Taming a Wicked Problem: Energy Access Planning From an Energy-Poor Perspective

Taming a Wicked Problem: Energy Access Planning from an Energy-Poor Perspective

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Abstract

In practice, addressing universal energy access has largely been treated as a simple planning and delivery problem – identifying the target, selecting the least-cost technology, and implementing the recommended solution. In reality, a look at the underlying dynamics suggests that we're dealing with a more complex "wicked problem" that requires a different approach. Geographic Information System (GIS) based energy access decision tools have emerged which offer a quick assessment of potential electrification options from a least cost of electrification (LCOE) perspective. Broadly speaking, these tools tend to take a top-down, grid-centric approach biased toward investment level decisions by national energy planners and donor funding institutions – leaving off-grid solar home system pay-as-you-go (SHS PAYG) service providers to make risky, empirical decisions regarding markets entry and expansion.

The hypothesis I examined is that SHS PAYG market penetration can be increased in the Economic Community of West African States (ECOWAS) through the development of an enhanced GIS-based energy access decision tool framework which overcomes institutional barriers and leverages enabling environment conditions. Overcoming the market distortion introduced by energy consumption subsidies (i.e. the institutional barrier) and leveraging the energy addressable market (i.e. the enabling environment condition) created by the faster pace of mobile service last-mile distribution (versus the pace of electrification) are proposed as the initial elements of this framework.

The research questions explored to support my hypothesis include: 1) Why has

SHS PAYG market penetration remained limited in the face of a significant addressable market in the ECOWAS region? 2) How do energy consumption subsidies, which are intended to benefit low-income consumers, distort the market and impact progress toward achieving universal energy access? 3) How can the mutual goals of SHS PAYG service providers and mobile network operators (MNOs) be leveraged to accelerate the pace of SHS PAYG scale up? 4) What are the best subsidy reform options to create a level playing for SHS PAYG service providers? 5) How can existing GIS-based energy access decision tools be enhanced to support the energy access planning process from an energy-poor perspective?

My research methods included computer simulations of the SHS PAYG addressable market, the "energy addressable market", and connection subsidies and results based financing schemes using the Open Source Spatial Electrification Toolkit (onSSET). In addition, the set of existing GIS-based energy access decision tools was evaluated to identify the platforms most suitable for enhancement to address SHS PAYG business decision needs. My results show a sharp contrast between a robust SHS PAYG addressable market of 40 to 80 million (~10-20 million households) and the 13 to 17 million people (3 to 4 million households) who are currently served by mini-grids and SHS PAYG across the region. Examination of the current status of each ECOWAS member states, coupled with projections using the historical pace of electrification, indicates that the 2030 universal energy access goals are unlikely to be met without a significant shift in the current planning paradigm. Evaluation of the existing decision tools suggests that onSSET and GeoSim® are the most suitable for future enhancement from an energy-poor perspective.

My conclusion is that my proposed enhanced GIS-based energy access decision tool framework points to a prioritization scheme employing two levels of geographic selection. First, the energy addressable market can be used as a geospatial indicator for communities which have mobile phone service but no electricity access - representing a pent-up demand for SHS PAYG service providers, increased revenues for MNOs, and critical lighting and phone charging services for energy-poor consumers. Second, geographic selection can then be applied to this result to identify connection subsidy programs (market entry) or results based financing programs (market expansion) – allowing SHS PAYG service providers to "follow the money."

In terms of future research, immediate efforts should include pilot studies of the proposed geographic selection prioritization scheme in both established and nascent SHS PAYG markets. In the mid-term, datasets from the World Bank's ongoing multi-tier framework baseline surveys should be considered as an opportunity to use the geographic selection and prioritization approach to target communities with minimal/no electricity access. Finally, development of a geospatial coordination platform designed to mitigate the risk of stranded assets for SHS PAYG service providers and mini-grid developers due to unexpected grid encroachment should be explored in the long term.

Dedication

This thesis is dedicated to my wife Sherry and my daughters Ellen and Emily. Thank you for the gift of your love, time, and patience throughout this research journey and for giving me the opportunity to pursue the international energy access work that I love. This thesis is also dedicated to the memory of my late grandfather and hero, Harold James Still, a self-made man who taught me the value of education from an early age – reminding me that it is the one thing that can never be taken away. Lastly, my work is in memory of Carlos Eduardo Ray, my friend and Harvard classmate who lost his battle with cancer and will be sorely missed at graduation and for years to come.

Acknowledgements

Thanks to all of the fellow researchers, energy access practitioners, SHS PAYG providers, and energy access decision tool developers for sharing so generously of your time and insights. I am inspired by this community of practitioners working to achieve universal energy access. Special thanks to Daniel Paco at the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) who went out of his way to provide key information and introductions and to Francis Kemausuor at the Kwame Nkrumah University of Science and Technology (KNUST) in Ghana for his insights on GIS-based energy access decision tools. My gratitude goes out to Dan Waddle of National Rural Electric Cooperative Association (NRECA) International and Ellen Morris of Sustainable Energy Solutions (SES) for the opportunity to contribute to meaningful projects as an Energy Access Consultant. Thanks are also due to Massachusetts Institute of Technology (MIT) researcher Yael Borofsky whose framing of the rural electrification challenge as a "wicked problem" helped to expand my thinking. Finally, many thanks to my Thesis Director, Tim Reber, at the National Renewable Energy Laboratory (NREL) who helped me to focus my efforts when I got stuck in the academic weeds.

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Definition of Terms

AfDB	African Development Bank
AGSI	Association of Ghana Solar Industries
ARPU	Average Revenue per User
BPR	Business Process Requirements
CDO	Community Development Organization
CIEMAT	Research Centre for Energy, Environment, and Technology
CNSE	Cost of Non-Served Electricity
csv	Comma separated variables
DFI	Donor Funding Institution
DFID	UK Department for International Development
ECOWAS	Economic Community of West African States
ECREEE	ECOWAS Centre for Renewable Energy and Energy Efficiency
EnDev	Energizing Development
EPASES	ECOWAS Program on Access to Sustainable Electricity Services
ECOWREX	ECOWAS Observatory for Renewable Energy and Energy Efficiency
EREP	ECOWAS Renewable Energy Policy
EU	European Union
EUEI PDF	European Union Energy Initiative Partnership Dialogue Facility
GEAR	GIS-Based Energy Access Review
GEDAP	Ghana Energy Development and Access Project

GIS	Geographic Information System
GPOBA	Global Partnership on Output Based Aid
GSM	Global System for Mobile Communications
GSMA	Global System for Mobile Communications Association
GSS	Ghana Statistical Service
gTIGER	GIS Group for Regional Integration of Renewable Energies & Rural Electrification
hh	household
HV	High Voltage
IBT	Increasing Block Tariff
IDCOL	Infrastructure Development Company Limited
IFC	International Finance Corporation
IFD	Indicators for Development
IED	Innovation Energie Development
KNUST	Kwame Nkrumah University of Science and Technology
kWh	kilowatt hours
LCOE	Least Cost of Electrification
LEIA	Low Energy Inclusive Appliance
LEC	Levelized Electric Cost
LED	Light Emitting Diode
LV	Low Voltage
M4D Utilities	Mobile for Development Utilities
MFI	Microfinance Institution
MoE	Ministry of Energy

MID	Mean Inter-household Distance
MIT	Massachusetts Institute of Technology
MNO	Mobile Network Operator
MTF	Multi-Tier Framework
MTN	Mobile Telephone Network
MV	Medium Voltage
MV_{max}	Maximum Medium Voltage Feeder Length
M&V	Monitoring and Verification
NCWIT	National Council on Women in Information Technology
NEDCo	Northern Electricity Distribution Company
NGO	Non-Governmental Organization
NREL	National Renewable Energy Laboratory
NRECA	National Rural Electric Cooperative Association
onSSET	Open Source Spatial Electrification Toolkit
PO	Partner Organization
PPEO	Poor People's Energy Outlook
PR	Penetration Rate
PV	Photovoltaic
QC	Quality Control
RBF	Results Based Financing
REA	Rural Electrification Authority
REM	Reference Electrification Model
RGC	Rural Growth Center

RISE	Regulatory Indicators for Sustainable Energy
RNM	Reference Network Model
SA PV	Standalone Solar Photovoltaic
SDG	Sustainable Development Goal
SEB	State Electricity Board
SES	Sustainable Energy Solutions
SHS	Solar Home System
SHS PAYG	Solar Home System Pay-As-You-Go
SMS	Short Message Service
SSA	Sub Saharan Africa
T&D	Transmission & Distribution
TV	Television
UNDESA	United Nations Department of Economic and Social Affairs
UNFCCC	United Nations Framework Convention on Climate Change
UNICEF	United Nations International Children's Emergency Fund
UN SE4ALL	United Nations Sustainable Energy for All
USD	United States Dollar
VDT	Volume Differentiated Tariff
WB	World Bank
WTP	Willingness to Pay

Chapter I

Introduction

In his vision statement for the launch of the United Nations Sustainable Energy for All (UNSE4ALL) initiative, Secretary General Ban Ki-Moon stresses the need for a shift in perspective as he asserts that:

> Building out a national electricity grid has historically been a successful strategy for achieving high rates of energy access in many countries, but it is not as well suited to serving sparsely populated or remote areas. Such solutions require business models that are commercially viable, entrepreneurial supply chains that can reach remote areas, increased consumer acceptance, community-based service delivery models and innovative financing mechanisms (Nique, 2013).

The UN SE4ALL initiative was borne out of the 2015 Sustainable Development Goals (SDGs). Among these, SDG 7 calls for us to "secure access to accessible, reliable, sustainable, modern energy for all by 2030" (UNSE4ALL, 2017). Translating this aspiration into measurable goals gives rise to the pillars of the UNSE4ALL initiative: 1) ensure universal access to modern energy services by 2030, 2) double the global rate of improvement in energy efficiency, and 3) double the share of renewable energy in the global mix (UNSE4ALL, 2017). Throughout my thesis, the focus is on the goal of universal energy access.

At its heart, the limited penetration of off-grid solutions into energy-poor communities does not seem to be a technology barrier, but more of a planning and institutional challenge. Conceicao and Heitor's (2003) work on techno-economic paradigms suggests that the transition from one technology to another requires a shift not only in technological and economic factors, but in the broader social and institutional frameworks as well. In other words, simply having a new technology available doesn't result in the expected impact if the other factors don't support it (Conceicao & Heitor, 2003). Looking at this gap between innovation and technology adoption in the context of my research, solar home system pay-as-you-go (SHS PAYG) solutions have emerged as a proven technology - but struggle to achieve the degree of market penetration that least cost of electrification (LCOE) planning models would suggest.

The Economic Community of West African States (ECOWAS) was selected as a representative example of the electrification challenge and serves as the geographic focus of my research. On one hand, member states Cape Verde; Ghana; and Cote d'Ivoire are among the electricity access leaders on the continent. At the other end of the spectrum - member states Niger, Nigeria, and Burkina Faso rank among the twenty (20) "hot spot" countries which account for two thirds (2/3) of the electrification challenge globally (World Bank, 2015). From an institutional perspective, the electricity access and geospatial planning missions of the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) provide a vehicle for ongoing progress in the region.

A number of GIS-based energy access decision tools have been emerged in recent years in response to the need for quick assessments for government, utility, and donor funding institution energy planners (Mentis et al., 2015). Among these tools, the LCOE methodology represents a common thread for identification of the cost-optimized electrification solution for a target population (Mentis et al., 2015; GeoSim®, 2017; Kemausuor, Adkins, Adu-Poku, Brew-Hammond, & Modi, 2012; Borofsky, 2015; Ellman, 2015; Dominguez Bravo & Pinedo-Pascua, 2009). Utility grid extension, mini-grid development, and solar home system pay-as-you-go (SHS PAYG) deployment also represent a common thread as electrification options. The Reference Electrification Model (REM), Intigis, Network Planner, and onSSET decision tools are open-source platforms developed by researchers at the Massachusetts Institute for Technology (MIT); the Research Centre for Energy, Environment, and Technology (CIEMAT); Columbia University; and the KTH Royal Institute of Technology in Stockholm, respectively. In contrast to the open source approach, GeoSim® is a commercial product developed by Innovation Energie Development (GeoSim®, 2017). From a broad perspective, these tools appear to find their primary value in informing national and sub-national electrification investment decisions – as opposed to providing support to inform business decisions for off-grid service providers.

Research Significance and Objectives

The significance of my research lies in the opportunity to "flip the paradigm" on the current energy access planning approach. While existing GIS-based energy access planning models delineate cost-optimized target areas for grid extension, mini-grid development, and SHS PAYG market penetration, the outputs of these models don't seem to be reflected in the mix of electrification options which are implemented in practice. Instead of driving the ECOWAS region toward achievement of the 2030 universal energy access goals, the dynamics underlying the disparity between energy access planning and adoption appear to be stalling the progress of grid extension, financially crippling distribution utilities, weakening social acceptance of off-grid technologies, and suppressing the scale up of SHS PAYG market penetration. My research objectives include: 1) understanding the factors driving the disparity between rural electrification planning and results, 2) identifying catalysts which can accelerate progress toward universal energy access, 3) assessing the capabilities and limitations of existing GIS-based energy access planning tools, and 4) creating a framework which rethinks the energy access planning process from an energy-poor perspective.

Background

My thesis explores the potential solutions to these research objectives by reviewing 1) the capabilities and limitations of existing GIS-based energy access decision tools, 2) the risky business decision faced by SHS PAYG providers, 3) the institutional barriers and enabling environment conditions which may represent roadblocks or catalysts to the current energy access planning process, 4) the current electrification status for the ECOWAS member states, and 5) the value of treating this as a "wicked" problem to tame – as opposed to a simple planning problem to solve.

Existing GIS-based Energy Access Decision Tools

The LCOE methodology (Figure 1) is at the heart of the current energy access planning process – identifying which target areas (communities) are best served by grid extension, mini-grid development, or solar home system deployment (Kemausuor et al., 2012).

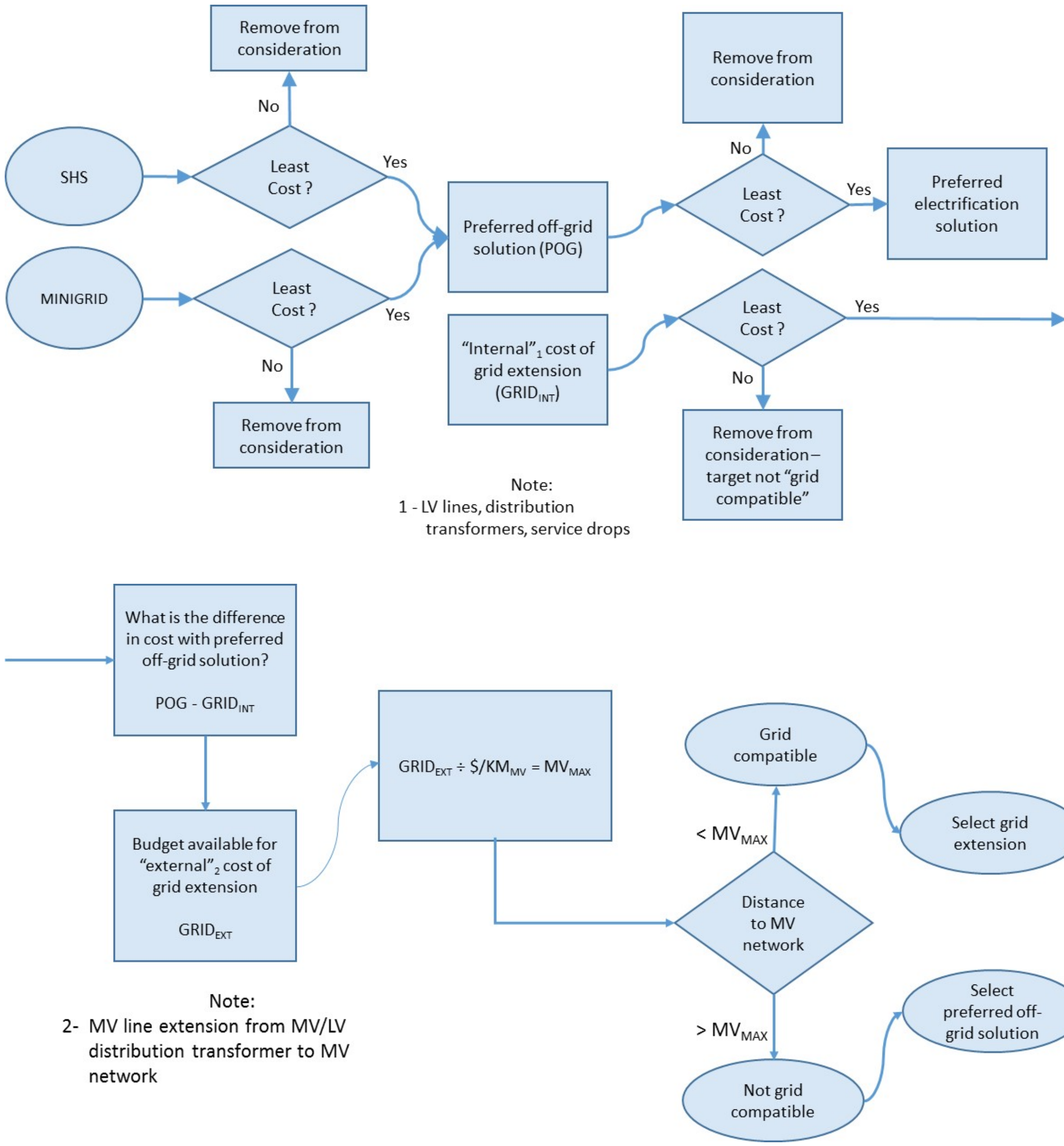

Figure 1. LCOE methodology flowchart (Kemausuor et al., 2012, 2014).

In the illustration above (Figure 1), MV indicates the medium voltage (typically 11 or 33 kV) utility network, while LV describe the low voltage (430 V) distribution network. The least cost decisions (denoted by the diamonds) are based on calculations of the initial and recurring cost for each technology option using equipment catalogs, construction costs, and operations/maintenance data. The key steps in the LCOE approach include: 1) comparison of the potential off-grid technologies, 2) comparison of the preferred off-grid technology with the "internal cost" of utility grid extension, 3) determination that the target community is not "grid compatible" if the internal cost is greater than the cost of the preferred off-grid solution, and 4) determination of the maximum allowable distance to the existing MV network if the internal cost is less than the cost of the preferred off-grid solution. Looking at this decision parameter from a mathematical perspective:

$$LOE = \sum_{t=1}^{n} (lt + O\&Mt + Ft)/(1+r)t \;\div \sum_{t=1}^{n} (\frac{Et}{(1+r)t})$$

(l_t = investment expenditure for a specific system in year t, $O\&M_t$ = operation and maintenance expenditure, F_t = fuel expenditure, E_t = generated electricity, r = discount rate, and n = lifetime of the system). By this definition, LCOE represents the final cost of electricity (typically in $/kWh) required for the selected system to break even over the project's lifetime (Mentis et al., 2015).

In theory, energy planners are using existing GIS-based energy access decision tools to identify and implement the least cost electrification option for a target community. In practice, this process often falters in the space between the output of these decision tools and initiation of energy access projects and market penetration initiatives. In an effort to clearly communicate this key concept, the difference between the "business as usual" (Figure 2) and enhanced energy planning (Figure 3) processes illustrate a strategy to close the gap between decision tool outputs and project implementation/technology adoption.

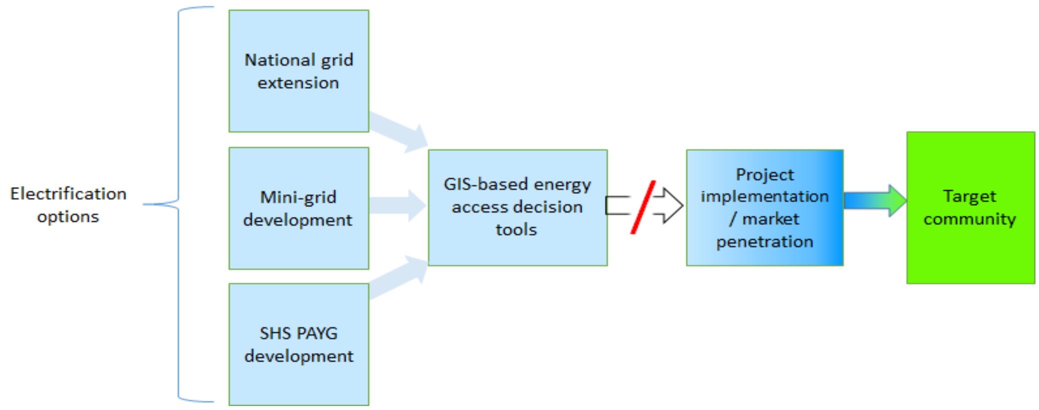

Figure 2. Current energy access planning process (author's elaboration, 2017).

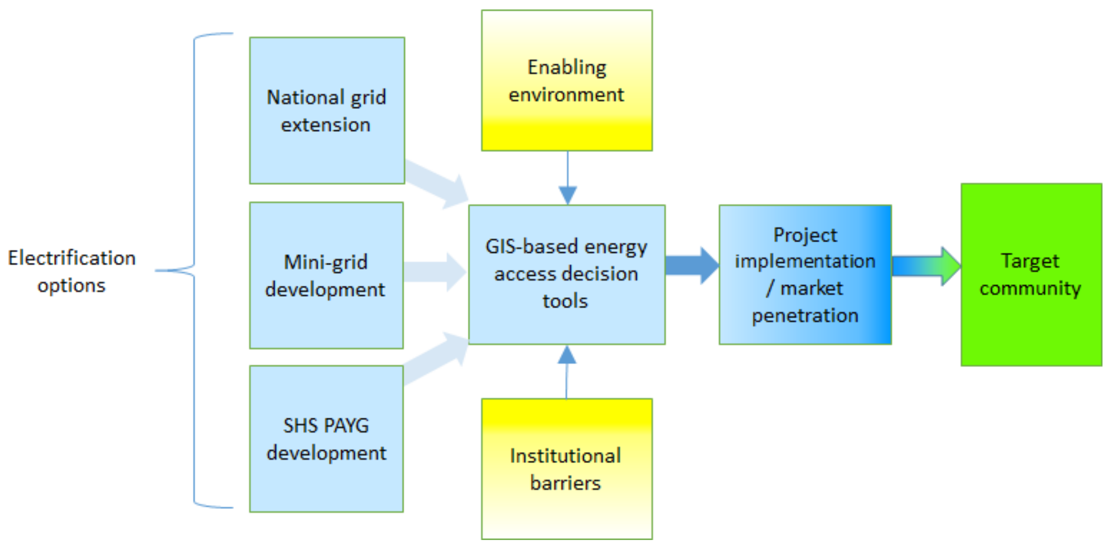

Figure 3. Enhanced energy access planning process (author's elaboration, 2017).

In a well-functioning planning system, the outputs of the GIS-based energy access decision tools would identify the least cost solution (national grid extension, mini-grid development, or SHS PAYG deployment) which would then translate into project implementation or market penetration. The "business as usual" situation (Figure 2) points to the gap (signified by the break in the figure) between decision tools outputs and household electrification benefits. This wedge can be driven by political interference, grid-centric market distortion, and limited awareness of off-grid technology. The enhanced energy access planning process (Figure 3) proposes to fill this gap and move toward the ideal of a "well-functioning system" by introducing geographic selection to identify and prioritize addressable markets for SHS PAYG solutions. In concept, this geographic selection can be accomplished by integrating geospatial indicators which are used to overcome institutional barriers (removing the negative roadblocks) and leverage enabling environment conditions (accentuating the positive opportunities). In both figures, the blue shading indicates the process moving from consideration of the electrification options to project implementation/market penetration. The green shading denotes the end goal of electricity access for target communities. Finally, the yellow shading (Figure 3) illustrates the introduction of new geographic selection layers to existing GIS-based energy access decision tools.

Prior to reviewing the relevant capabilities and limitations of each of the existing GIS-based energy access decision tools, a broader review of the development, adoption, and the use of such tools across the ECOWAS region was conducted. The progress of each member state was compiled from the outcomes of a Regional Training Workshop on GIS for Energy Planning organized by ECREEE in 2014 (Figure 4).

The horizontal axis in the matrix illustrates member states' progress in the development of energy planning GIS tools, while the vertical axis communicates the level of development of institutional frameworks. Progress among the member states ranges from minimal progress in Gambia, Sierra Leone, Guinea, and Guinea-Bissau, to the deployment of GIS tools for energy access analysis in Senegal, Ghana, and Burkina Faso. In terms of institutional frameworks Cote d'Ivoire, Togo, and Niger show little

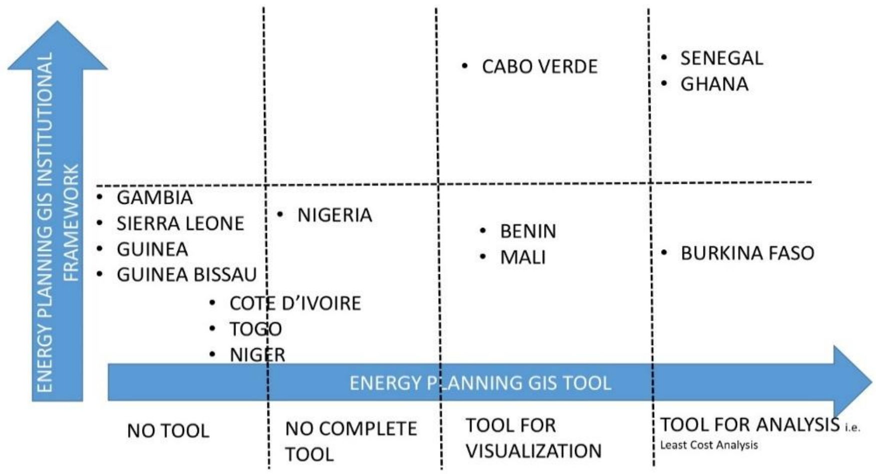

Figure 4. Energy planning GIS tool development status (ECREEE, 2014).

progress, while Senegal, Ghana, and Cape Verde (referred to as Cabo Verde in the figure) have developed robust frameworks.

While the outcome of this workshop suggests that Senegal, Ghana, and Burkina Faso are in the best position to benefit from an enhanced GIS-based energy access decision tool framework, ECREEE (2014) reported that there is a strong interest and commitment toward making significant progress across the region. Expanding on the insights introduced in the matrix above, a more detailed review (Table 1) describes the development of institutional frameworks, adoption of a specific energy access decision tool, utilization of particular GIS platforms (i.e. ArcGIS), and energy planning GIS tool deployment status for each of the ECOWAS member states. This detailed review points to Ghana and Senegal as regional leaders across the board, while Burkina Faso has an analytical tool in place but needs to strengthen its institutional frameworks. According to this assessment, Network Planner has been utilized in Ghana and GeoSim® deployed in

Burkina Faso (ECREEE, 2014). A broader literature review, however, reveals a broader GIS decision tool adoption throughout the region, with an onSSET case study in Nigeria (Mentis et al., 2015) and GeoSim® projects in Benin, Cote d'Ivoire, Liberia, and Senegal (C. Perret, personal communication, January 14, 2017).

Table 1. ECOWAS GIS development status (ECREEE, 2014).

Member State	Institutional Framework	Energy Planning Tool	Platform	Status	Comments
Benin	Directorate of Energy (DGE), l'Agence Beninoise d'Electrification Rurale et de Maitrise d'Energie (ABERME)	none	ArcGIS	Building geodatabase with consultant support	community electrification status, demographic data, economic development data, electricity grid
Burkina Faso	Ministry of Mines and Energy , Mainstreaming Energy for Poverty Reduction and Economic Development (MEPRED) Project, Rural Electrification Study Project (DECON)	yes	GeoSim/Manifold - MEPRED, ArcView - DECON	GeoSim used to run energy planning simulations	none
Cabo Verde	Ministry of Tourism, Industry, & Energy, Public Utility Company (ELECTRA), National Statistics Institute of Cabo Verde (INECV)	no	Information Territory System (SIT) set up by Ministry of Environment, Housing, and Territorial Planning (MAHOT)	SIT serves as a map viewer and visualization tool only	none
Cote d'Ivoire	Energy Ministry, la Societe des Energies de Cote d'Ivoire (CI-ENERGIES), l'Autorite Nationale de Regulation du Secteur de l'Electricite (ANARE)	no	None	ANARE & CI-ENERGIES plan to use GIS for energy planning in the future	GIS used for hydrology modeling. Ivory Electricity Company considering use of GIS
Gambia	Ministry of Energy (MoE), National Water and Electricity Company (NAWEC)	no	None	Work in progress to equip NAWEC with GIS tools and integrate into planning framework	none
Ghana	Ministry of Energy & Petroleum, Energy Comission (EC), Electricity Company of Ghana (ECG), Northern Electricity Distribution Company (NEDCo), Kwame Nkrumah Univeristy of Science and Technology Centre (KNUST), Center for Remote Sensing and Geographic Information Systems (CERGIS)	GIS-Based Energy Access Review (GEAR) Toolkit	Network Planner, ArcGIS	Energy planning framework - Ghana Energy Development and Access Project (GEDAP), National Electrification Scheme (NES), Ghana Open Data Initiative, Ghana Energy Access Database (GhEA Database), Ghana Energy Access Data (EAD) Task Force	Key challenges - technical expertise and data availability
Guinea	Lead Institution - Le Ministere de l'Energie et de l'Hydraulique, Stakeholders - le Direction Nationale de l'Energie (DNE), Electricity Guinean Company (EDG), le Bureau d'Electrification Rual Decentralise (BERD), l'Agence Nationale d'Electrification Rurale (ANER), & l'Agencie de Regulation du secteur de l'eau et de l'electricite	Systeme d'Information Energetique (SIE)	to be determined	BERD leading rural electrification, ANER not currently functional	SIE development under PREREC project, funded by African Development Bank (AfDB)

Member State	Institutional Framework	Energy Planning Tool	Platform	Status	Comments
Guinea Bissau	Ministry of Energy and Industry	None	None	Ministry of Energy and Industry interested in GIS for rural electrification	Capacity building and support from ECREEE desired
Mali	le Direction Nationale de l'Energie (DNE, Energy Ministry), l'Agencie Malienne pour le Development de l'Energie Domestique et de l'Electrification Rurale (AMADER, public institution), & l'Energie du Mali-Societe Anonyme (EDM-SA, electricity utility)	ArcER (ArcGIS for Rural Electrification)	ArcGIS	Energy planning framerwork through Programme Decennal d'Electrification Rural (PRODER) & Plan Directeur d'Electrification Rural, 2007-2020 (PDER)	Capacity building needed to take full advantage of ArcER
Niger	le Ministere de l'Energie et du Petrole, le Ministere de l'Hydraulique et de l'Assainissement, l'Agence Nigerienne Pour l'Electrification Rurale (ANPER), le Direction des Energies renouvelables et des Energies Domestiques (DEREO), & la Societe Nigerienne d'Electricite (NIGELEC)	none	Model for Analysis of Energy Demand (MAED), Model for Energy Supply System and General Environmental Impacts (MESSAGE), and Financial Analysis of Electric Sector Expansion Plans (FINPLAN)	Information Energy System (SIE) - collecting, processing, disseminating energy data	Interest in the use of GIS for energy planning
Nigeria	Federal Ministry of Power, Transmission Company of Nigeria (TCN), Nigeria Rural Electrification Agency (REA), Energy Commission of Nigeria (ECN)	none	None	Program with GIZ to promote GIS for rural electrification in selected states	
Senegal	le Ministere de l'Energie, l'Agence Senegalaise d'Electrification Rural (ASER), la Societe Nationale d'Electricite (SENELEC)	SIERS (Energy Information System for Rural Electrification	ArcGIS	ASER, SENELEC, & PETROSEN using GIS tools for energy planning. SIERS used for achieving rural electrification targets through Priority Programs for Rural Electrification (PPER) & Poverty Reduction Programs (PREMs)	SIERS used to monitor electrification access rates, identify and georeference electric utility infrastructure
Sierra Leone	Ministry of Energy (MoE)	None	None	GIS task force established - National Bureau of Statistics, National Planning Comission, Transmission Company, National Ministry of Energy	none
Togo	La Direction Generale de l'Energie (DGE, Ministry of Mines and Energy), La Compagnie Energie Electrique du Togo, la Communaute' Electrique du Benin	none	none	GIS under consideration by Ministry of Mines and Energy	none

In order to rank their suitability for enhancement from an energy-poor perspective, each of the existing GIS-based energy access decision tools was reviewed to understand its input data requirements, calculation methods, strengths/weaknesses, practical applications, and unique features.

