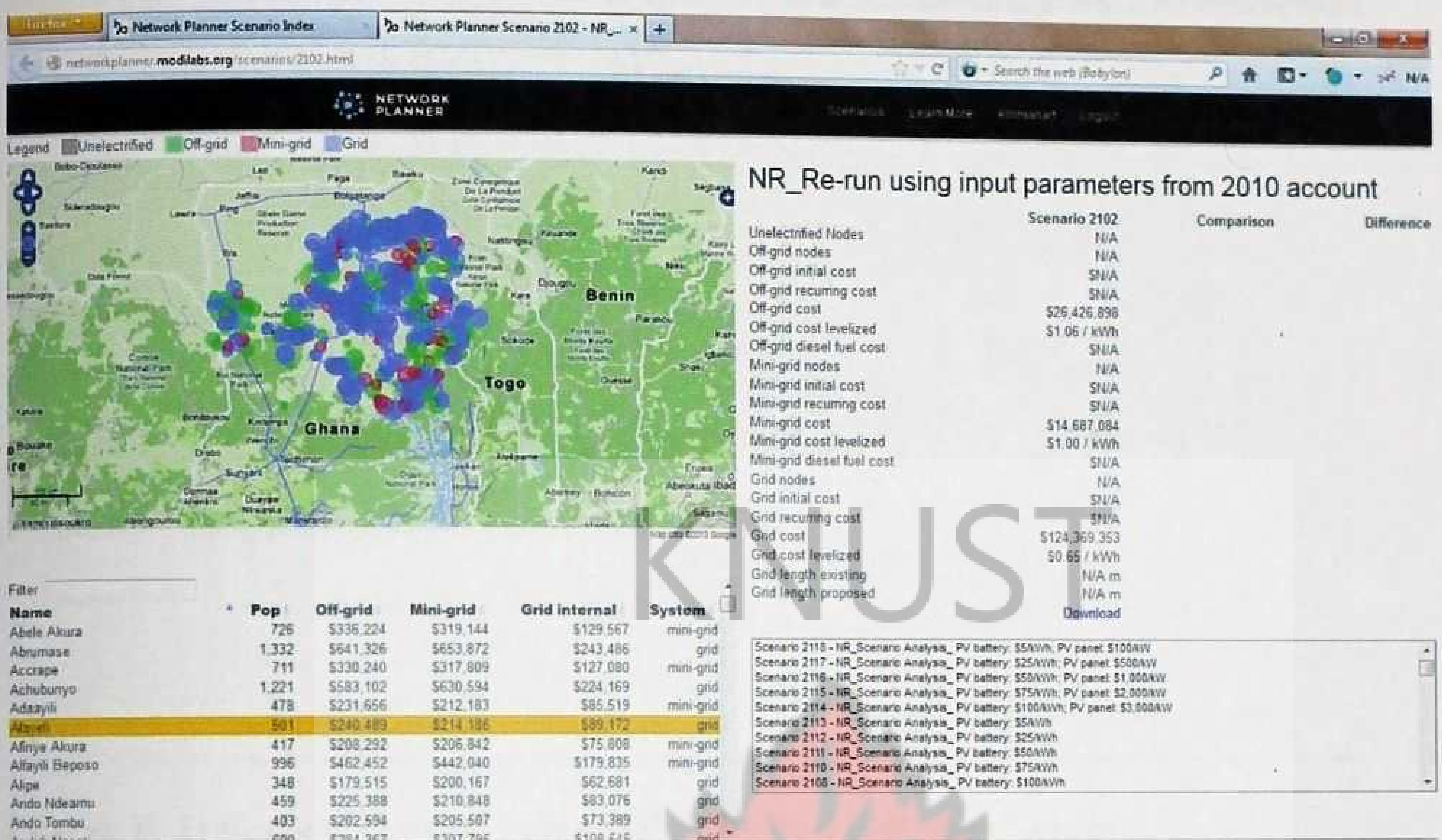

Figure C-1: Screen shot showing NP re-run for the NR using values from 2010 NP account