Network Planner. Key research insights from an assessment of the Network Planner tool included: 1) illustration of the sensitivity of model results to changes in mean inter-household distance, household electricity demand, and penetration rate, 2) urban versus rural differences in energy demand, and 3) explanation of Ghana's historical preference for utility grid electrification. Much of the information regarding Network Planner available in the literature is from Kemausuor's (2012) European Union Energy Initiative Partnership Development Facility (EUEI PDF) report entitled GIS-Based Support for Implementing Policies and Plans to Increase Access to Energy Services in Ghana as well as a companion article (2014) which summarizes the larger report. The Network Planner input data requirements (Table 2) provide a starting point for this assessment.

Table 2. Input data requirements - Network Planner (Kemausuor et al., 2012, 2014).

Data Category	**Data Requirements**
Geospatial	Locations of un-electrified communities and existing MV grid network
Socio-economic	Interest rate, economic growth rate, elasticity of electric demand per year
Demographic	Initial population, population growth rate, mean household size
Electricity Demand	Household, productive use (grinding mills), commercial (shops), and institutional (schools, health clinics)
Cost	Initial and recurring cost for each electrification solution

While the bulk of these input data requirements are similar to those encountered in the competing energy access decision tools; the segregation of household, productive use, commercial, and institutional electricity demand was noted as a strength of Network Planner. Kemausuor's (2012, 2014) Ghana case study introduces a number of critical parameters (Table 3) which shed light on the geospatial dynamics at work in the energy access planning process.

Table 3. Critical geospatial parameters – Ghana case study (Kemausuor et al., 2012, 2014).

Parameter	Description	Modeling Assumptions
Household Demand (kwh/hh/year)	Electricity demand	150 kWh/hh/year (pop. 500), 900 kWh/hh/year (pop. 5,000)
Urban Threshold (community population)	Higher electricity demand/household for urban versus rural communities	Population of 5,000 specified by Ghana Statistical Service (GSS)
Mean Inter-household Distance (MID) (meters)	Average distance between houses	25 m
Penetration Rate (PR)	Percentage of households in a community with an electrical connection	100%, 60%, and 30%

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Network Planner characterizes (Table 3) urban areas with a higher electricity demand per household than small villages. The model also uses an urban threshold (5,000 people) which describes the population below which a community is deemed rural and above which it is deemed urban (Kemausuor et al., 2014). This urban threshold will differ from country to country throughout the ECOWAS region and is commonly established by the national statistical service. This treatment of target communities as urban versus rural is based on the assumption that urban households tend to have higher incomes and greater access to electrical appliances than their rural counterparts (Kemausuor et al., 2014).

Looking at each of these critical parameters in greater detail, the mean inter-household distance (MID) is used to describe the dispersion of households in a community. The higher the MID, the more distance there is between houses - representing a more rural community. The lower the MID, the less distance there is between houses, indicating a more peri-urban or urban community. MID directly impacts the extent and cost of the LV network needed to serve a target community (Kemausuor et al., 2014). The Ghana case study uses a MID default value of 25 meters throughout the country. In my view, this is a significant limitation, since the actual distance between houses will be much lower in urban neighborhoods and much higher in rural communities. In an enhanced GIS-based energy access decision tool framework, this limitation could easily be overcome by selecting appropriate rural and urban MID default values and interpolating between those values for specific target communities.

Penetration rate is another critical geospatial parameter used in the Network Planner model. Full penetration (100%) represents universal electricity access for a target community. While this approach represents the highest first cost for all three electrification modes, it spreads the infrastructure cost for grid extension and mini-grid alternatives among a greater population of households. Penetration rates less than 100% indicate that only a portion of the households in a target community will be served through an electrification program. In contrast to full penetration - this reduces the first cost for all electrification modes, but spreads the infrastructure costs among a smaller number of households (Kemausuor et al., 2014)

Perhaps the most valuable insights gained from the Network Planner tool assessment emerged from the sensitivity analysis which examined the impact of varying household energy demand, MID, and PR from the baseline conditions. This sensitivity analysis was quite helpful in understanding the geospatial dynamics at work in the LCOE based approach, as well as the stark differences between the electrification of urban and rural target communities. The Ghana case study used Greater Accra (urban) and the Northern Region (rural) for this analysis since they represent the two extremes of population density in Ghana. From my own experience, these two areas feel like different countries: Accra is modern and metropolitan, while the agricultural lifestyle in much of the Northern Region doesn't seem to have changed in centuries. Putting these demographic differences in perspective, the Northern Region includes 660 (25%) of Ghana's twenty-six hundred (2600) un-electrified communities, while Accra has only 11 (<1%) of the total (Kemausuor et al., 2012). Likewise, the population density varies from a low in the Northern Region (35 people/km^2) to a high in Greater Accra (1,303 people/km^2) (Kemausuor et al., 2012). The first step in the sensitivity analysis (Table 4) illustrated that a reduction in the household demand from the baseline value drives a dramatic increase in the number of un-electrified communities which are off-grid compatible in the Northern Region.

Table 4. Household electricity demand – sensitivity analysis (Kemausuor et al., 2012, 2014).

Household Demand (kwh/hh/yr)	**Off-grid (% of communities)**	**Mini-grid (% of communities)**	**Grid (% of communities)**
50	83.2 %	0.3 %	16.5
100	42 %	10 %	48 %
150 (baseline)	20 %	10%	70 %

This analysis (Table 4) that the preferred electrification solution was quite elastic to a reduction in household electricity demand, with the percentage of off-grid compatible households doubling when demand was reduced to 100 kWh/hh/year and quadrupling when demand was reduced to 50 kWh/hh/year. In fact, off-grid became the predominant electrification solution (83% of communities) for the Northern Region at the minimum household demand level.

This behavior points to the importance of accurately setting demand levels for target communities in determining the least cost electrification mode. As an example, an optimistic approach which overestimates household demand (kWh/hh/year) can have the effect of drastically underestimating the potential market for SHS PAYG solutions and distort planning decisions in favor of mini-grid or national grid solutions. This result also suggested an opportunity to explore a "service level targeting" strategy for SHS PAYG in rural communities by matching the system capacity to the household demand. In practice, this would allow SHS PAYG companies like Fenix International to target their 10 W Ready Pay Home Eco II system to communities with lower household demand while deploying their 34 W Ready Pay TV Kit to communities with greater electricity demand (Fenix, 2017). In a similar fashion, competing providers such as Mobisol who offer larger systems could tailor their sales strategy based on household demand, offering solutions ranging from a 30 W household system up to a 200 W business kit depending on the needs of the target community (GSMA, 2016b).

The next element of the sensitivity analysis examined the impact of varying the mean inter-household distance, revealing that an increase in the MID (more dispersed households) tended to shift un-electrified communities to off-grid compatibility, while a reduction in the MID (more compact communities) shifted target communities toward mini-grid and utility grid compatibility in the rural Northern Region (Table 5).

Table 5. Mean inter-household distance - sensitivity analysis (Kemausuor et al., 2012, 2014).

MID (m)	**Off-grid (% of comm)**	**Mini-grid (% of comm)**	**Grid (% of comm)**
15 m	13 %	15 %	72 %
25 m (baseline)	20 %	10 %	70 %
40 m	30 %	3 %	67 %
100 m	67 %	-	33 %

This analysis (Table 5) illustrated a significant shift in off-grid compatibility, with an increase from the baseline condition to a more rural community (MID = 100 m) causing more than a three-fold increase in the number of off-grid compatible communities. On the other hand, reducing the MID from the baseline condition to a distance of 15 m between houses corresponded to a modest 35% reduction in off grid compatibility. This sensitivity analysis pointed to the importance of using community specific household dispersion data to the greatest extent possible, as the default value used for the Ghana case study (Kemausuor, 2012, 2014) would appear to underestimate the number of off-grid compatible communities.

Finally, scenarios covering a range of penetration rates (Table 6) were examined to gauge the impact of national policies focused on achieving universal electrification (100%) versus more modest goals of a 30% or 60% penetration rate. The full electrification (100% PR) scenario resulted in the highest percentage of un-electrified households being grid-compatible – while a reduction in the penetration rate shifted

Northern Region communities toward mini-grid and off-grid compatibility.

Table 6. Penetration rate - sensitivity analysis (Kemausuor et al., 2012, 2014).

PR (%)	**Off-grid (% of comm)**	**Mini-grid (% of comm)**	**Grid (% of comm)**
30 %	35 %	32 %	33 %
60 %	25 %	25%	50 %
100 % (baseline)	20 %	10 %	70%

This analysis (Table 6) showed a modest shift in off-grid compatibility as the penetration rate was reduced, with the fraction of off-grid compatible communities nearly doubling with a drop from 100% to 30% PR. From a research perspective, these findings raise the question regarding the practicality of achieving universal electricity access in the ECOWAS region. Specifically, this analysis points to the identification of an optimum penetration rate which offers a balance between the portion of the population to be served and the overall cost of electrification. One means to explore this dynamic would be to vary the penetration rate at the target community level to maximize the number of households that fall within an established LCOE ($/kWh) "financial feasibility" threshold.

Independent of the LCOE results and sensitivity analysis discussed above, Kemausuor's (2012) reflections on his experience showed that Ghanaian communities have often preferred grid-connectivity due to its capability to support higher wattage appliances. In terms of social acceptance, many considered solar power to be inferior and some have discontinued using off-grid systems to put political pressure on governments – particularly if the grid has been extended to neighboring communities. In an effort to mitigate this drop in social acceptance, Kemausuor (2012) suggested the development of consumer education "in a manner that highlights the role of off-grid systems in providing smaller amounts of power in the short term – anticipating grid extension in the future as demand rises." The motivation to use Network Planner to address electrification in Ghana emerged from challenges encountered in the effort to meet national energy access targets. These barriers included increasing demand without sufficient investment to provide the needed capacity, inefficient pricing of energy services which resulted in utility insolvency, high energy losses, and under exploitation of renewable energy sources (Kemausuor et al., 2012). Kemausuor also pointed to a number of institutional barriers standing in the way of achieving universal energy access in Ghana. Fifty percent (50%) of the population without electricity live in settlements with populations of less than 500 people, whereas government electrification programs are focused on settlements with greater than 500 people. In practice, communities of less than 500 people (many of which are not grid compatible based on the LCOE methodology) are often electrified as part of grid extension programs – largely to avoid political conflict (Kemausuor et al., 2012). These government practices have the effect of reducing interest among rural communities in SHS PAYG or mini-grids, leaving many rural communities un-electrified and defeating the poverty alleviation goal of electrification (Kemausuor et al., 2012). In a number of egregious examples of market distortion, political candidates have contributed their own money to fund community grid extension projects even when there is no connection to the existing MV network (Kemausuor et al., 2012).

In summary, assessment of the Network Planner decision tool illustrates the impact of varying household electricity demand, MID, and PR on the number of communities which are utility grid, mini-grid, and off-grid compatible using the LCOE methodology.   Kemausuor's insights also shed some light on the market distortion dynamics at work in stalling the progress of rural electrification.

Open Source Spatial Electrification Toolkit (onSSET). A key insight gained from my assessment of the onSSET energy access decision tool was the robust "science- policy interface" that is provided through interactive dashboard hosted by United Nations Department of Economic and Social Affairs (UNDESA) (UNDESA, 2017). Likewise, this tool stood out relative to its peers due to the integration of the multi-tier framework for electricity access (UNDESA, 2017). Input data requirements (Table 7) for the onSSET tool illustrate both a grid centric (power plants, mineral reserves) and an off-grid (renewable energy potential maps) perspective.

Table 7. Input data requirements for onSSET (Mentis et al., 2015).

Data category	**Description**	**Reference**
Administrative Areas	Definition of the boundaries of the studied country	(GADM, 2015)
Transmission Network	Existing and planned transmission network	(African Development Bank (AfDB), 2017)
Power Plants	Direct correlation to location of high voltage (HV) lines – impacts future electrification options	(AfDB, 2017)
Travel time to big cities	Estimate transport cost impact on diesel cost	(JRC, 2014)
Mineral Reserves	Income source for utilities	(USGS, 2017)
Population Map	People in a 2.5 km^2 grid cell	(EUEI, 2017)
Renewable Energy Potential Map	Solar and wind potentials	(IRENA, 2014) (UNIDO, 2016)

The first step in the process is the calculation of the electricity demand forecast and determination of the planned grid expansion (Mentis et al., 2015). In this step, projections from the present day to the 2030 universal access deadline are made regarding population density and electricity demand. Energy access targets are established at 170 kWh/capita/year (rural) and 350 kWh/capita/year (urban) (Mentis et al., 2015), representing a higher demand than the 150 kWh/ hh/year (rural) and 900 kWh/ hh /year assumed by Network Planner, based on a typical household size across the region of four to five people. The next step is the LCOE calculation, which is computed for each grid cell using the following parameters: 1) target level and quality of energy access (kWh/household/year), 2) population density (households/km^2), 3) local grid connection characteristics (distance from closest grid connection (km), national cost of grid electricity ($/kWh)), and 4) local energy resource availability (Mentis et al., 2015). In contrast to Network Planner, the onSSET LCOE calculation approach differs depending on the electrification options. For mini-grid and solar home system options the total system cost is considered, while for utility grid extension the calculation adds the average LCOE of the national grid to the marginal LCOE required to extend the grid to the demand location from the existing network (Mentis et al., 2015). The electrification algorithm then utilizes a settlement table and a reference matrix to evaluate whether the minimum population requirement is satisfied to make the target settlement "grid compatible". The settlement table is used to catalog the settlement location and its electrification status. The reference matrix then provides a set of standard distances to the grid with corresponding minimum population requirements for grid extension to be competitive (Mentis et al., 2015) This section of the algorithm then examines two conditions to test a potential grid extension decision: 1) higher number of people (thus higher demand) than the minimum demand required to justify a connection depending on the distance to the closest electrified grid cell, and 2) not causing the total additional MV grid length to exceed 50 km if the settlement is connected (Mentis, et al., 2015).

The second step in the onSSET tool analysis approach involves the diesel generator LCOE calculation which incorporates the price of diesel in major cities as well as the distance to cities from each grid cell. This step also incorporates the availability of renewable resources such as solar irradiation and wind power capacity factors (Mentis et al., 2015). A more limited sensitivity analysis indicates that lowering rural electricity demand from the baseline condition of 170 to 150 kWh/capita/year causes a shift from utility grid and mini-grid compatibility toward SHS PAYG solutions, while increasing rural electricity demand to 190 kWh/capita/year results in higher grid compatibility (Mentis et al., 2015) – illustrating the same geospatial behavior that we saw using the Network Planner tool (Kemausuor, 2012, 2014).

One of the clear limitations of the onSSET tool is the modeling assumption that electrification investments can be made “overnight” - implying that there are funds and human capacity available to do so. In reality, grid extension and mini-grid development are time consuming design and construction efforts which will leave many without electricity for a long period of time. In contrast, SHS PAYG can provide an “energy access dividend” through immediate benefits which are not considered in onSSET’s modeling approach. One option to mitigate this shortcoming would be the introduction of a new geospatial layer which would account for project implementation/market penetration timelines. Potential variables might include the maximum km/year pace (grid extension), design and construction duration (mini-grid), and sales/adoption cycle

(SHS PAYG). Since project implementation timelines will naturally vary from immediate (SHS PAYG) to short term (mini-grid) to long term (grid extension) – this approach offers a more realistic picture of electricity access benefits.

The “science-policy” user interface which was noted at the outset of this assessment has proved to be a vital element of my research. Coupled with the ability to vary the electricity access goal from MTF Tier 1 through Tier 5, the UNDESA hosted interactive dashboard provided the necessary simulation and data acquisition capabilities to determine the SHS PAYG addressable market for each member state and to test the institutional barrier and enable environment condition elements of my hypothesis.

Reference Electrification Model (REM). While the assessment of the Network Planner and onSSET decision tools was supported by case studies in Ghana and Nigeria, information on the capabilities and limitations of the Reference Electrification Model (REM) was obtained from theses documenting Yael Borofsky (2015) and Daniel Ellman’s (2015) recent contributions to the MIT Universal Energy Access Research Group’s work in rural India. Key insights from Borofsky’s work included the consideration of integrating non techno-economic factors into the energy planning process and the tool’s capability to provide detailed network distribution designs for utility grid and mini-grid solutions (Borofsky, 2015). In contrast, Ellman’s contributions focused on exploration of the repercussions of a universal service obligation adopted by utilities and development of an innovative approach to energy access planning from an off-grid perspective (Ellman, 2015).

In her research, Borofsky asserted that techno-economic planning methods dominate rural electrification planning, yet many obstacles confront rural electrification planners that are not techno-economic in nature. Her thesis suggested that the best aspects of technocratic and communicative planning should be integrated into a transdisciplinary methodology that will incorporate techno-economic, socioeconomic, sociotechnical, social, political, and regulatory factors into a comprehensive energy access planning approach (Borofsky, 2015). Borofsky's research provides the valuable insight that "many of our Indian counterparts believed that the electrification challenge was not a technology problem, but a human problem" (Borofsky, 2015). Reflecting on her perspective inspired me to take a deeper look into the notions of taming a "wicked problem" and "flipping the energy planning paradigm" as core elements my research (Rittel & Weber, 1973; Practical Action, 2016).

As an example of the market distortion created by a purely techno-economic planning approach, Borofsky (2015) pointed to four electrification strategies which are common in the developing world: 1) integrated rural development, 2) area coverage, 3) grid extension, and 4) densification (Munasinghe, 1988). In her view, these are "broad strategies that seem to have as their focus a push for speed and scale with an assumed solution, rather than an embedded process of solution determination that seeks to understand the preferences of the population to be served" (Borofsky, 2015). In other words, she suggested that common planning electrification strategies take a grid-centric rather than an energy-poor approach. In terms of its relevance to my research, Borofsky's argument suggests that this market distortion can be driven by the planning process itself. If we accept that the explicit goal of modeling is to automate energy access planning, then the implicit goal is to minimize participation, since participation carries transaction costs that make work in a resource constrained environment more time consuming (Borofsky, 2015). In light of this automation versus participation dilemma, perhaps the best way to integrate an energy-poor perspective into the planning process is to imagine how we introduce proxies for consumer participation, such as mobile phone ownership in un-electrified communities.

Strong interest from stakeholders in rural India resulted in the development of REM through collaboration between the Universal Energy Access Research Group at MIT and researchers at IIT-Comillas in Spain (Borofsky, 2015). A core assumption of the development process was the need to integrate socio-economic, political, regulatory, and other local variables into electrification planning (Borofsky, 2015). While a number of breakthroughs in the development process improved REM's capacity to accurately account for consumer demand (through satellite imagery and pattern recognition algorithms) and to provide robust technical network designs for each of the electrification options, these advances came with a real trade-off. The resulting network designs could be analyzed only in terms of financial costs. Socioeconomic, political, and regulatory factors have to be addressed a priori or ex post outside the automated model algorithms, falling short of the goal of implementing a trans-disciplinary approach (Borofsky, 2015). Input data requirements for REM (Table 8) move beyond what was required by onSSET and Network Planner to address grid reliability and to introduce the notion of the cost of non-served energy (CNSE).

Once the model's input data requirements are met, REM then proceeds with its robust data processing and cost comparison functions, which are organized as follows: 1) determination of analysis region, 2) pre-clustering steps, 3) clustering steps, and 4) design

Table 8. Input data requirements for REM (Borofsky, 2015).

Input Variable	Description	Comments
Building location	Latitude and longitude of all buildings in study area	
Distribution Feeder and Transformer Locations	Existing MV grid network	Data may be incomplete or out-of-date
Administrative Boundaries	Ensure that proposed system does not cross jurisdictional boundaries	
Un-electrified Households	Connection status to the grid or other electrification means	
Energy Resources	Solar irradiation, diesel availability, biomass resources, mini-hydro sites	
Cost of Non-Served Energy	Cost to consumers of energy not served – accounts for system reliability. REM considers two Cost of Non-Served Electricity (CNSE) values – essential and non-essential load.	Intended to represent the loss of utility incurred by a customer when there is no electricity at a time when they were planning to use it.
Generation Equipment Catalog	Solar panels, diesel generators, inverters, etc.	Technical specifications and cost
Network Technical Requirements and Equipment Catalog	Load voltage, generator voltage, network lifetime, reliability targets, cost of network losses	Includes cost and failure rates of conductors, transformers, and substations
Grid Reliability Existing	Number of hours per year (and when) the grid is expected to provide electricity	Categorize in terms of peak and off-peak hours if possible
Price of Diesel Fuel	Used as primary of supplementary source of electricity	Official fuel price does not include cost of transport to rural communities
Discount Rate	Determination of the Net Present Value (NPV) of a specific project	
Building Classification	Categories include household, school, hospital	Individual input requirement (remainder are considered regional inputs)
Electricity Demand	Hourly demand profile	Individual input requirement (remainder are considered regional inputs)

and comparison of options (Borofsky, 2015). The pre-clustering steps include construction of a lookup table of potential mini-grid design configurations. The clustering steps then consider buildings within each analysis region and organize them into clusters which are likely to be served by the same electrification mode. The clustering process proceeds by evaluating clusters of building to determine whether it is more cost-effective to connect them to the existing grid, treat them separately as a mini-grid, or serve them through isolated home systems (Borofsky, 2015).

While it has not been integrated into the REM decision tool at this point, the most relevant aspect of Borofsky's work to my own research was the stakeholder engagement process which identified the most important socioeconomic, political, and regulatory factors recommended for integration into the energy access planning process. These non-technical factors were narrowed down to those which were considered "important" or "critically important" by respondents (Table 9).

While Borofsky's work centered on the identification of non-technical factors recommended for integration into the energy access planning process, Ellman's research shed light on the repercussions generated by a perceived utility "universal service obligation" and offered an innovative approach to energy planning from an off-grid perspective. Ellman (2015) noted that electric distribution utilities in India are set up as monopolies with a "universal service obligation" for all customers within their geographic service region. In other words, they are obligated to provide electricity service to any customer who wants it and pays the tariff (Ellman, 2015). Even if a distribution utility has the financial resources to provide reliable grid service to all households in a geographic service area, Ellman suggested that this universal service obligation mindset is not the best use of its funds. While distribution utilities could potentially expand their scope of services to deploy off-grid solutions as a means to meet

Table 9. Integration of non-technical factors into energy access planning (Borofsky, 2015; author's elaboration, 2017).

Non-technical Factor	Geospatial Indicator	Potential Data Source	Strategy	Research Insights
Appliance and Electricity Affordability	Appliance Availability and Market Penetration	Manufacturers Sales Data	Greater appliance availability provides expanded energy services	Low efficiency inclusive appliances (LEIA) emergence creates higher MTF tier access for same watts peak (Wp) system capacity
CDO Presence	Registered Organizations	Further investigation required	Facilitator & champion for community needs	Further investigation required
Neighboring Community Electrification	Connected communities within specified radius of unconnected communities	Utility commercial data	Adjacent community grid connection decreases LCOE for targeted community	Build on GeoSim® poles and hinterlands methodology
Social Acceptance	Further investigation required	MTF baseline surveys, household WTP surveys	Provide education & awareness campaigns to increase social acceptance	Geographic targeting of low (needs education) and high (target for adoption) social acceptance
Utility Tariff	$/kWh	Africa Information Highway, ECOWREX, National PURC's	Compare to LCOE & utility cost of service	High tariff improves acceptance of off-grid, lifeline tariff weakens utility
Grid Reliability	System Average Interruption Duration Index (SAIDI), System Average Interruption Frequency Index (SAIFI)	Africa Information Highway, Distribution Utility Data	Poor grid reliability increases WTP for SHS	Explore adjustment of LCOE results based on utility grid reliability
Lighting Quality	Product Certification	Lighting Global Quality Assurance Framework	Availability of certified products increases social acceptance	Suggests integration of certified products into SHS connection subsidy and RBF programs
Access to Finance	MFI, Community Banks, Mobile Money	FINclusion Lab	Local partners for SHS PAYG deployment & RBF implementation	Provides credit history for consumers, leverages energy addressable market

their universal service obligation, Ellman (2015) asserted that this need is better served whose cost-optimized electrification mode is a grid connection. In other words, a target community should only be grid connected if the LCOE results indicate that it is grid compatible. Following this logic, different regulatory approaches could be applied to each electrification mode and decision models like REM could be enhanced to guide subsidy dollars to where they are most effective (Ellman, 2015). In an effort to provide a practical guidance toward moving away from the unrealistic goal of a universal service obligation, Ellman also offered an innovative approach (Table 10) for off-grid electrification planning.

As it relates to my research, this off-grid electrification planning approach offers a structure which would allow each electrification mode to be implemented in target areas where it is the least-cost solution as well as providing safeguards against unexpected encroachment from other service providers. This planning approach may serve as a useful starting point in the development of a geospatial electrification mode coordination platform, which should be considered as an avenue for future research.

Table 10. Innovative off-grid electrification planning approach (Ellman, 2015; author's elaboration, 2017).

Recommendation	**Benefit**
Minimum standard for access	Ensure provision of modern energy access
Identify geographic areas with reliable grid connections	Don't need to be addressed by electrification planning
Identify grid connected areas with unreliable service	Implement service quality reforms. Provide basic service through standalone systems if reliable grid service cannot be established rapidly.
Identify areas not currently grid connected but designated as grid compatible	Prioritize and establish a timeline for grid connection
Option for grid compatible areas projected to be connected in near term	Deploy SHS in the interim to meet universal service obligation of utility

Option for grid compatible areas not projected to be connected in near term	Provide 10-15 year concessions for grid-compatible mini-grids
Identify remaining areas without grid service best served by off-grid systems	Manage mini-grids and SHS PAYG via "light handed" regulation and consumer protections. Target mini-grid incentives to incremental cost of grid compatible infrastructure. Target SHS subsidies to buy-down capital cost of down payment.

<u>GeoSim®.</u> The key research insights (Table 11) emerging from the GeoSim® tool assessment include its prioritization scheme which utilizes indicators for development (IFD), incorporation of a high-isolation indicator for remote communities, and targeting studies for SHS PAYG and mini-grid development in southeast Asia.

In terms of geospatial modeling, these capabilities (Table 11) give GeoSim® an energy-poor perspective that is not evident in the remaining GIS-based energy access decision tools considered by my research. The IFD functionality is used as a prioritize scheme to target communities for electrification based on their potential for development. Going forward, this functionality may provide a model for the integration of geographic selection schemes emerging from the examination of institutional barriers and enabling environment conditions explored by my research. In terms of practical applications, the

Table 11. GeoSim® research insights (C. Perret, personal communication, January 10, 2017).

Feature	Description	Benefit
Indicators for Development (IFD)	Health, education, economic development	Communities prioritized based on development potential
Off-grid electrification targeting studies	Identification of target locations for SHS PAYG and mini-grid development	SHS – 10,000 units in Laos & Cambodia (incorporated grid encroachment into selection algorithm) Mini-grid – 100 sites in Tanzania (incorporated anchor loads into selection algorithm)
High isolation indicator	Identify small communities, low population, remote location	Initial screening of communities likely to be best suited for SHS PAYG

use of GeoSim® to support SHS deployment targeting demonstrated an off-grid perspective not available in REM, Intigis, onSSET, or Network Planner. Finally, the use of a “high isolation indicator” to identify the most remote communities provides the capability to implement geographic selection which ensures that the least-cost technologies reach these locations.

GeoSim® is organized around a modular structure (Table 12) which is composed of four primary building blocks.

Table 12. IED electrification planning software modules (GeoSim®, 2017).

Module Name	Function	Comments
Spatial Analyst®	Identifies settlements with strong potential for development	Maximizes social and economic impact of rural electrification
Network Options®	Defines communities not likely to be grid connected in near future, identifies best off-grid option	Criteria include geographic accessibility, lack of financing, socio-economic constraints
GeoSim®	Management tool used to create rural electrification planning scenarios	Decentralized options include mini-hydro, biomass, diesel generator, & solar
Demand Analyst®	Predicts electrical demand for a cluster of villages	1) 24-, 10-, and 5-hour supply, 2) 20-year planning horizon, 3) connection rates, 4) households versus community infrastructure, 5) population density and growth, 6) poor, medium, rich income, 7) appliance quantities and load curves

Intigis. Intigis is the last of the energy access decision tools reviewed as part of my research. Unfortunately, the limited amount of English language information available on this model hampered my ability to conduct a thorough assessment. The business case which initially drove the development of the Intigis decision tool can be summarized as: 1) geographic connection to a target area for electrification, 2) analysis of the target area, and 3) integration of economic, social, and environmental issues (Dominguez Bravo & Pinedo-Pascua, 2009). Intigis was developed by the GIS Group for Regional Integration of Renewable Energies & Rural Electrification (gTIGER) which is a part of the CIEMAT in Madrid, Spain (Dominguez Bravo & Pinedo-Pascua, 2009). Based on its origin, the LCOE result for this model is described in Euro/kWh (€/kWh) for each technology option – versus the use of $USD/kWh for the remaining tools (Dominguez Bravo & Pinedo-Pascua, 2009). The primary goal of SOLARGIS was to demonstrate the value of GIS methods in evaluating the use of renewable energy sources in rural electrification programs (Dominguez Bravo & Pinedo-Pascua, 2009). The evolution of this decision tool began with SOLARGIS which was improved to establish SOLARGIS II, concluding with the current Intigis platform (Table 13).

Table 13. SOLARGIS to Intigis evolution (Dominquez Bravo & Pinedo-Pascua, 2009).

Decision Tool	Key Parameters/Improvements	Comments
SOLARGIS (1990s)	• Household SA systems – PV, diesel, wind • Small villages – hybrid systems • Connection cost – community to MV network • Capacity factor • Highlight high potential communities	
SOLARGIS II (2000)	• Minimization of uncertainties • Technical and economic parameters • Demand characterization • Spatial distribution of optimum technology • Spatial sensitivity analysis	Improvements in demand characterization focal point of this development
Intigis (current)	• Distance from MV grid to target community • Population density • Solar irradiation	

In terms of practical applications, results from the Guama case study in Cuba suggest the solar home systems offer the least-cost solution for ninety-three percent (93%) of the fifty- eight (58) studied communities (Dominguez Bravo & Pinedo-Pascua, 2009).

The assessment of the Network Planner, onSSET, REM, GeoSim®, and Intigis GIS-based energy access decision tools offered a methodological foundation and a springboard for development of an enhanced framework which takes an energy-poor perspective. The key elements from the GIS tool assessment process are summarized (Table 14) to address the ECOWAS applications (if available) for each tool, the range of input data requirements, unique features, and research insights.

SHS Business Model and Addressable Market

As they work to scale-up across sub Saharan Africa, SHS PAYG service providers are largely left to fend for themselves, without the benefit of GIS-based energy access decision tools which are suited to their needs. They must rely on guesswork and making "seat of the pants" decisions based on contacts with local utilities, gathering anecdotal information from community leaders, identifying available financial subsidy programs, and investing their time and money in market research. For entities which are often high risk social enterprises, this gap in the availability of suitable energy access planning tools limits their ability to make confident, well-informed business decisions regarding entry market entry (new countries) and market expansion (existing countries).

In addition to this apparent gap in planning tools for off-grid service providers, there is a deficit in tools to manage coordination between electrification modes. My research indicates that there is no common platform in place which provides reliable geospatial tracking and coordination between utility grid extension, mini-grid

Table 14. Existing GIS tool assessment summary (Borofsky, 2015; Ellman, 2015; Kemausuor et al., 2012, 2014; Mentis et al., 2015; GeoSim®, 2017; Dominguez Bravo & Pinedo-Pascua, 2009).

Decision Tool	ECOWAS Applications	Input Parameters	Unique Features	Research Insights
REM	None (India)	Building location, distribution feeder/transformer location, administrative boundaries, un-electrified households, energy resources, cost of non-served energy, generation equipment catalog, network equipment catalog, grid reliability, price of diesel fuel, discount rate, building classification, electricity demand	Mini-grid and grid extension technical network designs	Identification of critical non-technical factors for energy access planning, universal service obligation reform, energy access planning from an off-grid perspective
Network Planner	Ghana, Senegal	Location of un-electrified communities, location of MV network, interest rate, economic growth rate, elasticity of electricity demand/year, initial population, population growth rate, mean household size, household/productive use/commercial/instituational electricity demand, initial and recurring cost for electrification options	Ghana Energy Commission adoption of GIS-based Energy Access Review (GEAR) Toolkit	Geospatial impact of urban threshold, mean inter-household distance (MID), penetration rate (PR)
onSSET	Nigeria, all member states except Cape Verde via UNDESA dashboard	Administrative areas, transmission network, power plants, travel time to big cities, mineral reserves, population map, renewable energy potential map	MTF integration, user-friendly interactive dashboard	Simulation of SHS PAYG addressable market Tier 2 and Tier 3 electricity access, comparison with mature East Africa market
GeoSim®	Benin, Burkina Faso, Cote d'Ivoire, Liberia, Senegal	24, 10, and 5 hour supply; 20 year planning horizon; connection rates; household versus community infrastructure; population density and growth; poor/medium/rich income levels; appliances quantities and load curves	Indicators for development (IFD) prioritization scheme, high isolation indicator, SHS targeting in Laos & Cambodia	IFD prioritization scheme may provide a model for energy addressable market geographic targeting
Intigis	None (Latin America, Caribbean)	Distance from MV grid to target community, population density, solar irradiance	Limited information due to Spanish language development	Insufficient information

development, and SHS PAYG market penetration. While some national energy planners are documenting and tracking the existing and planned utility grid network configuration, these systems don't extend to mini-grid and off-grid solutions. In other words, it's often impossible to know who is serving a particular community and what might be planned for the future without visiting the community and consulting with local stakeholders. From an off-grid developer's perspective, this basic coordination is a critical part of the risk management process. In order to avoid the financial loss associated with stranded assets from unexpected grid encroachment, Reynolds (personal communication, November 10, 2016) noted that SHS PAYG providers would like to target communities which are not expected to see grid connections for 3 to 5 years. By the same token, mini-grid developers would like to see geographic concessions for a period of 10 to15 years with regulatory provisions for future grid connection (D. de Haan, personal communication, February 15, 2017). Although addressing this electrification mode coordination challenge was outside the scope of my research, this discussion offers a glimpse of another underlying dynamic affecting the scale up of off-grid solutions, and the value that an enhanced GIS-based energy access decision tool framework and reliable, current data could bring to the table.

In an effort to "ground truth" the business decision processes employed by SHS PAYG providers, stakeholder feedback was obtained through communications with Fenix International and Azuri Technologies. Both firms represent leaders in this space - Fenix recently reached 100,000 customers in Uganda (Fenix, 2017) while Azuri boasts a presence in eleven (11) sub Saharan African countries (SSA) (Azuri, 2016). Mitch Sauers (personal communication, February 8, 2017), Sales Strategy Associate at Fenix International, describes his empirical decision process as follows: 1) How large is the market?, 2) What is the customer repayment risk?, 3) Is there a local town where equipment stock can be stored safely?, and 4) How does this new area relate to the location of existing sales staff? His colleague, Lab Manager John Foye (personal communication, February 9, 2017) questions the use of US dollars per kilowatt-hour ($/kWh) as the key decision variable for all of the existing LCOE tools – when his practical experience suggests that off-grid consumers are most interested in energy services such as mobile phone charging, TV viewing and lighting hours/day, and the quality of modern lighting technology (versus traditional fuels such as kerosene and candles). Conversations with Mr. Foye and Mr. Sauers also point to a pent up demand for a GIS-based energy access decision tool that would reduce their level of guesswork in assessing new markets as well as exploring expansion of their existing territories (J. Foye: M. Sauers, personal communication, February 9, 2017).

In a similar vein, Kieran Reynolds, Vice President of Operations at Azuri Technologies described his organization's business decision process. As Kieran put it, "Are there enough people, with enough money, close enough together?" (K. Reynolds, personal communication, February 16, 2017). Last-mile distribution relationships with local partners were described as critical to Azuri's business model, but the selected partner organizations will vary from country to country (K. Reynolds, personal communication, February 16, 2017). This partnering dynamic means that Azuri's relationships with MNOs are a secondary relationship which varies depending on the country and geographic region. Reynolds was also quite clear about the need for a mobile money presence in target areas, because having a means to digitize the often informal, local cash economy was a critical factor in entering a new market. From a financial perspective, the presence of government subsidies, donor funding institution programs, and results based financing grants was also reported to have an impact on Azuri's decisions to pursue one potential market over another. In considering the value of an enhanced GIS-based energy access decision tool, Reynolds (personal communication, February 16, 2017) suggested that the value of an enhanced GIS-based energy access decision tool framework was in “not going down so many rabbit holes” in making these business decisions, with the caveat that the quality of the data must be current and reliable.

Historically, electricity access has been viewed in binary terms - a household either has a connection or it doesn’t. While this perspective may make sense in developed countries where reliable utility connections are taken for granted, it doesn’t paint the full picture in a developing country context. For rural customers in sub Saharan Africa, the number of hours of service per day and the range of appliances (lighting, phone charging, TV, fan) that their connection will support is most critical. In an effort to address this issue, the World Bank has developed the multi-tier framework which describes household electricity access in terms of technical criteria (Table 15) as well as the “energy ladder” of lighting technology and appliances (Figure 5).

In order to assess what is necessary to support the scale up of SHS PAYG deployment in the ECOWAS region, a basic understanding is required of SHS technology, the business model, and market dynamics. Reflecting on the market dynamics, an International Finance Corporation’s (IFCs) report (IFC, 2012) asserts that “Device companies do best when the enabling environment provides a level playing field: sufficient technology awareness, product standards in place, tax and duty regimes that do not discriminate against them”. Instead of dwelling on the negative and viewing energy access as a development gap, the IFC insists that this situation offers a real market

Table 15. Energy ladder measuring level and quality of household electricity (Bhatia, Angelou, & Portale, 2015).

Multi-tier Matrix for Measuring Access to Household Electricity Supply

ATTRIBUTES		TIER 0	TIER 1	TIER 2	TIER 3	TIER 4	TIER 5
1. Peak Capacity	Power capacity ratings[28] (in W or daily Wh)		Min 3 W	Min 50 W	Min 200 W	Min 800 W	Min 2 kW
			Min 12 Wh	Min 200 Wh	Min 1.0 kWh	Min 3.4 kWh	Min 8.2 kWh
	OR Services		Lighting of 1,000 lmhr/ day	Electrical lighting, air circulation, television, and phone charging are possible			
2. Availability (Duration)	Hours per day		Min 4 hrs	Min 4 hrs	Min 8 hrs	Min 16 hrs	Min 23 hrs
	Hours per evening		Min 1 hr	Min 2 hrs	Min 3 hrs	Min 4 hrs	Min 4 hrs
3. Reliability						Max 14 disruptions per week	Max 3 disruptions per week of total duration <2 hrs
4. Quality						Voltage problems do not affect the use of desired appliances	
5. Afford-ability					Cost of a standard consumption package of 365 kWh/year < 5% of household income		
6. Legality						Bill is paid to the utility, pre-paid card seller, or authorized representative	
7. Health & Safety						Absence of past accidents and perception of high risk in the future	

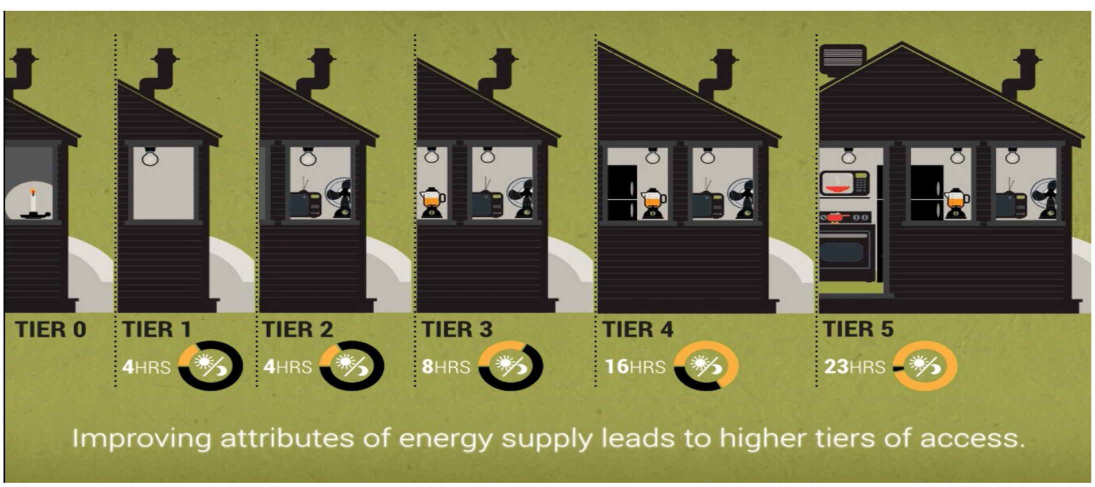


Figure 5. Lighting and appliance illustration of household electricity access tiers (Rysankova, Portale, & Carletto, 2016).

opportunity for the private sector (IFC, 2012). Using this affirming perspective, SHS PAYG enabling environment conditions include: 1) making products affordable to customers with low and irregular incomes, 2) making financing available for SHS, 3) developing and leveraging distribution networks, 4) strengthening customer confidence in energy devices, 5) increasing technology awareness, and 6) enhancing product quality awareness and creating quality standards (IFC, 2012). These enabling environment conditions posed by IFC and their relevance to SHS PAYG scale up (Table 16) were documented.

Table 16. IFC enabling environment conditions for SHS PAYG scale up (IFC, 2012; Winiecki & Kumar, 2014; Sanyal, Prins, Visco, & Pinchot, 2016; Alstone, 2015).

Enabling Environment Conditions	**Explanation**	**Leveraging Strategy**
Product Affordability	PAYG billing systems are designed to mimic consumer spending patterns on small increments of traditional fuels	Monthly utility billing is not affordable for consumers with low and irregular cash incomes, PAYG approach increases WTP
Access to Financing	PAYG rent-to-own agreement offers credit to unbanked consumers	Allows low-income households to develop a credit history, increases consumer confidence
Developing & Leveraging Distribution Networks	MNOs have established last mile distribution networks	Leverage brand recognition and trust established by MNOs
Strengthening Consumer Confidence in Energy Devices	See access to financing, technology awareness, & product quality standards	See access to financing, technology awareness, & product quality standards
Technology Awareness	Consumer education and awareness	Increases consumer confidence, increases WTP, improves social acceptance
Product Quality Standards	Lighting Global Quality Assurance Framework	Increases consumer confidence, increases WTP, avoids market spoilage

As noted above (Table 16), product quality and reliability is an important element of strengthening consumer confidence in off-grid solar devices. As the IFC report rather bluntly asserts, “If the device breaks down before it breaks even, the customer will be financially worse off, deterring future customers and leading to market spoilage” (IFC, 2012). The Lighting Global Quality Assurance Framework was established (Lighting Global, 2014) to address this market need for product standards. Key elements of the framework include finding a balance between affordability and product quality as well as ensuring clear communication of performance information to enable informed decisions by consumers (Lighting Global, 2016a). Lighting Global has recently expanded the framework to go beyond solar lanterns and pico PV to include solar home systems. Key elements of the new SHS standard include truth in advertising, lumen maintenance, health and safety, battery protection, quality and durability, and consumer information (Lighting Global, 2016b). Echoing many of the themes of the IFC *From Gap to Opportunity* report, the United Kingdom’s Department for International Development (DFID) launched the Energy Africa Program in October 2015 to address the following policy areas: 1) removing policy uncertainty by including off-grid electrification as part of national electrification strategies, 2) providing a level playing field for the household solar sector, 3) protecting customers by holding solar system providers accountable and enforcing quality standards, 4) increasing customer awareness, 5) facilitating the import of solar equipment, and 5) mobilizing access to finance (Sanyal et al., 2016).

The Rural Electrification and Renewable Energy Development Project (RERED) in Bangladesh stand out as the world’s fastest growing SHS program (Khandker et al., 2010), employing a combination of up-front capital subsidies for consumers and results based financing incentives for service providers. Since 2011, this program has supported the annual installation of nearly one million systems, overshadowing the acknowledged success of SHS scale up in East Africa (100,000 units/year) for leading providers by an order of magnitude (Khandker et al., 2010). In addition to its market penetration success, the RERED program offers a best practices structure that could be replicated in the ECOWAS region. In this World Bank supported program, funds were channeled through the Infrastructure Development Company Limited (IDCOL) which was established as a government-owned financial intermediary (Sanyal et al., 2016). RERED was launched with a capital subsidy directed to households and a results-based grant provided to implementing partners, with the intent to phase out these subsidies over time (Sanyal et al., 2016). The key elements of the RERED program (Table 17) led by IDCOL offer a framework for potential ECOWAS replication.

Table 17. RERED SHS program elements evaluated for ECOWAS replication (Sanyal et al., 2016).

IDCOL Program Role	Description	Comments
Results Based Financing (RBF)	Development grant to implementing partners per system installed	Phased out over time to ensure sustainability
Capital Buy-Down Grants	Capital subsidy to household (hh) to purchase SHS	Phased out over time to ensure sustainability
Technical Standards	Independent Technical Standards Committee	Ensure product quality and reliability
Vendor Certification	Independent Testing Centers	Ensure product quality and reliability
Installation Areas	Priority for off-grid populations	Ensure that SHS installations are implemented in off-grid areas
Environmental Standards	Battery Recycling	Ensure health and safety
Monitoring and Verification (M&V)	QC offices, quality inspectors, field auditors, customer call center	Ensure that technical standards were implemented

In addition to the program structure, a critical element of RERED's success lies in its innovative financing model (Table 18) which generates income for each stakeholder and maintains interest rate alignment through its spread of lending terms. For the first

Table 18. Innovative RERED SHS program financing model (Sanyal et al., 2016).

Loan Source	**Loan Recipient**	**Interest Rate (%)**	**Loan Term (years)**
World Bank	Government of Bangladesh	1-2	40
Government of Bangladesh	IDCOL	3-6	15
IDCOL	POs	6-9	10-15
POs	Off-grid Households	12	3

five years, an RBF approach was used which provided a grant to the local partner organization (PO) for every SHS installed. The grant amount declined each program year and was withdrawn in Year Six. Successful phase-out of the initial grants and subsidies provided strong evidence that this program has introduced a self-sustaining, commercial solution to the energy access challenge (Sanyal et al., 2016). In order to ensure proper subsidy targeting, the program was implemented only in confirmed "off-grid" areas. As an additional risk mitigation measure for participating consumers, POs were required to offer a buyback guarantee with the option for households to sell their SHS back to IDCOL at a depreciated price in the event that the household became grid connected within a specified time frame following the SHS purchase (Sanyal et al., 2016). While this guarantee did not offer compensation to SHS PAYG service providers to address these stranded assets, this buyback approach did serve to maintain social acceptance levels for program consumers.

Reflecting on the relevance of the RERED program's success, what becomes immediately clear is that a combination of the right market conditions can drive significant market penetration and scale up of SHS PAYG solutions. Critical lessons learned include the combination of up-front subsidies to consumers, results-based grants to implementing service providers, integration of product standards, market competition, and declining incentives to encourage long-term sustainability. While much of the discussion of subsidies to this point has focused on the unintended negative consequences of energy consumption subsidies (lifeline tariffs), the RERED design of consumer connection subsidies and service provider grants have been effective in making SHS adoption more affordable and encourage service providers to extend their sales territories to more remote communities.

Institutional Barriers and Enabling Environment Conditions

In order to equip SHS PAYG service providers with an enhanced tool to support their business decision needs, building on the foundation established by existing GIS-based energy access decision tools would seem to be the most expedient approach. Given that assumed starting point, the pressing question then becomes one of identifying a rational framework for further development of this automated energy access planning process. From a practical standpoint, such a framework should also offer the flexibility to incorporate future improvements, providing long-term value for off-grid service providers. Looking at this dilemma from a systems perspective generates two key questions: 1) what stands in the way of scaling up SHS PAYG market penetration in the ECOWAS member states, and 2) are there market conditions in place which could be used to accelerate this process? Conceptually, the answers to these questions appear to center on identifying institutional barriers (i.e. roadblocks) and enabling environment conditions (i.e. catalysts) which can be used to structure an enhanced GIS-based energy access decision tool framework. Since this methodological approach will naturally reveal multiple roadblocks as well as catalysts, it offers options for a long-term development strategy instead of a one-time solution. I have compiled a list of institutional barriers and enabling environment conditions (Table 19).

The "Enhancement Options" column (Table 19) describes a broad strategy for GIS decision tool development. The "Institutional Barrier and Enabling Environment Condition" columns then define each option as a roadblock to be overcome or a catalyst to exploit. Finally, the "Enhancement Strategy" column offers an actionable initiative for implementation. In order to select an institutional barrier and an enabling environment condition to guide my research, the following assessment was conducted:

- Energy addressable market (geographic targeting): direct GIS application through geospatial mapping of mobile money service coverage
- Electrification mode coordination platform: direct GIS application, involves complex regulatory, political, utility, off-grid service provider, and donor funding institution stakeholder engagement process
- Subsidy reform (geographic targeting): direct GIS application through geospatial mapping of existing/potential SHS connection subsidy and RBF incentive programs
- Product standards adoption and capacity building: no direct GIS application, long term institutional development issue which could be initiated at any time

Table 19. Energy access decision tool enhancement strategies (Nique & Thasarathakumar, 2011; Kemausuor et al., 2014; Komives, Foster, Halpern, Wodon, & Abdullah, 2005; Lighting Global, 2014; UNSE4ALL, 2017; ECOWREX, 2017; EPASES, 2017).

Enhancement Options	Institutional Barrier	Enabling Environment Condition	Enhancement Strategy
Last-Mile Distribution		SHS PAYG & MNO partnerships	Geographic targeting of the "energy addressable market"
Electrification Mode Coordination (NG, MG, SA PV)	Risk of stranded assets due to unexpected grid encroachment		Development of a common electrification mode coordination platform
Energy Consumption Subsidies (lifeline utility tariffs)	Regressive subsidy regime, creates utility insolvency		Subsidy reform through geographic targeting of SHS connection subsidy (new markets) and RBF (expansion of existing markets) program locations
Social Acceptance	Off-grid options considered inferior and expensive by rural consumers		Member state adoption of Lighting Global Quality Assurance Framework for off-grid products, regional consumer education & awareness campaign
Political Environment	Promises that the "grid is coming", government intervention in areas which are not "grid compatible"		Implementation of rural electrification projects based on the least cost of electrification solution
MTF Baseline Surveys (see Table 15 and Figure 5)		Geospatial dataset indicating current level of electricity access (Tier 0-5)	Geographic targeting of households with minimal/no electricity access (Tier 0 and Tier 1)
UN SE4ALL 2030 Goals		Adoption of universal energy access goals by all ECOWAS member states	Translate adoption and public commitment into aggressive investment and actions
ECOWREX & EPASES Collaboration		Regional champion for the use of GIS-based energy access decision tools	Leverage regional leadership to foster progress among member states

- Government intervention: no direct GIS application, institutional reform needed to calibrate government intervention to least-cost electrification mode recommendations

- MTF Tier 0-1 (geographic targeting): direct GIS application through geospatial mapping of households from ongoing baseline surveys
- UNSE4ALL goals: no direct GIS application, long term institutional benefit in providing a common, aspirational goal
- ECOWREX and EPASES collaboration: institutional collaboration and GIS data acquisition opportunity

Screening this list for options that include a direct GIS application reduces this list to: 1) energy addressable market, 2) electrification mode coordination, 3) subsidy reform, and 4) MTF Tier 0-1. Development of an electrification mode coordination platform is sorely needed, but would require significant stakeholder buy-in, coordination, and negotiation which is not expected to provide immediate results. At this time, the MTF baseline surveys are ongoing and are limited to a few member states (Liberia and Nigeria) – which suggests that this initiative would be best implemented in a second phase of development. Based on this assessment, the energy addressable market (enabling environment condition) and subsidy reform (institutional barrier) initiatives were selected as the focus of my research and are described in greater detail below.

While energy consumption subsidies are intended to provide a social benefit to the energy-poor, they can create a barrier to universal energy access - financially crippling distribution utilities and suppressing the scale-up of off-grid solutions. In an effort to provide affordable electricity to low-income consumers, national governments in the ECOWAS region (and across sub-Saharan Africa) have commonly established “lifeline” tariffs which are set below the distribution utilities cost of service, with the belief that the resulting financial shortfall will be addressed by cross-subsidies from other customer rate classes or funded by government reimbursement to the utilities (Komives et al., 2005). In reality, rural areas often do not have a sufficient population of large commercial and industrial customers to offset the financial loss created by lifeline tariffs. Insights from my recent project experiences in northern Ghana provide a classic example of this cross-subsidy imbalance, “The biggest issue facing Northern Electricity Distribution Company (NEDCo) is that a large percentage of its customer base is on a tariff that is too low (lifeline customers), and the utility simply has insufficient revenue to offset expenses. The lifeline tariff is an explicit subsidy and the challenge is to set the lifeline at a level that provides necessary social benefits without compromising the ability of NEDCo to operate” (CH2M Hill, 2014). This lifeline tariff regime often results in distribution utilities losing money with every connection in rural areas, robbing them of the financial resources to maintain and upgrade their aging infrastructure and comprising their ability to maintain the necessary pace of grid extension. As a result of deferred maintenance and equipment upgrades, high technical losses emerge which degrade the quality and reliability of service to existing customers. Under these lifeline tariffs, low-income consumers don’t see the real cost of their utility connection and monthly usage, which distorts their perception of the cost of off-grid solutions as unaffordable. Coupled with the vicious cycle created by this subsidy approach, political promises that the “grid is coming” and lack of regulation for off-grid products reduces social acceptance and limits adoption of SHS PAYG – even in areas where it represents the least cost solution. (Komives et al., 2005)

In stark contrast to the institutional barriers fueled by energy consumption subsidy regimes, SHS PAYG service providers have the opportunity to leverage the enabling environment opportunity presented by last-mile distribution partnerships with MNOs. Market penetration by mobile service providers continues to outpace the rate of electrification, which results in an "energy addressable market" of low-income mobile phone users living in un-electrified communities. This market penetration gap (and opportunity) has been expanding (Figure 6).

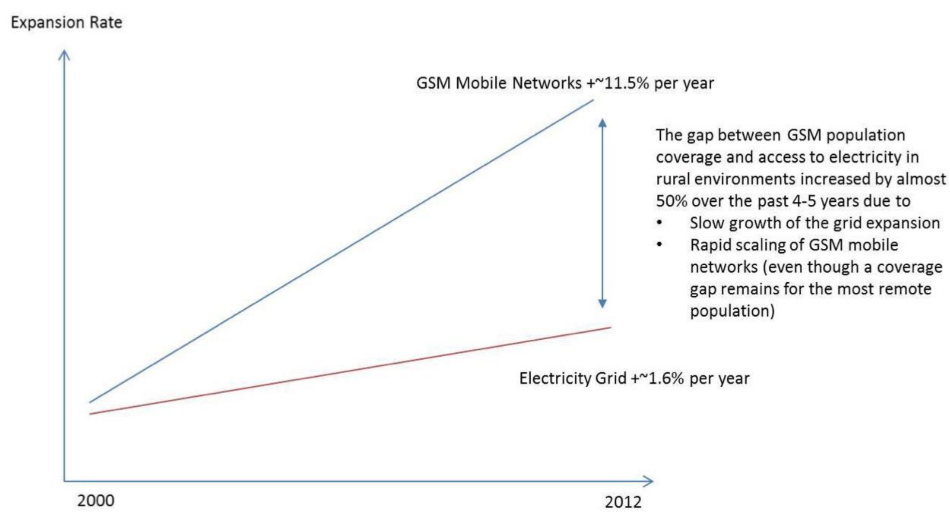


Figure 6. Mobile service access versus grid extension growth. (Nique & Thasarathakumar, 2011).

In addition to the pent-up demand created by this market penetration gap, MNOs have already established robust last-mile distribution networks which their SHS PAYG partners can use to take advantage of the MNOs brand recognition and local trust. These relationships also offer benefits to the MNOs -- when consumers are able to keep their phones charged through the adoption of SHS PAYG solutions, MNOs can see an increase in their average revenue per user (ARPU) of 10-14% (Nique & Thasarathakumar, 2011).

In the absence of electricity access, mobile phone users typically have to spend time and money to travel to the closest village and pay a fee at a charging shop – limited their ability to purchase air time on a consistent basis.

Overcoming an Institutional Barrier

In order to understand the institutional barriers created by energy consumption subsidies throughout the ECOWAS region it was necessary to: 1) characterize the market distortion created by these subsidy regimes, 2) examine the mathematical models describing the benefit targeting indicator for energy consumption and connection subsidies, 3) explore the opportunities for subsidy reforms with the potential to support SHS PAYG scale-up, and 4) integrate these insights into an enhanced GIS-based energy access tool framework. At the heart of the market distortion dynamic is the "utility insolvency trap" (Figure 7).

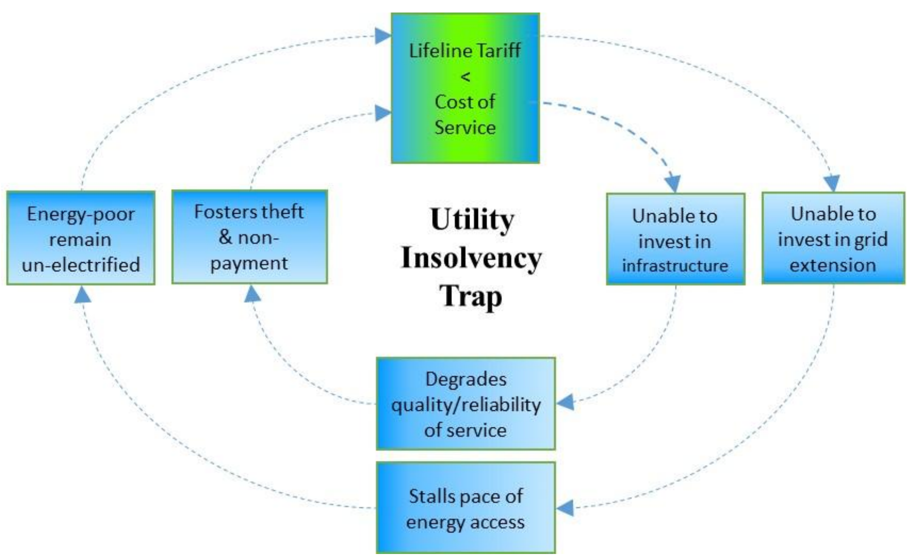


Figure 7. A vicious circle - the utility insolvency trap (Alleyne, 2013; author's elaboration, 2017).

Historically, energy consumption subsidies are popular in developing countries due to the fact that they are readily available through lifeline tariffs, require minimal administrative capacity, and provide (what appears to be) a highly visible benefit (Alleyne, 2013). The inherent cost structure of distribution utilities serves to make these subsidies tempting candidates for politicians, policy makers, utility managers, and the public in meeting the goal of affordable electricity for low-income households. In reality, these consumption subsidies serve to undermine electricity access objectives and introduce market distortion by reducing a distribution utility's economic incentive to expand the utility grid to low-income areas (Komives et al., 2005). In practice, distribution utilities in sub-Saharan Africa often find themselves in a "loss making" situation due to government subsidized "lifeline" tariffs which are charged to rural customers. These tariffs are often set well below the utility's cost of service, with the assumption that the financial loss will be offset through cross-subsidy from other rate classes and/or reimbursement from the national government. This pattern of financial insolvency means that the power sector in most sub Saharan African (SSA) countries is unable to extend the grid to new customers at an acceptable pace – or provide reliable service existing customers (Trimble, Kojima, Perrez Arroyo, Mohammadzadeh, 2016). Trimble explains this shortfall mathematically (Equation 1) through the concept of hidden costs:

$$Hidden\ costs = Underpricing + T\&D\ losses + under\ collection\ of\ bills + overstaffing$$ (Equation 1) (Trimble et al, 2016).

Review of the elements (excluding overstaffing) of the hidden cost model offers an illustration (Figures 8 – 10) of this crippling market distortion dynamic across the ECOWAS region.

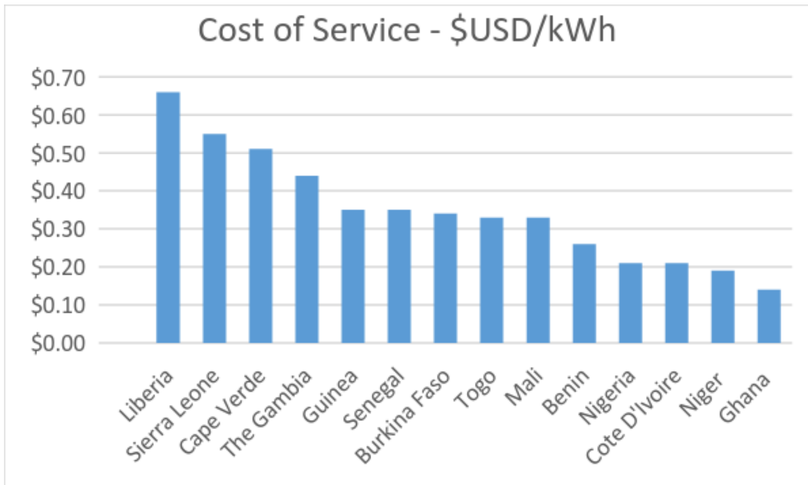


Figure 8. ECOWAS utilities cost of service (Trimble et al., 2016).

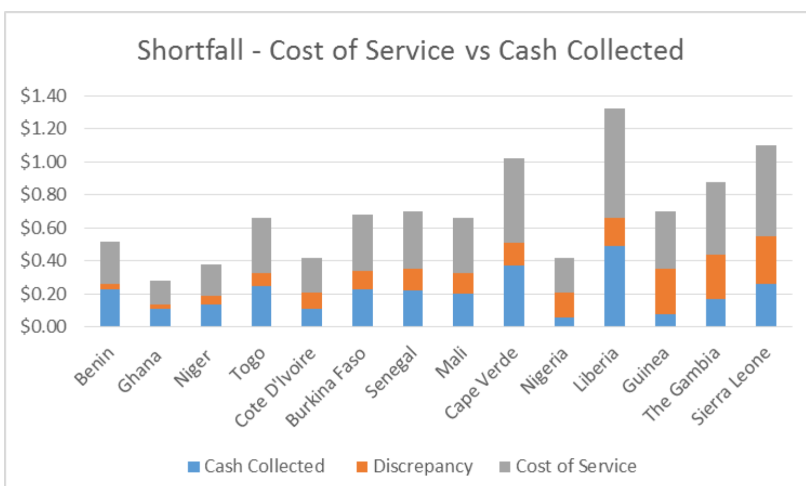


Figure 9. ECOWAS utilities cost of service versus cash collected. (Trimble et al., 2016).

This analysis documents a utility cost of service ranging from a low of $0.14/kWh (Ghana) to a high of $0.66/kWh (Liberia). The utility cost of service is $0.34/kWh (median) and cash collected is $0.21/kWh (median): indicating that utility tariffs would need to increase by $0.13/kWh, on average, to cover this deficit (Trimble et al., 2016). Examining Figure 9 above, it is quite telling that all of the ECOWAS member states shows a shortfall in cash collected versus the cost of service. Ghana and Niger are in the best position financially, while Guinea, Gambia, and Sierra Leone show an alarming deficit of nearly $0.30/kWh. While this pattern of underpricing fuels the utility insolvency trip, the high level of transmission & distribution (T&D) losses (Figure 10) results from an ongoing shortfall in infrastructure investment. From a practical perspective, these T&D losses present themselves as power quality and reliability problems for consumers and lost revenues for distribution utilities.