APPENDIX D: SCREEN SHOT OF NP BASE SCENARIO

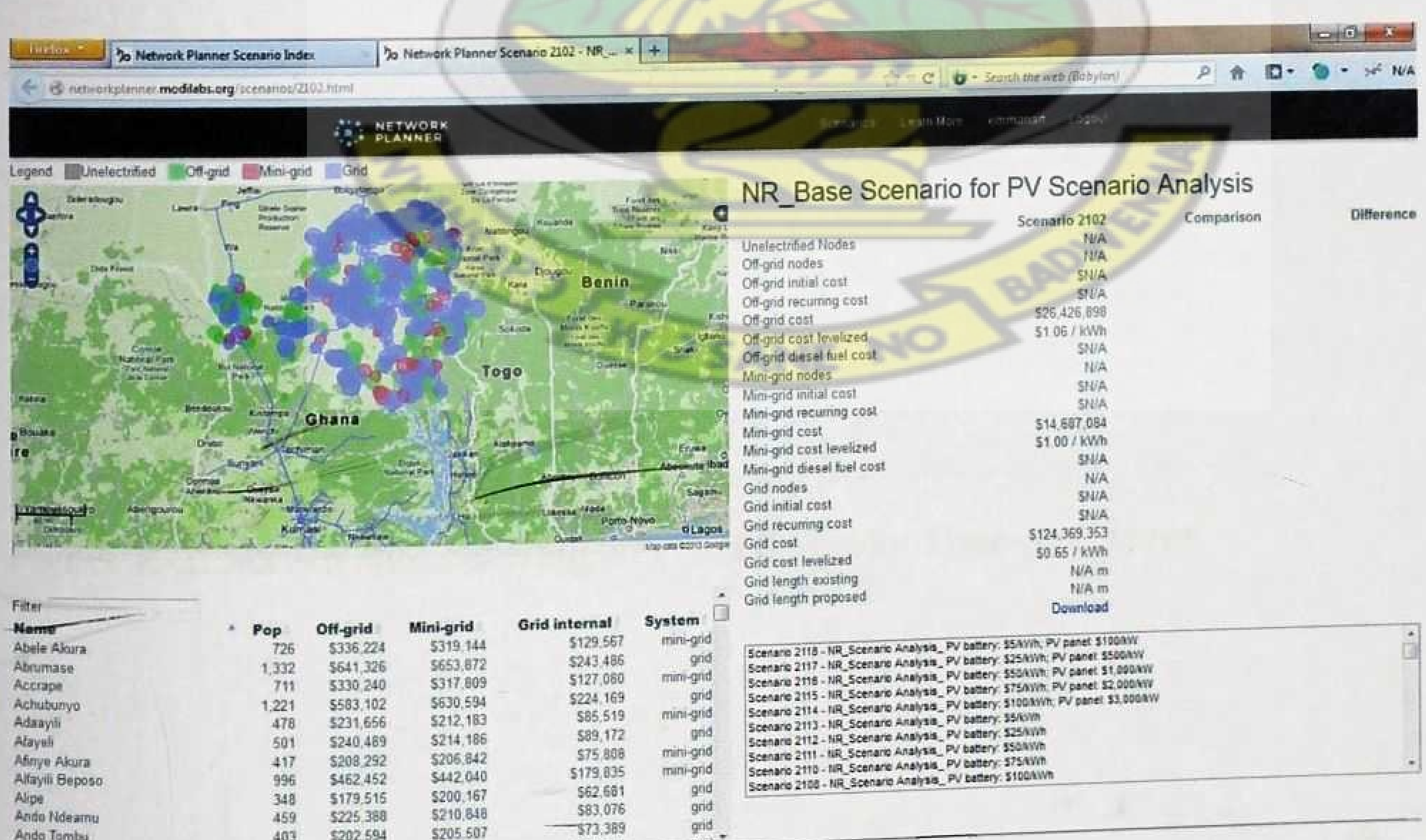

Figure D-1: Screen shot showing NP base scenario for the sensitivity analysis

APPENDIX E: ERROR SCREENS FROM NP SERVER

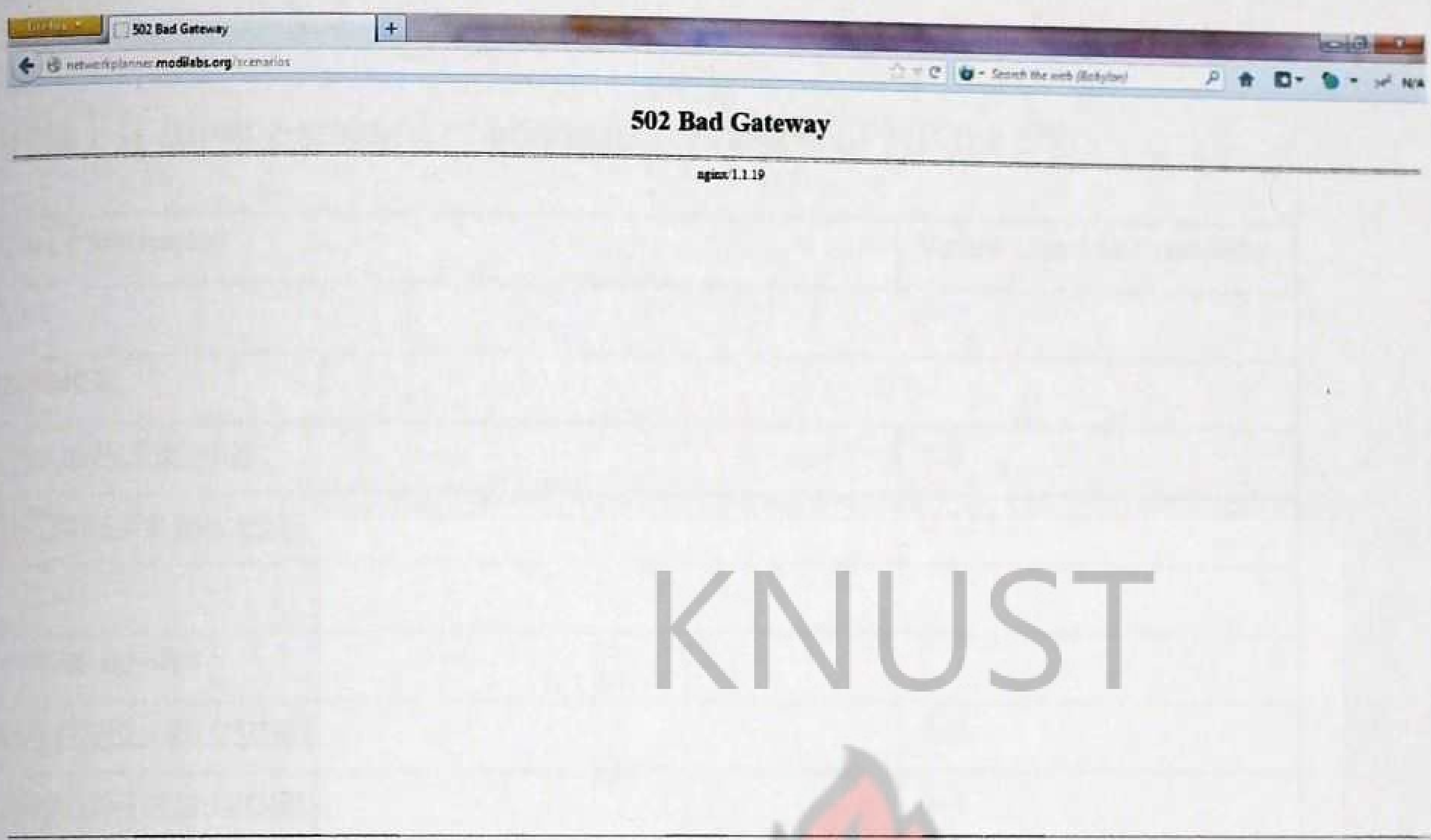

Figure E-1: Screen shot showing NP "502 Bad Gateway" error

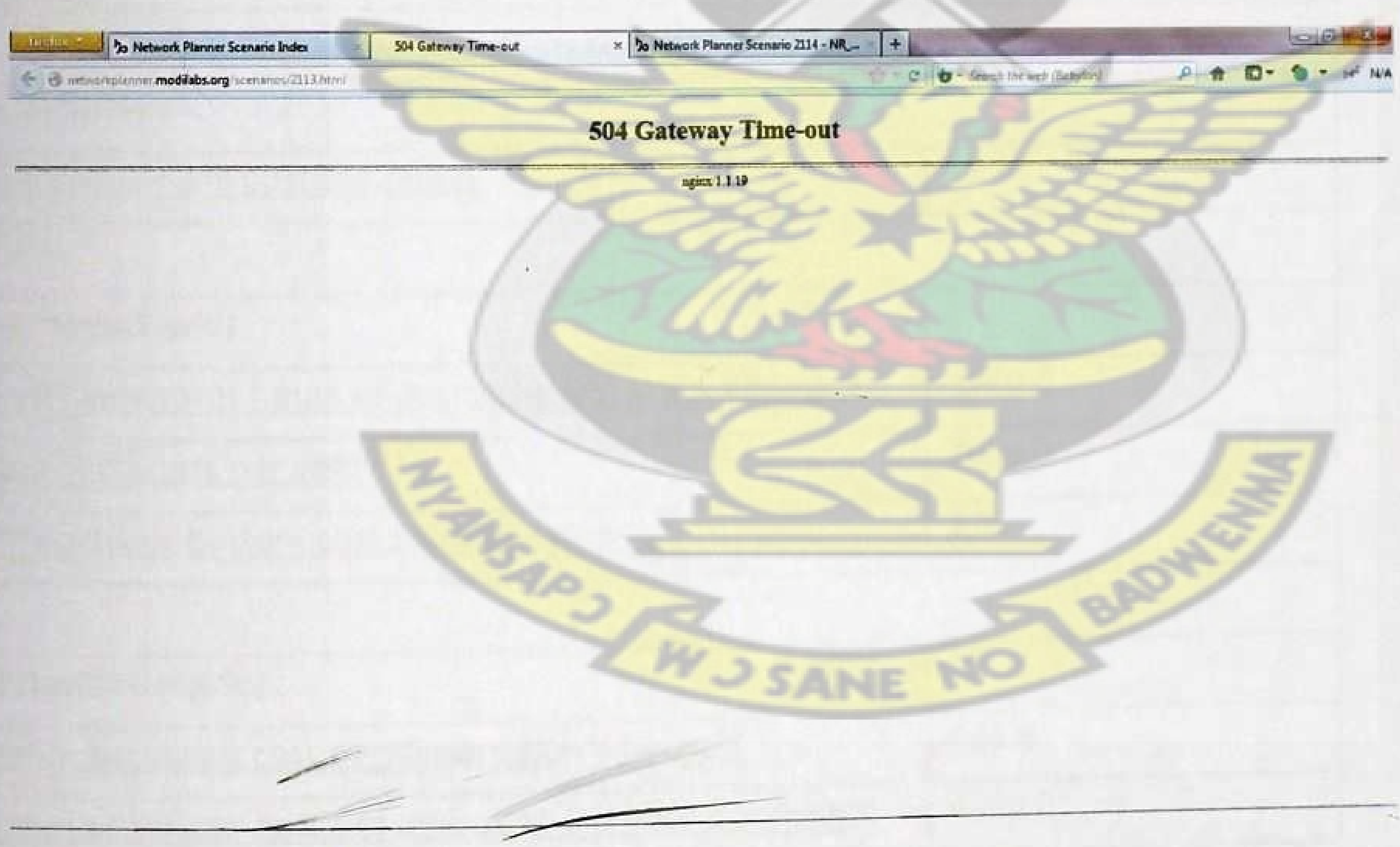

Figure E-2: Screen shot showing NP "504 Gateway Time-out" error

APPENDIX F: PARAMETERS CHANGED FROM DEFAULT PARAMETER LIST FOR USE IN RE-RUN OF NP FOR NORTHERN REGION

Table F1: Input parameters changed for re-run of NP for NR

Input Parameter	Value Used for running
FINANCE	
Electricity demand	1.8
Interest rate per year	0.1157
Demographics	
household size (rural)	7.5
household size (urban)	5.8
Demand(household)	
household unit demand per household per year	150
Distribution	
Low voltage line cost per meter	12.0
System(off grid)	
Diesel generator hours of operation per year (minimum)	1460.0
Peak sun hours per year	2099.0
Photovoltaic battery cost per kilowatt-hour	125
System(mini grid)	
Diesel generator cost per diesel system kilowatt	441.8
Diesel generator hours of operation per year (minimum)	4380.0
Diesel generator operations and maintenance cost per year as fraction of generator cost	0.01
System(Grid)	
Distribution loss	0.2
Transformer lifetime	30