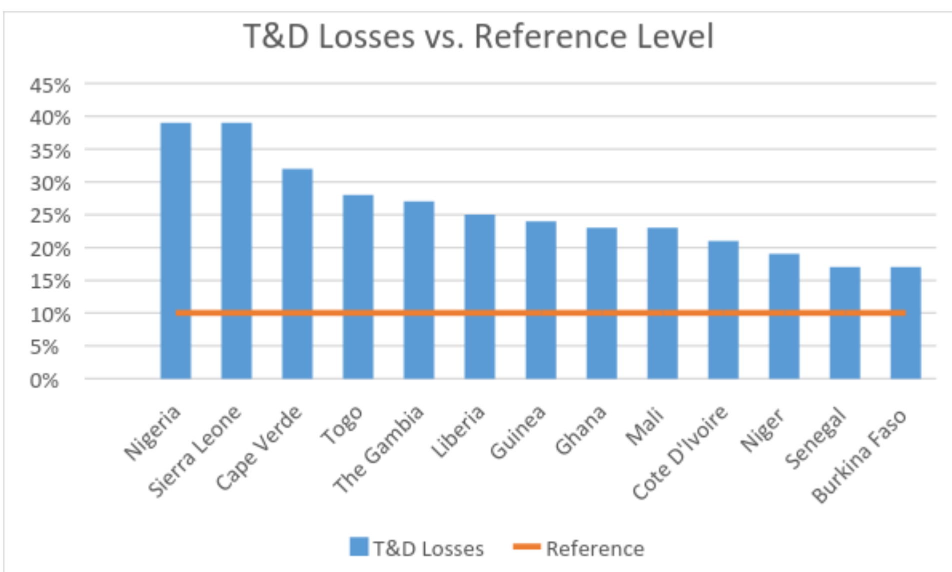


Figure 10. T&D losses vs reference level. (Trimble et al., 2016).

Analysis of these data (Figure 10) indicates a level of 24% T&D losses (median) across the region. A reference level of 10% is widely recognized as a benchmark for a typical developed country utility network (Trimble et al., 2016). Comparing the range of member state's performance (17-39%) to this reference level shows a systemic gap across the region.

Connecting the dots between underpricing and T&D losses helps to get at the underlying dynamics of the market distortion which is fueled by energy consumption subsidies. The financial shortfall created by underpricing prevents distribution utilities from making appropriate investments in maintenance and upgrades to their overhead pole network, metering technology, and distribution equipment. Lack of maintenance results in losses from excessive voltage drop and reduced transformer efficiency. In addition, lack of maintenance increases network outages increase and degrades service reliability. Ultimately, this ripple effect slows the pace of grid extension and means that existing utility customers in remote, rural communities cannot count on the utility grid to meet their daily needs (Komives et al., 2005). Documentation of outages (Figure 11) and customer service response time (Figure 12) provides further characterization of the level of utility performance facing consumers across the ECOWAS region.

Consumers in a number of member states (Ghana, Mali, The Gambia, and Benin) experience delays of 30 days or more (Figure 11) in obtaining an electrical connection, with Benin and The Gambia ranking among the worst in sub-Saharan Africa. An alarming level of service interruptions (250-400 outages/year) is seen in Niger, Nigeria, The Gambia, and Guinea (Figure 12). To put these performance metrics in perspective, the data above equates to an average of an outage every other day (178 outages/year) and a month's delay (32 days) in obtaining an electricity connection across the ECOWAS

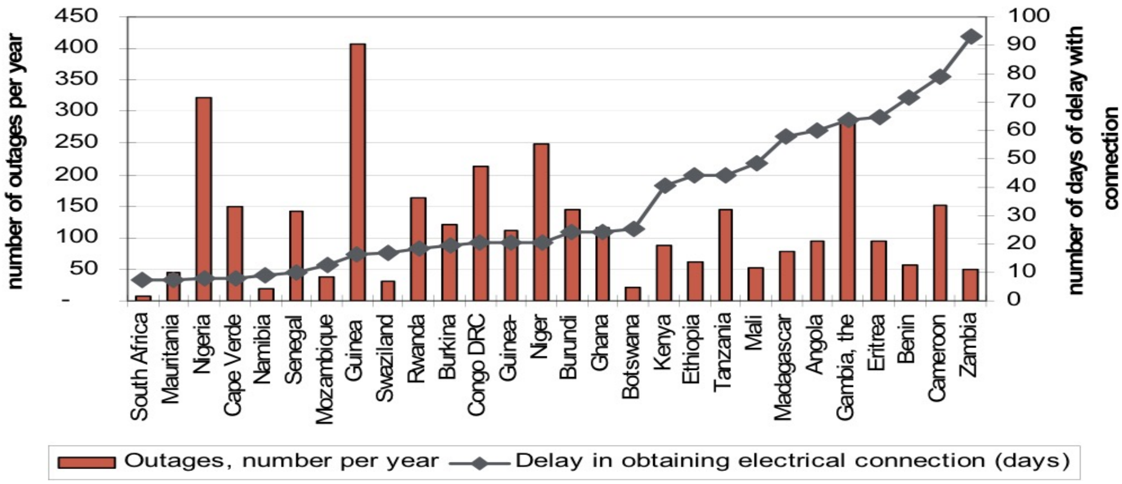


Figure 11. Outages and connection delays, sorted by delays (Tallapragada et al., 2009).

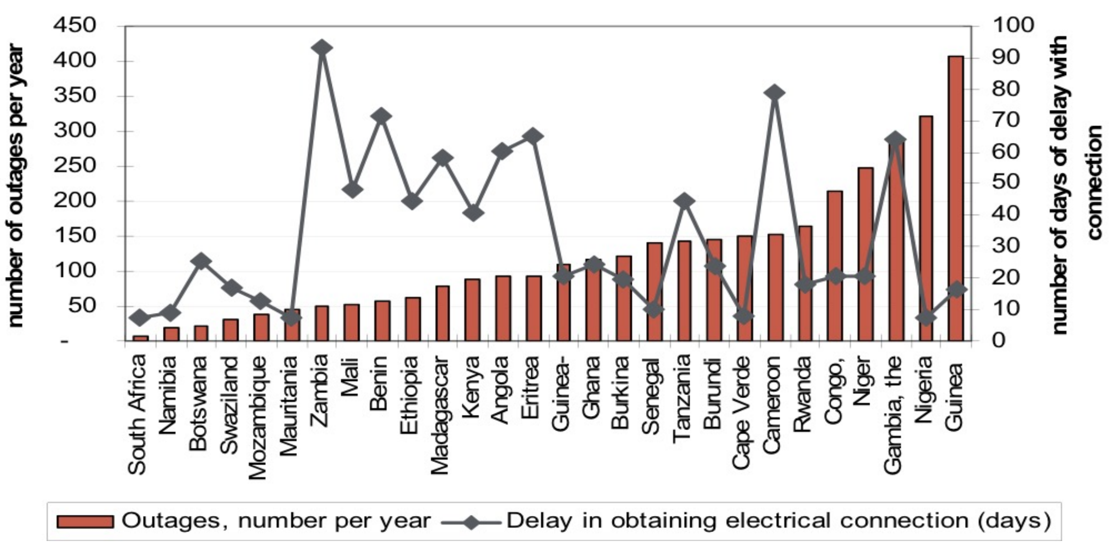


Figure 12. Outages and connection delays, sorted by outages (Tallapragada et al, 2009).

region. In comparison, US Energy Information Administration data reports an average of only one outage per year in the USA (USEIA, 2016).

In order to identify the subsidy reforms that may help to overcome the market distortion caused by energy consumption subsidies, the mathematical models which govern subsidy beneficiary targeting performance were examined. In practice, the targeting performance indicator (Ω) (Table 20) is commonly used as a measurement of subsidy effectiveness (Komives et al., 2005).

Table 20. Targeting performance indicator (Ω) (Komives et al., 2005).

Value of Ω	**Subsidy Distribution**	**Comments**
>1.0	Progressive	Poor benefit from a larger share of the benefits than their share of the population
< 1.0	Regressive	Poor receive a smaller share of the benefits than their population share
0.0	None	None of the subsidy is accruing to poor households

Komives et al., (2005) provides a thorough mathematical derivation of **Ω** for readers who are interested in more detail on this concept. Jumping to the result of this derivation, the targeting performance indicator **Ω** (Equation 2) (Komives et al., 2005) is defined as:

$$\Omega = \frac{Ap}{Ah} x \left(\frac{Up|a}{Uh|a}\right) x \left(\frac{Tp|u}{Th|u}\right) x \left(\frac{Rp|t}{Rh|t}\right) x \left(\frac{Qp|t}{Qh|t}\right) \quad \text{(Equation 2)}$$

Conceptually, this equation can be interpreted as the product of five (5) ratios which compare the situation of poor households to that of all households in a targeted population. These ratios include: A = access ratio, U = uptake ratio, T = targeting ratio, R = subsidy ratio, and Q = quantity ratio (Komives et al., 2005). In geographic areas cases where electricity access is not universal, the combined effects of the access ratio and uptake ratio produces an "access handicap" which works against providing the intended subsidy benefits to the poor (Komives et al., 2005). From a practical standpoint, if poor households have no electricity access ($A_p = 0$) then Ω is zero, indicating that no subsidy benefits accrue to the poor. Looking at the second component of the access handicap, even if $A_p/A_h = 1$, then a low uptake ratio $U_p|_a/U_h|_a$ (perhaps caused by an unaffordable connection fee) can result in a value of $\Omega < 1.0$, which represents a regressive subsidy regime. In rural settings, it is common for electricity consumption (Q) to be much lower for poor households than wealthier households. If poor households are assumed to consume half as much energy as wealthy households then this would equate to Q = 0.5, likely driving the subsidy to be regressive.

Reflecting on the impact of this mathematical analysis to my research, it is clear that the dynamics which are typically at play in remote, rural communities result in minimal or no benefits to poor households. Instead of providing a social benefit by making electricity service affordable for low-income households, this energy consumption subsidy regime is shown to be an ineffective use of national financial resources. A similar equation is derived by Komives to describe the targeting performance indicator for connection subsidies Ω_C.

$$\Omega c = \frac{1-Ap\ x\ Up|a}{1-Ah\ x\ Uh|a}\ x\ \frac{Tcp|u}{Tch|u}\ x\ \frac{Rcp|t}{Rch|t}\ \frac{xUcp|t}{Uch|t}$$ (Equation 3) (Komives et al., 2005).

The performance targeting indicator Ωc can be interpreted as the product of four ratios: unconnected households (A, U), targeting ratio (T), future uptake ratio (Uc), and subsidy rate ratio (R) (Komives et al., 2005). From a practical standpoint, the fact that connection subsidies are directed at un-connected households means that are naturally progressive, where energy consumption subsidies were shown to be regressive by nature. In the context of utility grid extension, connection subsidies are typically used to buy-down or eliminate the service connection fee - which can often serve as the barrier to electricity access for low-income households (Komives et al., 2005) Reflecting on the relevance to my research, connection subsidies could be used to buy down the SHS PAYG system down payment to a level where it is comparable to a household's current monthly expenditure on traditional fuels - increasing consumer adoption of these solutions. Examining Equation 3, if the majority of unconnected households are also poor households, then it is clear that the unconnected-households ratio and targeting ratio will tend to drive Ωc to be progressive. Now that a theoretical foundation for subsidy targeting performance has been established, it can be used to examine the effectiveness of a number of subsidy reform options. The literature suggests a number of approaches including: 1) administrative selection, 2) service level targeting, 3) connection subsidies, 4) results based financing, and 5) pay-as-you go billing and payment systems.

A common use of administrative selection is the targeting of specific geographic locations. Geographic targeting combined with an increasing block tariff (IBT) or volume differentiated tariff (VDT) rate structure has been shown to work well if neighborhoods, cities, or regions can be identified where poor households live. In order for this strategy to work, the location of the household must be a reliable proxy for income status (Komives et al., 2005). Administrative selection can also be implemented by identifying other categorical variables that are a good predictor of poverty. In the context of my research, geographic targeting of communities where consumers have mobile phone service but no electricity – known as the "energy addressable market" - appears to be a promising strategy for integration into an enhanced GIS-based energy access decision tool framework.

Service level targeting offers a second option for subsidy reform, allowing households to "self-select" by opting for a particular level of electricity service (Komives et al., 2005). This approach has largely been viewed as ineffective in a utility grid context where wealthier households are unlikely to find lower quality, less reliable, less convenient service attractive. In practice, this strategy is often employed by diesel mini-grids that provide only six (6) hours of service per day – during times of peak demand for household lighting and appliances. Service level targeting may be quite attractive in remote, rural areas where the pace of grid extension is slow or stalled and off-grid alternatives are more cost appropriate (Komives et al., 2005). With the advent of reliable pico-solar lighting, solar kits, and solar home systems – the reality is that service level targeting may serve as the best fit in terms of subsidy models for energy-poor communities. Most SHS PAYG service providers offer a range of system capacities, so increasing the subsidy level as the system capacity expands seems to be a tailor-made application of service level targeting.

Shifting from energy consumption to connection subsidies is another option for reform. By their nature, consumption subsidies provide an ongoing benefit while connection subsidies only offer a one-time benefit (Komives et al., 2005). However, the long-term effects of obtaining an electricity connection may far exceed the initial connection subsidy benefit (Komives et al., 2005). In contrast to the regressive nature ($\Omega < 1.0$) of consumption subsidies, connection subsidies are nearly always progressive ($\Omega > 1.0$) (Komives, 2005). From a grid connection perspective, a drawback inherent in the use of connection subsidies is that households also face the cost of installing internal wiring in their homes, which may limit the uptake rate in poor areas due to affordability limitations (Komives et al., 2005). In the context of my research, this is not a barrier for SHS PAYG solutions which do not require internal wiring, so a connection subsidy could be employed to buy-down or fully subsidize the initial costs (down payments) associated with obtaining these systems.

While energy consumption and connection subsidies are targeted to energy-poor consumers, results based financing schemes are targeted to service providers and offer payments based on the achievement of specified results (Energizing Development, 2017). The primary goals of RBF schemes are to boost energy access markets, support private companies along the value chain, and remove temporary financial barriers. The Energizing Development (EnDev) RBF Facility outlines the key principles of this innovative approach as follows: 1) Pre-determined results are broadly defined to encourage product and service innovation, 2) Eligible service providers participate on a competitive basis, 3) Monitoring and verification systems are the trigger for financial disbursement, and 4) Disbursement is contingent upon the delivery of predetermined, verified results (EnDev, 2017). Based on the success of applying RBF to support SHS scale up in Bangladesh and Ghana an expanded discussion of this subsidy reform option is provided below.

Wrapping up the examining of subsidy reform options, pay-as-you-go billing and payment systems offer a better match for the irregular cash flow patterns of the poor (Komives et al., 2005). Since low income, energy-poor households often face cash flow problems, lack financial reserves, and have limited access to credit - then the more frequent billing, offer of credit, and payment amounts which mirror household expenditures on traditional fuels make SHS PAYG solutions more appropriate to the consumer willingness to pay of many low-income households (Komives et al., 2005).

Among the subsidy reform options examined in my research, results based financing (RBF) has recently emerged a successful tool for accelerating the scale-up of SHS PAYG, as illustrated by the success of the RERED program in Bangladesh and the GPOBA funded program in Ghana (GPOBA, 2016; Sanyal et al., 2016). Looking more broadly in the region, RBF is currently being utilized by the Energizing Development (EnDev) consortium in the Promotion of the Market for Quality PV Products in Benin (ProMaBiP) Program which seeks to deploy 400,000 pico PV lamps, 2,500 PV street lamps, and 260 solar pumps (EnDev, 2016b). In addition to this RBF program, EnDev is active in Burkina Faso, Liberia, Mali, Ghana, and Senegal (EnDev 2015). Relevant to the scope of my research, EnDev also supports SHS financing programs in member states Liberia, Mali, and Senegal (EnDev Annual Planning, 2016a). Since the application of the RBF approach is not limited to a specific technology, one option for the scale-up of SHS PAYG across the ECOWAS is the expansion of the scope of the ProMaBiP program in Benin program to include SHS and modification of the ongoing EnDev SHS programs in the region to incorporate an RBF pilot program. As the original DFID business case for RBF asserts, "For markets with a degree of capacity in place in a few firms – using a technology reasonably well developed elsewhere and no critical policy barriers – RBF is considered to have important market acceleration potential" (DFID, 2013).

EnDev recently brought stakeholders together for a lessons-learned exercise which was documented in their March 2017 report entitled *Driving markets to scale: Lessons learned from stimulating energy access markets with results-based financing* (EnDev, 2017). Key outcomes from this stakeholder engagement process included the need to 1) develop the market, 2) find the right participants, and 3) run the project successfully. In terms of developing the market, the primary recommendation was to keep an eye on the target market, both before and during a project. Participants outlined the common market barriers that they encountered including: 1) limited distribution channels for energy companies, 2) lack of access to finance for energy companies and consumers, 3) lack of consumer trust in and awareness of technology, 4) limited business and technical capacity of energy companies, and 5) unfavorable policy frameworks (EnDev, 2017). Likewise, finding the right program participants required a clear business proposition, since an RBF scheme can't succeed if private service providers refuse to commit to the program requirements. This lessons learned exercise documented the key elements of the business proposition to include: 1) What's expected of the service provider?, 2) What is the application process and cost to apply?, 3) What extra costs are involved?, 4) What is the risk exposure if the project fails or the market changes?, 5) What results are needed to qualify for incentives?, and 6) What administrative duties are involved – particularly as it relates to monitoring and verification? (EnDev, 2017). Lessons learned relative to running the project include thinking about the exit strategy and adjusting the M&V approach to the market conditions and common business practices appropriate to the project location. In looking at the exit strategy, it is recommended that there is a steady decrease in the incentives as the market matures in order to ensure the long-term sustainability of this initiative (EnDev, 2017).

Communications with members of the EnDev RBF team provided a number of additional insights based on their implementation experience. Among the lessons learned was the need for close coordination with governments and utilities to identify the geographic areas where the grid is not projected to arrive in the foreseeable future (D. de Haan, personal communications, February 15, 2017). Poor coordination where multiple energy access schemes arrive at the same time or where unexpected grid encroachment occurs can significantly dilute the benefits of RBF for solar technologies. Derk de Haan (D. de Haan, personal communication, February 15, 2017) made it quite clear that RBF is not a good fit for markets at the infant stage, but is designed to stimulate and expand existing markets. If you assume that you have a healthy SHS PAYG provider such as Fenix International in Uganda, for example, then the function of the RBF subsidy is to entice them to put forth the extra effort to penetrate the more remote, rural communities that remain un-electrified.

In addition to the efforts led by the European led EnDev consortium, the World Bank funded Global Partnership on Output Based Aid (GPOBA) has illustrated the benefits of results based financing on SHS scale-up in the ECOWAS region. A case study developed by GPOBA illustrates this an application of RBF in Ghana. This project focused on remote, rural communities in the Volta Lake Islands where SHS and solar lanterns are most cost effective. At the outset of the project, consumer awareness of solar technology in rural areas was quite low. In some communities, social acceptance of solar technology was low due to negative experiences poor quality equipment from local traders. SHS and solar lantern prices had dropped locally, but still remained out of reach for many rural households (GPOBA, 2016). In 2009, this output based aid project was initiated through a $4.35 United States Dollar (USD) million grant targeted to impact 15,000 households. In terms of institutional coordination, this project was a component of the renewable energy portion of the larger Ghana Energy Development and Access Project (GEDAP). Local stakeholders included ARB Apex Bank, which served as a mini-central bank for rural/community banks. In addition, service providers included private dealers who were recruited and organized by the Association of Ghana Solar Industries (AGSI). In addition to serving as a local liaison and facilitator, AGSI was responsible for increasing awareness of SHS, capacity building, and enabling service provider access to finance (GPOBA, 2016). The subsidy design outlines the service provider requirements, equipment subsidy, and expected consumer contribution for this program (Table 21).

Table 21. Ghana GPOBA subsidy design (GPOBA, 2016).

Target	**Service Provider Requirements**	**Subsidy (USD)**	**Consumer Contribution**
Subsidy directed to service providers, designed to offset 50-60% of cost to purchase/maintain SHS	• Supply & install SHS • Maintenance/repair for 3 years • Battery replacement at Year 2 or 3 • Lighting Africa certified products	Solar lantern - $40 Small SHS - $300 Medium SHS - $450 Large SHS - $550	Remaining 40-50% of cost through loans for SHS, out of pocket for solar lanterns

In the subsidy column (Table 21), a small SHS is 10-20 Wp, medium SHS is 21-49 Wp, and a large SHS is 50 Wp. Results for this project included a high level (93%) of customer satisfaction with the solar products, with 97% of respondents indicating willingness to pay for future maintenance and repairs, 91% of households reporting increased study/reading time for children, and 18% of SHS customers reporting direct income generation (GPOBA, 2016). This project exceeded its targets, supporting the purchase of 8,831 SHS and 7,991 solar lanterns for 16,500 households (~100,000 rural residents). In addition, twelve (12) rural banks provided $1.6 million USD in consumer loans for SHS purchase with seven (7) banks reporting a 98% or higher repayment rate and an overall loan recovery rate of 78% (GPOBA, 2016).

Reviewing and summarizing the options for subsidy reform (Table 22), it was quite promising to note that nearly all of these strategies can be applied to the scale up of SHS PAYG solutions in the ECOWAS region.

Table 22. SHS PAYG scale-up – summary of subsidy reform options (Komives et al., 2005).

Subsidy Reform Options	Integration Opportunities
IBT to VDT	Not applicable
Administrative Selection	Geographic targeting using energy addressable market and subsidy availability locations
Service Level Targeting	Subsidy levels correspond to a range of SHS capacity (Wp)
Connection Subsidies	Defray the cost of down-payment in new markets
Results Based Financing	Stimulate and expand SHS penetration of existing markets
PAYG Billing & Payment Systems	Inherent feature of SHS PAYG solutions

Embracing an Enabling Environment Condition

From an energy-poor perspective, mobile phones rank as a critical “basic needs technology”: linking people with family and friends, connecting them to the marketplace, and facilitating overall access to information. In order to access these services, people in the most remote, rural communities are willing to invest time, money, and take risks (Alstone, 2015). The time investment involves traveling to the nearest village to charge mobile phones at a shop or kiosk. In addition to paying the charging fee, the consumer’s cost often includes transportation to and from the nearest village. Finally, the potential risks include gender based violence directed at women and the theft of one’s handset during this process (Alstone, 2015). The Global System for Mobile Communications Association (GSMA) defines the “energy addressable market” as the number of people owning a mobile phone before having a place to charge it (GSM Nigeria, 2016). MNOs such as MTN, Airtel, Tigo, and Vodaphone stand to benefit when this population of customers gains electricity access. Newly connected consumers are able to increase their airtime as a result of keeping their phones charged more consistently – driving an increase of ten to fourteen percent (10-14%) in the average revenue per user (ARPU) for MNOs (GSM Nigeria, 2016). SHS PAYG providers stand to benefit from the last mile distribution networks established by the MNOs, the mobile money backbone that is used for their payment systems, and the customer trust which is engendered through the pay-as-you–go financing offer. The combination of electrical services including lighting, mobile phone charge, and the capacity to support small appliances suggests that these consumers would be more prone to adopt solutions such as SHS PAYG. The mutual benefits gained by MNOs, SHS PAYG service providers, and energy-poor customers suggests that the "energy addressable" market" may prove to be an enabling environment benefit for each of these stakeholders.

Data compiled by GSMA and MTN (Table 23) quantifies the size of the energy addressable market across the ECOWAS member states as well as calculating the revenue benefits to MNOs as a result of an ARPU increase following electrification. This data (Table 23) suggests initially targeting Burkina Faso, Cote D'Ivoire, Mali, Niger, and Nigeria for SHS PAYG scale up as they account for nearly eighty percent (80%) of the potential energy addressable market in the region. Looking beyond the ECOWAS region, SHS PAYG adoption in East Africa is widely regarded as a success story, which suggests comparing the energy addressable market in East Africa (Table 24) to the growth potential in West Africa.

Table 23. Energy addressable market for the ECOWAS member states (Nique & Thasarathakumar, 2011; MTN, 2016; author's elaboration, 2017).

Member State	Energy Addressable Market (population in millions)	Portion of ECOWAS Total	ARPU 2015 ($/mo)	ARPU 2015 Avg ($/mo)	ARPU 2015 Avg ($/yr)	10% ARPU Increase	14% ARPU Increase	1% SHS Market Penetration	1% HH	Base Revenue	10% Increase	14% Increase	MTN @14%
Benin	2.78	2.2%	5.8	$ 4.01	$ 48.10	$ 52.91	$ 54.84	27,834	6,958	$ 1,338,894	$ 1,472,783	$ 1,526,339	$ 2,208,459
Burkina Faso	13.77	10.7%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	137,697	34,424	$ 6,623,634	$ 7,285,997	$ 7,550,942	
Cape Verde	0.12	0.1%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	1,205	301	$ 57,973	$ 63,770	$ 66,089	
Cote D'Ivoire	7.57	5.9%	4.69	$ 4.01	$ 48.10	$ 52.91	$ 54.84	75,659	18,915	$ 3,639,437	$ 4,003,380	$ 4,148,958	$ 4,854,251
Gambia	1.04	0.8%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	10,421	2,605	$ 501,288	$ 551,416	$ 571,468	
Guinea	5.58	4.3%	2.15	$ 4.01	$ 48.10	$ 52.91	$ 54.84	55,837	13,959	$ 2,685,925	$ 2,954,517	$ 3,061,954	$ 1,642,281
Guinea Bissau	0.32	0.2%	3.15	$ 4.01	$ 48.10	$ 52.91	$ 54.84	3,221	805	$ 154,945	$ 170,439	$ 176,637	$ 138,804
Ghana	4.50	3.5%	3.09	$ 4.01	$ 48.10	$ 52.91	$ 54.84	44,961	11,240	$ 2,162,760	$ 2,379,036	$ 2,465,547	$ 1,900,562
Liberia	3.03	2.3%	4.31	$ 4.01	$ 48.10	$ 52.91	$ 54.84	30,313	7,578	$ 1,458,138	$ 1,603,952	$ 1,662,277	$ 1,787,274
Mali	9.79	7.6%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	97,894	24,474	$ 4,709,001	$ 5,179,901	$ 5,368,261	
Niger	11.62	9.0%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	116,208	29,052	$ 5,589,952	$ 6,148,947	$ 6,372,545	
Nigeria	59.39	46.0%	4.87	$ 4.01	$ 48.10	$ 52.91	$ 54.84	593,879	148,470	$ 28,567,274	$ 31,424,001	$ 32,566,692	$ 39,565,165
Senegal	2.82	2.2%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	28,184	7,046	$ 1,355,747	$ 1,491,322	$ 1,545,552	
Sierra Leone	4.34	3.4%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	43,422	10,856	$ 2,088,740	$ 2,297,614	$ 2,381,164	
Togo	2.33	1.8%		$ 4.01	$ 48.10	$ 52.91	$ 54.84	23,300	5,825	$ 1,120,797	$ 1,232,876	$ 1,277,708	
							Total	1,290,038	322,509	$ 62,054,502	$ 68,259,952	$ 70,742,132	
							Increase				$ 6,205,450	$ 8,687,630	$ 12,089,425

Table 24. East Africa - energy addressable market (Nique & Thasarathakumar, 2011).

Country	**Energy Addressable Market (population in millions)**
Kenya	28.4
Tanzania	26.7
Uganda	27.0
Rwanda	9.3
Region Total	91.3

If we view this population in East Africa as a contiguous market for SHS PAYG products, it suggests identifying a comparable region in for market penetration and expansion in West Africa. Using the data (Table 23) above, one can see that a sub-region formed by Cote D'Ivoire, Burkina Faso, Ghana, Togo, Benin, and Nigeria represents an energy addressable market of ~90 million off-grid mobile phone users, comparable to energy addressable market in East Africa (Table 24).

From an off-grid consumer's perspective, phone charging services are quite high, often accounting for up to fifty percent of monthly mobile expenditures. This process is also time consuming, with a round trip often requiring a full day's travel to the nearest urban area to access electricity (Nique, 2013). The literature does not provide sufficient information to assess the number of days/week that travel to a phone charging shop is required, but my experience as an energy access consultant in West Africa suggests that two to three times per week is realistic. In this context, obtaining an SHS PAYG connection offers a time savings (reduced travel to charging shops), cost savings (reduced charging expenses), and potential income generation through the ability to charge multiple devices (Nique, 2013). Alstone's research (2015) suggest that access to recharging power suitable for mobile phones is at least ten times less costly through SHS PAYG (on a $/kWh basis) than fees at a charging shop. Field studies conducted by GSMA in Kenya and Uganda illustrate the high cost of phone charging for off-grid consumers living in remote locations (Table 25).

Table 25. Phone charging rates for off-grid consumers (Nique & Thasarathakumar, 2011).

Country	Elec Access Rate	Mobile Penetration	GSM Pop Coverage	ARPU	Charge cost/month	Monthly Expense
Kenya	18% (2009)	58%	95%	$4.33	$1.5 – 6.0	10-50%
Uganda	9%	40%	97%	$4.2	$1.0 – 7.0	10-50%

Monthly expense (Table 25) refers to the phone charging expense as a percentage of a consumer's monthly expenses. This is quite high considering that energy expenses as a fraction of total household expects is generally expected to fall in the 5-10% range.

In addition to the data quantifying charging costs (Table 25), travel costs are also quite high. It is not uncommon for people in remote areas to travel up to 20 km (12 miles) to charge their phones, often spending up to 50,000 Ugandan Shillings ($25) per month on transportation alone (Nique & Thasarathakumar, 2011), dwarfing the cost of the charging fees. To put this monthly travel expense in perspective, the gross national annual income for Uganda was reported as $440 (2012), which equates to approximately $36/month (UNICEF, 2015).

GSMA's Mobile for Development Utilities (M4D Utilities) recently completed a "proof of concept" study to explore the partnership between MTN and Fenix International (SHS PAYG). One of the key findings was that more than more than twenty percent (20%) of respondents earned income through phone charging services after making the investment in Fenix's ReadyPay SHS product. It was noted through this study that even the smaller home systems can provide sufficient power for phone charging beyond a family's normal daily use – defraying the recurring cost of owning the Ready Pay system (GSMA, 2015). Through the author's organization of the data (Table 26) from this case study, a simple cost benefit analysis was developed.

Table 26. Simplified SHS customer cost-benefit analysis (GSMA, 2015; author's elaboration, 2017).

SHS Product	Vendor Fee ($/charge)	Monthly Fee ($)	Ready Pay Installment ($/day)	Income Potential Minimum ($/charge)	Income Potential Maximum ($/charge)	Typical Volume (phones/day)	Monthly Cost ($)	Monthly Income Min ($)	Monthly Income Max ($)	Net Monthly Benefit Min ($)	Net Monthly Benefit Max ($)
Ready Pay Home Plus (10 W)	$0.17	$5.10	$0.40	$0.11	$0.18	4.9	$12.00	$16.17	$26.46	$4.17	$14.46
Ready Pay Home Comfort (17 W)	$0.17	$5.10	$0.49	$0.11	$0.18	8.3	$14.70	$27.39	$44.82	$12.69	$30.12

This analysis offers a clear picture of the immediate benefits available to a customer who has entered into a lease-to-own agreement for one of these systems. If we look at the cost-benefit proposition solely in terms of phone charging, an off-grid customer would have been paying $5.10/month to a local vendor for daily phone charging prior to purchase of the Ready Pay unit. By leveraging the phone charging capacity of these systems to generate income, the net monthly benefit ranges from $4.17 to $14.46 for the 10 W system and from $12.69 to $30.12 for the 17 W system, either defraying or exceeding the $12.00 to $14.70 monthly cost of the SHS PAYG system. In addition to the consumer benefits, the Uganda case study also reports a number of benefits accruing to MTN (the Mobile Network Operator) from this partnership. These include 1) new subscriber acquisition, 2) new subscriber revenue generation from fees on mobile money energy payments, 3) increased subscriber use of mobile money for other transactions, 4) increased subscriber use of voice, SMS, data, and other value added services due to having phones consistently powered and on-network, and 5) brand loyalty and stickiness due to the regular and frequent use of the MTN mobile wallet (GSMA, 2015).

Similar to the findings from the Fenix International proof of concept study in Uganda, another GSMA study in Rwanda reported that Mobisol entrepreneurs can earn ~25,000 RWF ($35 USD) per month from a mobile phone and lantern charging business, which exceeds the monthly recurring cost ($23.94 USD) of the 100 W business system (GSMA, 2016b). Reflecting on the results of this study, MTN Rwanda's former CEO Ebenezer Asante points to this enabling environment condition as he asserts that "MTN's mission is to make our customers lives a whole lot brighter, and the partnership with

Mobisol is literally doing this. We initially partnered with Mobisol to enable customers to effortlessly buy prepaid solar power via MTN mobile money. MTN's digital connections and mobile payments help transform economies and societies, and we have seen an increase in mobile money penetration in the areas where Mobisol is delivering solar solution thus reflecting a positive impact in our partnership" (GSMA, 2016b). In contrast to these success stories described in Uganda and Rwanda, high national utility connection rates in Ghana creates an expectation among rural consumers that the national grid will eventually reach their village, so they are less willing to adopt SHS PAYG solutions in the face of heavily subsidized national grid prices (GSMA, 2016c). As an example, a case study of PEG Ghana's efforts shows that they did not meet their ARPU target, indicating that the SHS PAYG value proposition was not strong enough for customers in this context (GSMA, 2016c).

A summary of the SHS PAYG and MNO mutual benefits (Table 27) ties the key elements of the business case for SHS PAYG/MNO partnerships together.

Table 27. SHS PAYG/MNO mutual benefits summary (Nique, 2013; Winiecki & Kumar, 2014).

Category	Description	Value Proposition
Infrastructure	Cellular towers in off-grid communities	Charging solution, anchor load
Last-Mile Distribution	Mobile Money Agent Networks	Leverage local presence and trusted brand
Machine to Machine Connectivity	PAYG transaction backbone, usage and benefits data	PAYG matches variable and inconsistent consumer income, regular messaging and remote sensing provides customer usage and impact data
Payment System	Means of digitizing cash economy	Financing and affordable solutions for consumers
Mobile Services	Voice, SMS, USSD, Apps	Communicate information regarding electrification solutions

ECOWAS Member States - A Representative Example

The ECOWAS Program on Access to Sustainable Energy Services (EPASES) recent report on rural and peri-urban areas provides a snapshot (Table 28) of the current electrification status for each member state:

Table 28. ECOWAS electrification status and off-grid contributions (Bugati, Elhadji, & Handem, 2015; author's elaboration, 2017).

Country	Population (millions)	National Electricity Access	Rural Electricity Access	MG & SA PV Contribution	MG & SA PV Population (millions)
Benin	10.6	32%	6%	9.0%	0.95
Burkina Faso	17.6	17%	2%	3.0%	0.53
Cape Verde	0.514	95%	90%	NA	NA
Cote D'Ivoire	22.2	77%	30%	8.0%	1.78
The Gambia	1.92	40%	37%	1.0%	0.02
Ghana	26.8	76%	50%	23.0%	6.16
Guinea	12.3	18%	2%	0.0%	0.0
Guinea-Bissau	1.8	12%	2%	2.0%	0.04
Liberia	4.4	1%	0%	0.2%	0.01
Mali	17.1	32%	18%	5.0%	0.86
Niger	19.1	10%	0%	1.0%	0.19
Nigeria	177.5	40%	28%	NA	NA
Senegal	14.7	54%	24%	10.0%	1.47
Sierra Leone	6.3	13%	1%	6.0%	0.38
Togo	7.1	35%	5%	3.0%	0.21

With the exception of Cape Verde (95%), Cote D'Ivoire (77%), and Ghana (76%): national electrification rates across the region are quite low, with nine (9) of the fifteen member states falling at or below thirty-five percent access. Using a historical energy access annual growth rate of 1.2% (World Bank, 2015), only Cape Verde (95%) appears to be in a position to meet the 2030 universal access goal. Rural electrification rates are also quite low across the region – with more than half of the member states falling below ten percent, making the ECOWAS Renewable Energy Policy (EREP) rural electrification goals of 22% (2020) and 25% (2025) a difficult goal for these member states to achieve over the next few years (EREP, 2015). At twenty-three percent of the population, Ghana stands out as the only member state with a significant contribution from mini-grids and SA PV (SHS PAYG) systems, while none of the other member states has achieved more than a ten percent contribution. Aggregating the off-grid contribution across the region, the EPASES report documents a total population served by MG & SA PV (2015) of 12.6 million people. If we adjust that total to reflect an assumed 2.5% contribution (half of the regional average) in Cape Verde and Nigeria (where data was not provided) then the estimated population served by off-grid technology rises to 17.0 million. In principle, all of the ECOWAS member states have made a public commitment to the UNSE4ALL 2030 universal energy access goal (SE4ALL, 2017). In reality, the current electrification status across the region suggests that the off-grid contribution toward that goal appears to be slowed or stalled.

From an institutional standpoint, the presence of the ECOWAS Centre for Renewable Energy and Energy Efficiency (ECREEE) represents a potential champion and collaborator in rethinking the trajectory of energy access planning across the region. Within the broader organizational structure of ECREEE, the ECOWAS Observatory for Renewable Energy and Energy Efficiency (ECOWREX) is tasked with improving existing knowledge, mitigating information barriers, and developing planning strategies (ECOWREX, 2017). The ECOWREX2 project entitled "Promoting Sustainable Energy Access through the use of geospatial technologies in West Africa" suggests some kinship with the goals of my research (ECREEE, 2017a). From a practical standpoint, the

ECOWREX map viewer provides open source access to more than 100 geospatial layers related to energy resources and energy planning (ECOWREX, 2017). While a detailed review and assessment of this resource was beyond the scope of my research, it may well serve as a reliable source of background data for future pilot studies. In addition to the geospatial mission of ECOWREX, the ECOWAS Program on Access to Sustainable Energy Services (EPASES) is charged with monitoring and addressing the challenge of rural electrification throughout the region (ECREEE, 2017). Expanding on the summary of the current electrification status and off-grid contribution (Table 28), the pace of electrification (Table 29) required to meet the established national, rural, and off-grid energy access goals was evaluated.

The "national access, rural access, and MG & SA percent annual growth by 2030" columns in the table above reflect the pace of annual growth necessary meet the goals. This analysis uses the historical pace of electricity access growth of 1.2% (1990-2010) (WB, 2014) as a baseline. It shows that, on average, the ECOWAS member states would have to accelerate their progress by more than two and a half times (2.5x) the historical pace to meet the 2030 national goals. If the historical pace of electricity access growth at the national level has been just over one percent over the last twenty years – it would stand to reason that the pace of rural electrification growth and off-grid technology market penetration would proceed at a slower rate. In order to estimate those rates, the ratio of the regional average of rural electricity access versus the regional average of national electricity access was calculated to be 0.53 while the ratio of off-grid technology penetration to national energy access was determined to be .15. These factors equate to a

Table 29. ECOWAS progress toward 2030 electrification goals (Bugatti et al., 2015; author's elaboration, 2017).

Country	Population (millions)	National Electricity Access Target	National Elec Access (% of pop)	Effective Year	Rural Elec Access (% of pop)	Effective Year	Rural Elec Access by 2030 (EREP) (%)	Pop Served by Mini-Grid and Standalone (%)	Pop Served by MG and SA by 2030 (EREP)	National Access Percent Annual Growth to Meet 2030 Goal	Rural Access Percent Annual Growth to Meet 2030 Goal	MG and SA Percent Annual Growth to Meet 2030 Goal	Years to Achieve 2030 Target at 1.2% Annual Growth
Benin	10.6	100%	32.0%	2015	5.5%	2015	50%	9.0%	25%	4.53	2.97	1.07	57
Burkina Faso	17.6	36%	17.0%	2013	2.0%	2013	50%	3.0%	25%	1.12	3.20	1.47	16
Cape Verde	0.514	100%	95.0%	2015	90.0%	2015	50%	NA	25%	0.29	-2.67	NA	4
Cote D'Ivoire	22.2	100%	77.0%	2014	30.0%	2014	50%	8.0%	25%	1.44	1.33	1.13	19
The Gambia	1.92	100%	40.0%	2013	37.0%	2013	50%	1.0%	25%	3.53	0.87	1.60	50
Ghana	26.8	100%	76.0%	2015	50.0%	2013	50%	23.0%	25%	1.60	0.00	NA	20
Guinea	12.3	100%	18.0%	2013	2.0%	2013	50%	0.0%	25%	4.82	2.82	1.67	68
Guinea-Bissau	1.8	80%	11.5%	2014	2.0%	TBD	50%	2.0%	25%	4.28	3.20	1.53	57
Liberia	4.4	TBD	1.4%	2010	0.0%	2010	50%	0.2%	25%	TBD	2.50	1.65	
Mali	17.1	87%	31.7%	2013	18.0%	2013	50%	5.0%	25%	3.25	1.88	1.33	46
Niger	19.1	60%	10.0%	2010	0.4%	2010	50%	1.0%	25%	2.50	2.48	1.60	42
Nigeria	177.5	90%	40.0%	2015	28.0%	2015	50%	NA	25%	3.33	1.47	NA	42
Senegal	14.7	100%	54.0%	2015	24.0%	2015	50%	10.0%	25%	3.07	1.73	1.00	38
Sierra Leone	6.3	92%	12.5%	TBD	0.5%	2013	50%	6.0%	25%	5.30	2.91	1.27	66
Togo	7.1	100%	35.0%	2013	5.0%	2013	50%	3.0%	25%	3.82	2.65	1.47	54
Total (millions)	339.9	Average	37%		20%			5%	Average	3.06	1.82	1.40	41
1.2% (National)	4.1			Ratio	0.53			0.15	Min	0.29	-2.67	1.00	
0.6% (Rural)	2.0								Max	5.30	3.20	1.67	
0.12% (MG & SA)	0.4								Average/Typical	255%	341%	938%	

rural pace of ~45% and an off-grid pace of ~13% of the historical national pace. The most recent rural electrification goal was 36% of the population by 2015, a goal that was only met by Cape Verde, Cote d'Ivoire, and Ghana. Since there is no established goal for rural electrification by 2030, a benchmark of 50% was used for this analysis, which is in line with the 2015 goal. In order to achieve this goal, member states would need to accelerate their pace by nearly three and a half times the rate that was derived above. Likewise, in order to meet the 2030 goal of a 25% contribution from mini-grid and standalone solar PV solutions, member states would need to improve their pace by nearly nine and one half times the rate that was derived above. On balance, this analysis illustrates that member states in the ECOWAS region will fall far short of meeting the 2030 energy access goals without a significant, disruptive change in direction. Use the historic annual electricity access growth rate described above, the 2030 goal would not be reached until 2058 (on average) at the national level, twenty-eight years beyond the 2030 goal!

Using a Service Delivery Approach to Solve a Wicked Problem

Historically, the challenge of rural electrification has often been framed as a straightforward service delivery problem. In an effort to re-frame this challenge, I have found it helpful to explore the ten (10) characteristics of a wicked problem (Rittel & Weber, 1973) and relate them to my research questions (Table 30).

In the same spirit as Rittel & Weber's framing of the characteristics of a wicked problem, Practical Action (2016) suggests that we consider "flipping the paradigm" and approaching energy access planning from an energy-poor perspective.

Table 30. Ten characteristics of a wicked problem (Rittel & Weber, 1973; author's elaboration, 2017).

No.	Definition	Explanation	Insight	Research Focus
1	No definitive formulation of a wicked problem	Information needed to *understand* the problem depends on ideas for *solving* the problem	Is the goal a household connection, service reliability, or market penetration?	Modern electrical access (MTF Tier 3) for rural households
2	Wicked problems have no stopping rule	Planner stops due to lack of time, money, or patience with the problem	Is universal electricity access really achievable in the ECOWAS region?	Narrow the gap between LCOE recommended solutions and electrification results
3	Solutions are not true-or-false but good-or-bad	Multiple stakeholders involved - whose judgements are based on personal interests and values	Whose priorities are most important - government energy planners, distribution utilities, off-grid service providers, or rural consumers?	Focus on the energy-poor perspective of un-served households
4	No immediate/ no ultimate test of a solution	Repercussions and unintended consequences are common	Energy consumption subsidies do not provide intended benefits for consumers drive financial insolvency for utilities	Are there subsidy reform options which improve benefit incidence and offer utilities relief?
5	No opportunity for trial and error	Every solution leaves traces which cannot be undone	Grid-centric energy planning focus puts remote, rural communities at risk of long term delays	Explore options which level the playing field for SHS scale-up
6	No well described set of solutions	Planner and client trust drives feasible options	Explore new perspectives for energy access planning	Explore opportunities to overcome institutional barriers and leverage enabling environment benefits
7	Every problem unique	Solution to a previous problem may not apply	Regulatory, political, geographic, and socio-economic conditions differ among ECOWAS member states	Develop a framework which reflects differences between target populations
8	Every problem a symptom of another problem	Removal of a discrepancy between what is and what ought to be – poses another problem	Lifeline utility tariffs create the perception that off-grid electrification solutions are inferior and expensive	Intervention through education & awareness campaigns, adoption of Lighting Global product standards
9	Explanation of the problem determines nature of the solution	Everyone picks the explanation that best fits his intentions	Energy planners typically based in grid connected, urban communities – limited appreciation of rural electrification challenges	Provide capacity building for national energy planners through insights gained from enhanced GIS tools
10	Planner has no right to be wrong	Planners liable for consequences of actions they generate	Universal energy access ranks as a global development priority	Adopt the UN SE4ALL 2030 goals as a common target

For the purposes of my research, an "energy-poor perspective" represents a remote, rural consumer with an irregular cash income, no banking or credit history, and whose electricity service priorities include basic household lighting and phone charging. This PPEO 2016 report clearly echoes many of the themes of my research, as it asserts that "Much current national energy planning and international donor support is disjointed and focuses disproportionately on large infrastructure that, as evidenced in this publication, is not aligned with the global 2030 timeline, does not make economic sense in most energy-poor contexts, and is out of touch with the needs of the energy-poor" (Practical Action, 2016). From an institutional perspective, Practical Action suggests that flipping the paradigm to put the energy-poor at the heart of the issue "fundamentally changes the outlook of national energy plans" by focusing on the use of smaller technologies, faster implementation timelines, and the growth of rural economic empowerment (Practical Action, 2016).

Research Questions, Hypothesis and Specific Aims

The research questions explored by my thesis include: 1) Why has SHS PAYG market penetration remained limited in the face of a significant addressable market in West Africa? 2) How do energy consumption subsidies designed to benefit low-income consumers distort the market and impact progress toward achieving universal energy access? 3) How can the mutual goals of SHS PAYG service providers and MNO's be leveraged to provide an enabling environment benefit? 4) What are the options for subsidy reform to create a level playing for SHS PAYG service providers? and 5) How can existing GIS-based energy access decision tools be modified to support the energy access planning process from an energy-poor perspective?

My primary hypothesis is that SHS PAYG market penetration can be increased in the ECOWAS region through the development of an enhanced GIS-based energy access decision tool framework which addresses institutional barriers and leverages enabling environment conditions. Overcoming the market distortion introduced by energy consumption subsidies (i.e., the "institutional barrier" to overcome) and taking advantage of the energy addressable market created by mobile service penetration in rural communities (i.e., the "enabling environment condition" to be leveraged) are explored as initial pillars of this framework.

In order to test my hypothesis, I:

1. Evaluated the existing set of GIS-based energy access decision tools (Network Planner, onSSET, REM, GeoSim®, and Intigis) to determine which is best suited for modification and expansion to meet SHS PAYG service provider's business decision needs.

2. Examined the impacts of existing energy consumption subsidies and explore the options for subsidy reform which may be beneficial to the scale up of SHS PAYG solutions.

3. Examined the nature of the energy addressable market and explore the factors which may make it an enabling environment catalyst for the scale up of SHS PAYG solutions.

4. Simulated the magnitude and nature of the SHS PAYG addressable market across the ECOWAS region.

5. Simulated the magnitude and nature of the energy addressable market across the ECOWAS region.

6. Simulated the potential benefits of proposed SHS PAYG focused subsidy reforms across the ECOWAS region.

Chapter II

Methods

The research methods employed to test my hypothesis across the ECOWAS region included: 1) evaluation and ranking of the existing GIS-based energy access decision tools, 2) simulation of the SHS PAYG addressable market, 3) simulation of geographic selection of the energy addressable market for SHS PAYG, and 4) simulation of geographic selection of connection subsidy and results based financing schemes for SHS PAYG.

Evaluation and Ranking of Existing GIS-based Energy Access Decision Tools

Evaluation and ranking of the existing GIS-based energy access decision tools included the development of evaluation criteria, assessment of the existing tools via a literature review, and ranking to identify the most suitable candidates for future enhancement and modification. The existing tools considered in this evaluation included Network Planner, the Reference Electrification Model (REM), the Open Source Spatial Electrification Toolkit (onSSET), Intigis, and GeoSim®. The evaluation criteria included ten (10) categories (Table 31) suggested by the literature review as most relevant to the goals of my research.

These categories were scored on a scale of 0-10 for a maximum aggregate score of 100 points using the following (Table 32) scoring assumptions. Based on the existing tool assessments developed in the Background section of Chapter I, an aggregate

Table 31. Existing GIS-based energy access tool evaluation criteria (author's elaboration, 2017).

Category	Explanation
Accessibility	Open source, licensed product
Web Interface	Interactive dashboard, user-friendly
Quality of Service	Addresses quality and reliability of grid connection
Integration of Multitier Framework	Incorporation of Tier 1-5 framework
Grid Centric Data Set Bias	Dataset requirements focused on grid extension
Intended Users	Utilities, government planners, donor funding institutions, SHS providers, mini-grid developers
Off-grid Indicators	Use of indicators conducive to SHS PAYG
Prioritization Scheme	Incorporation of prioritization methods overlaid on LCOE foundation
ECOWAS Applications	Case studies or projects in ECOWAS member states
Additional Factors	Intangible factors relative to each tool

score was developed for each model and they were then ranked from the most suitable (highest score) to least suitable (lowest score) for application to the enhanced GIS-based energy access decision tool framework.

Table 32. Existing GIS tool scoring assumptions (author's elaboration, 2017).

Category	Scoring Assumptions
Accessibility	10 – base score for open source, downgraded to 5 for licensed product
Web Interface	0 – no interface, 5 – interface available, 10 – interface available & user friendly
Quality of Service	0 – no functionality, 5 – proxy for quality/reliability, 10 – consideration of quality/reliability of grid connection
Integration of MTF	0 – no service level indicator, 5 – some service level indicator, 10 – MTF integration
Grid centric data set bias	10 – base score for no bias, 5 – downgrade for some input data bias, 0 – downgrade for significant input data bias
Intended Users	5 – base score for typical users, 10 – increase for inclusion of SHS & mini-grid, 0 – mismatch with energy planning stakeholders
Off-Grid Indicators	0 – no indicators, 5 – some indicators, 10 – indicators conducive to SHS & mini-grid
Prioritization Scheme	0 – no scheme, 5 – proxy for prioritization scheme, 10 – prioritization scheme available
ECOWAS Applications	0 – no case study or project applications, 5 – one regional application, 10- multiple regional applications
Additional Factors	0 – no additional factors, 5 – minimal additional factors, 10 – significant additional factors

Simulation of the SHS PAYG Addressable Market

Computer simulation of the SHS PAYG addressable market across the ECOWAS region utilized the UNDESA hosted onSSET interactive dashboard. This web-based platform provided LCOE results at the national level, indicating the population to be electrified by 2030 via national grid, mini-grid, and standalone electrification options. Critical to this simulation process, onSSET was the only existing tool considered addressed by my research which integrates the World Bank's multi-tier framework into the user defined energy demand for target countries. In order to estimate magnitude and location of the SHS PAYG addressable market, the onSSET web interface was used to determine the percentage of the population (and the corresponding 2.5 km^2 grid locations) suitable for SHS PAYG deployment to satisfy Tier 1 through Tier 5 demand requirements. Based on the PPEO 2016 recommendation, Tier 3 was considered as the minimum threshold for modern electricity access (Practical Action, 2016). Data from each of the five simulation runs for each member state was downloaded for further processing and analysis.

Recent improvements to the onSSET online user interface allowed for the download of data for each 2.5 km^2 grid which includes the grid location, the selected electrification technology, LCOE ($/kWh), and population to be electrified. This information was accessible as a comma separated values (csv) file representing a particular scenario. In order to model the geographic selection approach more rigorously and to simulate the impact of connection subsidies and results based financing scheme, a dataset was created for Tier 3 access for each member state. This dataset was then screened to identify the grid cells where SHS PAYG represented the least cost of electrification technology. These grid cells were then visually clustered to create contiguous sales territories. The total population to be electrified and average LCOE ($/kWh) were then computed for the SHS addressable market and the individual sales territories. No data were available via the onSSET dashboard for member state Cape Verde. Hyperlinks for the Tier 2 and Tier 3 simulation runs for each of the member states are available in Appendix 2 for readers who would like to explore the details of this platform and data acquisition process in more detail.

Simulation of the Energy Addressable Market

Computer simulation of the "energy addressable market" for the ECOWAS region was developed using the FINclusion Lab data analytics platform (FINclusion Lab, 2017). The dataset for this simulation was developed by selecting the country of interest on the dashboard, selecting "national overview" in the menu, unselecting "all" in the financial institution list, and selecting "mobile money" in the list of institutions. The results of this data acquisition process provide the quantity of mobile money "access points" within the appropriate sub-national boundary (state, region, department, or district) for each member state supported by this platform. In this context, an "access point" represents the location of a local mobile money vendor. The FINclusion Lab platform is limited to only twenty-three (23) countries. Only one-third (1/3) of the ECOWAS member states are support by the FINclusion Lab platform, including Benin, Cote d'Ivoire, Ghana, Nigeria, and Senegal. For the purpose of comparing the energy addressable markets in both East and West African countries, mobile money access point data were also downloaded for Kenya, Rwanda, Tanzania, and Uganda. In terms of the graphical illustration of the results, the quantity of mobile money access points were reported for the state, district, region, or department appropriate for the country of interest. While the FINclusion Lab dataset provided a starting point for examination of the "energy addressable market" geographic selection strategy, future research should work to identify datasets which cover all of the ECOWAS member states, illustrate mobile service signal coverage levels, and provide more granular information on the geographic location of mobile money access point. Corporate privacy and confidentiality barriers among the community of Mobile Network Operators made it challenging to obtain this level of data within the scope of my research.

Simulation of Connection Subsidy and Results Based Financing Schemes

Initial and recurring cost data for Mobisol's 200 W SHS PAYG system was used to simulate the potential benefits of a connection subsidy scheme. In the case of connection subsidies for utility grid extension, the connection fee which is typically charged by the distribution utility for obtaining a connection is reduced or eliminated, removing a significant financial barrier for low-income, energy-poor households. In order to accelerate the adoption of SHS PAYG systems, the equivalent strategy involves reducing the initial down payment to a level where it is comparable to the monthly recurring cost paid by the consumer. Since SHS PAYG billing schemes are typically set up to ensure that the monthly recurring cost is comparable to what a consumer is already paying for kerosene, reducing the cost of the initial down payment in this manner has a similar impact that the utility connection subsidy provides for an energy poor household. This connection subsidy equates to roughly a fifty percent reduction in the initial down payment for the Mobisol 200W system. The 200 W system was selected for this analysis based on its ability to provide a Tier 3 level of electricity access (Bhatia et al., 2015) which follows Practical Action's recommendation (PPEO, 2016) of this tier as the minimal level for modern electricity access.

In order to simulate the effects of a potential results based financing scheme, the subsidy design for GPOBA's successful pilot program in Ghana (GPOBA, 2016) was used to derive the appropriate incentive level to support the installation of the Mobisol 200W system through a curve fitting process. This derivation was necessary due to the maximum 50 Watts peak system size which was used for the Ghana program. This selection of this subsidy design was also influenced by the successful implementation of this RBF financing scheme in one of the ECOWAS member states (GPOBA, 2016).

Analysis of ECOWAS Electrification Status

The ECOWAS region provided a representative example of the universal energy access challenge. In order to support this research strategy, the current electrification status of each of the member states was documented (Bugatti, 2015) using data available from the ECOWAS Program on Access to Sustainable Electricity Services (EPASES). In order to assess the current status for each of the member states; national, rural, and off-grid electrification goals were set against the historical pace of electrification to frame the challenge in terms of member states projected to meet those goals as well as those who are likely to fall short. This methodology is outlined in detail in the Background section as it relates to the insights that were presented in Table 29.

Chapter III

Results

Reviewing my hypothesis, this research set out to examine if SHS PAYG service providers can increase their market penetration in the ECOWAS region through the development of an enhanced GIS-based energy access decision tool framework which addresses institutional barriers and embraces enabling environment conditions. A simulated case-study exploring the implementation of these strategies in member states Cote d'Ivoire, Burkina Faso, Mali, Niger, and Nigeria illustrated a significant SHS PAYG addressable market as well as providing preliminary validation of the energy addressable market and subsidy reform geographical selection strategies explored by my research. In terms of practical application, the existing GeoSim® and onSSET models proved to be strong candidates for future enhancement and modification to meet SHS PAYG service provider's business decision needs.

GIS-based Decision Tool Assessment Results

The results of the assessment, evaluation, and ranking of the existing GIS-based energy access decision tools (Table 33) help identify those most suitable for modification to meet the business decision needs of SHS PAYG service providers. The "quality of service" column (Table 33) refers to indicators which address power quality and/or service reliability performance for utility grid electrification. The "prioritization scheme" column (Table 33) points to the integration of an additional geospatial layer to rank the LCOE results based on a specific parameter. The "off-grid indicators" column (Table 33) refers to the use of specific indicators used to identify target communities most appropriate for off-grid electrification.

Table 33. Existing GIS tool evaluation matrix (author's elaboration, 2017).

Model	Accessibility	Web Interface	Quality of Service	Integration of MTF	Grid Centric data set bias	Intended Users	Off-grid Indicators	Prioritization Scheme	ECOWAS Applications	Additional factors
REM	Open Source	demonstration visualization only	Cost of Non-Served Energy	No	Utility grid and mini-grid design power distribution system design	Government, utility, and donor funding institution energy planners	Local REM (LREM) for mini-grid developers	none	None	Identification of non-technical factors for integration into energy access planning
Network Planner	Open Source	web interface with tutorial and reference material, not suitable for public use - research focused	none	No	none	Government, utility, and donor funding institution energy planners	none	none	Senegal, Ghana	Integrated in GEAR Toolkit (Ghana)
onSSET	Open Source	Interactive, user friendly dashboard	none	Yes	Power plant and mineral resources locations part of input data	Government, utility, and donor funding institution energy planners	none	none	Nigeria	UNDESA partnership
Intigis	Open Source	none	none	non	none	Government, utility, and donor funding institution energy planners	none	none	None	Platform, documentation, and case studies in Spanish
GeoSim	Licensed Product	software demos not available	Quality and reliability of service	No	none	Government, utility, and donor funding institution energy planners, SHS providers, mini-grid developers	High isolation indicator, anchor loads	Indicators for Development - health, education, economic development	Burkina Faso, Cote D'Ivoire, Benin, Liberia, Senegal	Consulting and training services available

The results of the ranking process (Table 34) indicated that GeoSim® appears to be the most suitable platform for enhancement to meet the needs of SHS PAYG service providers, closely following by the Open Source Spatial Electrification Toolkit

Table 34. GIS tool scoring and suitability ranking (author's elaboration, 2017).

Model	Accessibility	Web Interface	Quality of Service	Integration of MTF	Grid Centric data set bias	Intended Users	Off-grid Indicators	Prioritization Scheme	ECOWAS Applications	Additional factors	Score (out of 100)	Suitability Rank
REM	10	5	10	0	5	5	5	0	0	0	40	4
Network Planner	10	5	0	0	5	5	0	0	10	10	45	3
onSSET	10	10	0	10	5	5	0	0	5	10	55	2
Intigis	10	0	0	0	10	5	0	0	0	0	25	5
GeoSim	5	0	10	0	10	10	10	10	10	10	75	1

(onSSET). GeoSim®'s discriminators relative to the other tools included the broader range of intended users, incorporation of a high isolation indicator for remote communities, incorporation of a prioritization scheme, and extensive project experience in the ECOWAS region. The primary discriminator for the onSSET platform was its integration of the World Bank's multi-tier framework and user-friendly interactive dashboard. Limited information (English) was available for assessment of the Intigis platform, which may have suppressed its score and ranking relative to the other existing tools.

Geographic Targeting of the Energy Addressable Market

The energy addressable market (EAM) for the ECOWAS region was found to be one hundred twenty-nine (129) million people, with member states Burkina Faso, Cote D'Ivoire, Mali, Niger, and Nigeria representing 79% of that total, indicating that these countries should be prioritized in the piloting of this geographic selection strategy. Looking at the ECOWAS region from a different perspective, a subset of member states which includes Cote d'Ivoire, Ghana, Burkina Faso, Benin, Togo, and Nigeria revealed an energy addressable market of 90 million people, which is comparable in size to the energy addressable market of 91 million documented in the mature SHS PAYG market found in East Africa.

Using the simulation method, the results for the SHS PAYG addressable market (Table 35) are documented. Key insights from this examination of the potential SHS PAYG market across the region included: 1) the magnitude of the addressable market includes the population to be electrified over roughly two decades (2012-2030), 2) the member states are expected to experience a steady annual population increase of approximately nine percent across the region, 3) Nigeria dwarfs the remainder of the region in terms of the population to be electrified, accounting for forty-eight percent of the total, 4) Member states Burkina Faso, Cote d'Ivoire, Ghana, Mali, and Niger account for another thirty-one percent of the population to be electrified (totaling seventy-nine percent when combined with Nigeria), and 5) the impact of electricity demand on national grid versus mini-grid versus SHS PAYG compatibility is illustrated on a macro scale with the lowest level of grid compatibility associated with Tier 1 electricity access (and the highest level associated with Tier 5), while the reverse dynamic is true for SHS PAYG (labeled as SA PV in the onSSET model).

Table 35. onSSET MTF simulation (UNDESA, 2017; author's elaboration, 2017).

	Benin	Burkina Faso	Cote D'Ivoire	Gambia	Ghana	Guinea	Guinea Bissau	Liberia	Mali	Niger	Nigeria	Senegal	Sierra Leone	Togo	
Elec Access	38	13	56	35	64	26	61	10	26	14	56	56	14	32	
2030 Goal	100	100	100	100	100	100	100	100	100	100	100	100	100	100	
2012 Pop	10.05	16.59	21.1	1.81	25.54	11.63	1.71	4.19	16.11	17.64	168.24	13.78	6.04	6.75	
2030 Pop	15.59	27.24	32.14	3.1	36.87	18.28	2.54	6.41	27.37	35.97	262.6	22.8	8.6	10.49	
Pop to Elec	11.74	23.67	20.35	2.22	20.49	15.21	1.86	5.62	23.22	22.6	169.44	15.06	7.75	8.73	
															Average
Pop Growth	155%	164%	152%	171%	144%	157%	149%	153%	170%	204%	156%	165%	142%	155%	160%
Annual Growth	9%	9%	8%	10%	8%	9%	8%	8%	9%	11%	9%	9%	8%	9%	9%
							Tier 1								
Grid	38.38	21.56	55.87	48.88	64.11	26.36	39.84	18.88	25.73	19.09	55.73	56.21	14.04	26.06	
SA Diesel	49.11	0.11	38.7	39.12	31.48	58.51	33.46	67.18	0.02	0.04	33.14	31.36	82.02	62.64	
SA PV	12.5	78.33	5.44	12	4.41	15.13	26.7	13.93	74.25	80.87	11.48	12.43	3.94	11.3	
MG Diesel	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MG Hydro	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MG Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MG PV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Cost	0.94	1.48	2.62	0.13	2.6	0.5	0.25	0.12	1.62	1.68	16.41	2.27	0.27	0.44	
															Total
SA PV pop	1.47	18.54	1.11	0.27	0.90	2.30	0.50	0.78	17.24	18.28	19.45	1.87	0.31	0.99	84.00
Mini-grid pop	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SA Diesel pop	5.77	0.03	7.88	0.87	6.45	8.90	0.62	3.78	0.00	0.01	56.15	4.72	6.36	5.47	107.00
Grid pop	4.51	5.10	11.37	1.09	13.14	4.01	0.74	1.06	5.97	4.31	94.43	8.47	1.09	2.28	157.56
							Tier 2								
Grid	56.17	27.07	58.83	64.74	67.4	30.54	39.84	30.43	26.36	43.52	64.13	59.61	19.99	50.37	
SA Diesel	31.33	0.11	35.73	23.26	28.66	56.27	33.46	55.64	0.02	0.04	25.79	27.96	76.07	38.33	
SA PV	12.5	72.82	5.44	12	3.95	13.19	26.7	13.93	73.62	56.67	9.89	12.43	3.94	11.3	
MG Diesel	0	0	0	0	0	0	0	0	0	0	0.11	0	0	0	
MG Hydro	0	0	0	0	0	0	0	0	0	0	0.08	0	0	0	
MG Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MG PV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
Cost	2.61	7.74	4.39	0.47	4.38	1.92	0.5	0.71	7.67	9.46	37.24	3.99	0.74	1.69	
															Total
SA PV Pop	1.47	17.24	1.11	0.27	0.81	2.01	0.50	0.78	17.09	12.81	16.76	1.87	0.31	0.99	74.00
Mini-grid pop	0	0	0	0	0	0	0	0	0	0	0.32	0	0	0	0.32
SA Diesel pop	3.68	0.03	7.27	0.52	5.87	8.56	0.62	3.13	0.00	0.01	43.70	4.21	5.90	3.35	86.84
Grid pop	6.59	6.41	11.97	1.44	13.81	4.65	0.74	1.71	6.12	9.84	108.66	8.98	1.55	4.40	186.86
							Tier 3								
Grid	81.08	62.8	79.37	87.04	87.24	72.68	72.13	64.11	46.1	68.12	91.98	83.47	81.64	83.49	
SA Diesel	10.98	0.04	15.85	4.78	11.4	18.61	14.18	23.86	0.02	0.02	4.62	8.57	15.99	12.51	
SA PV	7.95	34.58	4.38	8.18	1.37	8.18	13.69	10.85	48.02	30.8	3.31	7.9	2.72	3.77	
MG Diesel	0	0	0.32	0	0	0	0	0.41	0	0	0	0	0	0	
MG Hydro	0	0.2	0.08	0	0	0.14	0	0.77	0.68	0.76	0.09	0.06	0.25	0.23	
MG Wind	0	0	0	0	0	0	0	0	0	0	0	0	0	0	
MG PV	0	2.38	0	0	0	0.39	0	0	5.17	0.3	0	0	0	0	
Cost	7.72	21.5	13.35	1.44	11.97	9.79	1.44	3.53	20.47	24.18	113.52	10.99	5.7	5.39	
															Total
SA PV Pop	0.93	8.19	0.89	0.18	0.28	1.24	0.25	0.61	11.15	6.96	5.61	1.19	0.21	0.33	38.03
Mini-grid pop	0.00	0.61	0.08	0.00	0.00	0.08	0.00	0.07	1.36	0.24	0.15	0.01	0.02	0.02	2.64
SA Diesel pop	1.29	0.01	3.23	0.11	2.34	2.83	0.26	1.34	0.00	0.00	7.83	1.29	1.24	1.09	22.86
Grid pop	9.52	14.86	16.15	1.93	17.88	11.05	1.34	3.60	10.70	15.40	155.85	12.57	6.33	7.29	284.48

Tier 4															
Grid	94.29	81.73	91.86	99.63	97.02	88.92	96.1	83.19	56.97	80.3	98.26	94.01	94.01	98.82	
SA Diesel	2.11	0.01	4.97	0.14	2.12	6.02	2.3	4.45	0.01	0.02	0.77	2.46	3.73	0.9	
SA PV	3.48	11.42	2.44	0.23	0.7	4.28	1.46	5.12	22.77	15.66	0.64	3.28	1.01	0.22	
MG Diesel	0	0	0.03	0	0.09	0	0.14	6.34	0	0	0.02	0	0.51	0	
MG Hydro	0.08	0.31	0.22	0	0.07	0.57	0	0.89	0.71	1.16	0.06	0.12	0.66	0	
MG Wind	0	0	0.15	0	0	0	0	0	0	0	0	0	0	0	
MG PV	0.05	6.54	0.05	0	0	0.21	0	0	19.55	2.86	0.25	0.14	0.08	0.06	
Cost	15.91	39.4	28.37	2.72	24.96	21.39	2.95	7.87	43.22	46.9	209	21.21	10.76	11.16	
															Total
SA PV pop	0.41	2.70	0.50	0.01	0.14	0.65	0.03	0.29	5.29	3.54	1.08	0.49	0.08	0.02	15.22
Mini-grid pop	0.02	1.62	0.09	0.00	0.03	0.12	0.00	0.41	4.70	0.91	0.56	0.04	0.10	0.01	8.60
SA Diesel pop	0.25	0.00	1.01	0.00	0.43	0.92	0.04	0.25	0.00	0.00	1.30	0.37	0.29	0.08	4.96
Grid pop	11.07	19.35	18.69	2.21	19.88	13.52	1.79	4.68	13.23	18.15	166.49	14.16	7.29	8.63	319.13
Tier 5															
Grid	96	83.56	93.76	99.88	97.83	92.81	97.73	84.67	58.8	81.91	98.9	95.32	95.05	99.6	
SA Diesel	0.95	0.01	3.64	0.08	1.43	3.42	1.41	2.53	0.01	0.02	0.44	1.8	2.96	0.37	
SA PV	2.56	5.22	1.85	0.05	0.55	3.24	0.72	3.84	16.74	11.92	0.28	2.56	0.77	0.03	
MG Diesel	0	0	0.42	0	0.12	0	0.14	8.13	0	0	0.02	0	0.66	0	
MG Hydro	0.07	0.21	0.17	0	0.04	0.35	0	0.83	0.69	1.14	0.04	0.09	0.51	0	
MG Wind	0	0	0.13	0	0	0	0	0	0	0	0	0	0	0	
MG PV	0.43	10.99	0.03	0	0.03	0.17	0	0	23.71	5.01	0.31	0.22	0.05	0	
Cost	18.44	44.57	32.89	3.09	28.97	25.36	3.33	8.96	50.54	53.91	238.73	24.28	12.18	12.7	
															Total
SA PV pop	0.30	1.24	0.38	0.00	0.11	0.49	0.01	0.22	3.89	2.69	0.47	0.39	0.06	0.00	10.25
Mini-grid pop	0.06	2.65	0.15	0.00	0.04	0.08	0.00	0.50	5.67	1.39	0.63	0.05	0.09	0.00	11.31
SA Diesel pop	0.11	0.00	0.74	0.00	0.29	0.52	0.03	0.14	0.00	0.00	0.75	0.27	0.23	0.03	3.12
Grid pop	11.27	19.78	19.08	2.22	20.05	14.12	1.82	4.76	13.65	18.51	167.58	14.36	7.37	8.70	323.24

The terms used above (Table 35) are defined (Table 36) to allow the reader to more easily interpret the simulation results. Based on the results for all electrification modes (Table 35), the results are consolidated (Table 37) to facilitate interpretation and analysis. These are organized by electrification mode to include SA PV (referred to as SHS PAYG throughout my research), SA diesel, mini-grid, and utility grid electrification options. The mini-grid results represent an aggregate of diesel, hydro, wind, and solar energy sources.

This analysis (Table 37) documented an SHS PAYG addressable market of 74 million people (Tier 2) or 38 million people (Tier 3). These two tiers of electricity access served as the focus of my analysis due to the range of commercially available SHS PAYG systems (50W – 200W) as well as the recommendation from the *Poor*

Table 36. Definition of terms for onSSET interactive dashboard (UNDESA, 2017).

Term	Definition	Data Source
Elec Access	Electricity access as a percent of the population	UNDESA onSSET database
2030 Goal	Electricity access goal by 2030	UNDESA onSSET database
2012 Population	National population in 2012	UNDESA onSSET database
2030 Population	Projected population by 2030	UNDESA onSSET database
Pop to Elec	Population needing electricity access between 2012 and 2030 to achieve 2030 goal	UNDESA onSSET database
Pop Growth	2030 population/2012 population (expressed as a percentage	Calculated
Annual Growth	Population growth/18 years	Calculated
Grid	Percentage of population to be served by utility grid connection	UNDESA onSSET database
SA Diesel	Percentage of the population to be served by standalone diesel generator	UNDESA onSSET database
SA PV	Percentage of the population to be served by standalone photovoltaic system	UNDESA onSSET database
MG Diesel	Percentage of the population to be served by diesel mini-grid	UNDESA onSSET database
MG Hydro	Percentage of the population to be served by hydropower min-grid	UNDESA onSSET database
MG Wind	Percentage of the population to be served by wind powered mini-grid	UNDESA onSSET database
MG PV	Percentage of the population to be served by photovoltaic powered mini-grid	UNDESA onSSET database
Cost	Cost ($USD) to provide electrification for a particular scenario	UNDESA onSSET database
SA PV Pop	Population to be served by standalone solar photovoltaic	Calculated
MG Pop	Population to be served by all mini-grid options	Calculated

People's Energy Outlook 2016 (Practical Action, 2016) to establish Tier 3 as the minimum level of modern energy access. In terms of identifying priority targets for scale-up, SHS PAYG represented the least cost solution for the majority of the un-electrified population in Burkina Faso (73%), Mali (74%), and Niger (57%) under the Tier 2 scenario totaling an addressable market of 47 million people. Examining the Tier 3 scenario, national grid became the preferred electrification option for all member

Table 37. ECOWAS addressable market – electrification modes (Tier 1 – 5) (UNDESA, 2017).

Electrification Mode	Tier 1 (millions)	Tier 2 (millions)	Tier 3 (millions)	Tier 4 (millions)	Tier 5 (millions)
SA PV	84.00	74.00	38.03	15.22	10.25
SA Diesel	107.00	86.84	22.86	4.96	3.12
Mini-grid	0.00	0.32	2.64	8.60	11.31
National grid	157.56	186.86	284.48	319.13	323.24

states. However, SHS PAYG ranked as the second option in Burkina Faso (35%), Mali (48%), and Niger (31%) for an addressable market of 26 million people. In light of the identification of these member states as priorities for future SHS PAYG scale up, it is worth noting that Burkina Faso, Niger, and Nigeria are among the twenty (20) countries that the World Banks's Global Tracking Framework (GTF) classifies as "hot spot" countries, representing two thirds of the global electricity access deficit (World Bank, 2015).

The trends clearly illustrate the shift toward grid compatibility as household demand increases, and conversely toward off-grid compatibility as household demand decreases (Table 37). In this analysis, the tiers of the energy ladder (Tier 1-5) described by the multi-tier framework serve as a proxy for household electricity demand. This analysis also illustrates the value of looking at electricity access through a tiered approach versus a binary connection/no connection perspective. If we take the binary approach and assume that the only valid electricity connection is a reliable grid connection (Tier 5) – then the SHS PAYG addressable market is only three percent (3%) of the regions' population, making my research on the scale-up of this off-grid technology somewhat irrelevant. If we instead take a tiered approach and look at electricity connections as steps on an "energy ladder" then the SHS PAYG addressable market expands by nearly four times (11%) for Tier 3 (4 x 3) and by seven times (21%) (7 x 3) for Tier 2. Finally, the limited mini-grid contribution (Table 37) for Tier 2 and Tier 3 electricity access confirms my research choice to focus on the scale-up of SHS PAYG through the development of an enhanced GIS-based energy access decision tool framework.

Having analyzed the onSSET LCOE simulation results, I proceeded to address my prediction that the energy addressable market can be used to provide geographic selection in an enhanced GIS-based energy access decision tool framework. In order to confirm that the EAM can be used as a geographic targeting indicator, the FINclusion Lab data analytics platform was used to obtain data representing the density of mobile money access points (local representative locations) in the ECOWAS member states. This platform provides information on mobile money service providers, banks, micro finance organizations, and other financial access providers in an effort to ensure that financial services are provided to underserved communities (FINclusion Lab, 2017). Links to FINclusion maps illustrating the quantity of mobile money access points at a sub-national level are provided in Appendix A. Unfortunately, the FINclusion Lab platform does not currently provide information on member states Burkina Faso, Mali, or Niger – which represented the greatest contribution to the SHS addressable market under the Tier 2 and Tier 3 scenarios (Table 35). However, since Cote d'Ivoire is among the group of member states that represent eighty percent of the energy addressable market of the region, it was selected as an example of the intersection between the onSSET LCOE simulation and the mobile money access point dataset. Future research and application of the energy addressable market strategy should work to identify more robust datasets that provide information on all of the ECOWAS member states. The graphical simulation process illustrated the mobile money access point density (Figure 13) and the Tier 3 addressable market (Figure 14) for Cote D'Ivoire. In both cases, the interactive dashboards utilized to obtain this data are available via hyperlinks or URLs found in Tables 45 and 46 in Appendices 1 and 2 for readers who wish to explore these tools in greater detail.

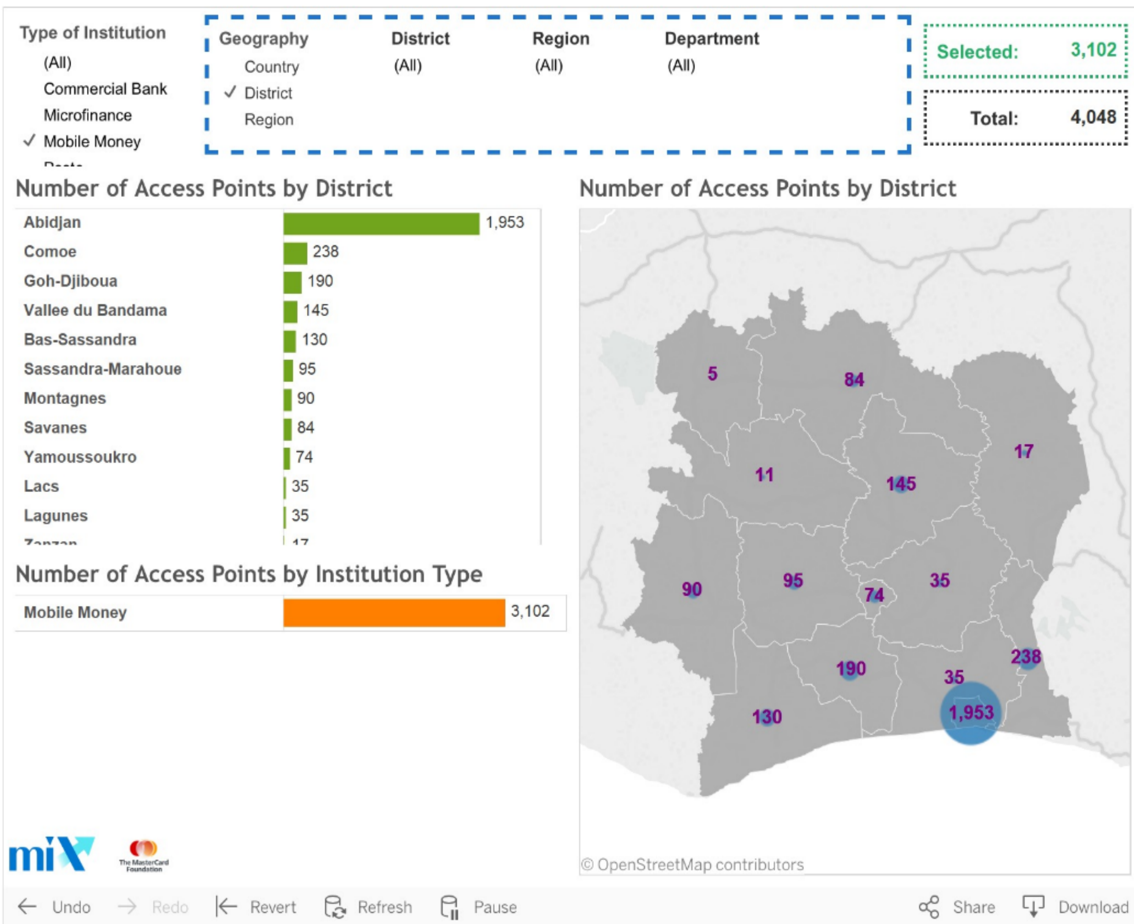


Figure 13. Cote d'Ivoire mobile money access point density (FINclusion Lab, 2017).

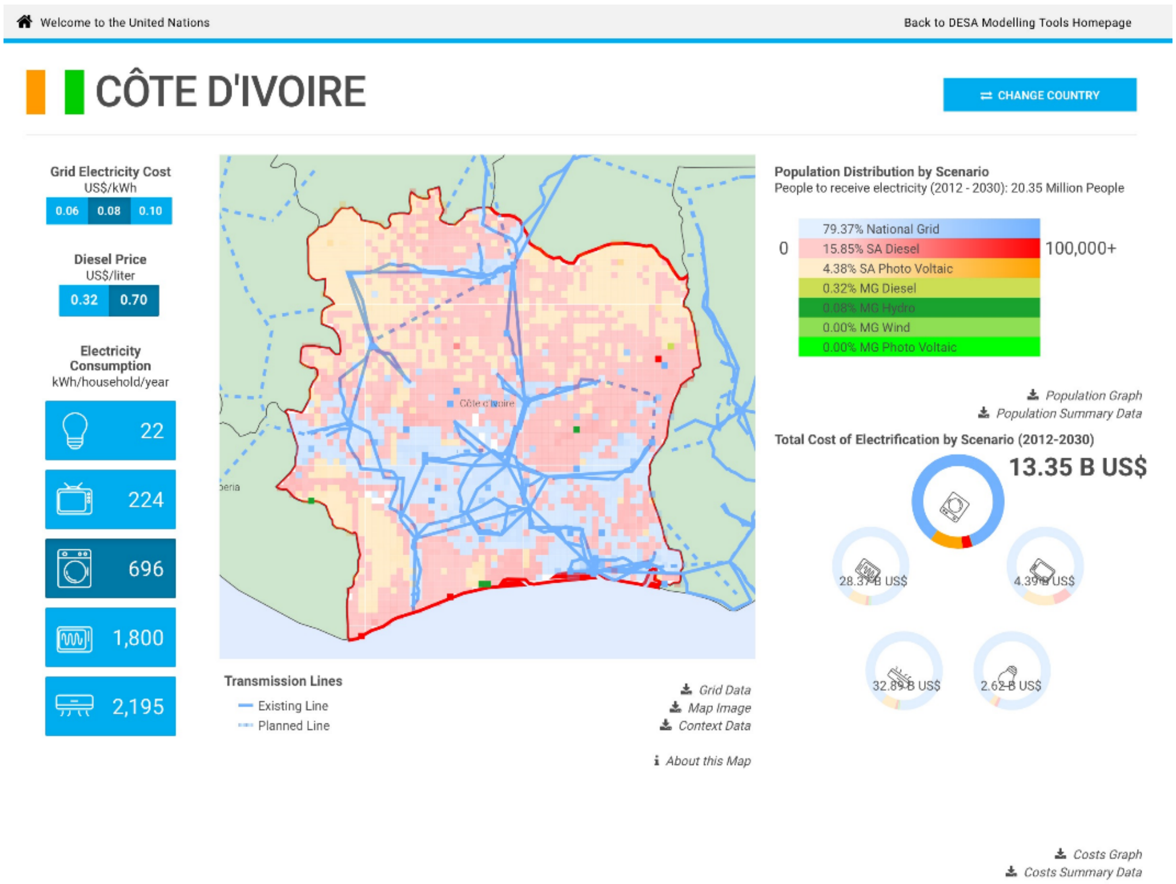


Figure 14. Cote d'Ivoire Tier 3 addressable market simulation result. (UNDESA, 2017).

Three regions are visually suggested for SA PV (SHS PAYG) electrification in the northwest corner, northeast corner, and central west/south west regions of the country (Figure 15). Comparing these potential markets to the mobile money access point density (Figure 13) the northwest corner has only 5 access points (Denguele District) while the northeast corner represents approximately 30 access points (Zanzan and a portion of Savanes Districts). In contrast, the central west/south west region appears to include approximately 100 mobile money access points (Figure 16), appearing to make it the best target for deployment among the three SHS PAYG addressable regions from an energy addressable market perspective.

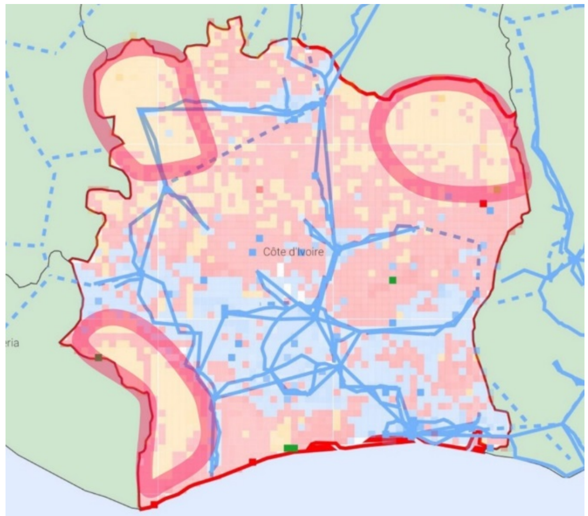


Figure 15. Cote d’Ivoire Tier 3 simulation annotated with potential SHS PAYG sales territories. (UNDESA, 2017).

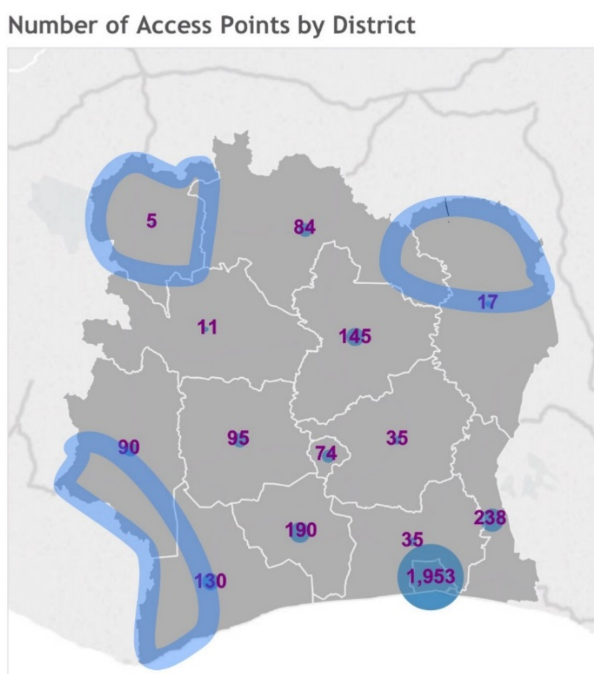


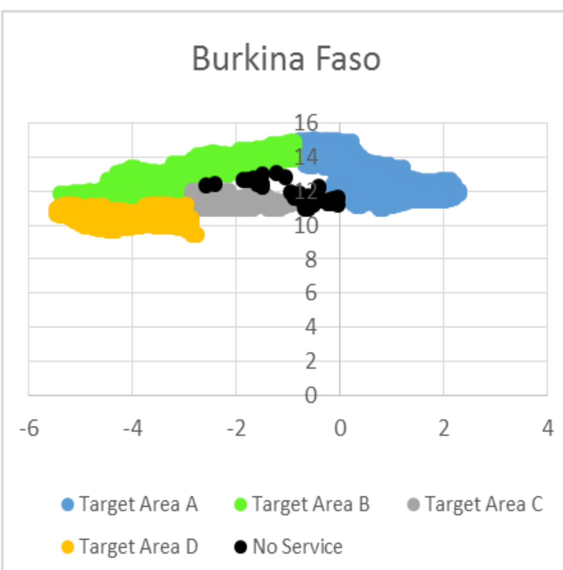
Figure 16. Cote d’Ivoire mobile money density annotated with potential SHS PAYG sales territories. (FINclusion Lab, 2017).

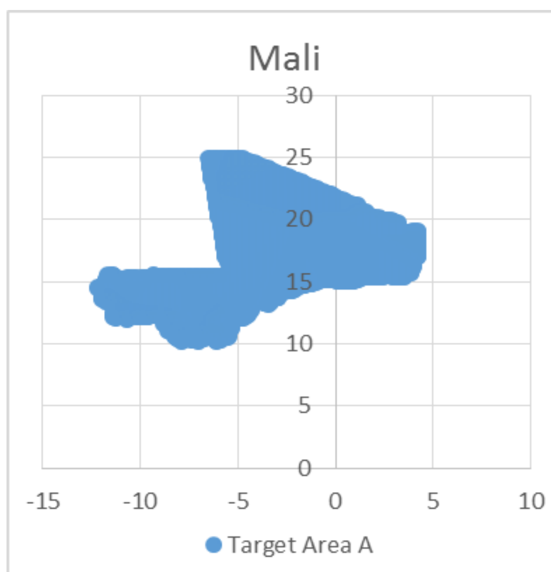
One of the drawbacks of using the onSSET platform to produce the LCOE simulations for this analysis is the fact that the results are provided based on a 2.5 km^2 grid which identifies the LCOE preferred technology, the population to be electrified, and the least cost of electrification in $/kWh. For this simulation to provide business decision value to an SHS PAYG service provider, these individual grid results need to be aggregated to form a contiguous territory where a sales team might be deployed. Using csv data which recently became available from the onSSET dashboard, a Tier 3 data set was created for each member state. Each csv file was then sorted and filtered (Table 38) to extract only the grid cells designated as SA PV.

Table 38. onSSET Tier 3 disaggregated data simulation results (UNDESA, 2017; author's elaboration, 2017).

Country	Average cost of SA PV ($/kWh)	Population to be Electrified by 2030	Sub Areas								
			A		B		C		D		No Service
			Population	Average $/kWh	Population	Average $/kWh	Population	Average $/kWh	Population	Average $/kWh	Population
BENIN	0.3550	1,238,972	647,991	0.3496							590,981
BURKINA FASO	0.3542	9,419,940	2,838,306	0.3332	4,360,383	0.3362	845,024	0.3512	1,225,687	0.3576	150,540
CÔTE D'IVOIRE	0.3765	1,407,030	341,535	0.3586	231,962	0.4053	245,167	0.3734			588,366
The GAMBIA	0.3515	254,005	254,005	0.3515							
GHANA	0.3727	503,695	503,695	0.3726							
GUINEA	0.3554	1,494,868	591,806	0.3530	361,161	0.3578	367,021	0.3541			174,880
GUINEA BISSAU	0.3535	347,879	75,432	0.3523							272,447
LIBERIA	0.4057	696,032	463,386	0.4102	161,988	0.3899					70,658
MALI	0.3277	13,143,967	13,143,967	0.3277							
NIGER	0.2984	11,077,479	11,077,479	0.2984							
NIGERIA	0.3462	8,699,842	1,502,097	0.3339	1,706,946	0.3544	1,228,453	0.3479	1,382,652	0.3304	2,879,694
SENEGAL	0.3444	1,800,534	1,715,361	0.3442							85,173
SIERRA LEONE	0.3712	233,480	233,480	0.3712							
TOGO	0.3704	395,659	395,659	0.3704							
Average	0.3559			0.3519		0.3687		0.3566		0.3440	
Total		50,713,382	33,784,199		6,822,440		2,685,665		2,608,339		4,812,739

In developing the dataset used to identify sub areas for each member state, scatter plots were created in order to visualize potential sales territories using the geospatial pattern of the grid cells identified for SHS PAYG electrification (Table 38). Using these scatter plots, "target areas" were then defined for each member state. For member states which did not show a clear pattern of distinct target areas, only Target Area A (Table 38) was identified on the scatter plots (Figure 17). Member states Burkina Faso, Mali, Niger, and Nigeria represent the largest SHS addressable markets and are identified for further analysis. The scatter plot for Cote d'Ivoire was included to support the energy addressable market analysis (Figures 14-16). The SHS PAYG addressable market for Mali and Niger (Figure 17) covers the entire country – so additional information will be needed to identify specific sales territories in those member states. Burkina Faso and Nigeria, however; reveal four target areas (A-D) (Figure 17) or potential sales territories. It should be noted that the scatter plots shown below have been compressed for presentation purposes and represent some distortion. Areas which were designated "no service" (Table 38 & Figure 17) were visually identified as remote and not a natural part of a contiguous sales territory.





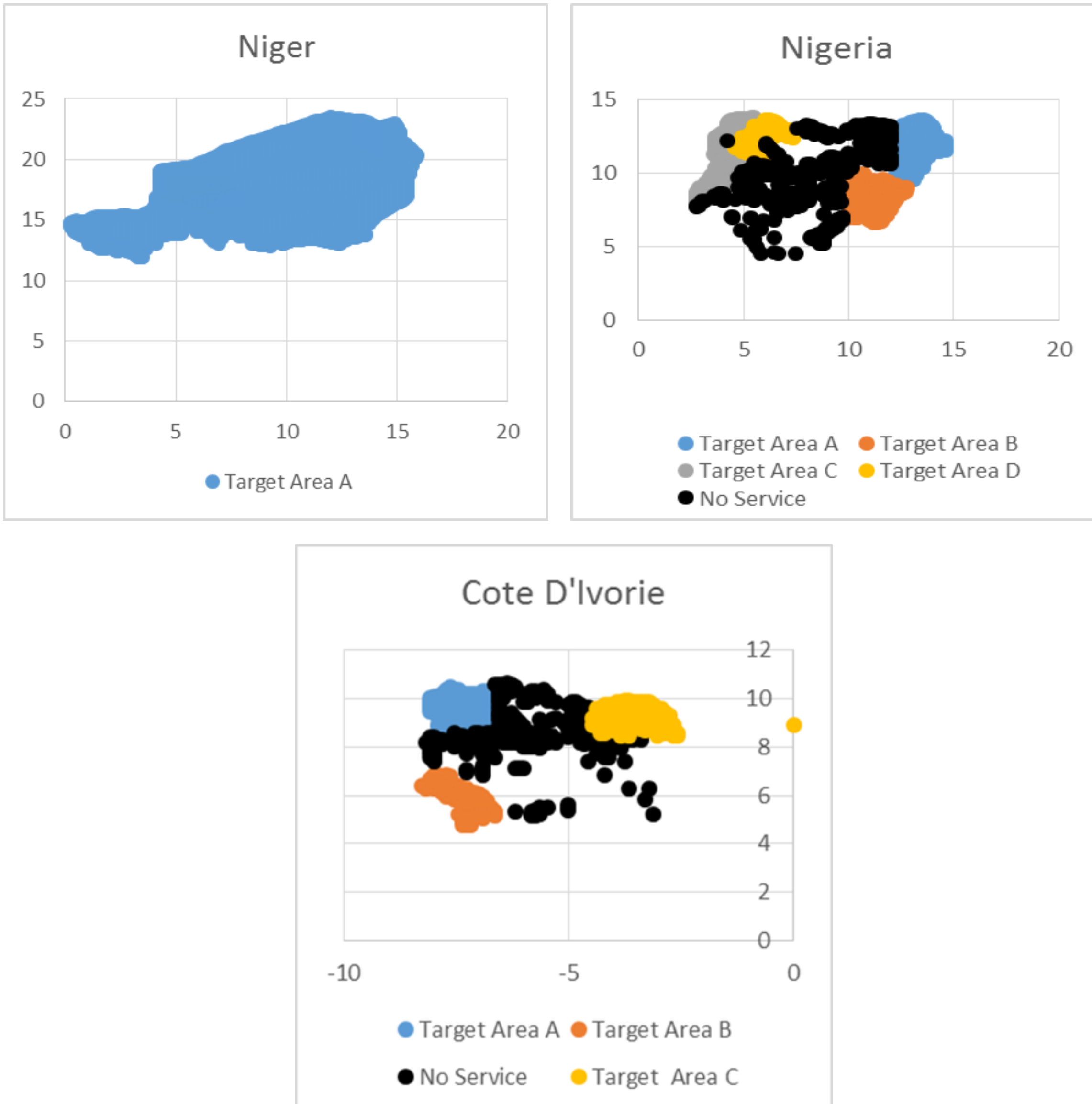


Figure 17. onSSET Tier 3 SA PV scatter plots – Burkina Faso, Mali, Niger, Nigeria, & Cote d'Ivoire (UNDESA, 2017).

Incorporating the population data (Table 38) as well as the scatter plot for Cote d'Ivoire (Figure 17), Target Areas B and C were found to have a comparable population to be electrified via SHS PAYG, but Target Area B contained three times the mobile money access points, making it the priority for market entry in Cote d'Ivoire. In addition to the data gaps noted for the FINclusion Labs platform in terms of ECOWAS member states coverage, the coarse presentation of this data and the inability to download the source dataset limited the energy addressable market analysis to visual inspection approach. More robust datasets illustrating mobile money service coverage should be explored for any future research.

The SHS PAYG addressable market for Burkina Faso, Mali, Niger, and Nigeria represented 83% of the total for the region (Table 38), so the potential for SHS PAYG scale up for these countries (Tables 39-41) is analyzed in greater detail for these member states.

Table 39. SHS PAYG addressable market – initial & recurring revenue (UNDESA, 2017; GSMA, 2016b; author's elaboration, 2017).

Country	Average cost of SA PV ($/kWh)	Population to be Electrified by 2030	Households	Initial Revenue	Recurring Revenue
Burkina Faso	0.3542	9,419,940	2,354,985	$190,895,084	$103,854,839
Mali	0.3277	13,143,967	3,285,992	$266,362,491	$144,912,236
Niger	0.2984	11,077,479	2,769,370	$224,485,112	$122,129,206
Nigeria	0.3462	8,699,842	2,174,961	$176,302,298	$95,915,758

In order to calculate the number of households (Tables 39-41) an average value of four people/household was assumed for the purposes of this calculation. The initial and recurring revenue potential (Table 39) for SHS PAYG service providers for each of the selected member states was calculated using recent cost data for Mobisol's 200W (Figure 18) system (GSMA, 2016b). The Mobisol 200W system was selected for this analysis based on the availability of recent pricing data and its capacity to meet the Tier 3 electricity access requirements. The analysis (Table 39) suggested an initial revenue potential (down payment) of ~$857 million USD and a recurring revenue (monthly payment) of ~$467 million USD between now and 2030 among these four member states, providing an ample market opportunity for the scale-up of SHS PAYG for numerous service providers.

FIGURE 3

Mobisol Products and Prices in Rwanda[17]

Panel Size/System Type	Down Payment	Monthly Payment
30W	USD 26.46	USD 9.66
100W	USD 37.66	USD 23.94
100W with business kit	USD 37.66	USD 31.92
200W	USD 81.06	USD 44.10
200W with business kit	USD 81.06	USD 53.20

Table 40. Mobisol SHS system pricing data (GSMA, 2016b).

The largest target area, in terms of population to be served, was then selected (Table 38) in order to explore the potential benefits (Table 41) of connection subsidies to accelerate market entry in Burkina Faso and Nigeria.

In each case, Target Area B was selected as the candidate for a connection subsidy. In order to estimate the sales cycle, or the length of time it may take to penetrate this addressable market, a group of ten SHS PAYG service providers was assumed

Table 41. SHS connection subsidy simulation results (UNDESA, 2017; GSMA, 2016b; author's elaboration, 2017).

Country	Sub Area	Population	Households	Sales Cycle - 10 SHS Providers (Years)	Down Payment ($)	50% Connection Subsidy ($)
Burkina Faso	B	4,360,383	1,090,096	11	88,363,161	44,181,581
Nigeria	B	1,706,946	426,737	4	34,591,261	17,295,630

to participate in this connection subsidy program. Based on recent marketing data from Mobisol, Fenix International, and Azuri Technologies (Fenix, 2017; Mobisol, 2017; Azuri, 2016) a realistic sales volume of ten thousand (10,000) units per year was assumed for this analysis. In the context of SHS PAYG system adoption, a connection subsidy would have the effect of offsetting the down payment cost to consumers. In this simulation, a fifty-percent connection subsidy was assumed, which would reduce the consumer's down payment to the level of the monthly payment for the 200 W system. Since SHS PAYG monthly payments are designed to mirror a household's current expenditure on traditional fuels – reducing the initial consumer investment to this level should have the effect of increasing the consumer's willingness to pay and driving the adoption of this technology.

The last analysis using this data set simulated the benefits of a results based financing scheme in Burkina Faso and Nigeria. In this case, it was assumed that SHS PAYG providers have established a mature market in Target Area B through the connection subsidy scheme described above and that an RBF program was launched in an effort to encourage them to expand into a more rural territory. Based on that approach, the smallest target area in each country was selected for the RBF simulation (Table 42).

Table 42. SHS PAYG RBF simulation results (UNDESA, 2017; GSMA, 2016b; GPOBA, 2016; author's elaboration, 2017).

Country	**Sub Area**	**Population**	**Households**	**Sales Cycle - 5 SHS Providers (Years)**	**Results Based Financing Incentive ($)**	**Total RBF Incentive ($)**
Burkina Faso	C	845,024	211,256	4	1635	345,403,560
Nigeria	C	1,228,453	307,113	6	1635	502,130,164

The number of SHS PAYG service providers was reduced from the 10 used for the connection subsidy to a group of five for the RBF program under the assumption that not all of the service providers are interested in expanding to the more remote, rural areas. The reader should keep in mind that the RBF incentive is paid to the SHS PAYG service provider only after achievement of the desired results and includes costs for market penetration as well as maintenance and repairs for the first few years of operation. The results based financing incentive (Table 42) was calculated by using incentive data from the GPOBA Ghana case study (GPOBA, 2016) for systems up to 50 W and curve fitting (Figure 18) to derive the incentive level for a 200 W system.

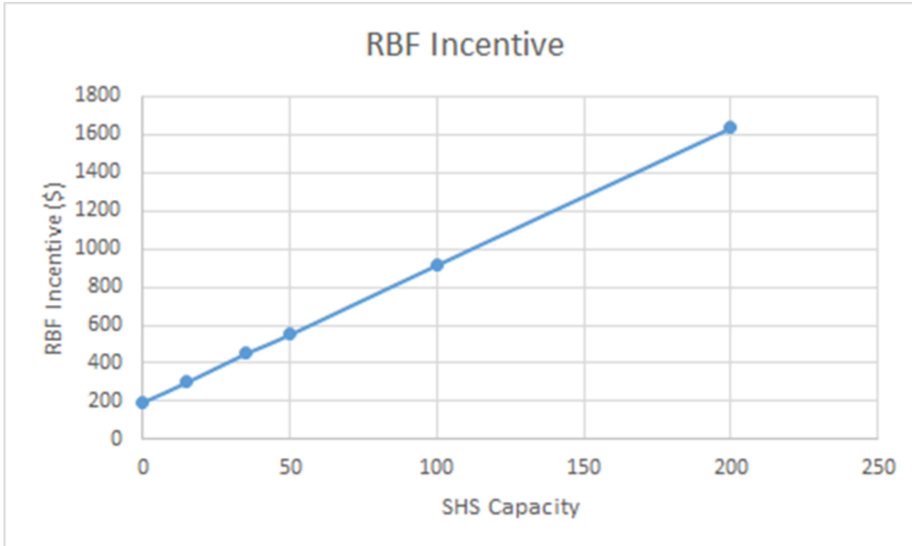


Figure 18. RBF incentive – 200 W system curve fitting (GPOBA, 2016; author's elaboration, 2017).

While my research has only scratched the surface in taming the "wicked" problem of rural electrification in the ECOWAS region, the results above clearly illustrate the rethinking the energy access planning process and introducing an enhanced GIS-based energy access decision tool framework to support the business decision needs of SHS PAYG service providers.

Chapter IV

Discussion

This research was initially inspired by conversations with SHS PAYG service providers – fueled by my curiosity regarding their plans to scale-up through entry into new markets and expansion of their existing territories. What I quickly discovered was a gap in the functionality of existing GIS-based energy access decision tools, which left these entrepreneurs to rely on their own empirical methods. While these existing tools are designed to identify the geographic locations that represent the least cost solution for utility grid extension, mini-grid development, and SHS PAYG deployment – their emergence in the planning process doesn't seem to produce an electrification pace which will meet the UNSE4ALL 2030 universal energy access goals across the ECOWAS region.

In this Chapter, I will work to pull all of the threads of my research together. First, I will look at the context of my research in areas which remain energy-poor. Following that; I will reflect on the limits of my research, needs for additional work, and implications for the energy access sector going forward. In his often-referenced book, *The Challenge of Rural Electrification – Strategies for Developing Countries*, Douglas Barnes echoes my disruptive perspective as he reflects that "This book has dealt mainly with grid-based rural electrification, which is often portrayed as being in competition with alternatives, especially PV systems. This is a mistake because there is little conflict between the two and, in fact, they can complement one another. Providing electricity to people in rural areas is a daunting task for organizations, whether it involves connecting communities to the grid or developing off-grid approaches to rural electrification" (Barnes, 2007).

Context

While the challenge of rural electrification initially appeared to be a straightforward service delivery problem. Digging a bit deeper revealed that it is akin to an untidy ball of yarn which desperately needs to be untangled. To that end, looking at my research from a perspective of "energy access market distortion" may help to identify leverage points (Figure 19) to tame this wicked problem.

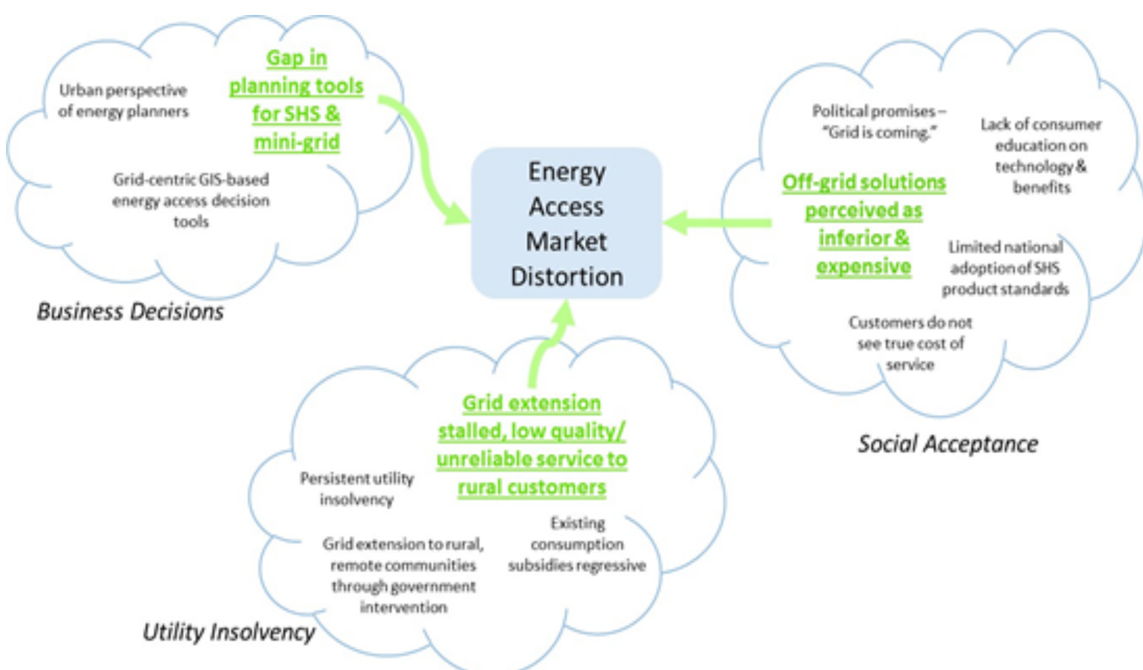


Figure 19. Energy access market distortion (Komives et al., 2005; Alleyne, 2013; Sanyal et al., 2016).

As an example, the social acceptance element of this system (Figure 19) includes limited national adoption of product standards, lack of consumer education and awareness of technology benefits, political promises that the grid is coming, and customers reacting to the wrong pricing signals, which can all combine to reduce social acceptance of off-grid solutions.

Taming a Wicked Problem

A common theme of rural electrification programs has been a strong focus on planning, serving the greatest number of people, with the least investment of resources, as quickly as possible. Historically, this planning focus seems to have come out of the industrial age where the idea of planning was "dominated by the pervasive idea of efficiency" ensuring that a specified task was performed with the least input of resources (Rittel & Weber, 1973). In their seminal work, Rittel and Weber (1973) suggested that science and engineering problems can be characterized as "tame", where the task is clear and it is obvious whether or not the problem has been solved. In contrast, they suggested that open societal problems such as poverty and healthcare should be addressed as "wicked" problems (Rittel & Weber, 1973). Based on my research, I would assert that rural electrification should be viewed in the same "wicked" light, not overlooking or underestimating its persistence and complexity.

Working through my research, I have found it helpful to consider my hypothesis and research questions through this more nuanced, underlying lens. The three (3) characteristics which appeared most relevant to my research are the notions that: 1) solutions to wicked problems are not black and white, they tend to be more "good-or-bad" or "good enough," 2) wicked problems have a wide range of possible options, and 3) there isn't a simple way to validate the solution to a wicked problem (Rittel & Weber, 1973).

The idea (1) that solutions to wicked problems are often framed as "good enough" suggested that the criteria for an initiative's success may depend on the differing goals of each stakeholder (Rittel & Weber, 1973). Looking at my research questions in this light suggested a bit of brainstorming to understand whose perspective is most important: Should we focus on the electrification goals adopted by national energy planners? Are the profitability and long-term financial solvency of distribution utilities most important? At a basic level, shouldn't we concentrate on ensuring that households have reliable and affordable access to electricity? How do we prioritize the broader health, education, and economic development benefits that are expected by donors as a result of electrification?

One of the most pernicious aspects (2) of dealing with a "wicked" problem is that you are never quite sure that all of the potential solutions have been discovered and addressed. As a result, formulation of the best approach to a particular problem has often relied on "fruitful collaboration between the planner and the client" (Rittel & Weber, 1973). Following this logic, if we accept that "business as usual" for energy access planning has taken a top-down, grid-centric approach, then expanding the range of options to pursue a more bottom-up, energy-poor perspective may reveal new opportunities. In practice, my research proposed that addressing this challenge might take the form of layering new geospatial indicators on top of the established LCOE foundation in an effort to prioritize the results from an SHS PAYG service provider's perspective. In addition, this line of thinking may help to foster the integration of socioeconomic, political, and regulatory factors into the energy planning process (Borofsky, 2015).

Finally, we find that solutions to wicked problems tend to "generate a wave of consequences over an extended period of time," creating a ripple effect (3) of repercussions and unintended consequences (Rittel & Weber, 1973). In the context of my research, I used this insight to examine the market distortion which is created by the use of energy consumption subsidies to make electricity affordable for low-income customers. Instead of providing the intended benefits to these "lifeline" customers, my research examined the vicious cycle generated when these "loss-making" connections prevent distribution utilities from investing in infrastructure – which slows the progress of grid extension, degrades the quality and reliability of service, and suppresses social acceptance of affordable and effective SHS PAYG solutions.

Reflecting on this challenge from a historical perspective, its persistent "wickedness" has left one to two billion people without electricity since the latter half of the nineteenth century. Despite our best efforts, we have just managed keep pace with global population growth for nearly one hundred and fifty years (Alstone, 2015)! In order to change this trajectory, we clearly need to consider a different approach.

Limitations/Future Research

My research focused on the ECOWAS member states in an effort to provide a representative example of the universal energy access challenge in an energy-poor environment. My work was limited to examination of SHS PAYG solutions, based on the immediate benefits available to energy-poor consumers. Due privacy and confidentiality barriers, data gaps were encountered in attempting to obtain mobile money coverage area information from MNOs.

Future research should include immediate pilot studies to implement the enhanced GIS-based energy access decision tool framework which has been put forward by my research. As an example, integration of the "energy addressable market" as a geographic selection layer should be piloted in collaboration with stakeholders which may include GSMA, MNOs, SHS PAYG providers, Practical Action, GIS-based energy access decision tool developers, and target communities. Future research and pilot studies should also consider the integration of geospatial data from the ongoing MTF baseline surveys. Conceptually, this effort would explore geographic selection of households which are currently at minimal/no electricity access (Tier 0 or Tier 1) for SHS PAYG adoption. Expanding the range of institutional barriers and enabling environment conditions which may accelerate the scale-up of electricity access for the energy-poor also offers a wealth of opportunities for future research. As an example, the development of a planning and coordination scheme to document, track, and periodically update the status of utility grid extension, mini-grid development, and SHS PAYG deployment is strongly recommended in an effort to mitigate the risk of stranded assets for off-grid providers.

While my research was limited to supporting the business decision needs of SHS PAYG providers, future efforts could extend this research approach to address the needs of mini-grid developers. In this context, overcoming institutional barriers might involve addressing regulatory reforms to establish equitable mini-grid concessions and prepare for future utility grid connections. Enabling environment conditions may include the development of criteria for a "mini-grid compatible community" which may incorporate the presence of an organized village center (market, school, and healthcare facilities), demand for productive uses (agricultural milling, grinding, and processing), and a compact residential footprint (minimal mean inter-household distance). In this light, the Rural Growth Centre (RGC) approach (Figure 20) suggested by the *Rural Electrification Master Plan for Zambia 2008-2030 – A Blueprint for Providing Electricity to All Rural Areas* (JICA, 2009) may serve as a starting point. In this long-range master plan, the Zambian government defined an RGC as a "rural locality with a high concentration of rural settlements and which is the centre of rural economic activities" (JICA, 2009). In these communities, people from the local villages come to the RGC to sell their agricultural goods and handicrafts, to shop for their daily needs, and to access public services (JICA, 2009). Looking at this organizational structure from the standpoint of GIS-based energy access planning, geographic targeting could be used to identify communities with this demographic profile, which would appear to be ideal candidates for mini-grid development.

While it was also outside the scope of my research, the Regulatory Indicators for Sustainable Energy (RISE) platform also warrant further exploration with a focus on identifying additional institutional barriers and/or enabling environment conditions. RISE is part of the Energydata.info open source data acquisition dashboard developed by the World Bank (World Bank, 2017). Its value is in providing a detailed scoring system to assess a country's progress in the areas of energy access, energy efficiency, and renewable energy put forth by the UNSE4ALL initiative. A summary of the

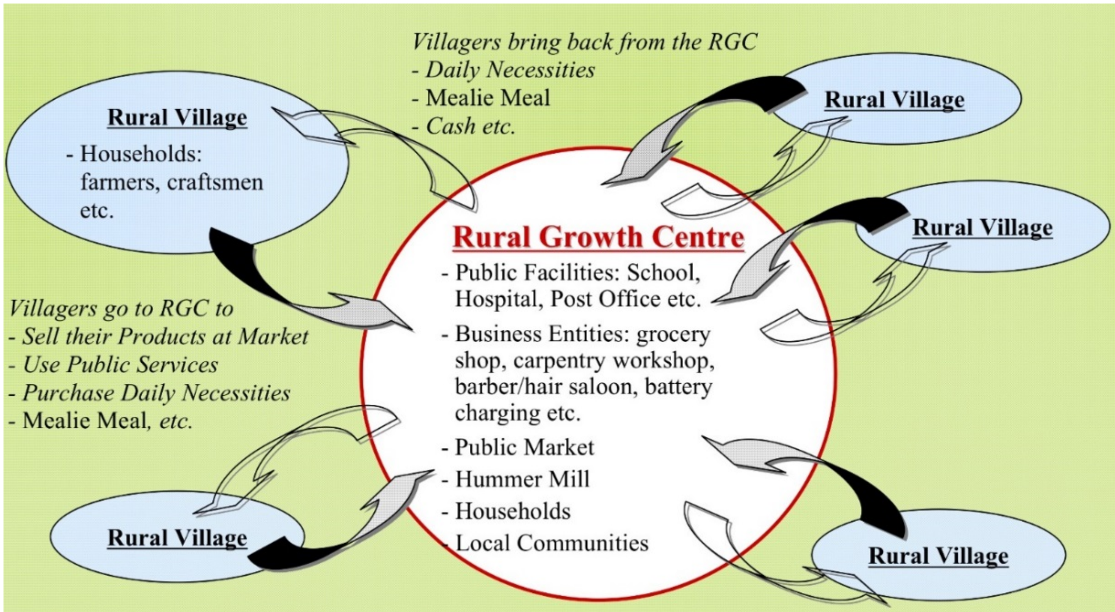


Figure 20. Zambia rural growth centre approach (JICA, 2009).

energy access score (Figure 21) for the Republic of Ghana offers an example of the capabilities of this platform.

RISE Regulatory Indicators for Sustainable Energy

Regulatory Indicators for Sustainable Energy (RISE)

2016 Country Data - Ghana

Energy Access

Indicator	Score
Existence and monitoring of officially approved electrification plan	80
Scope of officially approved electrification plan	50
Framework for grid electrification	33.33
Framework for minigrids	30
Framework for stand-alone systems	93.33
Consumer affordability of electricity	100
Utility Transparency and Monitoring	99.99
Utility Creditworthiness	14.29
Total	62.62

Figure 21. RISE energy access score – Ghana (RISE, 2017a).

The RISE scoring system ranges from 0-100 with a score of 0-33 indicating a weak regulatory environment, 34-66 a middle-of-the-road condition, and 67-70 a strong framework. The RISE energy access scores (where available) for the ECOWAS member states were compiled (Table 43) as an example.

With only one member state rated as strong, and nearly half of the ranked countries rated as low, future exploration of this platform is certainly warranted. In addition to RISE, the Energydata.info dashboard includes the Off-Grid Market Opportunity Tool (Table 44), which has been developed by the IFC to provide stakeholders with a high-level view of where markets for off-grid electrification may exist.

Table 43. RISE energy access scores – ECOWAS (RISE, 2017b).

Member State	RISE Energy Access Score	Indicator Strength
Sierra Leone	17	Low
Liberia	20	Low
Nigeria	22	Low
Niger	29	Low
Togo	32	Low
Mali	39	Medium
Burkina Faso	40	Medium
Cote d’Ivoire	46	Medium
Benin	49	Medium
Guinea	57	Medium
Ghana	63	Medium
Senegal	69	Strong

Table 44. Off-grid market opportunity tool parameters (OGMO, 2016a).

Category	**Input/ Output**	**Parameters**	**Research Value**
Social Use	Input	Healthcare (1-100 km), Education (1-100 km)	Geographic targeting of population centers, sector specific electrification programs
Productive Use	Input	Mining Sites (1-100 km)	Significant revenue source for distribution utilities, impact to geographic focus of grid extension
Infrastructure	Input	Distance from the Grid (5 km, 15 km, 30 km), Mobile Data (service/no service)	Geographic targeting of energy addressable market and grid corridors
Demographics	Input	Population Density (1-1,000,000 ppl/km^2)	Initial geographic targeting of user definable population ranges indicative of electrification solutions
Market Potential	Output	Population, Households, Annual Revenue (50% penetration, $10/hh/yr revenue defaults)	Calculation of potential annual revenue based on user definable market penetration rate and revenue per household

An example of the use of this tool (Figure 22) illustrates the results of geographically targeting those areas that are more than 30 km from the national utility grid.

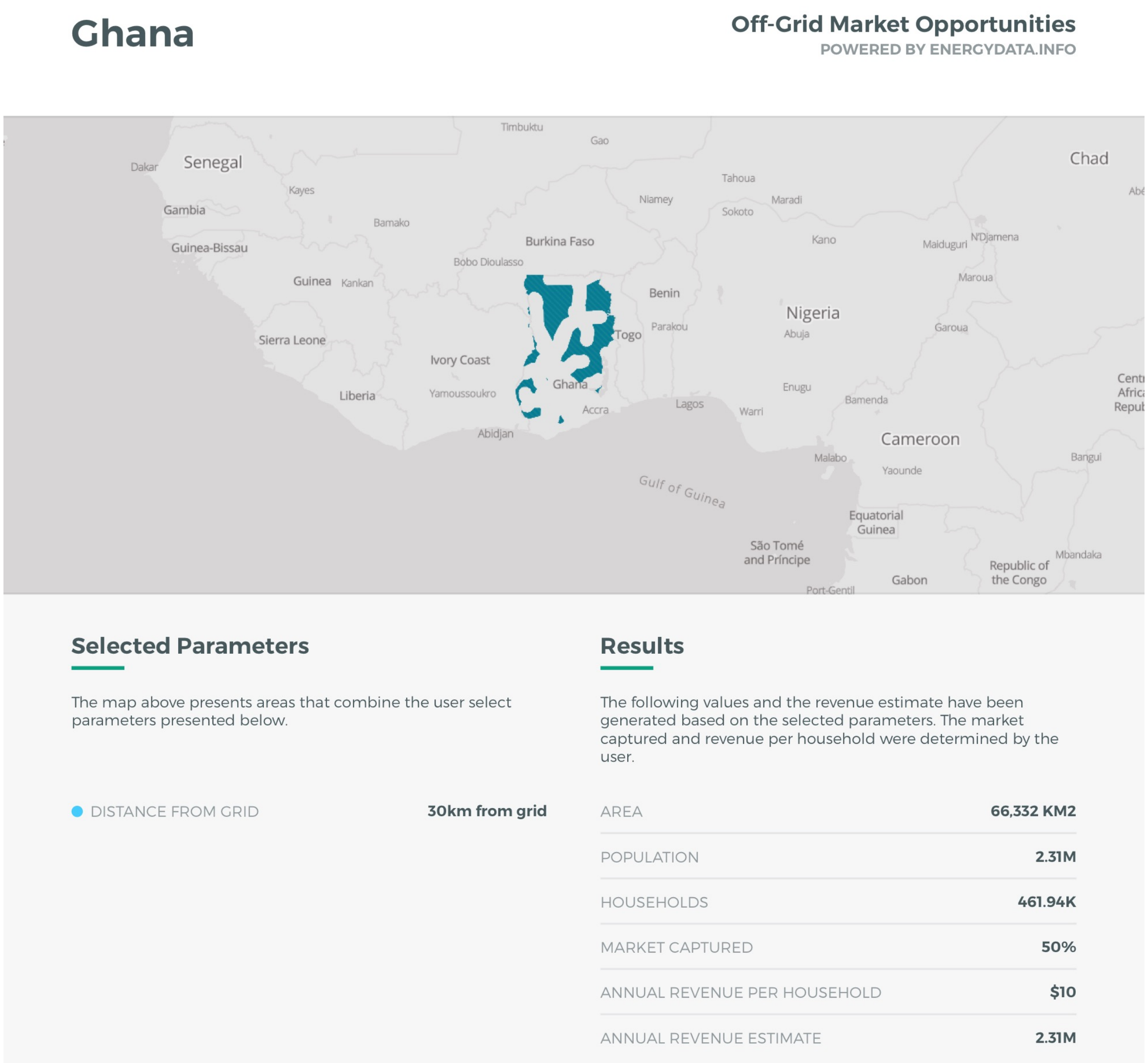


Figure 22. Off-grid market opportunity tool - Ghana input/output (OGMO, 2016b).

Implications

The implications of my research may include risk mitigation for SHS PAYG providers, insights to inform the ongoing evolution of GIS-based energy access decision tools, and a shift in perspective for national energy planners in the ECOWAS region. Equipped with enhanced GIS-based energy access decision tools, SHS PAYG service providers would be in a stronger position to attract donor funding, private investment, and impact investment to expand their existing market penetration and support new market entry. Using the established LCOE methodology as a foundation, my research offered the initial building blocks of a framework to support the evolution of GIS-based energy access decision tools from an energy-poor perspective. By questioning the value of the current grid-centric approach to energy access planning and the expanding the limits of existing GIS-based energy access decision tools - my research approach may meet with resistance from national energy planners and politicians among the ECOWAS member states. In facing that resistance, it is hoped that the ECOWREX and EPASES teams at ECREEE will be able to serve as advocates for reform – focusing on a common ground of enabling electricity access for the energy-poor. Personal communications with Daniel Paco (ECOWREX GIS Specialist) and Nicola Bugatti (EPASES Program Manager) acknowledge their agreement in the value of this research and a desire for future collaboration (D. Paco, personal communication, December 12, 2016; N. Bugatti, personal communication, January 5, 2017).

Stepping back from the data to look at the big picture, a conceptual illustration of the geographic selection process proposed as the core of the enhanced GIS-based energy access decision tool framework was developed (Figure 23). The broadest target is the un-electrified population (Step 1) for a particular country (Figure 23). The first layer (Step 2) of screening uses the LCOE methodology to identify those areas where SHS PAYG is the least cost solution, which broadly represents the limitations of the

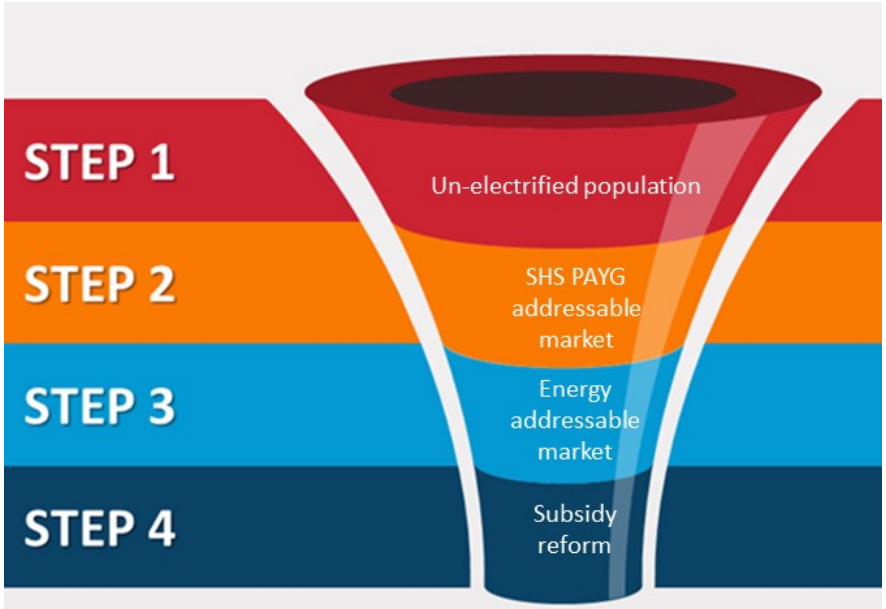


Figure 23. Geographic selection process (author's elaboration, 2017).

existing GIS-based energy access decision tools. My research takes this screening approach one step further to aggregate the grid cells from these tools into contiguous sales territories and prioritize (Steps 3 and 4) those communities which appear to represent the best opportunity for market penetration and scale-up. As an alternative to the funnel diagram above, the energy addressable market can also be understood (Figure 24) through a process flow diagram.

Conceptually, the energy addressable market (Figure 20) is created by the pace of mobile service market penetration (faster) versus that of rural electrification (slower), which gives rise to a population of mobile phone users without access to electricity. This market penetration dynamic provides benefits which include increased revenue potential for MNOs, pent up demand for SHS PAYG service providers, and household benefits (lighting and phone charging) for energy-poor consumers. My research proposes the

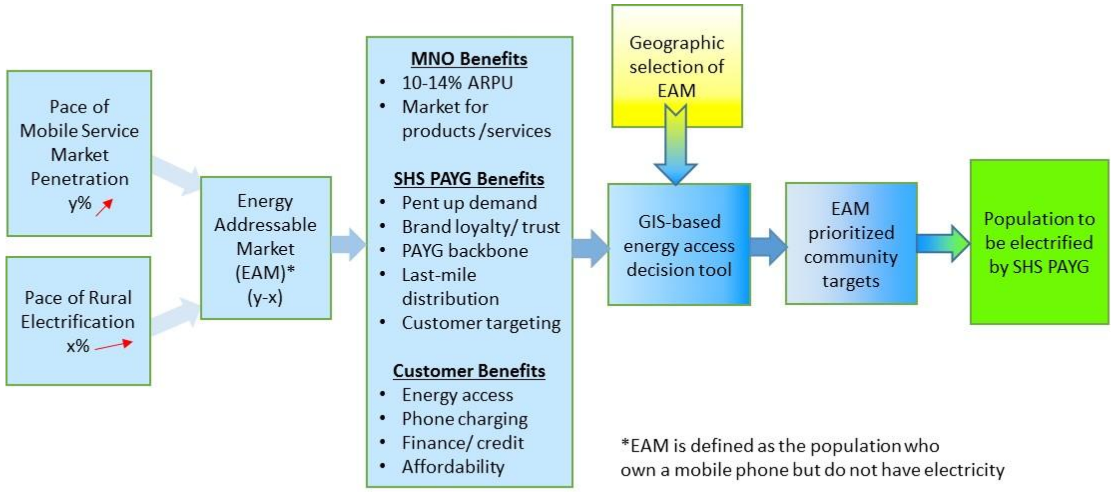


Figure 24. Energy addressable market process flow diagram (author's elaboration, 2017).

introduction of a new geospatial selection layer to map the location of this population in order to prioritize the targeting of the energy addressable market as a subset of the SHS PAYG addressable market defined by the established LCOE methodology.

Future research and practical applications of the enhanced GIS-based energy access decision tool framework will depend on the formulation of business process requirements to guide the development of an enhanced GIS decision tool suitable for use by SHS PAYG service providers. In order for such a tool to provide value across a number of target countries, it will need to be responsive to service providers that are considering entry into new markets (Figure 25) as well as expansion of their existing territories (Figure 26).

The proposed business process requirements (Figure 25) for SHS PAYG providers considering entry into new markets is indicative of the opportunity to serve ECOWAS member states in West Africa that have been the focus of my research. Step 1 would occur at the national level and would identify geographic areas where SHS

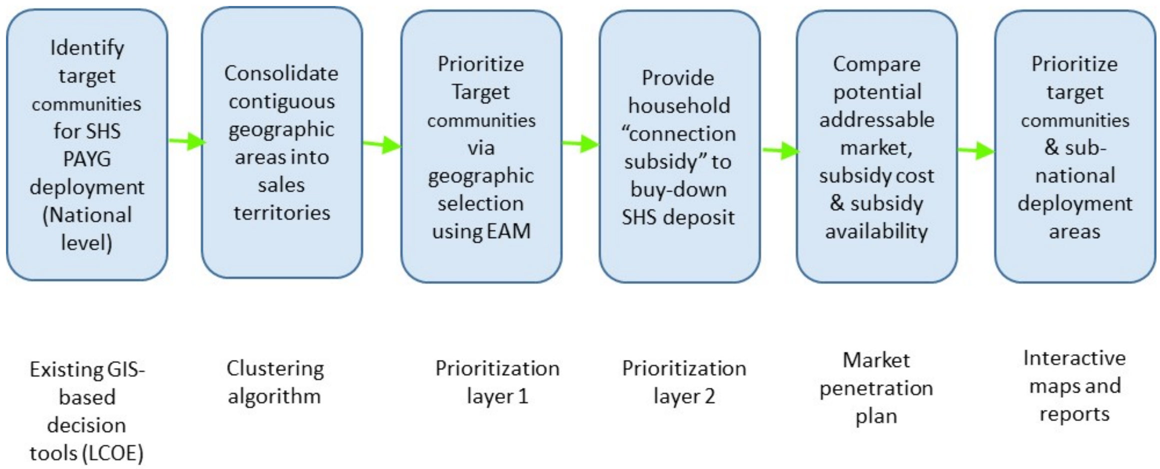


Figure 25. Market entry business process requirements (author's elaboration, 2017).

PAYG is the least cost of electrification solution. The geographic areas identified in Step 1 would then be consolidated into contiguous areas (Step 2) intended to represent realistic service provider sales territories. This process would utilize a geospatial clustering algorithm to identify such territories. Step 3 is the first prioritization layer which would identify the subset of the sales territories from Step 2 that represent the energy addressable market. Step 4 would introduce a second prioritization layer which would seek to identify existing connection subsidy programs which could be used to offset the consumer's down payment (typically by ~50%) to make it equivalent to their recurring monthly payment. If no such subsidy programs exist, this prioritization layer would be skipped. Step 5 would then allow ranking of the energy addressable market and connection subsidy results to support a market penetration plan. This ranking step would allow service providers to screen the results based on factors such as their existing MNO relationships, population size of the proposed sales territories, geographic accessibility (paved or dirt roads), population centers (villages) per sales territory. Finally, Step 6 would produce interactive maps and reports which could be used to communicate with sales team members, donor funding agencies, MNOs, rural electrification authorities, and local communities.

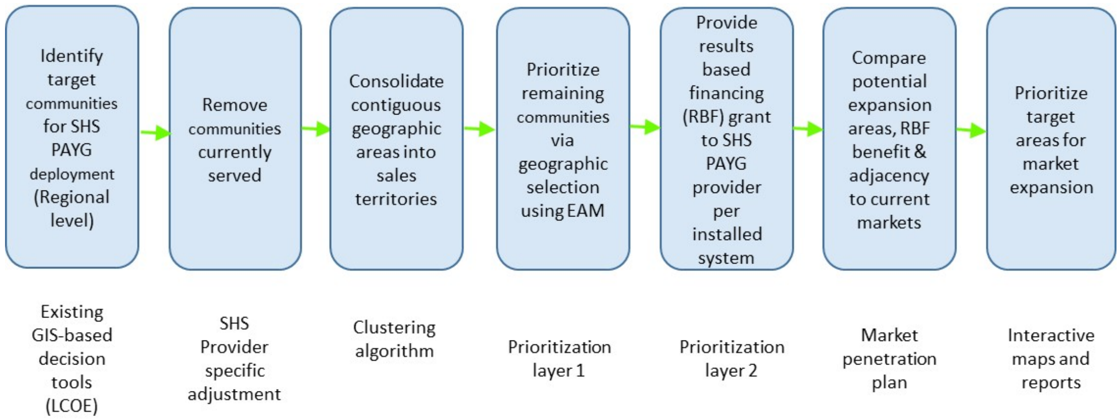


Figure 26. Market expansion business process requirements (author's elaboration, 2017).

While the previous discussion outlines the potential business process requirements (Figure 25) for entry into new markets, Figure 26 above considers the approach needed to address the expansion of existing service provider markets. Geographically, this approach would be most appropriate in countries such as Uganda, Kenya, and Tanzania in East Africa, which represent more mature SHS PAYG markets. In this case, Step 1 is the same, identifying geographic areas where SHS PAYG represents the least cost solution. Since this process involves expanding a service provider's sales territory, Step 2 would remove those areas which are already saturated by SHS PAYG adoption. Step 3 would then use the clustering algorithm described above (Figure 21) to create sales territories. The first prioritization layer would follow in Step 4, identifying the sales territories that represent the energy addressable market. While the business process for market entry identified connection subsidy programs to buy-down a consumer's down payment, the second prioritization layer (Step 5) for market expansion would identify sales territories from Step 4 where existing results-based financing programs are available to incentivize a service provider to expand their footprint. Step 6 would then allow ranking of the results to generate a market expansion plan. This ranking process would allow service providers to screen the results based on factors such as traveling time from existing service territories and areas which are believed to be served by competitors. Finally, Step 7 would provide interactive maps and reports for use by SHS PAYG service providers, donor funding institutions, MNOs, rural electrification agencies and local consumers.

In addition to using geographic selection to identify and prioritize areas which represent the energy addressable market, connection subsidy program locations, and results-based financing program locations, this methodological framework could also be used to simulate the cost/benefit proposition associated with the proposed launch of MNO mobile money rollout strategies as well as predicting the benefits associated with the launch of proposed connection subsidy and results-based financing programs. Finally, my proposed framework could be used to support SHS PAYG service provider business decision needs over time, providing the flexibility to track the rural electrification impact of their expanding SHS PAYG system and appliance portfolios going forward and modeling the combined effects of connection subsidies (front-end) and RBF incentives (back-end) as the market matures in a particular location over time.

Conclusions

National governments have made a public commitment to the goal of universal energy access by 2030 through their adoption of the UNSE4ALL principles. In response, GIS-based energy access decision tools have emerged to enable quick assessments of the geographic areas where grid extension, mini-grids, or standalone solar PV systems represent the least-cost electrification solution. Energy consumption subsidies have been put in place through lifeline tariffs which are intended to make utility service affordable for low-income consumers. While all of these factors would seem to support a rapid, cost-effective solution to this challenge, a deeper look at the underlying dynamics at play revealed a different picture. Examining the current status of member states and using the historical pace of electrification, only tiny Cape Verde (population ~500,000) was projected to achieve universal energy access by 2030. Existing GIS-based energy access decision tools are limited to supporting broad investment decisions versus enabling more discrete business decisions for individual service providers. Energy consumption subsidies have distorted the energy access sector by financially crippling distribution utilities financially and falling short of providing the benefits originally intended for energy-poor communities.

This disparity between universal energy access aspirations and results suggests an urgent need to re-examine the current energy access planning process – to put into practice the aspirations recommended by Practical Action to "flip the paradigm" and put remote, rural communities at the heart of the process going forward. To this end, my research has outlined a new framework designed to support the evolution of GIS-based energy access decision tools by overcoming institutional barriers and leveraging enabling environment conditions to begin to tame this wicked problem from an energy-poor perspective. It is hoped that this approach can offer a way to reduce the energy subsidy burden on national governments, provide some breathing room for distribution utilities in moving toward financial solvency, allow SHS PAYG providers to make confident business decisions on which countries and communities to target for expansion, and provide low-income consumers with affordable and reliable electricity. A mental map of my research (Figures 27 and 28) makes an effort to tie all of these threads together. The width of the arrows illustrates (Figure 27) the relative flow between each option. As an example, the rural population with no electricity access is described as much larger that the rural population with electricity access. The upper portion of the diagram (blue shading) illustrates the flow for urban populations, while the lower (yellow) portion describes rural populations. Following the green shaded boxes from left to right suggests a pathway for the scale up of SHS PAYG solutions. Examining the choices for remote, rural populations with no electricity access, the diagram suggests the strongest flow for SHS, followed by mini-grid and national grid extension. While the diagram (Figure 27) illustrates the expected results for a remote, rural community, the market distortion which is introduced by energy consumption subsidies and political intervention can often reverse these flows to favor grid extension and suppress the deployment of off-grid solutions.

Boiling my research down to its core, the enhanced GIS-based energy access decision tool framework suggests a prioritization scheme which employs two levels of geographic targeting. First, the energy addressable market (EAM) is leveraged as an enabling environment condition, prioritizing those households which have mobile phone service but no electricity access; this represents pent up demand for SHS PAYG service providers, increased revenues for MNOs, and critical lighting and phone charging

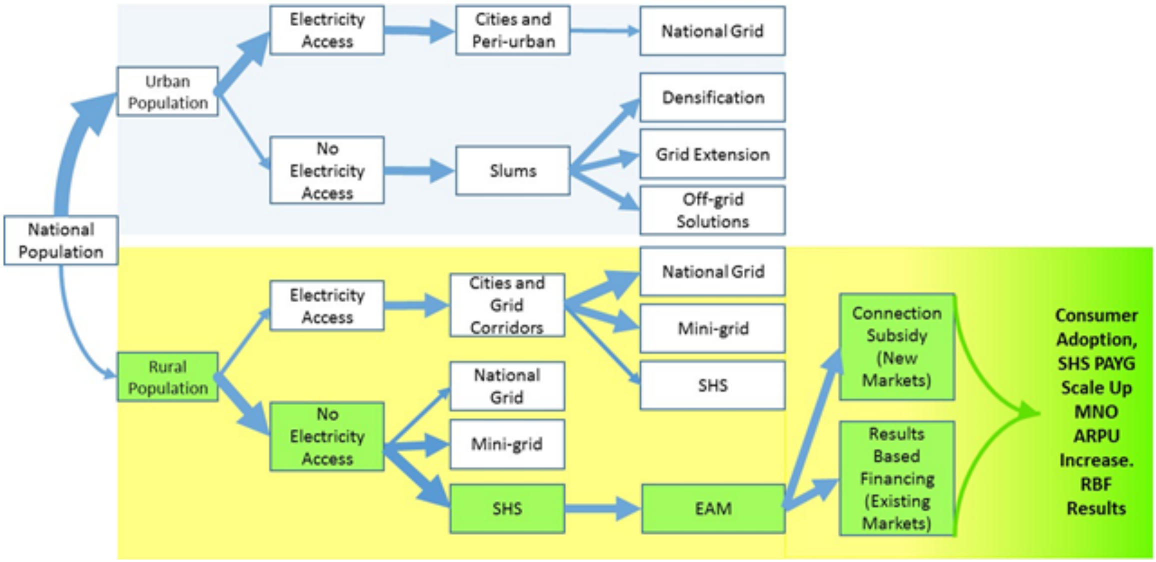


Figure 27. Enhanced energy access planning pathway - flow diagram (author's elaboration, 2017).

services for energy-poor consumers. A second layer of geographic targeting is then applied to the EAM result, "following the money" to target the locations of connection subsidy programs (for new markets) or results based financing programs (for expansion of existing markets). This geospatial prioritization approach also provides benefits for national governments, rural electrification agencies, and donor funding institutions by improving their confidence in the results stemming from their off-grid investments. A visual summary of my research process (Figure 28) revisits the key elements of this disruptive approach, staring with the initial challenge and looking toward future pilot studies.

The initial challenge addressed by my research came out of a process of questioning the merits of the current energy access planning process. Instead of driving the implementation of LCOE recommended electrification solutions, this "business as usual" process was shown to be distorted by the use of energy consumption subsidies

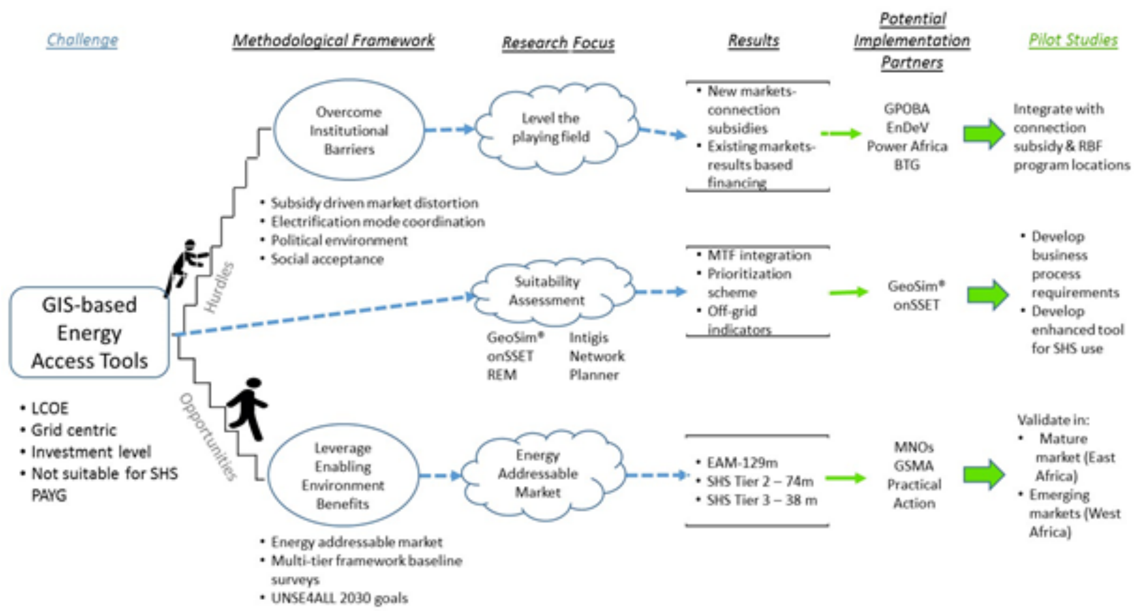


Figure 28. Taming a wicked problem - research process visual summary (author's elaboration, 2017).

biasing the planning process toward grid extension. In addition, the available GIS-based energy access decision tools were found to be focused on broader investment level decisions and not suitable to support the business decision needs of SHS PAYG service providers. In response to this challenge, a methodological framework was developed which sought to address the hurdles presented by institutional barriers and the opportunities made available through enabling environment conditions. Out of the hurdles and opportunities identified in this process, subsidy reform and the energy addressable market were selected as my research focus. In parallel with the exploration of these two research questions, a suitability assessment of the five (5) existing GIS-based energy access decision tools was conducted in order to identify which tool(s) are best suited for enhancement from an energy-poor perspective. My research results show that connection subsidies are best suited to address new markets, while results based financing programs should be targeted to expand the reach of existing markets. The GIS tool assessment revealed that integration of the multi-tier framework, incorporation of prioritization schemes, and utilization of off-grid indicators are the key elements which can make these tools suitable for future enhancement. The onSSET platform emerged from this process as a potential option largely due to its integration of the multi-tier framework. GeoSim® was also strongly recommended for enhancement due to its indicators for development (IFD) prioritization scheme and use of a high isolation indicator for remote, rural communities. Examination of the energy addressable market found a regional population of 129 million mobile phone users without access to electricity - representing significant pent up demand for SHS PAYG. From an LCOE perspective, computer simulations using the onSSET dashboard suggested a Tier 3 addressable market of 38 million people across the region. If this target is dialed back to Tier 2, the result is an addressable market of 74 million people. Since my research set out to establish a GIS-based energy access tool framework (versus building a new platform) - additional research and pilot studies will be necessary to translate these findings into practical applications.

Corresponding to each element of the research focus, potential implementation partners were identified. As an example; MNOs, SHS PAYG providers, GSMA, and Practical Action represent team members well suited to carry the energy addressable market thread forward. In addition to those partners listed above, the ECOWREX and

EPASES teams at ECREEE are positioned to provide additional value as a regional coordinator and champion. Finally, pilot studies are recommended as a vehicle to develop an initial implementation of an enhanced GIS-based energy access decision tool and to begin to create real value for SHS PAYG providers and energy-poor consumers.

As I look to what steps are needed to tame this wicked problem – to rethink energy access planning from an energy-poor perspective – E.F. Schumacher's revolutionary ideas come to mind. In his masterpiece, *Small is Beautiful – Economics as if People Mattered*, Schumacher muses that "the new thinking that is required for aid and development will be different from the old because it will take poverty seriously" (Schumacher, 1973). This new thinking will care for people and will do so from a pragmatic and practical perspective. In the case of my research, this new thinking takes the form of understanding the energy-poor lives of many who live in rural, remote communities throughout the ECOWAS region. It reveals a population who have cellular phones and mobile service, but no access to electricity. A population whose quality of life can be significantly improved by basic lighting and phone charging services, who are largely unbanked and have no credit history due to irregular cash incomes, and whose voice needs to be a real part of the energy planning process. If we don't shift our perspective, Schumacher exhorts us, "If they are left out, if they are pushed around by self-styled experts and high-handed planners, then nothing can ever yield real fruit" (Schumacher, 1973).

Appendix 1

FINclusion Labs Mobile Money Access Points

Table 45. FINclusion Labs mobile money access points (FINclusion Labs, 2017).

Country	Region	Access Points	Hyperlink	URL
Kenya	East Africa	65,943	Kenya	http://finclusionlab.org/country/Kenya/analytics?title=National-Overview
Rwanda	East Africa	38,049	Rwanda	http://finclusionlab.org/country/Rwanda/analytics?title=National-Overview
Tanzania	East Africa	16,540	Tanzania	http://finclusionlab.org/country/Tanzania/analytics?title=National-Overview
Uganda	East Africa	17,802	Uganda	http://finclusionlab.org/country/Uganda/analytics?title=National-Overview
Benin	ECOWAS	7,475	Benin	http://finclusionlab.org/country/Benin/analytics?title=National-Overview
Ghana	ECOWAS	3,373	Ghana	http://finclusionlab.org/country/Ghana/analytics?title=National-Overview
Ivory Coast (Cote d'Ivoire)	ECOWAS	3,102	Ivory Coast	http://finclusionlab.org/country/Ivory-Coast/analytics?title=National-Overview
Nigeria	ECOWAS	4,222	Nigeria	http://finclusionlab.org/country/Nigeria/analytics?title=National-Overview
Senegal	ECOWAS	9,165	Senegal	http://finclusionlab.org/country/Senegal/analytics?title=National-Overview

Appendix 2

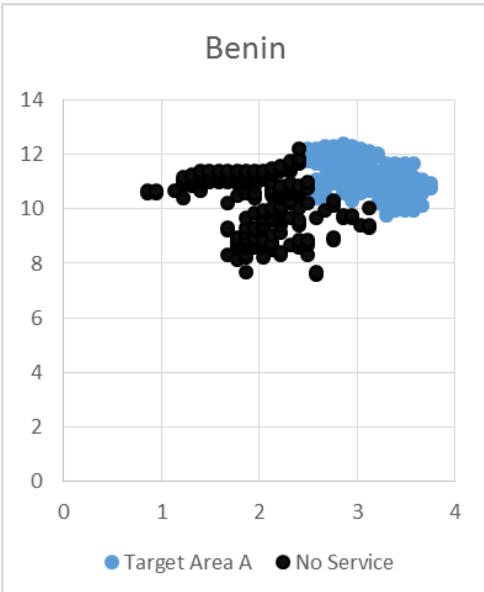
onSSET Tier 2 and 3 LCOE Simulations

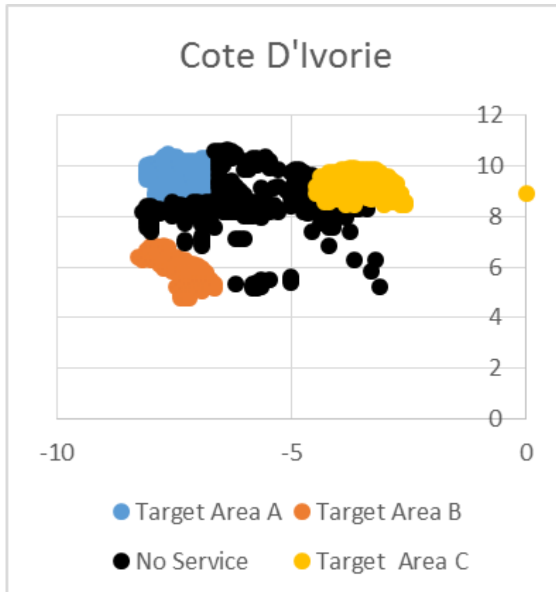
Table 46. onSSET tier 2 and tier 3 LCOE simulations – ECOWAS (UNDESA, 2017).

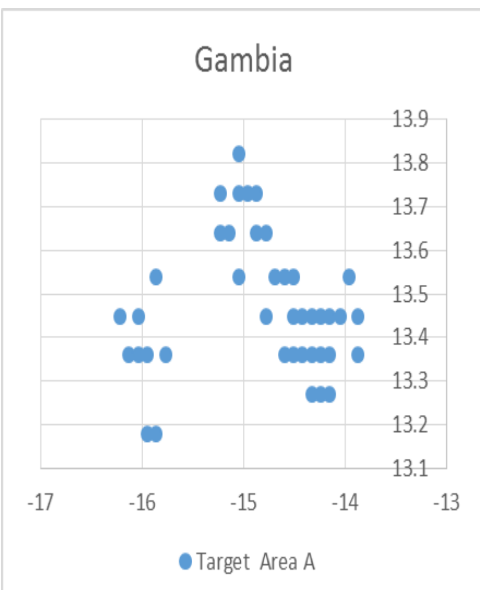
Country	Tier 2 Hyperlink	Tier 3 Hyperlink
Benin	Benin - Tier 2	Benin Tier 3
Burkina Faso	Burkina Faso - Tier 2	Burkina Faso - Tier 3
Cote d'Ivoire	Cote D'Ivoire - Tier 2	Cote D'Ivoire - Tier 3
Gambia	Gambia - Tier 2	Gambia - Tier 3
Ghana	Ghana - Tier 2	Ghana - Tier 3
Guinea	Guinea - Tier 2	Guinea - Tier 3
Guinea-Bissau	Guinea-Bissau - Tier 2	Guinea-Bissau - Tier 3
Liberia	Liberia - Tier 2	Liberia - Tier 3
Mali	Mali - Tier 2	Mail - Tier 3
Niger	Niger - Tier 2	Niger - Tier 3
Nigeria	Nigeria - Tier 2	Nigeria - Tier 3
Senegal	Senegal - Tier 2	Senegal - Tier 3
Sierra Leone	Sierra Leone - Tier 2	Sierra Leone - Tier 3
Togo	Togo - Tier 2	Togo - Tier 3

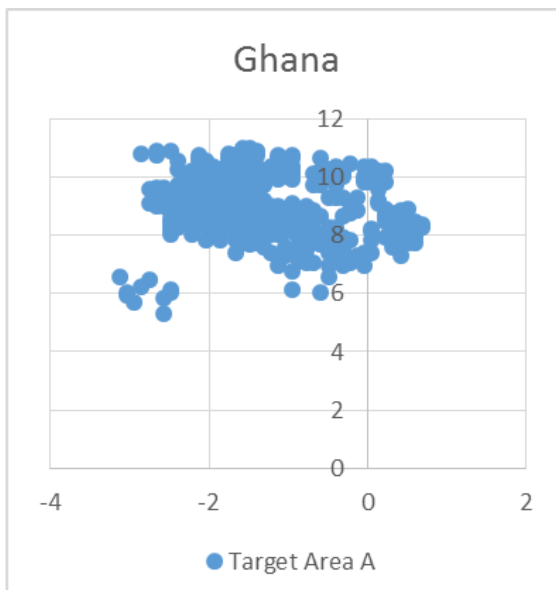
Appendix 3

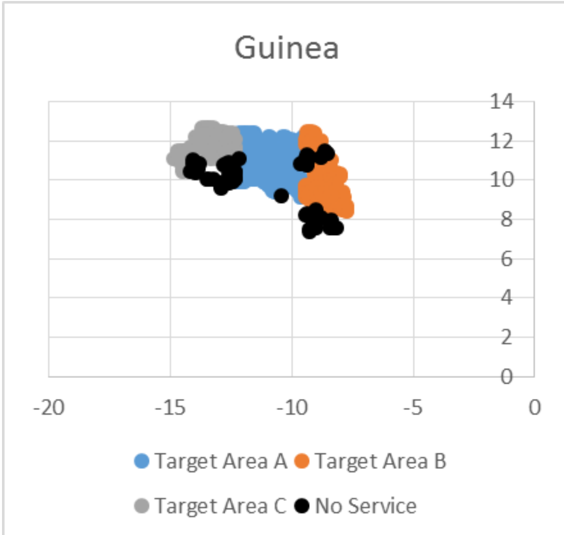
ECOWAS SHS Target Areas

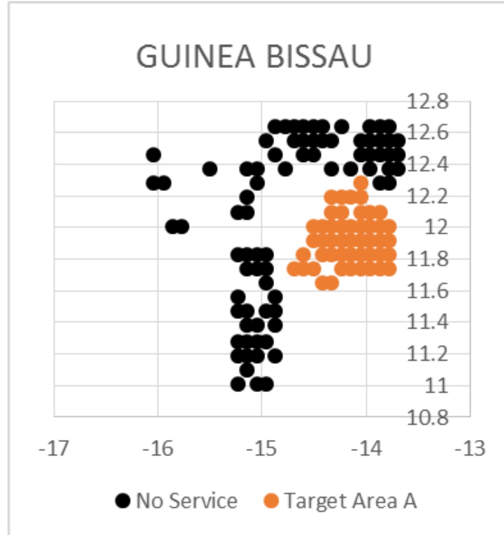


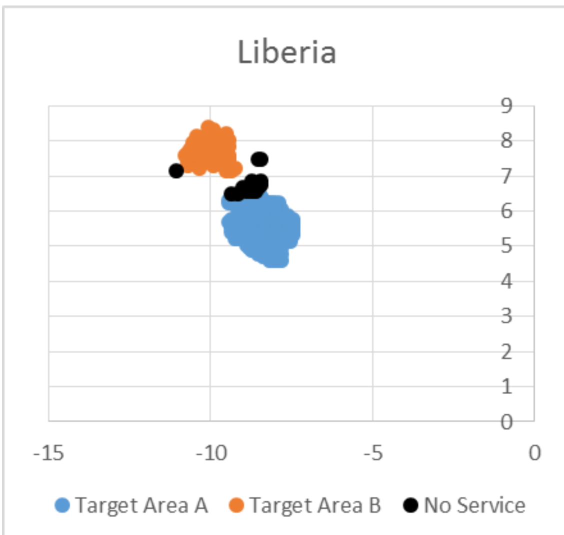


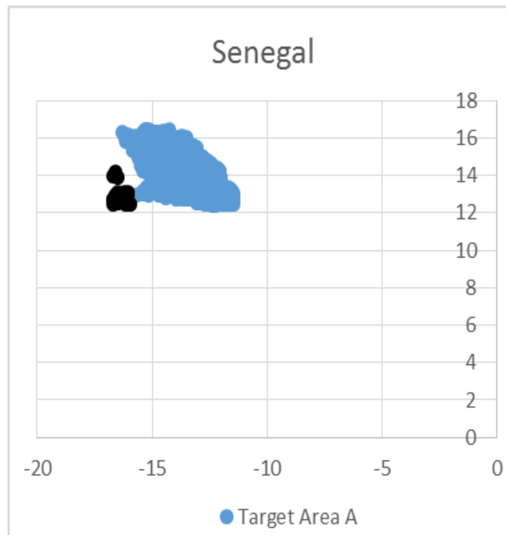





Guinea
14
12
10
8
6
4
2
0
-20
-15
-10
-5
0
Target Area A
Target Area B
Target Area C
No Service


GUINEA BISSAU
12.8
12.6
12.4
12.2
12
11.8
11.6
11.4
11.2
11
10.8
-17
-16
-15
-14
-13
No Service
Target Area A


Liberia
9
8
7
6
5
4
3
2
1
0
-15
-10
-5
0
Target Area A
Target Area B
No Service


Senegal
18
16
14
12
10
8
6
4
2
0
-20
-15
-10
-5
0
Target Area A

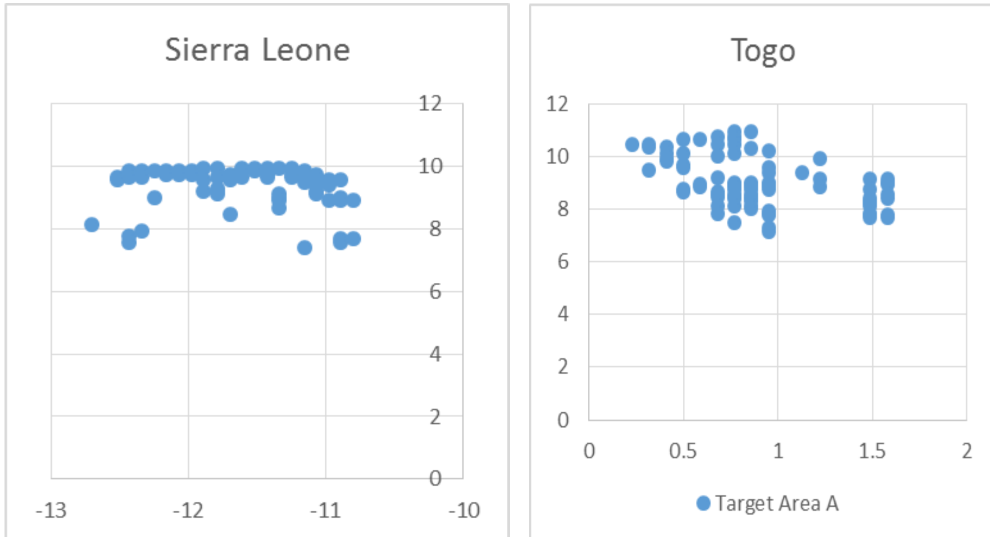


Figure 29. ECOWAS SHS target areas market simulation scatter plot results. (UNDESA, 2017).

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